


Operationalising positive tipping points towards global sustainability

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Review Article

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Non-technical summary. Transforming towards global sustainability requires a dramatic acceleration of social change. 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 and personal transport, but how can we 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-technological-ecological 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, altering social network structure, providing relevant information, reducing price, improving performance, desirability and accessibility, and coordinating complementary technologies. Actions that can trigger positive tipping include social, technological and ecological 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.

1. Introduction

A tipping point is where a small intervention leads 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 self-propelling and hard to reverse. 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 ‘negative’ 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 continuous, roughly 7% per year average global decline of greenhouse gas emissions from now on (Otto *et al.*, 2020a) exceeding 10% per year in advanced economies (Anderson, Broderick, & Stoddard, 2020). Hence, there is a growing consensus that some social actors need to identify and trigger ‘positive tipping points’ (or ‘sensitive intervention points’) to accelerate progress to achieve the required, transformative rates of change for everyone (Farmer

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et al., 2019; Jordan et al., 2010; Lenton, 2020; Otto et al., 2020a; 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' – meaning transformative changes in the identity and functioning of a complex system (here the Earth system) – long before humans evolved (Lenton & Watson, 2011). Several 'revolutions' in human history also appear unintentional, for example, the Neolithic revolution or the industrial revolution. These arguably hinged on changes in norms triggering reinforcing feedbacks, including innovation based on already-known technologies. Whether the social and technological innovators intended to revolutionise the world is unclear. 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. We define the goal of 'global sustainability' as the persistence of all components of the biosphere, including ensuring all humans have a quality of life beyond mere survival (Brown, Hanson, Liverman, & Merideth, 1987).

The emerging body of work identifying candidate 'positive tipping points' has recently focused on social-technological systems (or 'socio-technical systems') (Farmer et al., 2019; Otto et al., 2020a; Sharpe & Lenton, 2021) – that is, systems comprising interacting social and technological elements. However, earlier work identified multiple positive tipping points in social-ecological systems (Marten, 2005) – that is, systems comprising interacting social and ecological/natural elements. 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-technological-ecological systems – that is, systems comprising interacting social, technological and ecological elements (Ahlborg, Ruiz-Mercado, Molander, & Maser, 2019) – 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 in social-technological systems (Zeppini, Frenken, & Kupers, 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, Khosla, & Narayanamurti, 2020; Sharpe & Lenton, 2021). A much larger

set of previous socio-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, Kemp, & van Asselt, 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 (Sovacool, 2016). A synthesis of transitions theory and social movement theory may help elucidate how social innovations in niches – 'free social spaces' – can sometimes give rise to abrupt social mobilisations and construction of new political processes and structures (Törnberg, 2018).

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, Abson, & Lang, 2021; Meadows, 1999, 2008; Schlaile, Urmetzer, Ehrenberger, & Brewer, 2021). We focus on strengthening reinforcing positive 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 – but trying to instigate positive tipping points is all about putting some conscious 'intent' into social-technological-ecological 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 initial guidelines for those keen to trigger positive tipping points. Section 4 discusses an agenda for further research. Section 5 concludes.

2. Positive tipping points theory

First, we use integrative literature review (Torraco, 2016) to 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.

2.1 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

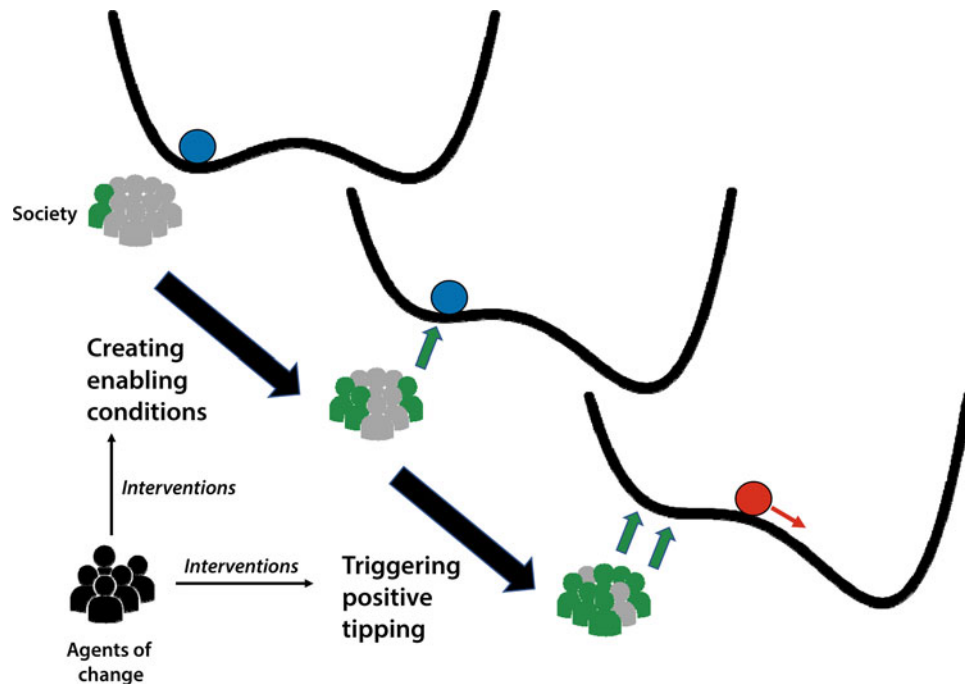


Fig. 1. A dynamical systems conceptualisation of positive tipping points.

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. Meanwhile, other actors argue the transformation needs to go even faster than that (Anderson et al., 2020). 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 (Smith & Christie, 2021).

The ‘Transitions Management’ literature argues that such systemic change is inherently slow, providing estimates ranging from >20 years for sustainable technology innovations (Gross, Hanna, Gambhir, Heptonstall, & Speirs, 2018), to ‘one generation or more’ for a socio-technical paradigm shift (Grin, Rotmans, & Schot, 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, Geels, & Sharpe, 2019) and there are past examples of rapid change (Sovacool, 2016). 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.

2.2 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, Tang, & Wiesenfeld, 1987). To bring a system to a tipping point typically requires some *forcing* – that is, 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 (noting that ‘control’ is meant mathematically and does not imply we can control such complex systems).

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. Whilst we can talk mathematically about ‘control’ variables, we cannot assume that such highly complex and interconnected systems can be ‘controlled’. Rather they may be ‘influenced’ to a limited extent, within particular (bounded) contexts of action or systems of reference. But it is meant to be viewed as a partial model of the key dynamics of tipping points, which helps agents within the system start to formulate interventions.

2.3 Existing tipping point models

We now turn to identifying different models of tipping points 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. In Figure 2, we schematically summarise and synthesise several of the different underlying tipping mechanisms, which we describe in the following sub-sections. 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.

2.3.1 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 population denoted in Figure 2 are shown at critical mass (the vertical dashed line) with those who have adopted shaded dark and those who have yet to adopt unshaded. 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. In Figure 2, we show the population (middle panel) and technology (bottom panel) following S-curves of adoption.

The original mathematical formulation of a critical mass tipping point was in a model of metropolitan segregation (Schelling, 1971).¹ It was later generalised 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). In Figure 2, this mechanism of contagion is shown with small arrows from one adopter to multiple others. Information, like diseases, can spread through simple contagion, only requiring contact with one other person to spread, whereas change of behavioural norms typically occurs through complex contagion requiring contact with multiple people (Centola & Macy, 2007). In Granovetter’s (1978) model, 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 – that is, people vary in the extent to which they are influenced by others. (In Figure 2, we denote the movable threshold for one individual who has just adopted.) 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 complex social contagion depends on the distribution of individual thresholds for adoption and on social network structure (Centola & Macy, 2007; Centola, Becker, Brackbill, & Baronchelli, 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, Gillingham, & Schultz, 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, for example, 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,² 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.

2.3.2 Increasing returns, coordination and herding

The positive feedback of *increasing returns* to adoption occurs when a behaviour or technology becomes more attractive (in quality or price) the more fellow users have already adopted it (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,

¹This connects back to the first use of ‘tip[ping] point’ (Grodzins, 1957).

²This supports interpretations of social-normative cohesion and competition for status (van den Bulte & Stremersch, 2004).

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, Mailath, and Rob (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)	Solar PV subsidies, hydrogen and fuel cell subsidies
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 and Johnsen (1991)	Renewable energy, energy storage and grid technologies
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 and resource level	Resource inflow, effort cost, ostracism strength	Lade et al. (2013)	Marine protected areas

1962); *economies of scale* – the more something is done/made, the more efficiently/cheaply it can be done/made (Bejan, Almerbati, & Lorente, 2017); and *technological reinforcement* – the more something is used, the more technologies emerge that make it more useful. In Figure 2, we denote the process of learning by doing in both technology developers (bottom panel) and the population of early adopters (middle panel) as an accumulation of knowledge about a new option in their minds as adoption proceeds – recognising that early adopters serve as early testers, providing feedback and helping in developing a solution. We denote economies of scale as a declining S-curve of price (bottom panel), mirroring the rising S-curves of adoption (middle panel) and quality/performance (bottom panel). We denote technological reinforcement as the cogs of core and supporting technologies coming together up the S-curve (bottom panel). A critical mass of adopters of a new technology can trigger a tipping point where increasing returns and associated adoption becomes self-propelling (middle panel). 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, McNerney, & Trancik, 2018), and of the batteries used in electric vehicles (EVs) (Nykqvist & 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 EVs and charging points compared to petrol/diesel cars and refuelling garages. The 'players' in such a 'game' could be technology developers, deployers or users. Accordingly, in Figure 2, we denote coordination as something spanning and connecting the realms of society and technology (as both people and technologies must be coordinated). The critical mass of coordinators required depends on the

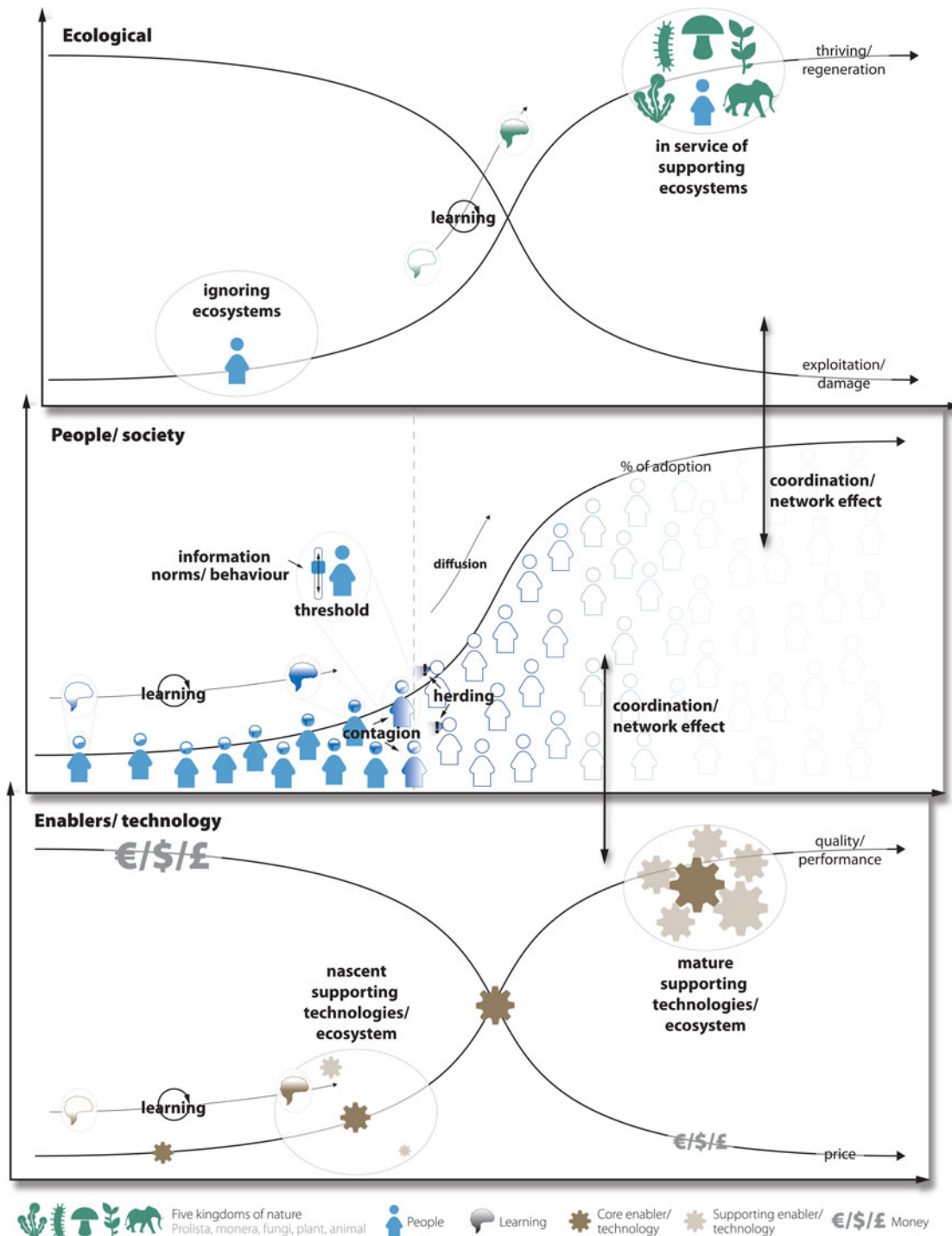


Fig. 2. Schematic synthesis of different mechanisms that can underlie positive tipping points across social-technological-ecological systems – explained in text Section 2.3.

benefit and cost of the new technology relative to the payoff for coordinating on an old technology suite (Zeppini *et al.*, 2014), where the benefits and costs of a new technology may be subject to positive feedbacks of increasing returns. A committed minority of ‘zealots’ can tip a contagious spread of cooperation (Masuda, 2012), which may also be sensitive to social network structure (Cardillo & Masuda, 2020). 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, Hirshleifer, & Welch, 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

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

(e.g. adopt a new technology) based purely on the behaviour of those before them, disregarding their own information. We denote this in Figure 2 (middle panel) as some of those about to adopt looking at and being influenced by those who have just adopted. 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, Genius, & Tzouvelekas, 2014).

A crucial question is in which fraction of the population is critical mass reached (Figure 2, middle panel)? 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 (Rogers, 1962), and for complex contagion ~25% of a population can tip a change in social convention (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.

2.3.3 Percolation, co-evolution and missing models

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

The spread of new norms or behaviours by information transfer through social networks can lead to a *percolation threshold* if people vary in their willingness to adopt (Solomon, Weisbuch, de Arcangelis, Jan, & Stauffer, 2000). Past such a tipping point, an innovation can diffuse throughout a networked population, whereas below it cannot (Zeppini et al., 2014). The percolation threshold can depend on the cost of adoption, the number of starting seeds from which the innovation spreads, and the network connectivity. 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 depend on other reinforcing feedbacks of, for example, 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).

Some observed social-technological tipping points are challenging to interpret through any of the above models, suggesting additional models may need to be developed. For example, a recent coal to gas tipping point in the UK power sector hinged on a change in their relative cost for power generation, which triggered withdrawal of investment from coal, and ultimately destruction of coal power stations (Sharpe & Lenton, 2021).

2.3.4 Tipping mechanisms involving ecology

Reinforcing feedbacks and co-evolution are of course not limited to the social-technological realm – they have a much longer history in the ecological realm. 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, Carpenter, Foley, Folke, & Walker, 2001). These are often called ‘regime shifts’ and there is a database of numerous examples (Biggs, Peterson, & Rocha, 2018). There are also many models of specific ecosystems and their specific tipping points. Most of the literature focuses on negative tipping points triggered by human activities, for example, lake eutrophication, but positive feedback can always operate in either direction. Positive tipping points towards preferred ecological states have been achieved, for example, 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, negative 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), sometimes described as ‘virtuous cycles’ (Morrison, 2016; Selman & Knight, 2006). For example, marine-protected areas rejuvenate fisheries causing people to create additional marine-protected areas (Mascia & Mills, 2018). Environmental stewardship improves reef ecology, enhancing social values and motivating further stewardship (Turnbull, Clark, & Johnston, 2021). 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 a state of over-exploitation of a common-pool resource (such as fish stocks) without human cooperation, and avoidance of over-exploitation through a cooperative social norm and social ostracism of non-complying harvesters (Lade, Tavoni, Levin, & Schlüter, 2013). In Figure 2 (upper panel), we capture positive tipping to a preferred social-ecological state as going up an S-curve, involving learning by doing, into a state in which humans and other species have positively reinforcing interactions. We denote

coordination spanning and connecting the realms of society and ecology, because people must coordinate with each other and must attune with other species in this form of positive tipping. Other generic models consider how tipping points in both social and ecological systems that are coupled interact (Mathias *et al.*, 2020), or how co-evolving environmental and strategy dynamics in the presence of an ecological tipping point can sometimes lead to persistent oscillations (Tilman, Plotkin, & Akçay, 2020; Weitz, Eksin, Paarporn, Brown, & Ratcliff, 2016).

Finally, there must be positive feedbacks where reinforcing changes in society, technology and ecology are all coupled together (hinted at by the interconnected nature of Figure 2). 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. We suggest the ‘green revolution’ would make an instructive historical case study where increasing population, food production and proliferation of new technologies all fed back to amplify each other. So too would contemporary initiatives co-opting ‘ecosystem engineers’ and utilising technology to trigger positive tipping in ecosystems harvested for food – such as blue mussel beds (Schotanus *et al.*, 2020).

2.4 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, von der Heydt, & Dijkstra, 2018; Klose, Karle, Winkelmann, & Donges, 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, Stirling, & Berkhout, 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).

3. Operationalising positive tipping points

Having reviewed and synthesised available models (Figure 2), we now outline a research agenda to operationalise positive tipping points (Figure 3). 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. We conceptualise operationalising positive tipping points in

three phases of action: creating enabling conditions; sensing the potential for positive tipping; and triggering positive tipping points. In each phase, changes already underway may be harnessed towards positive outcomes, and learning will be crucial to success. 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.

3.1 Identifying and creating enabling conditions for positive tipping points

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 system 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. However, 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, those are the factors affecting adoption and altering the value of the critical mass.

From the general models (Table 1, Figure 2) and from past examples, we have identified some key enabling conditions that may control positive tipping, depending on the context (Figure 3). We have sought to describe these in terms understandable to a wide range of practitioners. We offer them as a non-exhaustive list, proceeding from social to more social-technological variables, noting that ecological variables that can enable positive tipping tend to be context-specific (e.g. reducing nutrient loading of a eutrophic lake or reducing harvesting intensity of a fish stock).

3.1.1 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. More generally, a ‘sweet spot’ of population size for triggering action to scale Project Drawdown’s climate solutions has been identified at the community scale (~10,000 people) (Bhowmik, McCaffrey, Ruskey, Frischmann, & Gaffney, 2020). 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.

3.1.2 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). Weak ties across a social network can promote simple contagion but inhibit complex contagion (Centola & Macy, 2007). Complex contagion, for example, of social movements, benefits from clusters of strong local ties, hence efforts to trigger it could target tightly knit residential

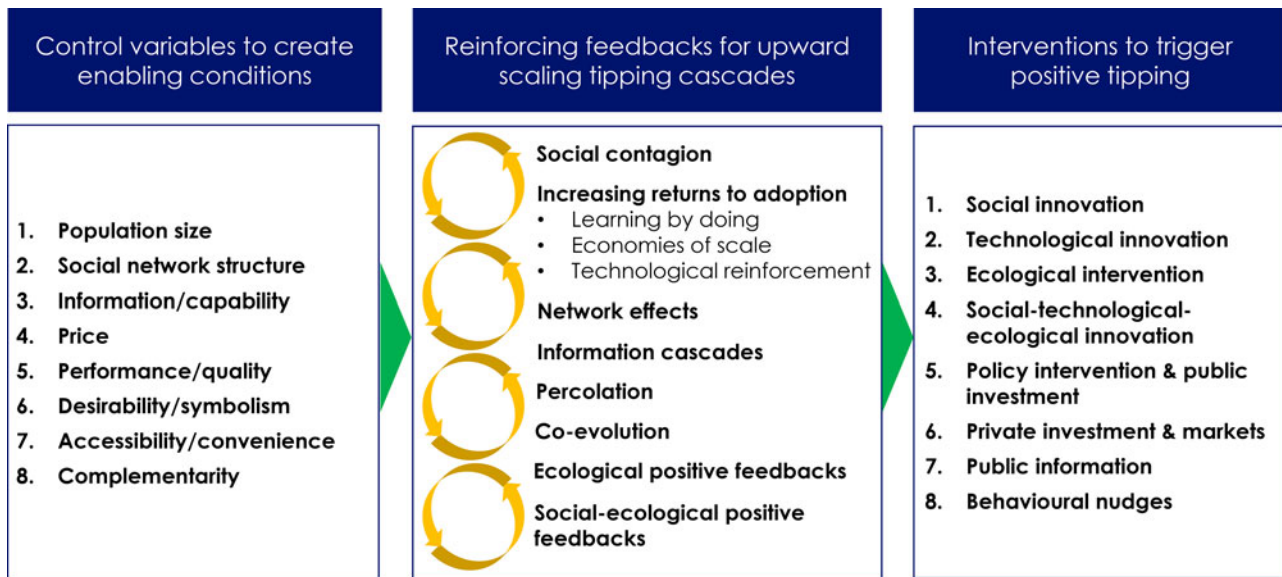


Fig. 3. Summary of framework for triggering positive tipping points.

networks (Centola & Macy, 2007) and committed minorities (Centola et al., 2018). Bottom-up social movements typically gestate in ‘free social spaces’ which protect them from mainstream society and generate new social networks that can be drawn upon to promote collective action (Törnberg, 2018). Hence supporting a diversity of such spaces within society should increase the potential for positive tipping. Clearly, context matters, but recognising the nature of a contagion phenomenon can help to draw out general rules.

3.1.3 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 scheme³ 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.

3.1.4 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, across Europe, where electric cars have reached purchase price parity with equivalent petrol/diesel cars – notably in Norway – this leads to a highly 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.

³<http://www.tist.org/welcome/>

3.1.5 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 – for example, 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.

3.1.6 Desirability/symbolism

A new alternative needs to be desirable to potential adopters, sometimes irrespective of price or performance, and may provide social distinction to owners – thus acting as a ‘positional good’ (valued because of its limited supply) (Hirsch, 1976). 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 – for example, 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.

3.1.7 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 systematically 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.

3.1.8 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.

Some innovations may change the structure of a system, not just the value of control parameters. For example, social network structure can be altered by changes in information technology, notably social media. By introducing new feedbacks this can alter the existence of tipping points, as well as proximity to them. For example, the climate protest movements appear to have reached a critical mass partly enabled by social media (Otto et al., 2020a). Technically, evolving structural change goes beyond the simple dynamical systems approach adopted above (Figure 1), but it is recognised in the leverage points framework.

3.2 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 to identify potential tipping points, as done for, for example, the Jordan River region (Rodríguez Lopez et al., 2019). This process can be aided by developing a system map, which involves drawing the interconnections and feedback loops in a system, and comparing the result to known system ‘archetypes’ (Stroh, 2015). Here this means looking for strong reinforcing feedback loops and the controls on them. We have been co-creating such a systems map in the lead author’s home city, utilising the ‘kumu’ software platform, as part of initiating an ‘Exeter living laboratory’.⁴ This is the start of developing a participatory model of a specific system. Additional exploration of different visions of a city’s future through software such as ‘Visionmaker’⁵ could help converge on a shared vision for positive tipping. Participatory methods such as citizens’ assemblies and juries could both help sense the potential for positive tipping and reach resolutions for action to try and trigger it. Once multiple examples are available for different systems then one can look for (and learn from) examples of comparable systems elsewhere that have tipped (Sharpe & Lenton, 2021).

⁴<https://kumu.io/james543/exeter-living-lab>

⁵<https://visionmaker.us/nyc/>

The next step may be to formalise a mathematical model of a specific system, as a tool for experimentation and learning. 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). For social contagion, one can retrospectively look at the distribution of individual thresholds within a population that has tipped. Then accounting for some uncertainty and variability, one can 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, Nikiforakis, & Siegenthaler, 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 experimental 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, Reese, & Obersteiner, 2019). Or an agent-based model that reveals the degree of intervention needed for positive tipping to cooperation over groundwater management in different national contexts (Castilla-Rho, Rojas, Andersen, Holley, & Mariethoz, 2017). More specific models have examined, for example, the role of reinforcing feedbacks in achieving a green growth trajectory for the EU (Tàbara et al., 2013), the conditions for a UK tipping point in EV uptake (Shepherd, Bonsall, & Harrison, 2012), or city scale reinforcing feedbacks between solar PV power and EVs (Shepero, Munkhammar, Widén, Bishop, & Boström, 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 the 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, Hommes, & Wang, 2019) 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, for example, EVs or alternative proteins, are getting more resilient (i.e. decaying more slowly) over time. Equally, the potential for tipping public values, attitudes and opinions may be sensed by looking at the strength of sentiment and its decay rate for particular topics in social media. This might be further explored by the deliberate experimental introduction of social media messages. 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.

3.3 Who and how to tip positive change?

What actions, by whom can create different types of positive tipping? Actions that trigger a tipping point, by definition, can be very small right at the tipping point, but variable amounts of effort may be needed to create the enabling conditions (Section 3.1) and to sense the potential for positive tipping (Section 3.2).

3.3.1 Who?

We should all feel a sense of agency and autonomy to be part of tipping positive change – and this includes collective and strategic agency as well as individual and everyday agency (Otto et al., 2020b). Indeed, reinforcing feedbacks can overturn conventional notions of who has power – witness the school strike movement. That said, different actors (and coalitions of 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 and coalitions that can be involved in sustainability transitions (Farla, Markard, Raven, & Coenen, 2012; Smith & Christie, 2021), 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 (Smith, Christie, & Willis, 2020). Researchers and technological innovators are the creators of novel alternatives and entrepreneurs can help propel their upscaling. Citizens are key to the uptake of alternative behaviours and products. Firms can actively engage in innovation trajectories and help build an innovation ‘ecosystem’ that learns by doing (Khoo, 2018). 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. Coalitions between different types of actor – united by common interests, ideas or values – can be key to triggering sustainability transitions, because rarely does a single actor have the necessary resources and usually there are other actors opposing transformation (Roberts et al., 2018). A historical example is the coalition of doctors and engineers that helped trigger the transition in wastewater management from cesspools to sewers in the Netherlands (Geels, 2006). More recently, a coalition from academia, NGOs and local constituencies started a ‘new water culture’ movement that triggered policy change in Spain’s Ebro river basin (Tàbara & Ilhan, 2008).

3.3.2 How?

Tipping points can be triggered by different types of intervention from different actors and coalitions. 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. From integrative literature review and past examples, we offer a non-exhaustive list of actions to trigger positive tipping (Figure 3), linked to particular actors and coalitions. We start by considering innovation within the social, technological and ecological realms, and across them (Figure 2), before turning to public and private institutions and capital, and changing information:

Social innovation: Coalitions of committed actors can tip complex social contagion, for example, protest movements that in turn trigger political change (Kuran, 1989; Smith et al., 2020). 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 crowdsourcing, radical transparency and leaderless structures (Heimans & Timms, 2019).

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.

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 engineers’ 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 amounts of carbon from the atmosphere.

Social-technological-ecological innovation: Innovations in social-ecological systems (Olsson & Galaz, 2012) can trigger positive feedback(s) in a desired direction (Marten, 2005; Pereira, Drimie, Maciejewski, Tonissen, & Biggs, 2020a). For example, feeding schoolchildren in Kenya boosted community agroforestry (Borish, King, & Dewey, 2017). Recreation of earthen dams to trap monsoonal rains in Rajasthan, refilled aquifers, supporting dry-season irrigation, successful cash crop production and community rejuvenation.⁶ Social-technological innovations can also create virtuous cycles. For example, the Net-Works partnership between a business and a charity has created a supply chain that engages coastal communities in the Philippines and Cameroon in collecting and selling discarded fishing nets, which are recycled into nylon yarn for carpet manufacture (Khoo, 2018). This also

⁶<http://ecotippingpoints.com/our-stories/indepth/india-rajasthan-rainwater-harvest-restoration-groundwater-johad.html>

benefits ecology because abandoned fishing nets can continue to trap marine life. Such innovations have the potential to trigger positive 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 and communication technologies (ICT) in a way that makes social network structures more amenable to tipping. The Internet began through government-funded research (Leiner *et al.*, 2009), and ongoing investment in ICT has sometimes had unintended consequences – for example, contributing to the loss of a 40-year monopoly on power in Malaysia (Miner, 2015). 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, Mills, & Verissimo, 2020). The movement from anonymous global food supply chains to food labelling and certification has triggered a shift to alternative food networks (Pereira *et al.*, 2020a). Equally, educational campaigns to expose and counter 'discourses of climate delay' could weaken these well-funded and well-organised negative feedbacks that oppose transformational change (Lamb *et al.*, 2020).

Behavioural nudges: 'Behavioural nudges' – and 'hyper-nudges' using big data (Yeung, 2017) – subtly editing the choice architecture for 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). However, 'green nudges' have variable effectiveness (Schubert, 2017), small levies on single-use plastic shopping bags have had variable effects (Nielsen, Holmberg, & Strippel, 2019; Rivers, Shenstone-Harris, & Young, 2017), and nudging can sometimes trigger shifts in the unintended (less sustainable) direction (Zorell, 2020).

4. Discussion

We have tried to synthesise and operationalise knowledge 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-technological-ecological systems. A first application of the framework to food and land system transformations is the subject of a separate report (FOLU/GSI, 2021). Looking ahead, the coupled dynamics of social-technological-ecological systems including their potential positive tipping points is a key target for research. So too is considering how intentional change is initiated (Smith *et al.*, 2020), particularly the role of coalitions of shared interest (Victor *et al.*, 2019), and how different agents and interventions can most effectively work together to create system-wide positive tipping points (Stadelmann-Steffen, Eder, Haring, Spilker, & Katsanidou, 2021). For example, through systems entrepreneurship (Schlaile *et al.*, 2021), policy packaging (Fesenfeld, Wicki, Sun, & Bernauer, 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. The 'Breakthrough Agenda' launched at COP26 puts such thinking into action with leaders of countries covering 70% of world GDP committing to work together to trigger positive tipping points in each emitting sector.⁷ 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). At a higher-level of synthesis, a transdisciplinary horizon scanning exercise could consider which systems are ready for tipping, which are not but need to be, and what past case studies can tell us about tipping pathways. Some actors are more attuned to the type of thinking outlined herein than others and may be natural instigators (e.g. '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. Perceived injustices can be a trigger of tipping. For example, in Chile a small increase in public transport fares in Santiago triggered a social outburst (*Estallido Social*) ultimately leading to constitutional change. Conversely, 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, 2021; Sovacool, 2021; Winkler, 2020).

⁷<https://ukcop26.org/cop26-world-leaders-summit-statement-on-the-breakthrough-agenda/>

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 et al., 2020b) 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.

5. 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, altering social network structure, providing relevant information, reducing price, improving quality/performance, increasing desirability, increasing accessibility and coordinating complementary technologies. Actions that can trigger positive tipping include social innovation, technological innovation, ecological intervention, social-technological-ecological 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, to ensure positive tipping points are aligned with a just transformation, and to link theory of positive tipping points to empirical studies, to enrich both theory and practice. But there is no better way forward than to learn by doing. Continuing to delay action to accelerate a just 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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