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Climate change induced socio-economic tipping points: review and stakeholder consultation for policy relevant research

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Abstract

Tipping points have become a key concept in research on climate change, indicating points of abrupt transition in biophysical systems as well as transformative changes in adaptation and mitigation strategies. However, the potential existence of tipping points in socio-economic systems has remained underexplored, whereas they might be highly policy relevant. This paper describes characteristics of climate change induced socio-economic tipping points (SETPs) to guide future research on SETPS to inform climate policy. We review existing literature to create a tipping point typology and to derive the following SETP definition: a climate change induced, abrupt change of a socio-economic system, into a new, fundamentally different state. Through stakeholder consultation, we identify 22 candidate SETP examples with policy relevance for Europe. Three of these are described in higher detail to identify their tipping point characteristics (stable states, mechanisms and abrupt change): the collapse of winter sports tourism, farmland abandonment and sea-level rise-induced migration. We find that stakeholder perceptions play an important role in describing SETPs. The role of climate drivers is difficult to isolate from other drivers because of complex interplays with socio-economic factors. In some cases, the rate of change rather than the magnitude of change causes a tipping point. The clearest SETPs are found on small system scales. On a national to continental scale, SETPs are less obvious because they are difficult to separate from their associated economic substitution effects and policy response. Some proposed adaptation measures are so transformative that their implementations can be considered an SETP in terms of 'response to climate change'. Future research can focus on identification and impact analysis of tipping points using stylized models, on the exceedance of stakeholder-defined critical thresholds in the RCP/SSP space and on the macro-economic impacts of new system states.

1. Introduction

In climate change research and communication, the concept of tipping points has received much attention. In the natural sciences, it articulates conditions at which the state of complex systems can abruptly alter as a result of small perturbations (Russill and Nyssa 2009). Concerns have been expressed about passing critical thresholds of large-scale elements of the climate system (Lenton *et al* 2008, Steffen *et al* 2018), although there is high uncertainty about the temperature thresholds at which these events occur (Kriegler *et al* 2009, Levermann *et al* 2012). Even small changes in climatic conditions can tip ecological systems to alternative states which can be hard to reverse (Scheffer and Carpenter 2003). Beyond the natural sciences, the notion of adaptation tipping points is used to assess under what conditions policies are no longer able to achieve their objectives, requiring additional action (Kwadijk *et al* 2010, Haasnoot *et al* 2013, Werners *et al* 2013). In the transformation and transition literature, tipping points indicate transformative changes in adaptation or mitigation strategies (Wise *et al* 2014, David Tàbara *et al* 2018, Farmer *et al* 2019). Besides their scientific use, tipping points have become a popular metaphor to communicate climate change impacts and their far-reaching consequences to a wider audience (Russill and Nyssa 2009, van der Hel *et al* 2018).

Various studies have given an overview of tipping points in environmental systems, such as the climate system (Schellnhuber *et al* 2006, Lenton *et al* 2008, Levermann *et al* 2012), ecological systems (Scheffer and Carpenter 2003) and the universal warning signals these systems exhibit (Scheffer *et al* 2009, Ratajczak *et al* 2018). These studies have a strong focus on the biophysical sphere, and only incidentally touch upon the socio-economic. There is an emerging field on tipping points in coupled socio-ecological systems (Milkoreit *et al* 2018, Reyers *et al* 2018). Here, a tipping point is defined as: '*a threshold at which small quantitative changes in the system trigger a nonlinear change process that is driven by system-internal feedback mechanisms and inevitably leads to a qualitatively different state of the system, which is often irreversible*' (Milkoreit *et al* 2018, p 11). However, in nearly all studies on coupled socio-ecological systems, the regime shift is located in the ecological rather than the socio-economic domain (Filatova *et al* 2016). In line with this observation, several authors have identified a lack of studies on tipping points in the socio-economic domain, whereas they might be highly policy relevant in the context of climate change (Filatova *et al* 2016, Kopp *et al* 2016, Biggs *et al* 2018, Kabir *et al* 2018, Milkoreit *et al* 2018).

The objective of the paper is therefore to help to fill this gap and describe the characteristics of climate-induced socio-economic tipping points (SETPs), in order to guide future research on assessments of these SETPs for informing adaptation and mitigation policy. We do so in three steps. First, we conduct a literature review to create a typology of different branches of the tipping point literature and to define and characterize the SETPs in the perspective of this literature (section 3). Second, we report on a stakeholder consultation that was undertaken to identify examples of SETPs with policy relevance on a European scale and to explore their characteristics (section 4). Third, based on the literature review and stakeholder consultation, we provide suggestions for future research on the assessment of societal impacts of SETPs in order to inform adaptation and mitigation policies (sections 5 and 6).

2. Methods

This paper combines two methods: literature review and stakeholder consultation.

2.1. Literature review

The literature review was structured along two criteria emerging from existing review articles (table SI 1.1 available online at stacks.iop.org/ERL/15/023001/mmedia):

(1) The type of systems on which the tipping point concept is applied: e.g. physical, biological and social systems, which is a major source of discussion on tipping point definitions (Russill and Nyssa 2009, Russill 2015).

(2) The characteristics of tipping point definitions: e.g. stable states, abruptness, feedbacks and limited reversibility (Milkoreit *et al* 2018).

We searched *'Tipping Point*' AND 'Climat* Chang*'* in the Web-of-Science core collection database ($n = 508$) (table SI 1.2), enriched by forward and backward citation tracking. To address criterion 1, this literature was positioned in a diagrammatic representation of systems exhibiting tipping points (figures 1, 3), after Barker (2003). To address criterion 2, after Milkoreit *et al* (2018), three qualitative questions were answered for each branch of literature: (1) *How are system states distinguished*? (2) *What is the role of mechanisms underlying state stabilisation and shifts*? (3) *How is abruptness or nonlinearity defined*? In addition, the purpose and policy relevance of each branch were addressed. The review process methodologically followed Berrang-Ford *et al* (2015), see the supplementary information, SI 1. This supplement also contains an overview of model approaches used in studies describing climate-induced tipping points in socio-economic and coupled socio-ecological systems (table SI 1.3).

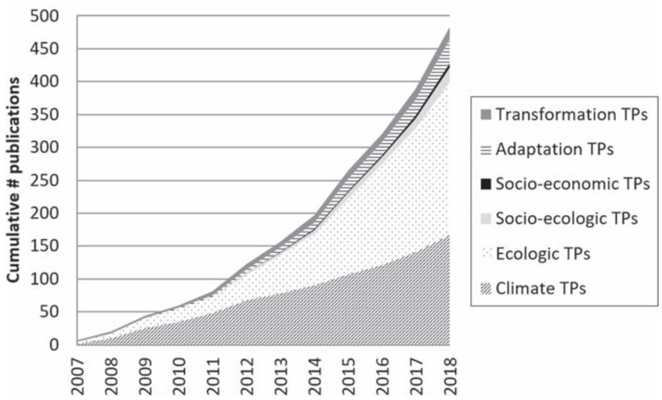


Figure 1. Development of different branches of tipping points (TPs) literature included in the web-of-science core collection database (from 1 January, 2007, until 31 December, 2018).

2.2. Stakeholder consultation

To derive an overview of policy relevant tipping points in Europe, we organized a stakeholder workshop and carried out 28 additional semi-structured interviews resulting in a list of 22 SETP candidate examples (table SI 2.1). The whole process followed a co-design and co-delivery protocol and used a set of research co-production success factors identified from the literature (Watkiss *et al* 2018). 24 stakeholders attended the workshop, representing a variety of sectors in Europe, including health, finance, public governance, tourism, agriculture, transport, insurance and nature conservation. Workshop attendants were divided in five thematic groups (table SI 2.2). Each group was asked to draw an inventory of SETPs in their sector, followed by a discussion on causal mechanisms. Similarly, the 28 semi-structured interviews (table SI 2.3) were used to identify SETP examples, to get insight in the mechanisms leading to their occurrence and to learn about past experiences and policy recommendations (table SI 2.4).

3. Literature review results: types of tipping points

We identified four branches of tipping point literature, that are further explained below (sections 3.1–3.4) and summarized in table 1. In section 3.5, we create a synthesis and typology of these, to define SETPs in section 3.6. The literature on biophysical tipping points is most substantial in size, the other branches are smaller (figure 1).

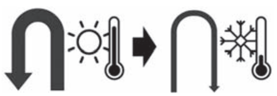
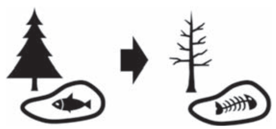
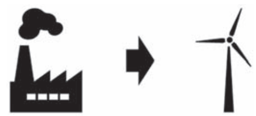
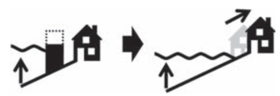
3.1. Climate tipping points

Climate tipping points describe critical thresholds at which large-scale components of the Earth's climate system, at least sub-continental in scale, switch to a qualitatively different state due to a small perturbation (Lenton *et al* 2008). The classic example is the potential collapse of the North Atlantic deep water formation and the associated Thermohaline Circulation (THC): an ocean current mechanism which is a key determinant of the global climate (Steflen *et al* 2004). Other examples are: the self-amplifying melting of the West-Antarctic and Greenland ice-sheet, sea-ice melt in the Arctic, and state changes in the El-Nino Southern Oscillation (Levermann *et al* 2012, Lenton 2013).

Concerning stable states (characteristic 1 in table 1), early models of the THC described two clearly distinguished stable flow regimes and critical transitions (or bifurcations) between them (Stommel 1961, as cited by Lenton 2013), although there is still a debate on whether unambiguous stable states can be distinguished (Caesar *et al* 2018, Thornalley *et al* 2018, Nature Editorial 2018). The mechanisms (characteristic 2 in table 1) causing different stable states, as well as abrupt transitions between states, are reinforcing and dampening feedback processes in the climate system leading to nonlinear system behaviour. Abruptness (characteristic 3 in table 1) can be understood in two ways: change is rapid compared to a geological timescale or rapid compared to a policy-relevant time horizon, such as 100 years (Lenton *et al* 2008, Kopp *et al* 2016).

The policy relevance of climate tipping points is mainly to inform about safe levels of climate change with respect to temperature stabilisation. Climate tipping points seem to have played a crucial role in the history of the Earth, and therefore, they also might have large impacts on current societies (Lenton 2013). This is for example reflected in the IPCC Fifth Assessment Report (IPCC 2014b)—with 'large singular events' as one of the 5 'reasons for concern' and in the IPCC 1.5 °C-warming report (IPCC 2018). They also have been used as major justification for ambitious mitigation policies (Knutti *et al* 2016, Lemoine and Traeger 2016), such as the European Union Long-Term Strategy (EC 2018). Framing of climate tipping points is predominantly negative. They are often seen as being beyond the limits of adaptation (Watkiss *et al* 2015), so they can only be addressed by insurance-like mitigation (Weitzman 2014).

Table 1. Characteristics of tipping points in four branches of literature.

Characteristics	Climate tipping points	Ecological tipping points	Transformation tipping points	Adaptation tipping points
				
Stable states (from state A to state B)	Qualitatively different states of a large component of the earth's climate system (A: strong ocean current; B: substantially weakened ocean current)	Distinct dynamic regimes of an ecosystem (A: oligotrophic lake state—'good' water quality; B: eutrophic lake state—'poor' water quality)	Shift in uptake of ideas, technology etc. (A: idea, technology or behaviour only for a small minority of 'early adaptors'; B: embraced by many people, on macro-level)	Formal or informal objective/performance threshold is exceeded, requiring a change in action (A: strategy 1; B: fundamentally different strategy 2)
Mechanisms	Internal system feedbacks explaining state changes as well as stabilisation	Internal system feedbacks	Diverse, mostly market mechanisms driven by human behaviour	Crossing acceptability, technical or economic threshold
Abruptness	Rapid on geological timescale and potentially relevant on a policy-relevant timescale	Rapid compared to typical change in the ecosystem	Rapid change compared to normal uptake of ideas or behaviour	Rapid change of policy or action
Other	Irreversible from human perspective Negative framing: to be avoided	Hysteresis: restoring original state through different trajectory	Positive framing: to be achieved	Can be used to construct adaptation pathways to meet objectives under changing conditions

3.2. Ecological tipping points

The second branch of literature is *ecological tipping points,* better known as 'critical transitions' causing 'regime shifts' in biological or ecological systems (Scheffer and Carpenter 2003, Biggs *et al* 2018). This branch of literature is much wider than climate change discourse alone, but here, we focus on climate related examples. For example, increasing temperature and nutrient concentrations can tip lakes into eutrophic states (Scheffer *et al* 2015). Climate change could potentially cause drought-induced vegetation shifts, such as desertification in the Sahara (Martínez-Vilalta and Lloret 2016). Increasing CO_2 concentrations may shift coral reefs to entirely different ecosystems (Hoegh-Guldberg *et al* 2007, Marzloff *et al* 2016, IPCC 2018). These systems often exhibit hysteresis: turning back to the original state is usually not possible by simply reversing the conditions (de Zeeuw and Li 2016).

Concerning stable states, the literature emphasises that the term 'dynamic regimes' would be more appropriate, because ecological systems are hardly ever completely stable in the sense that no fluctuations occur (Scheffer *et al* 2001). Concerning mechanisms, Van Nes *et al* (2016) distinguish two ways in which an ecosystem can be tipped to an alternative state. The first mechanism is erosion of system resilience. Normally, a small perturbation would have been within the coping capacity due to system resilience, but with the resilience eroded, it can cause a state shift. This highlights that many causal factors may have contributed before a perturbation in one variable causes the actual tipping to occur and these could have additive or even synergistic interactions (Scheffer and Carpenter 2003, Ratajczak *et al* 2018). The second mechanism is an unusual large perturbation in one driver which on its own pushes the system over a critical point, from which it cannot return (Van Nes *et al* 2016). This literature emphasises that internal system-feedbacks play a determining role in both the stabilisation and the rapid change between different dynamic regimes (Scheffer *et al* 2001). The clearest examples of tipping points are found in small-scale, heterogeneous and strongly interconnected systems (Scheffer *et al* 2012). Abruptness is defined as rapid change compared to typical rates of change in the ecosystem (Ratajczak *et al* 2018).

The policy relevance of this literature is that it gives insights as to how a desired state of an ecosystem can be maintained or achieved by describing a 'safe operating space' (Scheffer *et al* 2015). For instance, preventing tipping points in iconic ecosystems such as coral reefs received major attention in the recent 1.5 °C-warming report (IPCC 2018). Monitoring and early warning systems can be useful to indicate when ecosystems approach a tipping point, noting these are also relevant for climate tipping points (Scheffer *et al* 2009, Wang *et al* 2012, Camarero *et al* 2015, Clements and Ozgul 2018).

3.3. Transformation or transition tipping points

Whereas the above literature mainly draws on complex dynamic systems theory, the literature about *transformation tipping points* is more qualitative and descriptive, i.e. closer to Gladwell's (2000) popular understanding of tipping points. The roots of this literature are in innovation and change theory (Rogers 1962) which studies why and how ideas and trends spread. It seeks to build on these mechanisms to deliver transitions in society that meet the adaptation and mitigation challenges posed by climate change (Loorbach and Rotmans 2006, Moser and Dilling 2007, van der Brugge 2009).

Distinction of clear stable states is emphasised less in this body of literature. The tipping point is an approximate indicator of the point separating a state A, in which a new strategy, behaviour, idea or technology is only adopted by a minority of early adopters, from a state B, in which it is adopted by a large majority (Loorbach and Rotmans 2006, Moser and Dilling 2007, Patenaude 2011, Sperling 2018). Others define states as institutional settings with different actors and altered actor networks (Westley *et al* 2011, Fuchs and Thaler 2017). In contrast to the biophysical literature, this literature mainly talks about so-called 'positive tipping points' (David Tàbara *et al* 2018): the envisioned state B is more desirable than the current state A. One difficulty here is that only in retrospect, it is possible to properly describe shifts as being radical (Fuchs and Thaler 2017). Another complication is that these descriptions are subjective; whereas transformative change may pose opportunities for some stakeholders, it may be destructive for others, in particular those that depend on the established system (Young 2012).

The mechanisms that could cause a shift towards a 'fundamentally improved state' (Burch *et al* 2017) are diverse (Farmer *et al* 2019). In the mitigation domain, these could include policy instruments or market forces (EC 2018, Mercure *et al* 2018) as well as financial thresholds for competing technologies (IRENA 2018). However, it can also arise via other means. Westley *et al* (2011) highlight how institutional entrepreneurs can lower the threshold between the current and the envisioned state, causing tipping to occur. Geels and Schot (2007) articulate that slowly changing drivers may put pressure on an existing regime, so that at a certain point a window of opportunity may cause a breakthrough of a niche innovation. The policy relevance of this literature is that it gives insights into how governments could formulate policies and incentives in order to achieve successful change towards societies that embrace adaptation and mitigation strategies. It provides checklists for the design of 'transformative-oriented' climate policy (David Tàbara *et al* 2019, Fazey *et al* 2018).

3.4. Adaptation tipping points

The fourth branch is the climate adaptation literature. Here, *adaptation tipping points* indicate thresholds where the magnitude of climate change causes an adaptation action to fail in meeting key performance indicators, policy or management objectives (Kwadijk *et al* 2010). The origins of this branch are in the adaptation decision support literature and in particular the focus on decision making under deep uncertainty (Walker *et al* 2013, Ray and Brown 2015, Watkiss *et al* 2015). This field studies exceedance of threshold conditions under different futures using exploratory modelling approaches such as robust decision making (Hall *et al* 2012) and scenario discovery (Bryant and Lempert 2010). One of these adaptation decision support approaches is 'dynamic adaptive policy pathways', developed as a scenario-neutral approach to policy making (Haasnoot *et al* 2013). In order to illustrate these pathways using adaptation route-maps, the approach uses tipping point terminology to indicate the 'best-before' dates of policy actions for meeting a plan's objectives. It is best known from coastal and water management applications such as the Dutch Delta Program (Bloemen *et al* 2018) and the London Thames Estuary project (Ranger *et al* 2013), but has also been applied to other sectors including agriculture and forestry (Petr *et al* 2015, Prober *et al* 2017).

State descriptions of performance of actions across the pathway are binary: they either meet objectives (state A) or fail (state B). Descriptions of these thresholds can be formal, such as standards or laws, or informal, based on acceptability thresholds as assessed by stakeholders. In climate adaptation studies, the mechanism causing an 'adaptation tipping point', i.e. the exceedance of the threshold, is a change in climate conditions (e.g. sea-level rise (SLR), river discharge), causing a certain action or portfolio of actions to fail. Although this is a sudden and therefore an obvious nonlinear and abrupt switch, it does not necessarily correspond to a nonlinearity in the physical or socio-economic domain, nor does it have to be the result of internal feedback mechanisms for state stabilisation and change (Werners *et al* 2013, Kopp *et al* 2016). However, some shifts in adaptation actions are so transformative in nature that they could qualify as tipping points consistent with the other branches of literature. This is, for instance, explicitly recognised in the IPCC AR5 with the explicit definition of 'transformational' versus 'incremental' adaptation (Kates *et al* 2012, IPCC 2014a).

3.5. Synthesis and typology

Based on the above analysis of the tipping point literature, we propose the following typology of tipping points for climate change (figure 2). The state shifts have different positions in the cause-effect chain from climate change to adaptation and/or mitigation, as shown in figure 3. *Climate tipping points* highlight that increasing greenhouse-gas concentrations may trigger strong nonlinear responses of large elements of the climate system. *Ecological tipping points* may have climate change as one of their drivers, and describe cases that lead to state shifts in ecological systems. For both, the state shifts occur in the biophysical system. *Transformation tipping points* reflect radical changes in human response to the impacts or challenges of climate change, and can lead to different mitigation or adaptation strategies, while also some of the *adaptation tipping points* reflect climate-induced exceedance of criteria or policy thresholds requiring transformative adaptation. Note that the literature explicitly mentions adaptation tipping points, but not mitigation tipping points. This notwithstanding the ample research addressing the huge technological and behavioural changes implied by decarbonisation pathways leading to a 2 or 1.5 °C warming world. Transformational response, encompassing adaptation and mitigation, describes shifts in terms of climate action (by policy makers, private companies or individuals). We thus summarize *adaptation* and *mitigation tipping points* under the umbrella of *transformational response to climate change,* resting in the socioeconomic domain (figure 2).

Note that we contrast these tipping points in terms of *transformational response* (figure 3, top-right) with tipping points in terms of socio-economic *impact* (figure 3, bottom-right). Although both occur in the socio-economic system, the state shifts result from different mechanisms. Impact refers to cases where a state shift occurs in the socio-economic structure due to autonomous climate change and inaction or insufficient action from the human side. Response refers to cases where the socio-economic structure is deliberately and fundamentally altered, or planned to be altered, by human action, in anticipation or response to (potential) impacts (see Kates *et al* 2012). Also, an abrupt shift in response (such as a global carbon tax) may take a long time before it materializes in socio-economic benefits, whereas the consequences of an impact tipping point may directly hit the economy. In summary, SETPs encompass socio-economic impact tipping points, adaptation tipping points and mitigation tipping points.

3.6. Defining climate change induced SETPs

From the above exploration, we are now ready to define a *climate change induced* SETP. It is 'a climate change induced, abrupt change of a socio-economic system, into a new, fundamentally different state (beyond a certain threshold that stakeholders perceive as critical).' These have the following characteristics: (1) *Stable states:* substantially different, more-or-less stable states or dynamic regimes at either side of some critical threshold. This distinction can be made qualitatively: showing by narrative how state A is

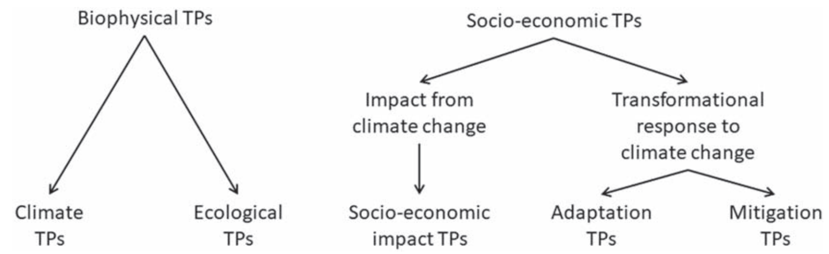


Figure 2. Typology of tipping points (TPs).

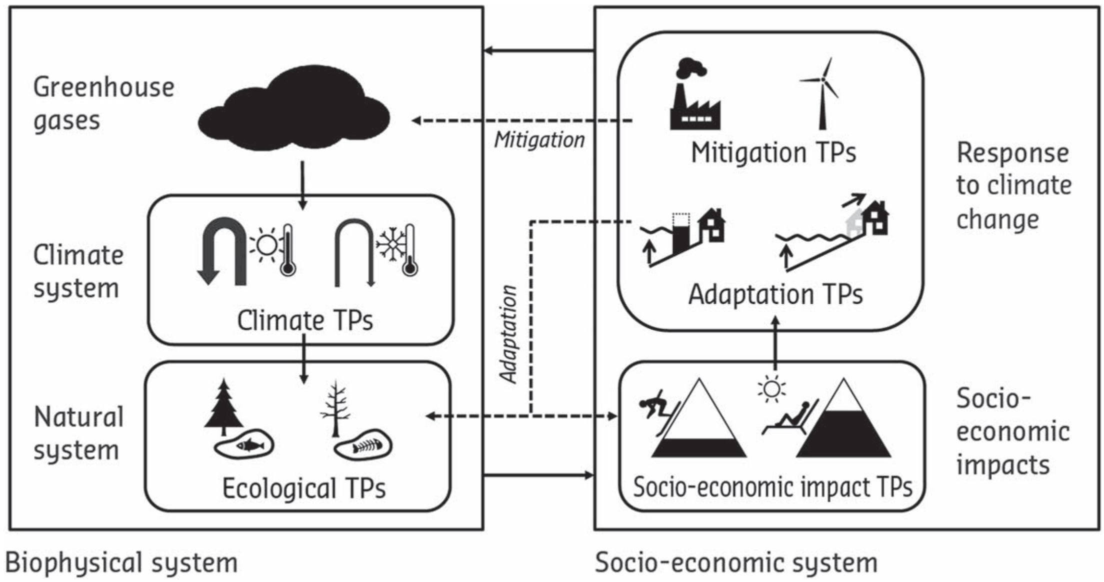


Figure 3. Diagrammatic representation of climate change, adaptation and mitigation showing the position of tipping points (TPs) (system blocks freely after Barker 2003, following IPCC AR3) Arrows indicate the archetypical cause-effect chain from increasing greenhouse concentrations (left-top) which change the climate system (left-middle) and the state of ecosystems (left-bottom). Biophysical changes in turn have an impact on the socio-economic system (right-bottom) and evoke a response of human actors (right-top) who may try to counter climate change (mitigation-arrow) or prevent it from having an impact (adaptation-arrow).

fundamentally different from state B, or quantitatively: showing an S-shaped nonlinearity between climate drivers and socio-economic indicators. (2) *Mechanism explaining nonlinear behaviour*. One should be able to provide a rationale—e.g. a causal pathway—on why these states are more or less stable and why there is a sudden transition between the two. (3) *Rapid, abrupt change.* The state change should be rapid compared to the change usually observed in the system. Additionally, for the scope of this paper we look for policy relevant examples where climate change is a significant driver of the tipping point. Also, we focus on impact SETPs (rather than transformational response SETPs), because these seem to have least coverage in the existing literature.

4. Stakeholder consultation results: SETP examples in Europe

Stakeholder consultation identified 22 potential SETPs with policy relevance for Europe (table SI 2.1). Most frequently mentioned during the workshop (5 of 5 groups) was migration towards Europe, due to adverse climate change impacts in other continents. Most groups (3 of 5) also mentioned the reconfiguration of the energy network due to the demand for renewable energy. Other EU-wide examples were: the introduction of new vectors causing the outbreak of diseases; extreme heat mortality and labour productivity impacts due to increasing temperatures; and cascading impacts of road network and supply chain disruptions due to floods. Most of the examples had adverse consequences (20 of 22); only the business group came up with opportunities arising from climate-induced market reconfigurations. In general, the workshop attendees thought about tipping points as large-impact events such as economic shocks and were less concerned with the underlying system dynamics (nonlinear behaviour, feedbacks, threshold effects etc). Intentionally, the setting was one where stakeholders should not be restricted by any concise SETP definition and resulted in a comprehensive collection of concerns. Consequently, not all the introduced examples exhibit all tipping point

Table 2. Characteristics of selected climate-induced socio-economic tipping points.

Characteristics\case study	Collapse of low-altitude ski resorts	Farmland abandonment and collapse of agricultural sector	Coastal retreat due to sea-level rise
Stable states (from state A to fundamentally different state B)	A: resort is profitable in most years; B: resort is not financially viable to maintain	A: farming is profitable, lively rural community; B: farmland is abandoned and rural area inhabited declines	A: high exposure of population and assets; B: low exposure
Mechanism (that explains state stability and non-linear transitions)	A series of unfavourable snow years (and rising snow machine costs) reduces profitability with depletion of financial reserves	Reduced productivity and water limits cause supply and price shocks and makes farming unprofitable; causing land abandonment and rural decline (feedback loop)	Forced displacement or relocation after a coastal disaster
Abruptness (rapid change compared to usual timescales of change)	The decision point to stop operations (including bankruptcy) could be very sudden, following an individual unfavourable year	High intensity or frequent droughts could trigger or accelerate this process	Displacement and relocation following a disaster are abrupt (in contrast to slow-onset migration)
Key insights	Reversibility: in the short term, some resorts are successfully reopened; in the long term, snow line shift is irreversible (but increased summer temperature also creates opportunities)	Reversibility: very hard to return to the previous state; in the long term: alternative land use possible	Human response may evoke a 'response to climate change' tipping point before SETP takes place

characteristics (table SI 2.1). However, several examples are promising SETP candidates, which often have not yet been approached from the perspective of tipping points in the existing literature. Below, we elaborate on three of these, representing different geographical locations, sectors, climate drivers and spatial scales (table 2). In the last subsection we generalize our findings by drawing from al 22 examples.

4.1. Winter sports tourism in low-altitude Alpine regions

Reduced snow conditions in Alpine regions are among the most visible early impacts of climate change in Europe. Numerous studies have identified a major risk to the Alpine winter sports industry (e.g. Köberl *et al* 2015, Marty *et al* 2017, Steiger *et al* 2017). In Austria, recurring unfavourable snow conditions have led to the collapse of several low-lying ski resorts (Falk 2013). This has caused societal concerns because of the economic significance of the sector and its contribution to cultural identity (Interview #22, see table SI 2.3).

The state (Characteristic 1, table 2) of an individual resort can be described in terms of financial profitability. The mechanism (Characteristic 2, table 2) causing a state shift can be understood as follows. When a resort does not succeed in making a profit for a number of successive years, it will reduce its reserves and eventually make a decision to withdraw from the sector, or in certain conditions, it may fall into bankruptcy. As a rule of thumb, a resort needs 100 days of good snow conditions a year to be financially viable. Based on this rule, the number of viable existing resorts in the Alpine region could reduce from the baseline 91% (in 2007) to 61% and 30% under warming of 0°, 2° and 4 °C, respectively (Abegg *et al* 2007, as cited in Damm *et al* 2014). Bankruptcy could occur abruptly (Characteristic 3, table 2), because there is large intra-annual variability in snow conditions on top of the slowly changing trend (Marke *et al* 2015). In the immediate term, bankruptcy is not necessarily irreversible, and some resorts have been successfully reopened (Falk 2013), but in the face of climate change, the viability of low-lying resorts for snow tourism in the medium to long-term is fundamentally irreversible, irrespective of supporting policies—e.g. the government privatizing unprofitable ski lifts and train lines (Interview #23).

From this case we take the following insights. First, the question whether collapse of a ski resort can be seen as a clear tipping point strongly depends on the scale of analysis. On a village scale, the disappearance of a resort may have large impacts, because a major share of local income is derived from it. On a larger spatial scale, the impacts are usually smaller because of economic diversification and substitution effects when tourism and employment shift to other areas. This is strongly region dependent (Abegg *et al* 2007), as can be seen by comparing two Austrian regions: Styria and Tyrol. Styria has many low-lying resorts but a diverse economy, so that individual resorts are likely to tip, but their overall economic impact may be limited. In contrast, Tyrol is very much dependent on income from winter tourism, but the resorts are situated at much higher altitudes, making them less likely to tip (Interview #22). Second, adaptation by artificial snow-making may significantly reduce the likelihood of tipping by prolonging the skiing season in the short or even medium term. However, this is very costly and has large environmental impact. Thirdly, there is a potential adaptation strategy to diversify. Several regions are considering a more fundamental shift towards gaining a large share of income from summer tourism. For example, they seek to revive the 'Sommerfrische', a historic fashion where rich families retreated from cities to spend the hot summer at higher altitudes (Interview #23). Whereas higher temperatures threaten winter tourism, it may be opportune in summer when people wish to escape the hot cities in Southern Europe.

4.2. Farmland abandonment in Southern Europe

In Southern Europe, climate change is projected to have disproportionally large impacts from the combination of higher temperatures and most likely lower precipitation (Vautard *et al* 2014, IPCC 2014b), with most studies showing large detrimental impacts on agriculture (Ciscar *et al* 2014). In the past, large parts of north-west and central Spain have seen widespread abandonment of farmland and migration from rural areas (Collantes *et al* 2014, Iglesias and Garrote 2017) due to a complex interplay of socio-economic, geographical and environmental factors (Terres *et al* 2015). Interviewees expressed concerns that climate change may trigger even more farmland abandonment with considerable social, and to a lesser extent, economic consequences (Interview #25, 26). Indeed, several studies have found that climatic determinants may explain land abandonment patterns (Gellrich and Zimmermann 2007, Arnaez *et al* 2011, García-Ruiz *et al* 2011, Hatna and Bakker 2011).

The *state* (Characteristic 1, table 2) of a piece of land can be described in financial terms. Whether the land provides a viable financial rate of return is determined by land, input and production costs; productivity and quality of outputs; market prices; and ancillary income from subsidies or other farm activities. Furthermore, the most profitable farming activity at any location is dependent on the local climate and biophysical context. Climate change may alter the relative productivity of crops in certain regions, making the crop more favourable (unfavourable) if, on average, climate moves closer to (further away from) the optimum conditions for cultivating that crop (Prishchepov *et al* 2013). If land eventually is abandoned, this also impacts wider rural communities. At some point, what once was a lively agricultural area may have become what one of the interviewees described as the 'Spanish Laponia': abandoned farmlands, villages with little economic activity inhabited by mainly elderly people and the schools, shops and churches closed (Interview #25). The *mechanism* causing farmland abandonment (Characteristic 2, table 2) is the choice-process of individual farmers, influenced by several feedback mechanisms. With migrants leaving the area, the rural area gets less attractive to live in—especially for younger people, and the infrastructure remains underdeveloped (Interview #25). This process is very hard to reverse, which is reflected by many failed governmental attempts to repopulate rural areas (Interview #6). Concerning *abruptness* (Characteristic 3, table 2), abandonment may happen either sudden or gradually, depending on the interaction between environmental and socio-economic conditions (Estel *et al* 2015, Levers *et al* 2018).

From this case we take the following insights. First, the clearest cases of tipping points are found on the community scale, where reinforcing mechanisms can rapidly change the socio-economic structure to a state of abandonment. Second, in many places, adaptation by irrigation has been effective in countering further farmland abandonment and rural exodus (Iglesias *et al* 2018, Interview #25). Southeast Spain and the Ebro Basin has taken-up a large amount of irrigation, and with that, a change of crops towards water-intensive cultivation such as maize (García-Ruiz and Lana-Renault 2011). This, however led to severe over-exploitation of water resources, aggravated by inappropriate crop choices due to subsidy schemes (González-Gómez *et al* 2012). Considering that the main social contribution of irrigation is rural employment (Gómez-Limón and Picazo-Tadeo 2012), decreasing water availability may also tip some of the currently irrigated areas to abandonment (Interview #26).

4.3. SLR-induced migration

SLR constitutes a major threat for the densely populated coastal zones in Europe (Hinkel *et al* 2010, IPCC 2014b, Vousdoukas *et al* 2018) and worldwide (Hinkel *et al* 2014, IPCC 2019). Although flood defences can be upgraded to reduce damage, this is economically efficient during the 21st century for only 13% of the global coastline (comprising 90% of today's global floodplain population and 96% of today's global floodplain assets) (Lincke and Hinkel 2018). For the protected areas, however, rising sea-levels increase the potential of larger and larger flood disasters in the case of defence failure, because the floodplains, and flood depth in case of a disaster, continue to grow with SLR irrespective of protection. Furthermore, coastal protection often attracts further development in the floodplain, which further increases potential flood damages (Brown *et al* 2014, Hinkel *et al* 2018). After the occurrence of a major flood disaster, affected regions can either decide to rebuild in the same site or to retreat from the coast, which is the tipping point considered here.

The state (Characteristic 1, table 2) of a coastal settlement can be described in terms of its population exposure: high and increasing exposure before and low and decreasing exposure after the tipping point. Three social mechanisms (Characteristic 2, table 2) can cause a state shift from high to low population exposure. The first process is migration, which refers to permanent or semi-permanent voluntary human mobility (Adger et al 2015). Migration is generally a slow process, driven by complex interrelations between many push and pull factors, and there is generally limited evidence that SLR (to date) has caused coastal migration (Adger et al 2015, McLeman 2018). The second process, displacement, refers to the involuntary and unforeseen movement of people due to armed conflicts or disasters (McLeman 2018, Mortreux et al 2018). Displacement is a fast process taking place during, or in the direct aftermath, of a disaster. The third process is relocation or managed retreat, initiated, supervised and implemented by governments (Hino et al 2017, Mortreux et al 2018). It is a slower process than displacement, but it is often initiated after people have been displaced by disaster. With rising sea levels, it is expected that governments will be confronted with this decision more frequently.

The change in population exposure induced by both forced displacement and planned relocation following a disaster is abrupt (Characteristic 3, table 2) as compared to normal changes in population exposure due to two reasons. First, displacement always is abrupt as this is caused by a fast flood disaster. Second, relocation decisions by governments generally provide incentives such as buy-outs for households to move out of the hazard zone. For example, in the aftermath of the coastal flooding brought by Xynthia, the French Government offered to fully compensate all homeowners, based on the value of the real estate prior to the storm and most homeowners accepted within a year (Lumbroso and Vinet 2011). These kinds of incentives are in addition to existing individual incentives for migration and thus lead to faster population change.

From this case we take the following insights. First, the SETP of retreat from a coastal zone may be more likely to be triggered by an extreme event (Interview #10). Second, however, it could also be that adaptation to the increasing flood risk in itself causes a reconfiguration of the system (Interview #27, 28) which can be so transformative that it is a 'response to climate change' tipping point. This is for example seen in The Netherlands, where new studies on extreme SLR (DeConto and Pollard 2016, le Bars et al 2017) have triggered the debate on a long-term water management policy (Haasnoot et al 2018). Some radically different strategies are mentioned: the construction of a large dike in front of the entire coast combined with a permanent closure of all estuaries; elevating new buildings above sea level (Aerts et al 2008); or strategic retreat from areas with economic stagnation and population decline (Olsthoorn et al 2008, van der Meulen 2018). Third, in this context it is not only the magnitude, but also the rate of SLR that could cause a policy shift. It typically takes decades to prepare for large infrastructural adaptation measures such as flood defences (Hallegatte et al 2012). The rate of change may exceed the capacity of society to adapt in the traditional way and trigger a shift towards more transformative policies.

4.4. Generalisation of results

Table 3 lists the characteristics that SETPs may share, drawing from the stakeholder interviews on other SETP candidates (table SI 2.3, 2.4).

Concerning SETP descriptions, there are two observations. First, it seems that the clearest examples of SETPs are found on small system scales (table 3). This not only holds for ski resorts, but also for agriculture, where interviewees (#2, 5, 6, 24, 25, 26, numbers refer to table SI 2.3, 2.4) could provide several examples of local, abrupt transformations, but hesitated to claim that this would lead to significant country-scale economic effects. Vice versa, even the interviewees that opposed the whole idea of the existence of tipping points in socio-economic systems, agreed that some of the dynamics could be seen on a small system scale, which they however did not consider of enough concern to be called 'real' tipping points (#27, 28). Second, it appears that descriptions of SETPs are prone to a large degree of subjectivity. This can relate to the fundamental question whether there are critical thresholds at all, at which strong non-linear behaviour occurs. For example, interviewee #20 says: 'In the health sector, we never speak of thresholds, it is not that when a temperature surpasses a certain degree that suddenly something happens.', whereas interviewee #18 gave several examples of outbreaks of infectious diseases following environmental conditions gradually moving beyond threshold conditions. Similarly, Interviewee #3 expects that in case of a catastrophic dike-breach in the Netherlands, 'they will think (…): there is no way of recovery', and the delta will be irreversibly changed. In contrast, interviewee #28 argues that 'even if there would be a large flood event, we probably will rebuild. We will not move to higher grounds. That is so contrary to Dutch nature.' On the same casus, Interviewee #27 highlights another dimension of subjectivity. Coastal retreat could be a tipping point from a social, but not an economic point of view—from which it simply is a continuation of the rational cost-benefit analysis which also underpins the current policy. 'People don't like change, but whether it is a dramatic problem from an economic point of view, remains a question.'

Concerning mechanisms causing SETPs, interviewees distinguished several mechanisms that can push the socio-economic system over a tipping point. Most frequently mentioned, was a series of unfavourable conditions, that eventually tips the system into a new state. Above, we illustrated this for ski resorts and interviewees highlighted similar dynamics for farmland abandonment, collapse of insurance markets and willingness to rebuild after devastating hurricanes (table 3). In many cases, these extremes are perturbations on top of a gradual trend moving towards

Table 3. SETP characteristics brought-up by stakeholders during interviews.

Characteristic	Examples in interviews (numbers refer to interviews in table SI 2.3, 2.4)
Definition and examples of SETPs, description of critical thresholds and description of stable states	
The tipping point occurs on a small system scale	Agricultural shifts and farmland abandonment happen in certain regions of Spain, but these contribute little to total national agricultural income (6, 24, 25, 26, see 2, 5). Many low-altitude ski resorts may collapse, but the most well-known ski resorts are located at higher altitudes (8, 22, 23). Outbreaks of vector-borne diseases are more likely in relatively warm cities (18)
Conflicting views on whether climate change may cause a tipping point in the sector	Large and abrupt socio-economic impacts upon falling below water availability thresholds (10 versus 19). Vector-borne diseases and epidemics (18 versus 20). The possibility of abrupt retreat from the Dutch Delta (3, 4, 15 versus 27, 28)
Tipping points are more likely in developing countries than in Europe	Explicit statement (8). Sea-level rise induced retreat is more likely in Island states and parts of Bangladesh (10). Heat stress is a larger concern in India (10). Droughts may cause migration out of the fertile crescent (10)
Whether the new state is (un)favourable is a subjective issue	Disappearing of rivers with large iconic/religious value is a tipping point for certain groups (10). Collapse of certain agricultural systems may be favourable for the environment (24). Collapse of ski resorts could be favoured over adaptation with adverse impacts on nature (23). Coastal retreat can be very unfavourable for some groups: a social tipping point, but still rational from a cost-benefit perspective: not an economic tipping point (27)
Mechanisms leading to the occurrence of SETPs	
Co-determining drivers contribute to eroding system resilience	Depletion of fossil fuels (1), consumer behaviour steering demand for cheap and unsustainable agricultural production (2), …,[a] main drivers for farmland abandonment are economic and demographic (25, 26), affordability of flood protection is determined by GDP-growth (27, 28)
SETP is caused by a gradual increase of risk or economic unfavourability, causing a market/policy reconfiguration	Insurance premiums rise above affordability threshold (3, 15). Collapse of a local ski resort because it is unprofitable (8, 22, 23). Nobody wants to take over a small, unprofitable farm (25). It is no longer cost-effective to protect a coastal community (4, 10, 27, 28). Traffic disruptions rise above formal or acceptability threshold (17). Economically (un) favourable climatic conditions shift and cause migration over the boundaries of nation states (10)
SETP is caused by a series of unfavourable climatic conditions	Recurring crop failures/droughts makes farmers stop their business (2, 6, 25). Frequent hits of hurricanes or floods prevents from rebuilding certain areas (3). Recurring droughts cause migration flows (2). Recurring unfavourable snow conditions cause collapse of ski resorts (22, 23). Two years of large damage push insurance premiums over affordability threshold (2)
Disaster triggers a response tipping point	A disaster triggers rapid uptake of sustainable energy (1, 12). Floods trigger retreat from vulnerable areas (3, 4) or a major revision of flood-risk strategy (4, 15)
The rate of change, rather than the magnitude of change, is causing an SETP	Explicit statement (10)
Tipping point is caused by cascading infrastructural effects	Floods disrupt the road network (15, 17, 21) and cause electricity failure (15)

[a] Almost each interviewee refered to co-determining drivers, see table SI 2.4.

threshold conditions. Many of these thresholds are an interplay between climatic and financial factors: for profitable operation, agriculture needs a minimum amount of water and ski resorts a minimum amount of days with sufficient snow cover. In some cases, this implies that favourable conditions (for example for a certain crop) may shift from one region to another, which on the local level causes relatively abrupt shifts (for example in agricultural practices). Sometimes, governments need to radically reform their policies to maintain certain levels of performance. As we illustrated for the case of SLR, it can be the rate rather than the magnitude of change which exceeds society's capacity to respond and causes a system shift. As interviewee 10 puts it: 'One of the biggest threats to society is that the changes in the climate and the weather happen so rapidly, that we do not, or inadequately, have abilities to adapt to these changes.'

In almost every case, interviewees highlighted a combination of climatic and co-determining socio-economic conditions, which together explain a state shift: the resilience of a system against biophysical change already has been depleted by economic, demographic or social mechanisms (table SI 2.4). Nonlinear positive (self-enforcing) feedbacks in the socio-economic system may accelerate a transition. For example, increasing risk raises insurance premiums, which reduces their affordability, which in turn decreases the insurance uptake, which raises the premiums even further (Interview #3, 15). Similarly, concerns about the profitability of ski resorts may hinder further investments in the winter tourism sector, and rumours about accelerating SLR may worsen the investment climate of a delta which reduces the funds available for flood protection.

5. Discussion

Reflecting on the results of the stakeholder consultation against what is present in the tipping point literature to date, we find the following.

First, change in the socio-economic system is the outcome of complex environmental and socio-economic drivers, as well as policy interventions. Consequently, the role of the climate driver can be difficult to attribute for each SETP example, particularly for impact SETPs. One should be careful not to overemphasize the role of biophysical change while neglecting the co-determining social, political and economic variables. Such a 'naïve' approach has received criticism in the literature on migration, the collapse of ancient societies and the impacts of natural disasters (Butzer 2012, Bettini 2017, Freeman 2017, Soens 2018). A relatively 'slow' process such as climate change will most likely only cause abrupt change of a socio-economic system when the system was already on the edge of its resilience due to co-determining factors, or when there is a very large disaster-like perturbation, or recurring smaller disasters, on top of the gradual trend (van Nes *et al* 2016). This also implies that impact SETPs are more likely to be found outside Europe, in developing countries with less socio-economic resilience against climate shocks (table 3, see Hinkel *et al* 2018 for an example for SLR).

Second, there are limitations to the proposed distinction between SETPs in terms of impacts and response. In practice, socio-economic impact and response are closely interrelated. Adaptation and mitigation measures can help to avoid some SETPs, although there are physical, economic and social limits to these measures, so that tipping points cannot always be avoided but possibly delayed. In some cases, the time required to implement adaptation measures becomes a limiting factor. This highlights that not only the magnitude, but also the rate of climate change may cause a tipping point. SETPs can thus occur because the rate of change exceeds society's capacity to adapt. Furthermore, some proposed adaptation measures are so transformative, that their mere implementation can be considered a response SETP.

Third, SETPs are more likely to be found on small system scales. On larger scales, economies are more diverse so that collapsing sectors may be substituted. At the same time, there are cases where small scale tipping points may aggregate to larger-scale socio-economic impacts, for example in a region with many low-lying ski resorts or a region with many vulnerable farms. This is in line with complex system theory, which indicates that homogeneous and interconnected systems are more likely to exhibit wide scale tipping (Scheffer *et al* 2012). This also confirms the finding that although societal-wide collapse is seldom observed, natural disasters may have a large local impact on individuals and communities (Soens 2018).

Fourth, in this context, the stakeholder workshop illuminated tensions between different ways of framing tipping points. The concept had large policy resonance because of its popular meaning as 'large impact event'. This, however, caused a disregard of the system-dynamic properties of tipping points among workshop participants. In contrast, strict system-dynamic definitions of tipping points are found on small system scales in which policy makers showed less interest from a macro-economic perspective. Consequently, stakeholder consultation does not guarantee that all collected examples align with a (stricter) tipping point definition and should therefore be complemented with a concise evaluation of the characteristics of the examples supplied, to identify those that classify as tipping points. Nevertheless, these academia-stakeholder conversations were perceived as helpful. For academia, because it helped to describe indicators for system states in a policy-relevant way. For policy makers, because dialogue on system dynamics enhanced system understanding and helped to find better management strategies to avoid impact SETPs.

Fifth, including socio-economic dynamics adds an extra layer of complexity compared to the studies which only include biophysical dynamics. Prediction of occurrence and likelihood of SETPs is complicated by (a) the complexity and dynamic character of the socio-economic system and (b) the fact that humans proactively and autonomously may alter the system. In response to changing conditions, the socio-economic system might deliberately have been changed before the tipping was predicted. There is an increasing body of regime shifts literature in which these biophysical and socio-economic dynamics are studied in an integrated way under headings like CHANS (coupled-human and natural systems); SES (socio-ecological systems) and CHES (coupled human-environment systems). The model approaches in this literature (such as system-dynamic and agent-based models, see table SI 1.2) are suitable to study the dynamics of stylized cases to increase system understanding. So far, however, this literature has little coverage from the perspective of climate change (Aerts *et al* 2018). Also, because of its often stylized character, it gives little concrete suggestions for adaptation and mitigation strategies for policy makers.

To illustrate the last point, consider the potential impacts of accounting for SETPs in cost-benefit-analysis (CBA), a common tool for guiding climate policy (Tol 2003). Accounting for climate tipping points may significantly alter CBA because the extra economic damage justifies more radical mitigation policies, such as a higher carbon tax reflecting the higher social cost of carbon (Lenton and Ciscar 2013, Cai *et al* 2015, 2016, Van Der Ploeg 2016). Similarly, any additional damage from passing impact SETPs increases the costs of inaction, making mitigation measures more cost-effective. On a local scale, the inclusion of SETPs will mainly increase the benefits of local adaptation measures. Furthermore, when evaluating a management strategy that could lead to an impact SETP, one should account for additional transfer costs to an alternative strategy at some point in the future (Haasnoot *et al* 2019).

6. Conclusion

This paper set out to define and characterize SETPs, to identify policy-relevant examples and to give recommendations for further research. We showed how SETPs can be defined along the same characteristics as biophysical tipping points and suggested a distinction between: (a) SETPs in terms of transformational response to climate change and (b) SETPs in terms of socio-economic impacts. Impact SETPs, where slow-onset changes in the biophysical system cause strong nonlinear behaviour in the socio-economic system, have least coverage in the literature. The stakeholder process delivered 22 candidate SETPs, which mostly have some general coverage in the literature, but not specifically from a tipping point perspective.

How could further SETP research support decision making on climate adaptation and mitigation? We propose the following research agenda:

- For small-scale SETPs, develop models (e.g. agent-based or system-dynamic) that can represent the nonlinear dynamics causing regime shifts in socio-economic systems upon gradual change in the biophysical system.

  Use these models to assess the effectiveness of different adaptation and monitoring strategies.

  Investigate the different mechanisms identified in the above stakeholder consultation, notably under what conditions the rate-of-change (rather than the magnitude of change) causes an SETP.

  Investigate how, and under what conditions, small scale SETPs may scale up to wider socio-economic impacts.

- Study the wider (macro)economic impacts of SETPs by representing the new states in partial equilibrium models of specific sectors, or in general equilibrium models to study economy-wide consequences. Investigate how the likelihood and impact of SETPs can be reduced by mitigation policy.
- When SETPs cannot explicitly be modelled or quantified, use stakeholder consultation to identify potential thresholds indicating SETPs and to investigate their causal mechanisms.
- Explore the exceedance of these thresholds in climate and socio-economic scenarios.
- Use stakeholder-thresholds to define maximum levels of change (e.g. a temperature limit, or several consecutive unprofitable years) at which SETPs most likely will not occur.

Finally, it is clear that impact SETPs could have major policy consequences but have been omitted from many European and national impact studies to date. Including them in the academic literature and in policy discussion is therefore a useful addition for informing sound mitigation and adaptation strategies.

Data availability statement

Any data that support the findings of this study are included within the article or the supplementary information.

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References

Abegg B, Agrawala S, Crick F and de Montfalcon A 2007 Climate change impacts and adaptation in winter tourism *Climate Change in the European Alps: Adapting Winter Tourism and Natural Hazards Management* ed S Agrawala (Organisation for Economic Cooperation and Development (OECD)) pp 25–60

Adger W N, Arnell N W, Black R, Dercon S, Geddes A and Thomas D S G 2015 Focus on environmental risks and migration: causes and consequences *Environ. Res. Lett.* **10** 060201

Aerts J C J H, Sprong T and Bannink B 2008 *Aandacht voor Veiligheid* (The Hague: The Netherlands Ministry of Infrastructure and Water)

Aerts J C J H, Botzen W J, Clarke K C, Cutter S L, Hall J W, Merz B, Michel-Kerjan E, Mysiak J, Surminski S and Kunreuther H 2018 Integrating human behaviour dynamics into flood disaster risk assessment *Nat. Clim. Change* **8** 193–9

Nature Editorial 2018 Watch the ocean: long-term monitoring is essential for working out how changes in the Atlantic Ocean current system will affect the planet *Nature* **556** 149–50

Arnaez J, Lasanta T, Errea M P and Ortigosa L 2011 Land abandonment, landscape evolution, and soil erosion in a Spanish Mediterranean mountain region: the case of Camero Viejo *L. Degrad. Dev.* **22** 537–50

Barker T 2003 Representing global climate change, adaptation and mitigation *Glob. Environ. Change* **13** 1–6

Berrang-Ford L, Pearce T and Ford J D 2015 Systematic review approaches for climate change adaptation research *Reg. Environ. Change* **15** 755–69

Bettini G 2017 Where next? Climate change, migration, and the (Bio)politics of adaptation *Glob. Policy* **8** 33–9

Biggs R, Peterson G D and Rocha J C 2018 The regime shifts database: a framework for analyzing regime shifts in social-ecological systems *Ecol. Soc.* **23** 9

Bloemen P, Reeder T, Zevenbergen C, Rijke J and Kingsborough A 2018 Lessons learned from applying adaptation pathways in flood risk management and challenges for the further development of this approach *Mitig. Adapt. Strateg. Glob. Change* **23** 1083–108

Brown S *et al* 2014 Shifting perspectives on coastal impacts and adaptation *Nat. Clim. Change* **4** 752–5

Bryant B P and Lempert R J 2010 Thinking inside the box: a participatory, computer-assisted approach to scenario discovery *Technol. Forecast. Soc. Change* **77** 34–49

Burch S, Mitchell C, Berbes-Blazquez M and Wandel J 2017 Tipping toward transformation: progress, patterns and potential for climate change adaptation in the Global South *J. Extrem. Events* **4** 1750003

Butzer K W 2012 Collapse, environment, and society *Proc. Natl Acad. Sci.* **109** 3632–9

Caesar L, Rahmstorf S, Robinson A, Feulner G and Saba V 2018 Observed fingerprint of a weakening Atlantic Ocean overturning circulation *Nature* **556** 191–6

Cai Y, Judd K L, Lenton T M, Lontzek T S and Narita D 2015 Environmental tipping points significantly affect the cost-benefit assessment of climate policies *Proc. Natl Acad. Sci.* **112** 4606–11

Cai Y, Lenton T M and Lontzek T S 2016 Risk of multiple interacting tipping points should encourage rapid CO_2 emission reduction *Nat. Clim. Change* **6** 520–5

Camarero J J, Gazol A, Sangüesa-Barreda G, Oliva J and Vicente-Serrano S M 2015 To die or not to die: early warnings of tree dieback in response to a severe drought *J. Ecol.* **103** 44–57

Ciscar J C *et al* 2014 *Climate Impacts in Europe. The JRC PESETA II Project. JRC Scientific and Policy Reports* EUR 26586EN Joint Research Centre European Commission (https://doi.org/10.2791/7409)

Clements C F and Ozgul A 2018 Indicators of transitions in biological systems *Ecol. Lett.* **21** 905–19

Collantes F, Pinilla V, Sáez L A and Silvestre J 2014 Reducing depopulation in rural Spain: the impact of immigration *Popul. Space Place* **20** 606–21

Damm A, Köberl J and Prettenthaler F 2014 Does artificial snow production pay under future climate conditions?-a case study for a vulnerable ski area in Austria *Tour. Manage.* **43** 8–21

David Tàbara J, Frantzeskaki N, Hölscher K, Pedde S, Kok K, Lamperti F, Christensen J H, Jäger J and Berry P 2018 Positive tipping points in a rapidly warming world *Curr. Opin. Environ. Sustain.* **31** 120–9

David Tàbara J, Jäger J, Mangalagiu D and Grasso M 2019 Defining transformative climate science to address high-end climate change *Reg. Environ. Change* **19** 807–18

DeConto R M and Pollard D 2016 Contribution of Antarctica to past and future sea-level rise *Nature* **531** 591–7

de Zeeuw A and Li C Z 2016 The economics of tipping points *Environ. Resour. Econ.* **65** 513–7

EC 2018 *A Clean Planet for All. A European long-term Strategic Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy* (Brussels: European Commission)

Estel S, Kuemmerle T, Alcántara C, Levers C, Prishchepov A and Hostert P 2015 Mapping farmland abandonment and recultivation across Europe using MODIS NDVI time series *Remote Sens. Environ.* **163** 312–25

Falk M 2013 A survival analysis of ski lift companies *Tour. Manage.* **36** 377–90

Farmer J D, Hepburn C, Ives M C, Hale T, Wetzer T, Mealy P, Rafaty R, Srivastav S and Way R 2019 Sensitive intervention points in the post-carbon transition *Science* **364** 132–4

Fazey I *et al* 2018 Transformation in a changing climate: a research agenda *Clim. Dev.* **10** 197–217

Filatova T, Polhill J G and van Ewijk S 2016 Regime shifts in coupled socio-environmental systems: Review of modelling challenges and approaches *Environ. Model. Softw.* **75** 333–47

Freeman L 2017 Environmental change, migration, and conflict in Africa: a critical examination of the interconnections *J. Environ. Dev.* **26** 351–74

Fuchs S and Thaler T 2017 Tipping points in natural hazard risk management: how societal transformation can provoke policy strategies in mitigation *J. Extrem. Events* **04** 1750006

García-Ruiz J M and Lana-Renault N 2011 Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region—a review *Agric. Ecosyst. Environ.* **140** 317–38

García-Ruiz J M, López-Moreno I I, Vicente-Serrano S M, Lasanta-Martínez T and Beguería S 2011 Mediterranean water resources in a global change scenario *Earth-Sci. Rev.* **105** 121–39

Geels F W and Schot J 2007 Typology of sociotechnical transition pathways *Res. Policy* **36** 399–417

Gellrich M and Zimmermann N E 2007 Investigating the regional-scale pattern of agricultural land abandonment in the Swiss mountains: a spatial statistical modelling approach *Landsc. Urban Plan* **79** 65–76

Gladwell M 2000 *The Tipping Point - How Little Things Can Make a Big Difference* (London: Little Brown)

Gómez-Limón J A and Picazo-Tadeo A J 2012 Irrigated agriculture in Spain: diagnosis and prescriptions for improved governance *Int. J. Water Resour. Dev.* **28** 57–72

González-Gómez F, García-Rubio M A and Guardiola J 2012 Introduction: water policy and management in Spain *Int. J. Water Resour. Dev.* **28** 3–11

Haasnoot M, Kwakkel J H, Walker W E and ter Maat J 2013 Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world *Glob. Environ. Change* **23** 485–98

Haasnoot M *et al* 2018 *Mogelijke Gevolgen van versnelde Zeespiegelstijging voor het Deltaprogramma. Een Verkenning* (Delft: Deltares)

Haasnoot M, van Aalst M, Rozenberg J, Dominique K, Matthews J, Bouwer L M, Kind J and Poff N L R 2019 Investments under non-stationarity: economic evaluation of adaptation

pathways *Clim. Change* (https://doi.org/10.1007/s10584-019-02409-6)
Hall J W, Lempert R J, Keller K, Hackbarth A, Mijere C and Mcinerney D J 2012 Robust climate policies under uncertainty: a comparison of robust decision making and info-gap methods *Risk Anal.* **32** 1657–72
Hallegatte S, Shah A, Lempert R, Brown C and Gill S 2012 *Investment Decision Making under Deep Uncertainty—Application to Climate Change* (Washington: The World Bank)
Hatna E and Bakker M M 2011 Abandonment and expansion of arable land in Europe *Ecosystems* **14** 720–31
Hinkel J, Nicholls R J, Vafeidis A T, Tol R S J and Avagianou T 2010 Assessing risk of and adaptation to sea-level rise in the European Union: an application of DIVA *Mitig. Adapt. Strateg. Glob. Change* **15** 703–19
Hinkel J, Lincke D, Vafeidis A T, Perrette M, Nicholls R J, Tol R S J, Marzeion B, Fettweis X, Ionescu C and Levermann A 2014 Coastal flood damage and adaptation costs under 21st century sea-level rise *Proc. Natl Acad. Sci. USA* **111** 3292–7
Hinkel J, Aerts J C J H, Scussolini P, Nicholls R, Lincke D, Jiminez J A, Brown S, Sanchez-Arcilla A, Vafeidis A and Appeaing Addo K 2018 The ability of societies to adapt to 21st century sea-level rise *Nat. Clim. Change* **8** 570–8
Hino M, Field C B and Mach K J 2017 Managed retreat as a response to natural hazard risk *Nat. Clim. Change* **7** 364–70
Hoegh-Guldberg O *et al* 2007 Change and ocean acidification *Science* **318** 1737–42
Iglesias A and Garrote L 2017 On the barriers to adapt to less water under climate change in Mediterranean countries *Eur. Water* **60** 1–8
Iglesias A, Santillán D and Garrote L 2018 On the barriers to adaption to less water under climate change: policy choices in mediterranean countries *Water Resour. Manage.* **32** 4819–32
IPCC 2014a *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects* ed V R Barros *et al* (Cambridge, New York: Cambridge University Press)
IPCC 2014b *Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects* ed C B Field *et al* (Cambridge, New York: Cambridge University Press)
IPCC 2018 *Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* ed V Masson-Delmotte *et al* (Geneva: World Meteorological Organization)
IPCC 2019 Summary for policymakers *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* ed H O Pörtner *et al*
IRENA 2018 *Power Generation Costs in 2017* (Abu Dhabi: International Renewable Energy Agency)
Kabir M E, Serrao-Neumann S, Davey P, Hossain M and Alam M T 2018 Drivers and temporality of internal migration in the context of slow-onset natural hazards: insights from north–west rural Bangladesh *Int. J. Disaster Risk Reduct.* **31** 617–26
Kates R W, Travis W R and Wilbanks T J 2012 Transformational adaptation when incremental adaptations to climate change are insufficient *Proc. Natl Acad. Sci.* **109** 7156–61
Knutti R, Rogelj J, Sedláček J and Fischer E M 2016 A scientific critique of the two-degree climate change target *Nat. Geosci.* **9** 13–8
Köberl J, Prettenthaler F, Nabernegg S and Schinko T 2015 Tourism *Economic Evaluation of Climate Change Impacts: Development of a Cross-Sectoral Framework and Results for Austria* ed K W Steininger *et al* (Cham: Springer International Publishing) pp 367–88
Kopp R E, Shwom R L, Wagner G and Yuan J 2016 Tipping elements and climate-economic shocks: Pathways toward integrated assessment *Earth's Futur.* **4** 346–72
Kriegler E, Hall J W, Held H, Dawson R and Schellnhuber H J 2009 Imprecise probability assessment of tipping points *Proc. Natl Acad. Sci. USA* **106** 5041–6
Kwadijk J C J *et al* 2010 Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands *Wiley Interdiscip. Rev. Clim. Change* **1** 729–40
le Bars D, Drijfhout S and de Vries H 2017 A high-end sea level rise probabilistic projection including rapid Antarctic ice sheet mass loss *Environ. Res. Lett.* **12** 044013
Lemoine D and Traeger C P 2016 Economics of tipping the climate dominoes *Nat. Clim. Change* **6** 514–9
Lenton T M, Held H, Kriegler E, Hall J W, Lucht W, Rahmstorf S and Schellnhuber H J 2008 Tipping elements in the Earth's climate system *Proc. Natl Acad. Sci. USA* **105** 1786–93
Lenton T M 2013 Environmental tipping points *Annu. Rev. Environ. Resour.* **38** 1–29
Lenton T M and Ciscar J C 2013 Integrating tipping points into climate impact assessments *Clim. Change* **117** 585–97
Levermann A *et al* 2012 Potential climatic transitions with profound impact on Europe *Clim. Change* **110** 845–78
Levers C, Schneider M, Prishchepov A V, Estel S and Kuemmerle T 2018 Spatial variation in determinants of agricultural land abandonment in Europe *Sci. Total Environ.* **644** 95–111
Lincke D and Hinkel J 2018 Economically robust protection against 21st century sea-level rise *Glob. Environ. Change* **51** 67–73
Loorbach D and Rotmans J 2006 Managing transitions for sustainable development *Understanding Industrial Transformation. Views from Different disciplines. Environment & Policy* vol 44 ed X Olsthoorn and A J Wieczorek (Dordrecht: Springer) pp 187–206
Lumbroso D M and Vinet F 2011 A comparison of the causes, effects and aftermaths of the coastal flooding of England in 1953 and France in 2010 *Nat. Hazards Earth Syst. Sci.* **11** 2321–33
Marke T, Strasser U, Hanzer F, Stötter J, Wilcke R A I and Gobiet A 2015 Scenarios of future snow conditions in Styria (Austrian Alps) *J. Hydrometeorol.* **16** 261–77
Martínez-Vilalta J and Lloret F 2016 Drought-induced vegetation shifts in terrestrial ecosystems: the key role of regeneration dynamics *Glob. Planet. Change* **144** 94–108
Marty C, Schlögl S, Bavay M and Lehning M 2017 How much can we save? Impact of different emission scenarios on future snow cover in the Alps *Cryosphere* **11** 517–29
Marzloff M P, Little L R and Johnson C R 2016 Building resilience against climate-driven shifts in a temperate reef system: staying away from context-dependent ecological thresholds *Ecosystems* **19** 1–15
McLeman R 2018 Migration and displacement risks due to mean sea-level rise *Bull. At. Sci.* **74** 148–54
Mercure J F, Pollitt H, Viñuales J E, Edwards N R, Holden P B, Chewpreecha U, Salas P, Sognnaes I, Lam A and Knobloch F 2018 Macroeconomic impact of stranded fossil fuel assets *Nat. Clim. Change* **8** 588–93
Milkoreit M, Hodbod J, Baggio J, Benessaiah K, Calderón-Contreras R, Donges J F, Mathias J-D, Rocha J C, Schoon M and Werners S E 2018 Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review *Environ. Res. Lett.* **13** 033005
Mortreux C, Safra de Campos R, Adger W N, Ghosh T, Das S, Adams H and Hazra S 2018 Political economy of planned relocation: A model of action and inaction in government responses *Glob. Environ. Change* **50** 123–32
Moser S C and Dilling L 2007 Toward the social tipping point: creating a climate for change *Creating a Climate for Change: Communicating Climate Change and Facilitating Social Change* ed S C Moser and L Dilling (Cambridge: Cambridge University Press) pp 491–516
Olsthoorn X, Van Der Werff P, Bouwer L M and Huitema D 2008 Neo-Atlantis: The Netherlands under a 5-m sea level rise *Clim. Change* **91** 103–22
Patenaude G 2011 Climate change diffusion: while the world tips, business schools lag *Glob. Environ. Change* **21** 259–71
Petr M, Boerboom L G J, Ray D and Van Der Veen A 2015 Adapting Scotland's forests to climate change using an action expiration chart *Environ. Res. Lett.* **10** 105005

Prishchepov A V, Müller D, Dubinin M, Baumann M and Radeloff V C 2013 Determinants of agricultural land abandonment in post-Soviet European Russia *Land Use policy* **30** 873–84
Prober S M *et al* 2017 Informing climate adaptation pathways in multi-use woodland landscapes using the values-rules-knowledge framework *Agric. Ecosyst. Environ.* **241** 39–53
Ranger N, Reeder T and Lowe J 2013 Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 project *EURO J. Decis. Process.* **1** 233–62
Ratajczak Z, Carpenter S R, Ives A R, Kucharik C J, Ramiadantsoa T, Stegner M A, Williams J W, Zhang J and Turner M G 2018 Abrupt change in ecological systems: inference and diagnosis *Trends Ecol. Evol.* **33** 513–26
Ray P A and Brown C M 2015 *Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework* (Washington: The World Bank)
Reyers B, Galaz V, Biggs R, Moore M-L and Folke C 2018 Social-ecological systems insights for navigating the dynamics of the anthropocene *Annu. Rev. Environ. Resour.* **43** 267–89
Rogers E M 1962 *Diffusion of Innovations* (New York: Free Press)
Russill C and Nyssa Z 2009 The tipping point trend in climate change communication *Glob. Environ. Change* **19** 336–44
Russill C 2015 Climate change tipping points: origins, precursors, and debates *Wiley Interdiscip. Rev. Clim. Change* **6** 427–34
Scheffer M, Carpenter S, Foley J A, Folke C and Walker B 2001 Catastrophic shifts in ecosystems *Nature* **413** 591–6
Scheffer M and Carpenter S R 2003 Catastrophic regime shifts in ecosystems: linking theory to observation *Trends Ecol. Evol.* **18** 648–56
Scheffer M, Bascompte J, Brock W A, Brovkin V, Carpenter S R, Dakos V, Held H, Van Nes E H, Rietkerk M and Sugihara G 2009 Early-warning signals for critical transitions *Nature* **461** 53–9
Scheffer M *et al* 2012 Anticipating critical transitions *Science* **338** 344–8
Scheffer B M, Barrett S, Folke C, Green A J, Hughes T P, Kosten S, Nepstad D C, Peeters E T H M and Walker B 2015 Creating a safe operating space for iconic ecosystems *Science* **347** 1317–20
Schellnhuber H J, Carmer W, Nakicenovic N, Wigley T and Yohe G 2006 *Avoiding Dangerous Climate Change* (Cambridge: Cambridge University Press)
Soens T 2018 Resilient societies, vulnerable people: coping with North Sea floods before 1800 *Past Present* **241** 143–77
Sperling D 2018 Electric vehicles: approaching the tipping point *Bull. At. Sci.* **74** 11–8
Steflen W *et al* 2004 Abrupt changes: the achilles' heels of the earth system *Environ. Sci. Policy Sustain. Dev.* **46** 8–20
Steffen W *et al* 2018 Trajectories of the earth system in the Anthropocene *Proc. Natl Acad. Sci.* **115** 8252–9
Steiger R, Scott D, Abegg B, Pons M and Aall C 2017 A critical review of climate change risk for ski tourism *Curr. Issues Tour.* **22** 1343–79
Stommel H 1961 Thermohaline convection with two stable regimes of flow *Tellus* **13** 224–30
Terres J M *et al* 2015 Farmland abandonment in Europe: identification of drivers and indicators, and development of a composite indicator of risk *Land Use Policy* 49
Thornalley D J R *et al* 2018 Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years *Nature* **556** 227–30
Tol R S J 2003 Is the uncertainty about climate change too large for expected cost-benefit analysis? *Clim. Change* **56** 265–89
Van Der Brugge R 2009 Theoretical framework: the multi-pattern concept *Transition Dynamics in Social-ecological Systems* (Rotterdam: University of Rotterdam) *PhD Thesis* pp 57–82
van der Hel S, Hellsten I and Steen G 2018 Tipping points and climate change: metaphor between science and the media *Environ. Commun.* **12** 605–20
van der Meulen G J M 2018 *New Netherlands* (Delft: Delft University of Technology) *MSc Thesis*
van der Ploeg F 2016 Climate change economics: reacting to multiple tipping points *Nat. Clim. Change* **6** 442–3
van Nes E H, Arani B M S, Staal A, van der Bolt B, Flores B M, Bathiany S and Scheffer M 2016 What do you mean, 'Tipping Point'? *Trends Ecol. Evol.* **31** 902–4
Vautard R *et al* 2014 The European climate under a 2 °C global warming *Environ. Res. Lett.* **9** 034006
Vousdoukas M I, Mentaschi L, Voukouvalas E, Bianchi A, Dottori F and Feyen L 2018 Climatic and socioeconomic controls of future coastal flood risk in Europe *Nat. Clim. Change* **8** 776–80
Walker W E, Haasnoot M and Kwakkel J H 2013 Adapt or perish: a review of planning approaches for adaptation under deep uncertainty *Sustainability* **5** 955–79
Wang R, Dearing J A, Langdon P G, Zhang E, Yang X, Dakos V and Scheffer M 2012 Flickering gives early warning signals of a critical transition to a eutrophic lake state *Nature* **492** 419–22
Watkiss P, Hunt A, Blyth W and Dyszynski J 2015 The use of new economic decision support tools for adaptation assessment: a review of methods and applications, towards guidance on applicability *Clim. Change* **132** 401–16
Watkiss P, Cimato F, McGlade K, Quevedo Q, Watkiss M and Troeltzsch J 2018 *D1.4 Co-design and Co-delivery Protocol. Deliverable from the COACCH Project* (under review)
Weitzman M L 2014 Fat tails and the social cost of carbon *Am. Econ. Rev.* **104** 544–6
Werners S E, Pfenninger S, van Slobbe E, Haasnoot M, Kwakkel J H and Swart R J 2013 Thresholds, tipping and turning points for sustainability under climate change *Curr. Opin. Environ. Sustain.* **5** 334–40
Westley F *et al* 2011 Tipping toward sustainability: emerging pathways of transformation *Ambio* **40** 762–80
Wise R M, Fazey I, Stafford Smith M, Park S E, Eakin H C, Archer Van Garderen E R M and Campbell B 2014 Reconceptualising adaptation to climate change as part of pathways of change and response *Glob. Environ. Change* **28** 325–36
Young O R 2012 Arctic tipping points: governance in turbulent times *Ambio* **41** 75–84