ENVIRONMENTAL RESEARCH
LETTERS

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To cite this article: Manjana Milkoreit *et al* 2018 *Environ. Res. Lett.* **13** 033005

Environmental Research Letters

TOPICAL REVIEW

OPEN ACCESS

RECEIVED
14 November 2016

REVISED
16 January 2018

ACCEPTED FOR PUBLICATION
25 January 2018

PUBLISHED
12 March 2018

Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review

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Keywords: non-linear change, tipping points, social-ecological systems, social tipping points

Supplementary material for this article is available online

Abstract

The term tipping point has experienced explosive popularity across multiple disciplines over the last decade. Research on social-ecological systems (SES) has contributed to the growth and diversity of the term's use. The diverse uses of the term obscure potential differences between tipping behavior in natural and social systems, and issues of causality across natural and social system components in SES. This paper aims to create the foundation for a discussion within the SES research community about the appropriate use of the term tipping point, especially the relatively novel term 'social tipping point.' We review existing literature on tipping points and similar concepts (e.g. regime shifts, critical transitions) across all spheres of science published between 1960 and 2016 with a special focus on a recent and still small body of work on social tipping points. We combine quantitative and qualitative analyses in a bibliometric approach, rooted in an expert elicitation process. We find that the term tipping point became popular after the year 2000—long after the terms regime shift and critical transition—across all spheres of science. We identify 23 distinct features of tipping point definitions and their prevalence across disciplines, but find no clear taxonomy of discipline-specific definitions. Building on the most frequently used features, we propose definitions for tipping points in general and social tipping points in SES in particular.

1. Introduction

The increasing popularity of the tipping point concept in both scholarship (Russill and Nyssa 2009) and political and social discourse (Russill and Lavin 2012), combined with increasingly diverse conceptualizations of tipping points across multiple disciplines (Kopp *et al* 2016), currently limit its scholarly utility. Research on social-ecological systems (SES) has contributed to the growth and diversity of the use of the term, treating tipping points as features of SES. Two trends are important to distinguish. First, SES scholars increasingly use the term tipping point to describe the well-known phenomenon of regime shifts in ecological systems. Second, a small number of more recent publications, not only in SES, have begun to refer to non-linear forms of change in social systems, such as economies or resource governance institutions, as social tipping points (STPs), social-ecological tipping points (SETPs), but also social-ecological regime shifts. Some of these publications frame STPs as desirable or necessary to address a range of sustainability challenges (e.g. Westley *et al* 2011) and seek to understand the conditions for creating tipping points in social systems. These trends raise important questions concerning the meaning and appropriate use of the term tipping point in SES research.

Being located at the intersection between the social and natural sciences, SES researchers need to tread carefully when borrowing concepts from other disciplines. Such a move often involves the crossing of ontological boundaries, where the metaphorical use of a concept can mask important differences between two objects of study. The two phenomena included in the analogy should be similar in the sense that they can be characterized by common laws or principles. The success of the analogy depends on whether attributes of tipping points in the target domain can be tested and assessed similar to the one in the source domain (Daniel 1955, Gentner 1983).

However, SES research pays little attention to whether the presumed observation of tipping behavior in a social system is conceptually equal or (partly) different than tipping processes in an ecological system. It remains unknown whether tipping points in natural systems, such as a lake or the climate, display the same underlying mechanisms as tipping points in social systems, such as in financial markets or political institutions. Hence the question whether the social tipping point is not only metaphorically powerful, but also appropriate to describe the phenomenon in question—is it a distinct type of social change? The analytic challenge is confounded by the fact that SES are inherently linked systems, with multiple feedbacks and interdependencies between the ecological and the social system components. Given this fundamentally important framework of linked SES, a separation of the ecological and the social system is generally perceived as counterproductive to the advance of scientific understanding in the SES community. Such a separation contradicts a core tenet of the discipline.

Whilst scholars might perceive the distinction we make here as artificial and counterproductive—questioning whether there could be fundamental, ontological differences between ecological and social systems—this paper aims to create the foundation for a discussion within the SES research community about the appropriate use of the term tipping point, especially the relatively novel use of the terms social tipping point and social-ecological tipping point. We do not ask whether certain types of social system change should be understood as a distinct class of tipping points—that is a matter for future research. Instead we analyze how scholars across multiple disciplines have defined tipping points in general, and how they use the term social tipping points in particular.

For this purpose, we seek to create a fuller understanding of the status quo of the scholarly use of the term tipping point and similar concepts by reviewing existing literature across all scientific spheres. Using a bibliometric approach, we examine temporal trends in terminology, identify different definitions and their components, and explore the corresponding phenomena these definitions address. Based on this review, we discuss the most appropriate use of the concept for the study of SES. To the extent that differences exist between tipping point definitions across disciplines, we identify key definitional features relevant for SES research. We hope to sensitize scholars to potential differences between the phenomena described with the term tipping point, and to encourage a more critical and consistent use of the term in the future. Given that the use of STP and SETP language is at an early stage, this is an opportune time for this discussion.

2. The history of tipping points as a scholarly concept

The tipping point concept traces its origins back to scientific papers in chemistry (Hoadley 1884) and mathematics (Poincaré 1885), which refer to a qualitative change in a system described mathematically as a bifurcation. Bifurcation theory is still used today in mathematics, physics, complex systems science, and related fields.

In the social sciences, tipping points originated much later to address neighborhood dynamics of racial segregation in political science (Grodzins 1957), sociology/urban planning (Wolf 1963), and economics (Schelling 1978). Social scientists began to develop similar concepts of social change without the tipping point language. For example, sociologist Mark Granovetter (1978) uses the term threshold to understand the differences in individuals' decisions to engage in a collective behavior, such as rioting. Another example in social theory is punctuated equilibrium, especially historical institutionalism (Gould and Eldredge 1993). These theories emerged in the 1990s, drawing on evolutionary biology to explain long periods of policy stability that are interspersed with dramatic moments of change (Baumgartner and Jones 1993). Instead of using the typical formalization used in bifurcation theory, social scientists either developed different mathematical models or used the concept metaphorically.

Whether or not it can be attributed to Malcolm Gladwell's book *The Tipping Point* (2000), starting around 2005, the term was widely adopted among climate scientists (Russill and Nyssa 2009, Kopp *et al* 2016) to describe rapid, non-linear change in parts of the climate system. Previously this phenomenon had been referred to with different terminology, such as critical points, but now climate scientists embraced tipping point language, with three papers using tipping point terminology to focus on ice sheet dynamics in the Arctic (Holland *et al* 2006, Lindsay and Zhang 2005, Winton 2006). A 2008 paper introduced the idea of tipping elements in the climate system, defined as subsystems of the climate system that can experience abrupt change, 'triggering a transition to a new state' (Lenton *et al* 2008, p. 1786).

The historical account of the movement of the concept from its origins in mathematics and chemistry to the social sciences, popular discourse and back to mathematical modeling in the climate sciences raises important scientific questions, as summarized by Russill and Nyssa (2009, 337):

> 'One difficulty in assessing the appropriateness of tipping point warnings is the frequent slippage from physical to biological to social referents,…. Is the notion appropriate as a description of the way physical components of the climate system change, or as a means of understanding social behavior, or both? Is it intended as a scientific concept, or as a metaphor?'

The increasingly frequent use of the concept of tipping points in both the natural and social sciences could be scientifically questionable: sociological and political tipping points might be very different phenomena than climatic tipping points, even if both natural and social systems may be subject to rapid qualitative change. If institutional tipping and ecosystem tipping are different 'things in nature'—different ontological entities—scientific language should not treat them as the same. Scientific language should clarify rather than veil potential differences between tipping points in different fields.

This is a challenge SES scholars will have to take up if they want to successfully grapple with dynamics of change in SES and the implications of linkages between natural system components and social system components, which are subject to different modeling challenges. The math applied to one might not transfer easily to the other.

SES scholarship has traditionally used two distinct terms to describe tipping point phenomena: regime shifts (also critical transitions (Scheffer 2009)) and transformations. Regime shifts are large, persistent changes in the structure and function of social-ecological systems (Folke *et al* 2004). Transformations are fundamental reorganizations of a system (Gunderson and Holling 2002, Olsson *et al* 2014) that might involve rapid, non-linear change or not. However, both regime shifts and transformations are the result of a system reaching and passing a tipping point rather than being synonymous with a tipping point. Hence, the use of the term tipping point to refer to these larger processes of change is imprecise.

Currently, regime shifts are generally thought of as undesirable processes that could and often should be prevented (Scheffer and Carpenter 2003), while (deliberate) transformations have primarily been framed as desirable and often guided change processes that communities and societies pursue in the face of sustainability challenges (Moore *et al* 2014). Westley *et al* (2011) have explicitly linked the idea of deliberate transformation to the tipping point concept, which has been picked up by policy makers and diplomats dealing with climate change and sustainable development. Against this background we aim to map and interpret the use of the term tipping point.

3. Methodological approach

We deployed two complementary data collection and analysis protocols in order to create a synthesis of the scholarly use of tipping points from a quantitative and qualitative perspective, using a bibliometric approach. We developed the approach for both the quantitative and qualitative analyses through an expert elicitation process (Ayyub 2001, Swor and Canter 2011). Four of the authors issued a call for scholars with an interest in social tipping points in a network of young resilience scholars. We repeated our invitation to the audience (n = 33) of a session on 'Concepts, Methods, and Measurements of Social Tipping Points,' which we co-chaired during the Complex Systems Conference 2015 at Arizona State University. The call targeted a very specific audience: early career scholars from various disciplines, primarily conducting research on SES and resilience. The respondents joined the lead authors to form the group of experts, whose perspectives guided this analysis (see table S1 for details).

4. Quantitative analysis

4.1. Methodology

We systematically collected and reviewed academic publications that discuss the concept of tipping points and related terms between 1960 and 2016[12]. The study period is tied to our interest in tipping points in SES scholarship, including the decade before the first seminal resilience paper was published by Holling (1973).

We utilized the expert elicitation to create a list of search terms (20) for tipping points or similar concepts of change to be used as strings (see table S2). Database searches were performed using Thomas Reuters' (ISI) Web of Science (WoS), an abstract and citations database of peer-reviewed data, between 15 May and 25 July 2017. For our purpose, WoS was preferable to Scopus despite its more narrow coverage

[12] We excluded existing records for 2017 because the number of publications entered into the database for this year was necessarily incomplete at the time of the analysis.

Table 1. Most frequent search terms, Web of Science. The ten most-reported search terms and the resulting number of peer-reviewed publications. For all searches with results of at least 100 publications, a second search was performed, adding 'AND social' to the search string. As per normal Boolean search rules, the specific phrase within speech marks will be found and an asterisk will highlight any word that begins with the root/stem of the word truncated by the asterisk.

Rank	1st iteration—all search terms	Publication count	Second iteration—select search terms adding 'AND social'	Publication count
1	'regime shift*'	3428	'regime shift*' AND social	223
2	'critical transition*'	1824	'critical transition*' AND social	83
3	**'tipping point*'**	**1718**	**'tipping point*' AND social**	**218**
4	'punctuated equilibrium'	822	'punctuated equilibrium' AND social	82
5	'alternative stable state*'	722	'alternative stable state*' AND social	22
6	'ecological threshold*'	471	'ecological threshold*' AND social	25
7	'state shift*'	425	'state shift*' AND social	15
8	'tipping point*' AND 'climate change'	357	'tipping point*' AND 'climate change' AND social	44
9	'tip point*'	178	'tip point*' AND social	0
10	'critical transition*' AND ecological	143	'critical transition*' AND ecological AND social	28

of journals (Guz and Rushchitsky 2009) due to its stronger historical records (Chadegani *et al* 2013).

Each search was carried out using one of the 20 search terms as a topic. The keywords were searched in title, abstract and keywords. For each string, we recorded the number of publications and then retrieved the available bibliometric information. For eleven terms that returned more than 100 records, we conducted a second-iteration search, adding 'AND social' in order to retrieve more focused results with relevance for the use of 'social tipping point.'

4.2. Results

In total, the 20 initial search terms resulted in 10 354 publications for the time period analyzed. Removing duplicates (n = 852), the final quantitative dataset included 9476 unique publications. Table 1 displays the ten search terms generating the largest number of results and the results for each term after adding 'AND social' to the search string (see supplementary material for a complete list—table S2 available at stacks.iop.org/ERL/13/033005/mmedia). Full records for all publications were downloaded into a dataset, and labelled as per the related search term.

The most popular search term from our honed list of disciplines was 'regime shift*', with 3428 publications, followed by 'critical transition*' with only half as many publications (1824) and 'tipping point*' ranking third with 1718. However, 'tipping point*' publications were much more likely to have a focus on social systems: there were 218 records for the search string containing 'AND social' (12.7% of 1718) compared to 223 'regime shift*' papers (6.6%). The dominant disciplines using the term 'regime shift*' were Ecology (784 papers) and Oceanography (666); 'critical transition*' was dominated by various sub-fields of physics. The majority of 'tipping-point*' publications were in the WoS categories Environmental Science (203) and Ecology (163).

All strings including tipping (tipping point, tip point, tipping element) appeared in 2342 unique records (25%). Specific uses of the term such as 'social tipping point*' and 'climate tipping point*' were found very few times—four and 34 respectively. The combination of 'climate change' and 'tipping point*' was used in 357 publications.

4.2.1. *Temporal developments of terminology*

Figure 1 shows how the prevalence of the concept tipping point began to increase in the early 2000s, growing rapidly over the last decade.

Figure 2 demonstrates the evolution of the five most popular search terms over time. The terms 'critical transition*' and 'punctuated equilibrium' emerged earlier than the others. Publication counts for 'punctuated equilibrium' have stabilized around 40/year, while critical transitions work continues to expand with 202 publications in 2016. 'Regime shift*' and 'alternative stable state*' became established terms in the 1990s; the former has experienced much more dramatic growth than the latter. 'Tipping point*' begins to spread after the year 2000, rapidly increasing after 2004. Since 2011, its annual publication count has been higher than that for 'critical transition*'. Given its late emergence—about a decade after 'critical transition*' and 'regime shift*', its high rank could indicate that its popularity is higher than that of other terms.

5. Qualitative analysis

5.1. Methodology

The aim of our qualitative analysis was to identify differences in the definitions of tipping points across different disciplines. The analysis combined an expert elicitation process (as described above) with qualitative content analysis (for details, see supplementary materials 3).

We elicited submissions of peer-reviewed publications familiar to or used by the expert group (97), manually clustered these according to scientific disciplines, and removed books (nine, see table S3) as well as 17 papers that did not focus on tipping point processes (see table S4), resulting in a final list of 71 papers (see table S5). Table 2 displays the cluster structure and the corresponding number of papers in each cluster.

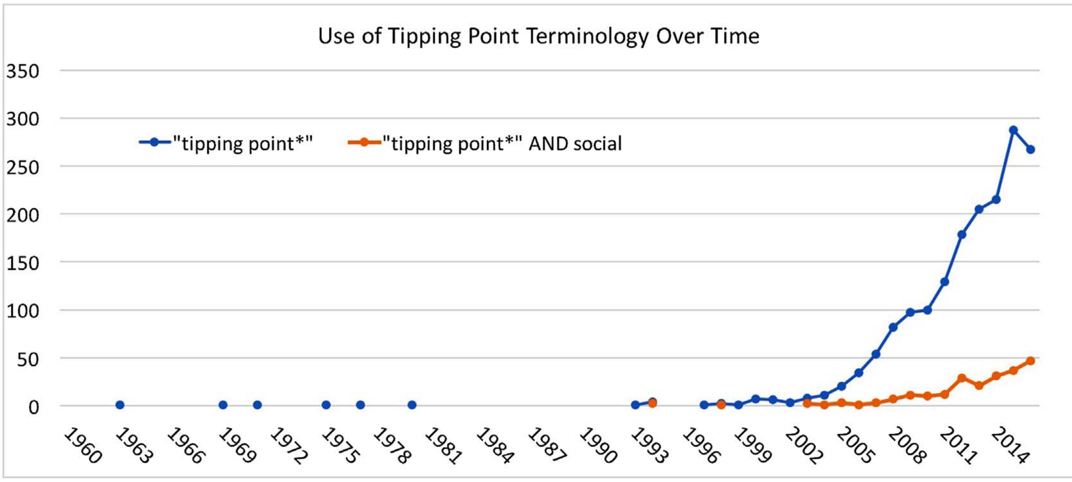

Figure 1. Total publication count for the search strings 'tipping point*' and ('tipping point*' AND social), 1960<2016, WoS.

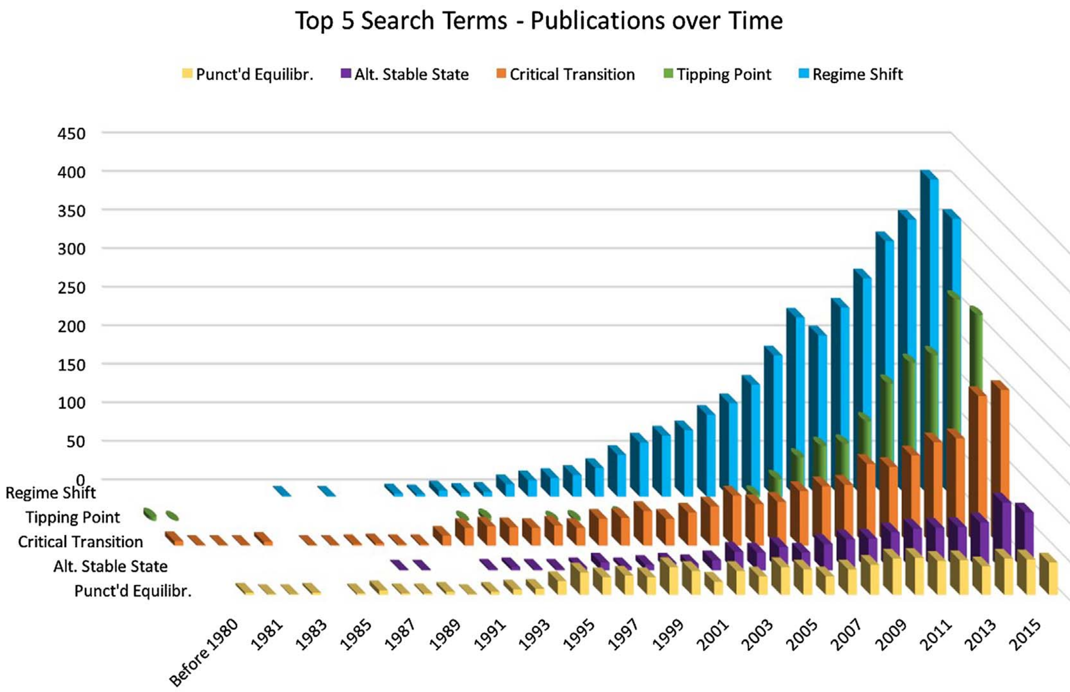

Figure 2. Frequency of occurrence for the six most popular terms in the WoS database between 1980 and 2016. All publications between 1960 and 1979 are displayed in aggregate.

We conduct the content analysis via NVivo. The code-book was developed in three steps. First, we identified a number of theoretically-driven codes to answer three questions: What terminology do authors prefer ('Terminology'), how do authors define tipping points ('Definition'), and which phenomena in nature do they address ('Phenomenon of Interest')? Second, we built on the Russill and Nyssa (2009) analysis of definitions of tipping points used by climate scientists since 2005 to identify an initial list of eleven codes for themes in tipping point definitions (table S6). Third, additional coding terms were added in the process of coding, using a grounded theory approach (Glaser 2017). Grounded theory aims at building theory from social data. The data is usually approached without a pre-existing set of theoretically informed codes or concepts. Instead, coding terms emerge, i.e. they are progressively revealed in repeated rounds of coding and theme identification. The final code structure is included in table S7.

We analyzed the coding results to identify differences and themes in tipping point definitions, the prevalence of themes in each cluster, and temporal changes in the preferred terminology and definitions.

Table 2. Database cluster structure.

No	Cluster		Sub-cluster	Items
1	Complex systems science			2
2	Earth system science	2a	Earth system science general	4
		2b	Climate change science	8
		2c	Land-use change science	2
3	Ecology			9
4	Non-linear social change	4a	General	6
		4b	Archaeology/History	1
		4c	Economics	9
		4d	Opinion dynamics	2
		4e	Philosophy	1
		4f	Politics and governance	6
		4g	Sociology	1
		4h	Transformations/social-technical transitions	4
5	Social-ecological systems/resilience			15
6	Reviews			1
	TOTAL			**71**

5.2. Results

5.2.1. Temporal developments of terminology

In the qualitative database, the term tipping point made its entrance first in the social sciences in the early 1970s discussing neighborhood segregation (Schelling 1971). After decades of dormancy, the term enjoyed almost explosive popularity across multiple social- and natural-science disciplines after 2008.

Non-tipping point terminology for particular change phenomena in both the social and natural sciences (e.g. regime shifts, critical transitions) emerges in the late 1990s, preceding the spread of the term tipping point by almost a decade. Once re-established, the tipping point first becomes a conceptual 'companion,' being used alongside one or even multiple other terms (e.g. threshold and/or regime shift), but referring to the same phenomenon. Only six papers in our database have a 'clean' tipping point terminology, avoiding other concepts. There are signals that after a period of conceptual bandwagoning, the tipping point becomes the preferred term in scientific publications on non-linear change, superseding others. In our qualitative database, it is overall the most frequently used term (59% of papers), followed by threshold (44%), critical transition (30%) and regime shift (20%).

SES research offers a good illustration for this supersedence pattern. SES papers in our database initially use the terminology of regime shifts, thresholds (Walker and Meyers 2004) and critical transitions. The first use of the phrase tipping point occurs in 2013 (Renaud *et al* 2013), and for a while the terminology is used in combination with the existing terms threshold and regime shift. Eventually the tipping point becomes the dominant concept. All three papers in the SES cluster published in 2016 use the term tipping point; only two of these also mention thresholds.

The specific terminology of 'social tipping points' emerges in 2008 in a social science publication by Skrimshire (2008), which made reference to Lenton *et al* (2008) and the concept of climate tipping points. Schellnhuber mentions the lack of evidence to analyze 'social tipping elements' in 2009. SES presents its own adaptation of the concept when moving from 'social-ecological regime shifts' (Lade *et al* 2013) to 'tipping points in social-ecological systems' in 2014 (Broderstad and Eythórsson 2014) and 'social-ecological tipping points (Serrao-Neumann *et al* 2016) in 2016.

5.2.2. Definitions and themes

The analysis identified 23 themes—distinct features of tipping point definitions referring to specific qualities of tipping point phenomena. Different clusters place different emphases on certain themes, but the analysis did not reveal any clearly distinguishable cluster-specific definitions. The supplementary materials contain a list of the top 15 themes, i.e. those mentioned by at least 10% of all papers in the qualitative database (table S8), and sample definitions for each cluster and their respective themes (table S9).

The relative importance of the top eight themes (mentioned in at least 20% of all papers) within and across all clusters and spheres of science[13] is illustrated in table 3 below. We used the ratio of papers mentioning a specific theme in each cluster to establish the importance of themes within and across clusters. This measure has limited power, especially with regard to clusters containing one or two papers only (e.g. Sociology, Philosophy). For this reason, one-paper clusters were removed from table 3.

Multiple Stable States is a common theme across all three spheres of science (social, natural, SES), it is the most popular theme in Earth System Science General (75%), Ecology (78%), Economics (67%), Opinion Dynamics (100%), and SES (60%). *Abruptness* is one of the two most important features in the SES cluster (60%), and is mentioned in at least 50% of the cluster

[13] We combined clusters to create three sets of documents: (1) all non-linear social change clusters formed the set 'Social Sciences,' (2) all three Earth System Sciences clusters, Complex Systems and Ecology formed the set 'Natural Sciences,' and (3) the cluster Social-ecological Systems formed its own set.

Table 3. Popularity of themes across clusters and scientific spheres. This table indicates the popularity of the eight most popular themes in tipping point definitions (mentioned in at least 20% of all papers) across different spheres of science and across different disciplinary clusters. For example, in the cluster Earth Systems, which consists of four papers, the themes Multiple Stable States and Non-linearity were most popular in the sense that at least 75% of the papers in the cluster (three out of four) mentioned these themes.

Popular Theme (appears in min 20% of all papers)	Natural Sciences					Social-ecological Systems	Social Sciences (excluding Archaeology & History, Philosphy, Sociology)				
	Complex Systems	Earth Systems	Climate Change	Land-use Change	Ecology		Non-linear change general	Economics	Opinion Dynamics/ Psychology	Political Science	Transitions
Total number of Papers	2	4	8	2	9	15	5	9	2	6	4
Multiple Stable States											
Abruptness											
Non-linearity											
Feedbacks											
Irreversibility											
Magnitude											
Predictve Challenges											
Disproportionality between Cause and Effect											

Color scheme: Theme appears in min 50% of Papers — *min 50%*, *min 75%*, 100%

items in Complex Systems, Non-Linear Social Change General, and all Earth System Science clusters. *Non-linearity*, which is related to the idea of abruptness, is popular in the clusters Earth System Science General (75%) and Economics (56%), but is not a frequent term in the SES cluster (13%).

Further, we observed differences between clusters that mention only few themes (maximum five) and clusters that rely on many themes (minimum ten) out of the top fifteen[14]. Clusters focusing on few themes only display a high level of convergence across papers, i.e. individual themes tend to mentioned in at least 50% of all papers in the cluster. The opposite pattern (moderate or low convergence) exists for clusters with many themes: different papers mention different themes, and few themes reach the 50% popularity threshold within a cluster.

The pattern few themes/high convergence was observed for the clusters Opinion Dynamics (two themes), Land-Use Change Science (three), and Complex Systems (four). All of these clusters consist of only two papers, which might explain the high convergence: the popularity threshold of 50% is reached if only one of these two papers mentioned a theme. The pattern many themes/low convergence was observed for the clusters Earth System Science (ten themes), Climate Change Science (eleven), Political Science and Governance (thirteen), Economics (thirteen), Ecology (thirteen), SES (fifteen). SES stands out as the only cluster that mentions all of the top fifteen themes. The popularity of each theme varies within the cluster. *Hysteresis* is the least popular (7%), *Multiple Stable States* and *Abruptness* are the most popular with 60% each, followed by *Feedbacks* (53%). SES displays a relatively low convergence across papers: only three of all the fifteen themes covered (20%) are mentioned in at least half of the papers. There is relatively little emphasis on *Nonlinearity* (13%), *Predictive Challenges* (13%) and *Irreversibility* (33%); themes that rank high in other clusters.

[14] Again, we excluded clusters with only one paper from this analysis: Archaeology & History, Sociology, Philosophy.

There are different ways to interpret this pattern of high versus low convergence. The use of many themes within a cluster might indicate a deepening of understanding concerning the phenomenon being studied, i.e. addressing and exploring more of its features. Such an increase in detail might imply an advance of knowledge. Alternatively, it could suggest a lack of focus and large disagreement between scholars concerning the phenomenon in question. Scholars might be using the same terminology to study diverse phenomena or be interested in different dimensions of tipping processes (e.g. causes vs. impacts). In our database, each of these possible explanations could apply to different clusters. For example, among the clusters with many themes, Climate Change and Earth System Science have the highest convergence levels (55% and 60% of the themes used in each cluster are popular). This moderate to high convergence despite the high number of themes (11 and 10 respectively) indicate a deepening of knowledge and increasing agreement among scholars. The opposite is the case in the cluster Political Science and Governance: among its thirteen themes, only one is popular.

Key themes in the group of eight papers that use the terms social tipping points and social-ecological tipping points are *Multiple Stable States* (75%), *Irreversibility* (75%), *Abruptness* (63%), *Magnitude of Change* (50%) and *Predictive Challenges* (50%). However, not all tipping point definitions offered easily fit the patterns described above. For example, philosopher Skrimshire discusses them as significant moments of deliberate social change: 'For climatic tipping points have a social counterpart that cannot be ignored: social and political 'turning points', historic moments of opportunity, 'now or never', social revolution' (2008, p. 3). Within the SES literature, some authors also depart from the standard themes when discussing social tipping phenomena. For example, Serrao-Neuman *et al* state 'In social contexts, tipping points can be defined as a technical or social point in which an indicator shifts 'from an acceptable to an unacceptable condition' (2016, p. 57).

More than a third of all papers in the qualitative database (26) mention or refer in some form to bifurcation theory, but many do so only in passing. Only eleven papers (15.5% of the database) offer a more serious treatment, applying the mathematical formalization of bifurcation theory, identifying and quantifying variables and displaying specific results. These studies are in the clusters Complex Systems (both papers in the cluster, 100%), Earth Systems (two out of four papers in the cluster, 50%), Climate Change (three out of eight, 38%), Ecology (one out of six, 17%) and SES (three out of 15, 20%). Among the remaining 12 papers in the SES cluster, four mention bifurcation theory and sometimes make reference to the theory, but they do not apply it themselves. Other authors, e.g. ecologist Huggett (2005), proceed in a similar fashion.

Not a single social science paper in our database actively uses bifurcation theory in their work. Among the 26 papers that mention the term bifurcation, seven are social science publications. However, the authors rarely use the term with a reference to bifurcation theory or a distinct mathematical model but instead make metaphorical use of the term. For example, Card *et al* (2008, p 182) state in a footnote 'Our definition of a tipping point as a 'bifurcation' has several advantages over this', but the term does not appear elsewhere in the paper. Thelen does not even refer to a tipping process, but a 'bifurcation in the literature' on historical institutionalism (1999, p 387). In one of the earliest publications, Goering states 'The process underlying this racial bifurcation was neighborhood tipping.' (1978, p 68).

5.3.3. Phenomena in nature—the objects of tipping point research

Different fields of science deploy tipping point terminology to study vastly different real-world phenomena. In the natural sciences (Ecology, Climate and Earth System Science), scholars are primarily interested in the tipping of ecological systems, e.g. the eutrophication of lakes, and of larger Earth System components, also called climate tipping elements (e.g. Arctic ice sheets). This research crosses multiple scales of interest, but focuses on a shared mechanism of change: positive, self-reinforcing feedbacks moving a system into a different stability domain. Key research challenges include the limited reversibility of a system to its previous state and significant predictive challenges related to tipping points. Methodologically, researchers distinguish slow and fast variables and work with time-series data for multiple key variables. For some ecological systems data gathering in real time is possible (e.g. lake eutrophication); for large Earth-system components, including the climate, paleontological methods and computational modeling (e.g. of ice sheet dynamics) are deployed.

While initial social science research focused on neighborhood segregation dynamics, the post-2000 wave of research across multiple disciplines is concerned with abrupt and major changes in social, political and economic systems (e.g. financial market crashes, economic crisis, political revolution), especially work on organizational and institutional change, norm shifts and cascades, the spread of beliefs or collapse of trust in social networks, and collective behavior. A small number of papers addresses societies' responses to environmental change, for example, the governance of resource extraction in ecological systems prone to tipping (Sakamoto 2014, Young 2010). Some of these diverse social phenomena might be subject to tipping behavior, but also other (e.g. linear) forms of change. There is no specific focus on positive feedbacks as a mechanism of change, even if feedbacks are at work (e.g. psychological-behavioral feedbacks in neighborhood segregation dynamics). Similar to the natural sciences, this work crosses multiple scales (neighborhood, institutions, states). However, there is less of a concern about irreversibility, because a return to the previous system state is possible in a limited sense, although difficult or often not desirable (e.g. some fads and fashion are cyclical, revolutions can be undone, opinion changes can revert over time). Instead, there is a stronger notion of path-dependency. It is often unclear whether there are actually any specific stable states, how one would identify the shape of the stability landscape and its determining variables.

SES research on tipping points and regimes shifts also addresses multiple different spatial-temporal scales, for example, the relationship between global environmental change and sustainable development, economic, ecological, climatic processes in the Amazon, or the SES that 'represents the Bangladesh south-western coastal zone' (Hossain *et al* 2016, p 429). SES scholarship tends to focus on tipping points in the ecological components of SES (e.g. marine fisheries or freshwater fisheries) that are at least to some extent affected by human behavior (e.g. resource extraction pressures). Methodologically, this work often uses a case-study approach, a range of explanatory conceptual frameworks, but also quantitative modeling, including bifurcation theory (Lade *et al* 2013, Sugiarto *et al* 2015, Biggs *et al* 2009). SES work using social tipping point language are interested either in social-economic collapse following ecological collapse or 'turning points' in the sense of conscious moments of change in response to changing environmental conditions.

6. Discussion

Both the quantitative and qualitative analyses have highlighted similar temporal patterns in the scholarly use of the term tipping points since 1960, especially the term's late re-entry into scholarly discourse compared to similar terms, and a major popularity boost after 2008 in all scientific spheres. In research post-2000, the tipping point is not used to describe a unique phenomenon in nature, but added on to previously existing research with well-established terminology, such as regime shifts and critical transitions. There are weak signals that after a period of 'conceptual companionship' the tipping point becomes the preferred terminology, leading to a decline of the previously dominant term. This pattern is not unique in the history of science; examples include the use of terms ecosystem (Tansley 1935), boundary object (Leigh Star 2010) and resilience (Brand and Jax 2007, Baggio *et al* 2015). While the excitement around new concepts might have positive effects, it also involves risks. Most importantly, the application of the same term to diverse phenomena that were previously studied with diverse terminology might create the appearance of similarity where there is significant difference. Existing differentiation and empirical diversity in the objects of study might be concealed, and diversity in the ways of thinking about non-linear change might be lost. The popularity of a term might lead to homogenization that is detrimental to scientific progress.

Despite its late emergence compared to other terms, and the tendency to combine multiple terms, tipping point was the most popular concept overall in the qualitative data set and ranked third (close to critical transitions) in the quantitative data set. While other terms do not seem to be in decline, their growth might be slowing due to the growing popularity of the tipping point as a synonym.

The analysis revealed substantial definitional diversity and a broad array of themes within the working definitions of tipping points in our dataset. A number of these themes overlap, are related to each other, or are synonymous; in other words, these are not 23 distinct features of tipping points, but different terms or phrases used by scholars to describe a smaller set of tipping-point characteristics. For example, the theme *Structural Reconfiguration* is different than, but closely related to, the idea of *Multiple Stable States*—the latter implies and requires the former. Another example of related themes concerns causality: *External Causes*, *Multiple Causes* and *Erosion of Current Attractor* form a thematic cluster. Further, some themes appear to be more important for establishing the existence of a tipping point, while others refer to aspects of tipping points that are subject to a specific disciplinary interest (e.g. governance implications in Political Science). Given these relationships between different themes and the potential for clustering, redundancy and hierarchy among them, not all 23 themes are necessary to define tipping points.

The analysis also suggests that different disciplines focus on different combinations of themes, but we were not able to identify discipline-specific definitions (i.e. distinct patterns of thematic combinations). However, the frequency (popularity) analysis we presented above offers a first indication of what might be a minimum set of necessary conditions to identify a tipping point. The eight most frequently used themes across all disciplines—without redundancies—can be reduced to four necessary (and potentially sufficient) conditions: **(1) Multiple Stable States** (implying a certain *Magnitude of Change* and a structural reconfiguration of the system), **(2) Abruptness** (also *Non-linearity* or *Disproportionality between Cause and Effect*), **(3) Feedbacks** as system-internal drivers of change between the two system states as well as state stabilizers, and **(4) Irreversibility**. The fourth condition needs to be weakened in the sense that limited reversibility (*Hysteresis*) and *Irreversibility* on a timescale relevant for human societies are sufficient to fulfill that condition. The remaining eighth popular theme—*Predictive Challenges*—is not so much a characteristic of tipping points themselves as a characteristic of tipping point research given current methodological and data gathering challenges. Figure 3 illustrates this differentiation between necessary conditions in the center of the concentric circles, and sets of additional themes grouped around these necessary conditions. The reasons for grouping certain themes and their presumed distance from the circle's center all raise questions for future research.

Figure 3. Necessary and non-necessary components of tipping point definitions: The four necessary conditions for defining a tipping point form the center of these concentric circles. Other themes can be grouped (e.g. multiple themes related to causality) in additional circles. These circles' proximity to or distance from the innermost circle might depend on additional criteria that specify their relevance for defining and understanding tipping points.

Based on these four minimum conditions, we suggest that tipping points *in general* can be defined as the point or threshold at which small quantitative changes in the system trigger a non-linear 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. This new state can be distinguished from the original by its fundamentally altered (positive and negative) state-stabilizing feedbacks.

Applying this general definition to social tipping phenomena in SES requires a number of additional specifications. Importantly, the tipping point has to take place in a social system, but be linked in some meaningful way to an ecological system change. That does not preclude social drivers or causes. Whilst a social tipping point with purely social system drivers and outcomes is of course possible (e.g. widespread opinion changes on same-sex marriage), this kind of STP would not necessarily be of interest to SES scholars. Therefore, a social tipping point can be defined as a point within an SES at which a small quantitative change inevitably triggers a non-linear change in the social component of the SES, driven by a self-reinforcing positive feedback mechanisms, that inevitably and often irreversibly lead to a qualitatively different state of the social system. Due to the interconnectedness between social and ecological system components, crossing a social (or ecological) tipping point leads to a qualitatively different SES, which is characterized by a different set of stabilizing positive and negative feedbacks.

This proposed definition offers an opportunity to narrow the focus of future SES research on STPs. Our analysis revealed that SES scholarship uses all of the 15 most popular themes with low convergence across papers. Advancing knowledge on STPs and coherence within SES research would benefit from a more clearly defined set of necessary and sufficient conditions, as we attempt to present above. These conditions would create much needed clarity by allowing researchers to distinguish cases of change that qualify as tipping points from those that do not. A focus on the four characteristics we emphasize above could be complemented by two or three additional ones that are of special interest to SES scholars. These additional features could include *Magnitude of Change* (as well as *Impact Severity*), which is important to distinguish exceptional, infrequent but high-impact events, delineating tipping point change from other forms of change, and drawing policy attention. Work on *Predictive Challenges* is already progressing in SES with regard to early warning signals for regime shifts in ecosystems (Scheffer *et al* 2009, Dakos *et al* 2012, Bauch *et al* 2016) and could be expanded to STPs.

However, even if we assume that STPs are ontologically similar to climate tipping points or ecological regime shifts, and hence can be defined as we have proposed, it is important to note that STPs require a different set of methodological approaches than natural science research on tipping points. Social systems have a number of characteristics that do not exist in an ecological system, decreasing their regularity compared to ecological systems, limiting comparability across locations and hence their predictability. These characteristics include phenomena such as power and inequality, agency, reflexivity, decision-making and strategic behavior at individual and collective system scales. The continuous collection of time-series data in a social system that would enable the observation and measurement of non-linear change, feedbacks and different stable states is challenging, if not impossible given currently available social scientific methods and approaches. If the relevant variables can be identified, they are often hard to quantify and measure over time. Even if they can be measured, continuous data collection for a specific system over years or decades is rare and would be extremely expensive. Some of the relevant social system variables include cognitive and emotional states of actors or institutional decision-making processes subject to political contestation, value judgements and other social processes that present significant data collection problems. Social scientific methods, such as interviews, surveys, process tracing, ethnography, or document analysis tend to be spotty, incomplete and not able to offer a sufficient, continuous database for quantitative tipping point analysis.

For instance, compare the possibility for observing an ecological or social tipping point in a community of resource extractors, such as a fishing village. Researchers could track variables related to the fishery, including fish stock and harvest size, water pollution, water temperature and state of the local reef, which would enable them to identify an ecological regime shift, leading to the potentially irreversible collapse of the fishery. An STP in the same village would be harder to determine because it would require measuring state variables such as identity or community values, but also somewhat easier-to-observe variables related to behavior. For instance, if fishermen cease to fish over time (maybe motivated by a decline in the fish stocks), and start taking up other income-generating activities, the community's identity as a fishing community may shift irreversibly to a different social state, altering the social-ecological feedbacks (e.g. loss of fishing knowledge, no investments in fishing assets etc.).

This methodological challenge might be related to a specific difference between tipping point research in the natural and social sciences we identified above. Natural scientists (especially in Earth system and climate science), complex systems scholars, and a small number of SES scholars (Lade *et al* 2013, Sugiarto *et al* 2015, Biggs *et al* 2009) apply bifurcation theory when studying tipping points, whilst research in the social sciences and the majority of SES work tends to use the term more loosely and metaphorically, lacking a formal or mathematical model. Of course, there are exceptions to this observation, both inside and outside of our limited dataset. For example, work in economics and sociology has developed different mathematical models to study tipping points (e.g. Sakamoto 2014). However, attempts to apply Poincare's math to aggregate social behavior in the social sciences and SES remain limited, leaving the question unanswered whether tipping points in natural and social systems are in fact similar, i.e. operating with the same underlying mechanisms of feedback-driven non-linear change.

7. Conclusion

We have explored the scholarly use of the tipping points concept across all spheres of science over the last five decades with the aim to discuss the appropriate use of the term in SES research, especially with regard to social tipping points. Our research found that the tipping point concept is applied to a vast array of change processes, ranging from ice sheet dynamics to societal transformations, which might mask ontological differences between these diverse phenomena. Concerned about the pattern of terminological replacement—the use of tipping point language instead of previously existing terms—and its potential effects on the quality of science, we encourage researchers to critically assess their terminological choices and avoid 'conceptual amnesia'.

Despite the historical roots of the concept in mathematics, very little work outside the natural sciences and SES uses mathematical models and bifurcation theory. SES scholarship could make a significant contribution to this debate, while addressing the lack of definitional focus and rigor, by applying existing mathematical models to the study of social tipping points. If one assumes that natural and social systems are ontologically similar enough to render the tipping point more than a conceptual metaphor, it should be possible to apply the same mathematical construct to study both, identifying slow and fast variables, underlying causal mechanisms and feedbacks, measuring and quantifying relevant variables. If one assumes STPs to be ontologically different, this could be explicitly formalized in the mathematical treatment of the specific phenomenon in question, for example, by incorporating agent based approaches to represent heterogeneity in agency and power dynamics, or unambiguously identifying the social mechanisms that are absent in the ecological counterparts of STPs (e.g. Alshams *et al* 2017). However, whether it is possible to apply these tools to social and social-ecological change phenomena remains unclear and is a subject that requires future research. Establishing such similarities would be welcome news for work in SES, which seeks to study linked natural-social systems as a single unit. More generally, SES researchers need to tend to the question whether there might be differences between tipping processes in ecological and social systems.

To conclude, we have proposed a unifying definition for tipping points, building on the most frequent themes identified in our analysis: a tipping point is a threshold at which small quantitative changes in the system trigger a non-linear 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. This definition establishes a minimum set of four constitutive features of tipping points that apply across disciplines (multiple stable states, non-linear change, feedbacks as driving mechanism, limited reversibility). If these four essential characteristics are given, the use of the term tipping point is justified. We have also proposed a definition for social tipping points specifically for use in SES scholarship. Future work in this area should include the application of these definitions to case studies of tipping points in the existing SES literature, and also within new research on tipping points in SES.

Acknowledgments

Research for this paper was not supported by any grants. We are grateful to the Department of Community Sustainability, Michigan State University; the Julie Ann Wrigley Global Institute of Sustainability, Arizona State University; and the Wageningen University & Research Investment theme Resilience (KB-29-006-003) for supporting the publication of this work.

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