Principles for a Case Study Approach to Social Tipping Points

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Abstract Recent interdisciplinary study has led to significant conceptual advances and a broad empirical evidence base for ecological and climate tipping points. However, the literature has yet to present convincing empirical case studies of social tipping, as the data-driven identification of social tipping points remains a challenge. Arguing that the barriers to such empirical research are largely methodological in nature, we develop methodological guidance to identify social tipping processes in social-ecological system case studies, based on four key elements—multiple stable states, self-reinforcing feedback dynamics, abruptness, and limited reversibility. We apply our approach to food system changes linked to the Flint Water Crisis between 2010 and 2020. We identify seven principles that can simultaneously serve as a seven-step process for social tipping point analysis in any social-ecological system. We highlight two major challenges: the limited availability of high quality, longitudinal social data, and the possibility that value-driven social processes tend to curb abruptness and non-linear change. Utilizing the seven prin-

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ciples to study historical, ongoing, or anticipated cases of social tipping processes could facilitate a deeper understanding of the conditions and limitations of non-linear social change and, therefore, inform efforts to facilitate change towards more sustainable futures.

Keywords Social tipping points · Case study · Qualitative methods · Food systems

1 Introduction

Over the last decade, the use of the term tipping point has dramatically increased across the natural and social sciences, including the social-ecological systems (SES) literature (Lauerburg et al., 2020; Milkoreit, 2023; Milkoreit et al., 2018). Concerns about undesirable non-linear change have been driving tipping point research in the natural sciences, especially in ecology and climate science, where scholars increasingly focus on challenging questions of predicting and avoiding ecological regime shifts and Earth system tipping points (Martin et al., 2020; Swingedouw et al., 2020). The parallel discussions in the social sciences have been following a different logic, exploring the effects of natural tipping dynamics on social systems or feedbacks between them (Howard & Livermore, 2021). First, there is a concern with the social impacts of Earth system and ecologic tipping processes, e.g., economic shocks (Kopp et al., 2016) or migrations. Second, there has been growing interest in generating non-linear change to counter and prevent potential Earth system tipping points, e.g., behavior changes that contribute to decarbonization, and, more generally, to create more sustainable relations between humanity and the biosphere (Egerer et al., 2021; Kull et al., 2018; Tàbara et al., 2018). The concept of anticipatory, deliberate, and desirable social tipping processes has led to calls to identify social tipping points (STPs) that could support necessary, rapid social system changes, e.g., in the process of decarbonization (Farmer et al., 2019; Lenton, 2020; Otto et al., 2020; Sharpe & Lenton, 2021).

While significant conceptual-theoretical progress has been made in the scholarship on social tipping, complex interactions within socio-ecological systems have so far prevented a systematic understanding of social tipping dynamics, and therefore empirical evidence of such dynamics remains scarce. Our aim is to advance the study of social tipping by developing methodological guidance for empirical, case-study based research to identify historical instances of STPs in social-ecological systems, especially their mechanisms of change. After a brief review of current methodological approaches and methods-related discussions in the literature, we use the Flint Water Crisis as an exemplary case study for a STP analysis to develop a set of principles that can guide social tipping case study research in a wide variety of systems.

2 Defining Social Tipping Points Through Common Criteria

Social tipping points in a sustainability context—those occurring as a consequence or in anticipation of Earth system or ecological tipping points—need to be studied through a social-ecological systems lens (Tàbara et al., 2021), thus social tipping refers to small initial changes in social system dynamics that trigger a nonlinear change driven by feedback mechanisms and lead to a qualitatively different state of the social-ecological system which is hard to reverse (Milkoreit et al., 2018; Winkelmann et al., 2022). This definition foregrounds four aspects of a tipping dynamic that inform our methodological approach and require empirical evidence: multiple stable states, abruptness, feedback dynamics as drivers of change, and limited reversibility. These four components have been characterized differently across different branches of literature (van Ginkel et al., 2020). Here, we present broad definitions applicable in social-ecological systems scholarship (Milkoreit, 2023).

- **Multiple stable states**: The stability of a social-ecological system can be defined by the capacity to remain in a limited and bounded state space with certain structures and functions when the system is subjected to a perturbation due to balancing (sometimes referred to as negative) feedback dynamics (Walker et al., 2004). However, multiple stable states have been demonstrated for many ecological systems, e.g., lake eutrophication (Scheffer et al., 1993), ice sheet collapse (Calov & Ganopolski, 2005), or desertification in drylands (Rietkerk & van de Koppel, 1997). A tipping process involves the system restructuring its core components and their relationships, moving from one stable state to another and altering the system's identity.

- Social systems can also exhibit multiple stable states in the sense that they can be configured in different ways. Key examples include societies before and after a political revolution or economic sectors before and after the emergence of a new technology (e.g., electricity generation before and after the spread of solar power technologies). Social systems are more likely to exhibit more than two possible stable states due to their complexity (Winkelmann et al., 2022).
- **Positive feedback dynamics as a driver of change**: As outlined above, feedback dynamics play an important role in creating both stability and change in social-ecological systems. Negative feedback dynamics maintain the current state while strong self-reinforcing (positive) feedbacks drive the establishment of alternative stable states (van Nes et al., 2016). A self-reinforcing feedback loop leads a system to respond to an incoming signal (e.g., disturbance) in a way that amplifies the signal (Meadows, 2008). With each iteration of the feedback loop, the social-ecological system moves further away from its original ability to perform its core functions, eventually moving to a stable state with different functions.
- Positive and negative feedback also exists in social systems. A number of positive feedback mechanisms that could play a role in tipping processes include social contagion, information cascades, and economics of scale (Lenton et al.,

2022; Sharpe & Lenton, 2021). Geels and Ayoub (2023) identified a set of 'interacting feedback loops' that cross political, economic, and technological domains, while Strauch (2020) looked at positive feedback dynamics across multiple scales within the multiple-level perspective theory of socio-technical transitions.
- **Abruptness**: Abruptness or non-linearity relates to the speed of change, more specifically to an exponential rate of change during the tipping process as compared to the general 'background' speed of the system in question (Bestelmeyer et al., 2011). To measure abruptness requires longitudinal data from which both rates can be quantified or at least approximated. Then abruptness may be assessed in different ways: for instance, Boulton and Lenton (2019) proposed to detect abrupt shifts in time series by analyzing significant changes in the gradient of the series.
- Abruptness in social systems is challenging to characterize empirically, but similar to natural systems, fast and slow change processes can be differentiated. Theories like punctuated equilibrium in institutional change grapple with these temporal qualities of the change process (Gould & Eldredge, 1993).
- **Limited reversibility**: While irreversibility is not a strict requirement (Winkelmann et al., 2022), change generated by a tipping dynamic tends to be hysteretic, i.e., returning to the initial stable state is difficult. Hysteresis implies that the changes persist even if factors that contributed to them are removed or returned to their pre-tipping conditions (Dakos et al., 2019).
- In social systems, hysteresis can be observed, e.g., when policies that foster the expansion of a new industry (e.g., feed-in tariffs in the German electricity market) are removed, the subsidized industry continues to grow without this driver because it has passed a critical threshold of maturity after which it is competitive enough to sustain itself.

An extensive body of research has identified these characteristics of tipping processes in the ecological components of social-ecological systems, but while empirical work on social tipping has been expanding rapidly, it remains scarce and is often directed at identifying and fostering future tipping processes (Lenton et al., 2022; Tàbara et al., 2021) rather than studying historical instances of social tipping.

3 Methodological Approaches to the Study of Social Tipping

The expanding scholarship on social tipping is driven by a diverse set of methodological approaches. Prominent among these are sophisticated dynamic modeling studies, including agent-based models (Kaaronen & Strelkovskii, 2020), that are usually based on theoretical-conceptual assumptions, but have no foundation in empirical observations of social-ecological system behavior (Mathias et al., 2020; Wiedermann et al., 2020). A growing body of work explores tipping in beliefs, i.e., the spread of social norms, and corresponding behaviors, with primarily lab-based experiments (Andreoni et al., 2021; Berger, 2021; Centola et al., 2018). The key objective of this work is to predict how many “committed individuals” (Andrighetto & Vriens, 2022) are needed to reach a threshold in norm adoption or behavior change within a community. While these approaches often do not identify feedback dynamics, measure abruptness, or engage with the question of hysteresis, Andrighetto and Vriens argue that insights from this type of experimental work could be fruitfully combined with computational modeling to create empirically calibrated agent-based models that could provide insights into social tipping mechanisms and dynamics. Other methodological approaches to the study of social tipping include network models, regression analysis and other statistical tools.

In the small but growing literature on empirical approaches to studying tipping dynamics, several useful methodological approaches and research challenges are becoming apparent. Multiple studies recognized the need for deliberate system bounding and description in the early stages of a case study analysis and tend to rely on participatory approaches for system modeling or mapping exercises (Lenton et al., 2022; Murphy et al., 2021; Riekhof et al., 2022). Researchers make important choices at this stage (e.g., regarding units, scales, processes to include and exclude), and scholars emphasize the corresponding need for reflexivity and transparency (Tàbara et al., 2021). Efforts to study social tipping empirically tends to rely heavily on the distinction of different system scales, including temporal scales, and cross-scale interactions. A central challenge consists of the identification of different system states, which cannot be easily derived from the different states of individual units (system components). Hence, system state descriptions have to include relationships between units and dynamics. Further, this early work recognizes the challenge to identify key driving variable(s) in complex systems and the need to identify positive feedback dynamics as drivers of change (Lenton et al., 2022).

While these advance methodological thinking for ongoing/anticipatory case studies, they largely ignore the need for and challenges of historical case studies—efforts to identify whether, how, in which systems and under what circumstances social systems have tipped in the past. This requires a different research strategy, which is our focus here.

What is lacking are convincing historical case studies of social tipping that can demonstrate whether, how (mechanisms) and under what conditions social tipping dynamics have occurred in the past. A case study approach can create in-depth understanding of a social-ecological system (Feagin et al., 1991), although it may not result in generalizable findings that apply to other contexts. We use a case study to develop methodological advances for the operationalization of tipping points in social contexts.

4 Our Methodological Approach

Considering the four characteristics outlined above as a minimum, non-exhaustive set of criteria for establishing a tipping point, we applied them in a historical case analysis of the Flint water crisis. The Flint Water Crisis resulted from a switch from

Detroit City water to the Flint River on April 25, 2014 (Clark, 2018). Enacted by a non-elected Emergency Manager, water was no longer properly treated which resulted in the systematic poisoning of residents as they were exposed to high concentrations of lead and bacteria (Hanna-Attisha et al., 2016). As a result, both Flint community members and external media often discuss the Water Crisis as a tipping point across a range of social and ecological variables, many of which have implications for food security in Flint e.g., in contaminant concentrations (Smith, 2019), public health (Hanna-Attisha, 2017), trust in government (Hughes, 2021), and economic development (Hanna-Attisha, 2017).

Previous analyses based on primary and secondary data from Flint over an extended time period have demonstrated that the Water Crisis caused a reorganization of the food system (Hodbod & Wentworth, 2021). Here, we use a similar interdisciplinary and longitudinal dataset to support a choice of tipping point candidates and independent variables that would influence them. Observed changes in these are then explored through a tipping point framework.

The case's complexity allowed us to identify multiple tipping point candidates. Below, we describe our analytic process and insights for one of these in detail: the food system. Given our purpose here, the analytic findings are less important than the process of generating them. Tracing and reflecting on our methodological and analytic experience, we describe likely typical patterns and challenges of a case study approach to STP research. Integrating insights from this experience and the expanding literature on the methodological challenges of studying STPs, we develop principles that can facilitate and support future case study work.

5 Operationalizing Social Tipping Points

5.1 Case Study Selection

Case study analyses begin with the identification of one or more suitable case studies. Typically, this will be a historical case study, i.e., the change process has concluded or is in its final stages. The existing scholarship on positive tipping rarely uses a historical approach; more work of this kind has been attempted by scholars of social innovation and social-ecological transformations (Olsson et al., 2008; Spielmann et al., 2016; Westley et al., 2017). Instead, current scholarship on social tipping focuses on systems where stakeholders seek to foster tipping processes. Rather than seeking insights from past tipping processes, this work is transdisciplinary, future- and solution-oriented (Feola, 2015).

If researchers take a more conventional historical approach, several challenges already arise at this early stage of case selection: detecting a social phenomenon with at least superficially perceived abrupt change and ensuring that data is available or can be collected for potential variables of interest. Longitudinal data will be needed to describe the social system pretipping and post-tipping and with a high-enough resolution to allow for the analysis of the speed of the change process.

We selected the Flint Water Crisis as a case study context. Based on existing data and prior research (Flint Leverage Points Project (FLPP; Gray, 2020)), we had reasonable grounds to believe that several rapid changes had occurred in a distinct time period in the Flint community. We had to make decisions regarding the specific social-ecological system to focus on (e.g., food system, water supply, local economy, health care, politics, …) and the temporal bounding of our study (i.e., number of years before and after the Water Crisis). We had to consider that different 'candidates' of tipping processes existed in different social domains, each with different temporal characteristics. For example, rapid changes in the Flint economy occurred long before the Water Crisis in relation to the closure of General Motors facilities and the exit of the automotive industry from the region. Focusing on the city's food system, we hypothesized that the Water Crisis had contributed to the reorganization of Flint's food system into a more equitable and food-secure state, and that this change had followed a tipping pattern.

5.2 Bounding the System

Next, we sought to identify the spatial, institutional, and temporal boundaries of the system of interest (Resilience Alliance, 2010). While the boundaries of ecological systems and their exogenous drivers can often be defined with reasonable clarity (e.g., lakes, ice sheets), bounding social systems is generally more difficult due to their higher complexity, connectivity across scales, multiple system interdependencies, and unclear causality patterns (Arias-Arévalo et al., 2017). Additionally, social-ecological systems include human agency, which can affect whether system's tip or not as well as affecting levels of hysteresis (Winkelmann et al., 2022). Nevertheless, (likely iterative) bounding efforts provide needed constraints for the analysis. Riekhof et al. (2022) introduce the concept of windows of tipping point analysis in which they bound the system of analysis at multiple scales to allow analysts to zoom in and out in order to define the elements of analysis, the temporal scale of relevance, the rate of change, the relationship between system components and the multiple possible states, among other items. This is analogous to the bounding we use in the Flint case as well as the pre-tipping and post-tipping descriptions identified below.

We bound Flint's city-scale food system, demarcating related systems and processes, and deliberately excluding some from the analysis. For example, we determined some water-system related variables were relevant for the food system (e.g., availability and quality of potable water), while others (e.g., water management, infrastructure) were not (Hodbod & Wentworth, 2021; Wentworth et al., 2022). However, given the nested nature of food systems, Flint is dependent on regional and international food production, trade, and transport. We used county boundaries to distinguish food produced within and outside the system given better data availability at that scale, while recognizing that the city of Flint only represents 24% of the Genesee County population (Wentworth et al., 2022). This choice influenced institutional boundaries, which consequently included institutions at the county, city, and neighborhood scale. We selected temporal boundaries based on data availability from the FLPP (1950–2020), focusing initially only on the most recent decade (2010–2020) to study the effects of the Water Crisis.

5.3 Pre-tipping and Post-tipping System Descriptions

It is valuable to create qualitative and/or visual descriptions of the presumed pre-tipping and post-tipping system states early in the analysis, and to update these after each step of the process. These description or maps should include the identification of key system components and their relationships (similar to steps 1 and 3 suggested in Riekhof et al., 2022), stabilizing feedback effects, and resulting functions, to provide insight regarding the existence of multiple stable states. A comparison of the system states before and after the change process is central for assessing whether the system has undergone structural reorganization, i.e., whether the identity of the system has changed.

System descriptions are highly dependent on the level of observability. Often, social scientists use indicators as proxies for complex variables characterizing the social state they want to track. For instance, the Gini index is used to quantify inequalities in a population. However, the resulting dynamics of the social system can be impacted by this observability, which may be biased by the observer. Therefore, it is crucial to consider and understand the limitations of observability when describing social system dynamics.

Identifying and describing distinct stable states involves temporal descriptions and corresponding observability issues (see step 2 suggested in Riekhof et al., 2022). During which time period (for how long) did the initial stable state exist? When did the change process start and when was the current or new stable state established? How do these time horizons relate to the study and observation period? The concept of stability depends on the observation timescale given that we cannot "prove" system stability in the absence of mathematical models. Therefore, it is important to consider multiple stable states according to the timescale of interest. Further, the question of irreversibility is a matter of time. As Riekhof et al. (2022, p. 3) observe, "If a period is chosen sufficiently long, most states become reversible, but only considering a long-enough time period may reveal different states in the first place."

System descriptions should contain how actors and their interactions form a social structure—shared culture, values, norms and beliefs with a shared goal, objective, or function (Parsons, 1991). In many cases researchers might find it easier to create a post-tipping system description first, since this might be the current system state. Here, we present our post-change system description and provide some comments regarding its differences to the pre-change state. We also developed a conceptual model to aid our understanding of important system components and processes.

Food systems consist of a set of activities broadly summarized as production, processing, distribution and consumption, pursuing three broad outcomes—food security, environmental security, and social welfare (Ericksen, 2008). We started a post-tipping description with key actors and their relationships, using the results of stakeholder mapping by FLPP which identified four groups in Flint's food system—consumers, commercial actors, supplemental actors (i.e., non-profits), and governance actors representing the city, county, and state, as shown in Fig. 1.

Figure 1 shows consumers tended to have extremely centralized networks, with multiple connections with commercial and supplemental food system actors. The latter two actor groups had more complex relationships with each other and the governance actors. The primary interaction modes included the exchange of food (for cash in the commercial sector or through public or non-profit supported free food programs) and information (i.e., between city government offices and non-profits). After reviewing the stakeholder mapping data and associated qualitative data from the conversations with community members while mapping, we decided that flows of food through commercial actors (i.e., supermarkets) were less

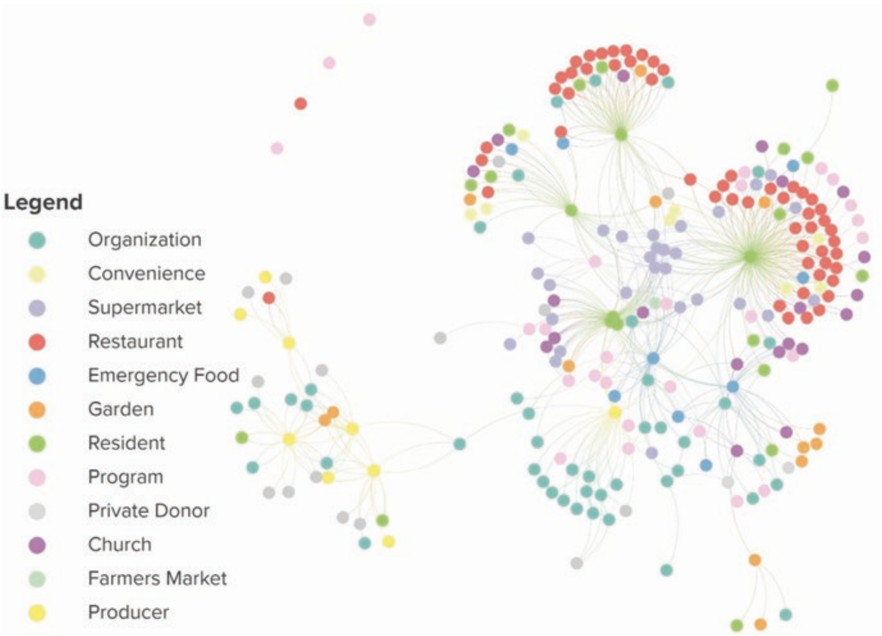

Fig. 1 Combined stakeholder map, created in Kumu.io from ten mapping workshops in Flint showing social interdependencies within the food system. The main cluster shows consumer groups (green) are linked with both commercial and supplemental actors, but that they are poorly linked with the local food production system (bottom left top cluster). Relationships with governance actors are indirect, through the programs they fund

indicative of food security than flows through supplemental actors (i.e., the Food Bank of Eastern Michigan), so we moved forwards with a focus on the supplemental and emergency food distribution.

Actors identified 16 core values and goals for the Flint food system, including food security but also social welfare (i.e., economic opportunity, comfort, safety) (Belisle-Toler et al., 2021). The current (post-tipping) food system was not perceived to support all these values, especially the overarching goal of food security. However, neither did the pre-tipping system, which was perceived to have a different social structure, with more competition over fewer financial resources in the supplemental system. To create a full pre-tipping system description, we examined key variables using longitudinal data.

5.4 Key Variables

Informed by the current system description, we selected key variables that could be subject to or indicators of rapid change. Ecological tipping point (regime shift) analysis often rely on measurements of a single variable that causes non-linear changes in the system once it reaches a threshold, such as levels of phosphorous in a lake eutrophication process (Carpenter et al., 1999), fish population (Cooper et al., 2020), or human population growth and land clearance (Brandt & Merico, 2013). Although at times the behavior of complex systems approaching a tipping point can be dominated by one single control variable (Lenton et al., 2022), in real world scenarios multiple, interacting, variables may be contributing to the tipping process by accelerating or hindering it (Winkelmann et al., 2022). Hence it becomes fundamental to identify the key control variables and their interaction, and, at the same time, confining the analysis to a manageable number (3–5, as per suggestions for other social-ecological systems analyses (Gunderson & Holling, 2002)). Balancing the complexity/simplicity is thus a key task if we are to assess a tipping process without being overwhelmed by information. Further, studies looking at single variables and tipping points are often based on system dynamics or agent-based models, however, assessing STPs requires multiple methodological approaches combining both quantitative and qualitative data (for qualitative longitudinal data, see Calman et al., 2013). To derive key variables of a system of interest it is then necessary to develop a system map, often with co-participation of stakeholders and experts of multiple disciplines (Lenton et al., 2022; Popa et al., 2015; Singletary & Sterle, 2020).

In the Flint case study, we moved in multiple iterations from a long list to a short list of food system variables that would explain the impact of the Water Crisis on food system outcomes, considering the availability of longitudinal data given it was often the limiting factor. We found that our conceptual model—part of our system description—was particularly helpful in identifying relevant variables.

We settled on food security rates and their key independent variables—poverty rates, resident's autonomy, trust between key actors, inflow of food-program funds, and pounds of food and water distributed through assistance programs as key

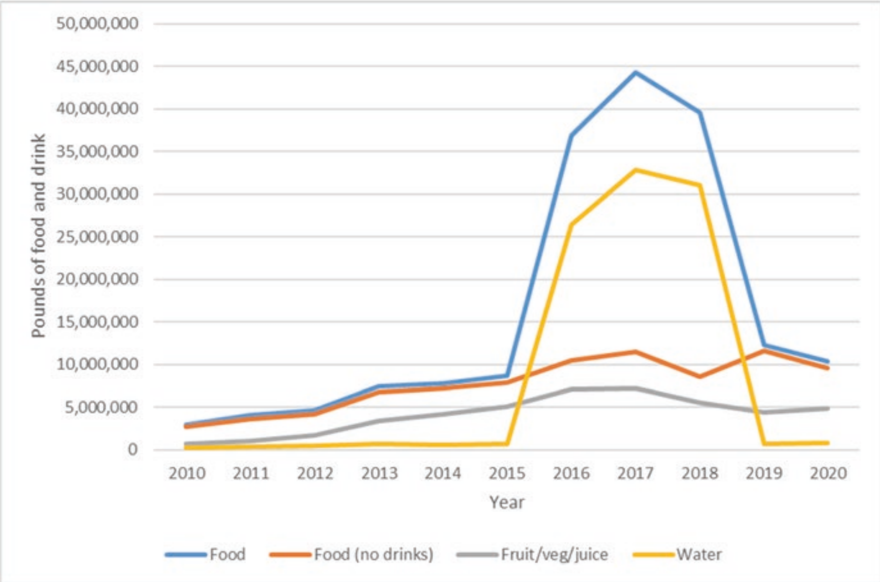

Fig. 2 Distribution of food from the Food Bank of Eastern Michigan in 2010–2020 increased rapidly in 2015, with the bulk of the increase in the distribution of water, but some increase proportionally in fresh fruit and vegetables and their by-products

variables. Some of these (i.e., pounds of food and water distributed) could be analyzed for shifts in trend. For example, Fig. 2 shows that in 2016–2018 the provision of supplemental and emergency food by the Food Bank of Eastern Michigan in Flint jumped drastically (326%). Bottled water accounts for most of this rapid increase as consumption of mains (tap) water was first under a 'boil water advisory' and then not trusted, although food provision did continue to increase. However, this change was temporary and distribution levels returned to pre-crisis levels in 2019.

5.5 *Tipping Dynamics*

Synthesizing the longitudinal food system dataset allowed us to add more context to the pre-tipping and post-tipping system descriptions, in particular regarding the extent of functions such as distribution of food and food security. Expanding our conceptual model, we integrated the independent variables to demonstrate the core relationships between these components (Fig. 3).

We created a table with the four tipping criteria and used the system descriptions and datasets (2010–2020) for the independent variables to assess whether all criteria were met during the study period.

We first explored the presence of multiple stable states. Our analysis revealed that the Water Crisis had triggered a reorganization of the actor relationships and

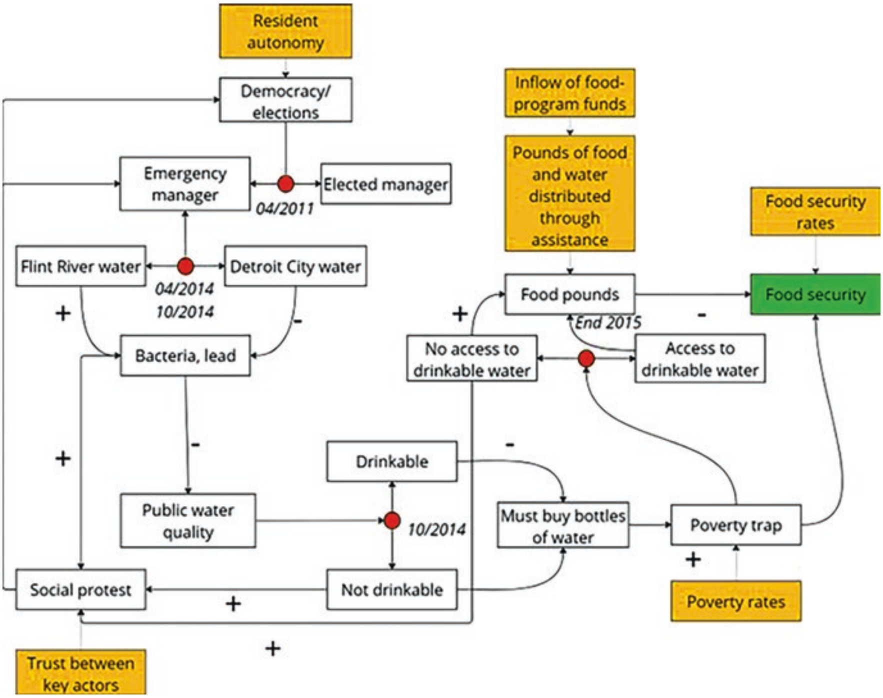

Fig. 3 Our conceptual model of potential tipping points that would influence the Flint food system, with independent variables in yellow and the dependent variable in green. Red points correspond to key-events that potentially tipped the dynamics of the system

institutional components of the food system, altering the flows of funds, food, and information in the city. Increased levels of funding coming into Flint after 2015, mostly from philanthropic organizations and to a lesser extent the government (Hodbod & Wentworth, 2021), supported and triggered collaboration between nonprofits where there previously had been competition, which increased distribution of food and bottled water and information about lead-mitigating foods. Nevertheless, food security rates did not change significantly during this period (Feeding America, 2023), indicating that other structural elements related to food access remained stable, likely poverty given per capita personal income rates were declining during this period, both shown in Fig. 4. Given these mixed results the lack of restructuring of the system identity while maintaining food security, we concluded that the food system as a whole had not transitioned between two stable states.

Regarding abruptness, our dataset (including primary data from stakeholder interviews and timelining) demonstrated rapid change in certain food system indicators during the initial years of the Water Crisis (2015–2017), for example, residents' autonomy decreased rapidly, the provision of food and water increased drastically (as shown in Fig. 2), funding from external actors flooded in, and collaboration between internal actors intensified. Note that the rate of change in a

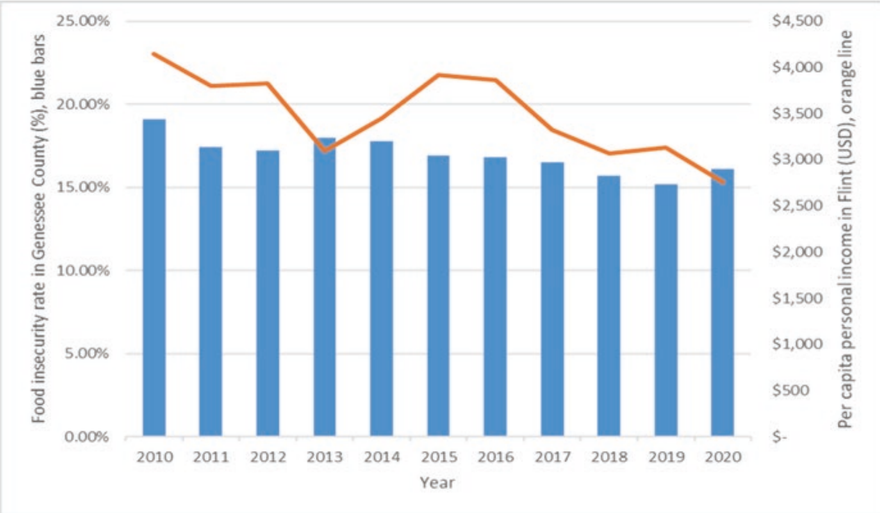

Fig. 4 Food security rates did not change significantly during the focal temporal scale (Feeding America, 2023)

social system is relative to past observations. When a change occurs that has not been previously observed, it may be described as rapid in comparison to historical dynamics. However, other system components did not demonstrate abrupt change (i.e., food security and income Fig. 4), and some of the abrupt changes were only temporary, indicating that the food system as a whole had not experienced significant and lasting identity change.

Identifying reinforcing feedback dynamics proved to be the most challenging and ultimately unsuccessful part of our analytic effort. Lenton et al. (2022) describes the difference between identifying system features (what tips) and control variables (what causes the tip or how it tips). Using our system description and conceptual model, we explored multiple effects of the Water Crisis on the food system, finding only examples of event chains at this scale, but not closed feedback loops. In our case, we were identifying control variables but not system features that tipped. For example, the lead contamination of Flint's drinking water in 2014 quickly increased awareness among citizens of the importance of fresh fruits and vegetables as lead-mitigating foods. However, the data did not demonstrate increasing uptake of related programs over time, or changes in diet or health outcomes because of this. When we ended our search for feedback dynamics, it remained unclear whether they did not exist (possibly explaining why the system did not move to a new state) or we had failed to identify them.

Given these results—no changes in system identity and absence of reinforcing feedback dynamics—we concluded that the Water Crisis did not create a STP for the Flint food system. While there may have been some changes in structure of and available resources in the food system, these changes cannot be characterized as a social tipping process. This rendered the question of reversibility (and hysteresis) irrelevant.

6 Principles and Process for Social Tipping Point Analysis

The above analysis allowed us to operationalize our definition of STP and create general principles for STP analysis that could offer a structure for future STP case studies, as shown in Table 1.

First, case studies should be selected carefully for their relevance, i.e., because they are potential instances of STPs (**principle 1**), rather than some other desirable characteristic (e.g., decarbonization potential). The observed social change should have clear social-ecological implications, and selection should acutely focus on data availability, especially time-series data that enables the study of abruptness. Multiple sources of data should be used, and a balance of qualitative (e.g., interviews, perception) and quantitative (e.g., assessment of economic indicators) data might be most insightful.

An awareness of data availability and data quality grounded in knowledge of the case study context is required to bound and describe the system (**principle 2**). The focal temporal and spatial scales should align with the characteristics of the social

Table 1 Emerging principles of STP analysis

Principles	How to operationalize?
1. Select case studies with a focus on data availability	Working with a clear definition of STPs, ensure you have the capacity to collect qualitative and/or quantitative time series data for the cases you believe are instances of social tipping
2. Bound and characterize the social-ecological system	Identify the focal spatio-temporal scale of the system of interest, as well as higher and lower scales that have important interacting dynamics. Create detailed system descriptions of the presumed pre-tipping and post-tipping (stable) states early in the process; keep updating these descriptions later
3. Identify and assess variables of interest	Identify 3–5 variables (indicators of structure and function) that can be used to explore the speed and nature of change. Assess them in an appropriate qualitative and/or quantitative manner
4. Measure abruptness	Using time-series data with a frequency appropriate for your system (i.e., tied to its 'background' speed), assess change in the rate of change to establish non-linearity in at least one of the variables of interest compared to 'background' change
5. Synthesize datasets to identify multiple stable states	Assess the existence of multiple stable states by synthesizing data to understand whether structure and function have changed significantly (structural reorganization)
6. Identify reinforcing feedback loops	Explore system dynamics to understand what is driving the non-linear change
7. Assess reversibility	Evaluate the conditions or required efforts to reverse the observed change and determine whether system is hysteretic

system, especially its governance systems. A system description can support the identification and measurement of 3–5 variables (**principle 3**) that characterize the system. The number of variables is a pragmatic choice but should be data driven, resulting in a robust dataset for fewer variables or considering more variables with partial datasets.

Data collection is followed by four analytic steps. First, variables for which time series data is available are analyzed for non-linear change over the study period to identify evidence of abruptness (**principle 4**). Abruptness is embedded in many definitions of tipping points (Kopp et al., 2016; Lenton et al., 2008) but is rarely assessed when discussing social tipping, possibly because time series analysis of social data can exhibit limitations and have a strong qualitative dimension. When, under what conditions, by whom, and why is a certain change considered abrupt? The answer depends on the social properties of interests and is at least to some extent a normative question involving those affected. If no abrupt pattern of change can be found, it is possible to return to principle 2 and adjust the temporal bounds of the case study. This is not just limited to quantitative analyses—qualitative data can be analyzed for significant changes between the beginning and the end of the study period.

Second, bringing together the quantitative and qualitative analyses of individual variables, a synthetic view across multiple interacting variables is required to determine whether the system has undergone a reorganization (and at what scale) leading to a change in structure and function (**principle 5**). With this understanding of the nature and extent of the system's change, third is to explore reinforcing feedbacks driving the observed changes and/or balancing feedback loops that explain the lack of change (**principle 6**). Is the process being described a loop that can close (feedback) or not (a chain of effects, or cascade)? At this point it is possible to determine whether the change is non-linear, thus a tipping point. We leave assessing limited reversibility (**principle 7**), i.e., the efforts required to reverse the social change and return to the previous set of functions, until last because it only becomes relevant if the analysis so far confirms a non-linear state change. This final step is particularly challenging if reversing the system's new stable state has not occurred, especially because intentional efforts to reverse state changes are not common beyond policy-based STPs. There are also significant questions regarding how to measure reversibility (or system identity) in social systems.

Principles 1, 4, 6, and 7 are specific to tipping point analyses; they determine whether the social dynamics observed in the case study represent a tipping process or some other form of change. Principles 2 and 5 are key for demonstrating that a significant change in the system's character—identity change, regime shift—has occurred. However, these principles could also be applied to transformation and transition analyses.

At this point, it should be possible to conclude whether the observed change in the case study is an STP. At a minimum, given the requirement of meeting the four criteria, it can be determined when there is *not* an STP.

7 Challenges

Two main challenges are tied to our definition and the need to provide evidence for the four STP criteria. First, data availability is the main barrier to the empirical study of social tipping processes, particularly sufficient longitudinal data frequency to observe abruptness. Data requirements are demanding, including quantitative and qualitative data regarding social and ecological variables. Currently, the feasibility of social tipping case studies is severely limited compared to ecological or even Earth system tipping points, given that high-quality quantitative data for statistical analyses is less common in social systems.

Second, not all social tipping criteria are clear-cut; they may be hard to identify or differ across groups. As Tàbara et al. (2021) convincingly argue, social system characteristics are open to interpretation and depend on specific stakeholder groups' goals, core values and beliefs, and resulting perceptions. Given that values and norms are embedded in social systems, desirability is a feature of stable states for stakeholders and becomes embedded in power dynamics and system structures. As a result, adaptive capacity, governance techniques, and foresight are utilized in social systems to prevent and mitigate abrupt change by strengthening stabilizing feedback dynamics and mitigating change (Angeler et al., 2020; Pahl-Wostl, 2009). The observation that complex-adaptive social systems might not lend themselves to non-linear, abrupt change raises fundamental questions regarding the prevalence of tipping dynamics in social systems.

These issues imply that a solid understanding of the social complexity of social-ecological systems is a prerequisite for the specification of data and knowledge needs that can enable the discovery STPs. Researchers should consider that non-linear change in coupled social-ecological systems might occur only under specific and rare circumstances, possibly because value-driven social processes tend to curb abruptness. However, the current challenges in building an evidence base for social tipping might simply be a result of data constraints and the corresponding analytic limitations that could be addressed by further case studies or methodological advances.

8 Conclusion and Outlook

Social tipping points are of great interest to the sustainability science community, but empirical research on social tipping dynamics has so far remained scarce. Here we developed methodological guidance for a case study approach to STP analyses that is closely tied to a common but specific definition of tipping. Our guidance takes the form of principles derived from our experience studying the food system of the city of Flint following the Flint Water Crisis. We identify seven principles that can simultaneously serve as a seven-step process for STP analysis.

Our discussion highlighted the significant challenges that remain regarding the empirical study of STPs, especially data availability. Looking ahead, we recommend an anticipatory approach to empirical social tipping research in addition to the exploration of historical cases. Our principles can help identify potential case studies and key variables that have a high chance of facilitating an analysis of ongoing and future change as a tipping point. Such a strategic approach could, for example, focus on social systems with a high CO_2 reduction potential, and start data collection—both quantitative and qualitative—ahead of expected changes. Data collection could be designed to enable time series analyses following experimental intervention, enabling observations of change dynamics in real time, but also process tracing and system mapping. For example, Otto et al. (2020) have identified removing fossil fuel subsidies, building carbon-neutral cities, and strengthening climate education as potential 'social tipping interventions'. An anticipatory and longitudinal approach would outline whether and how these interventions become STP but would also support broader analyses to understand the conditions and limitations of tipping points, critical for our understanding of how to create change to more sustainable futures. However, such an anticipatory approach to research is challenging, especially regarding the selection of variables and scales of analyses and will require relationships in the social-ecological systems of interest as well as support from funding institutions. The Long-Term Ecological Research (LTER) program of the National Science Foundation provides a good example for a funding model.

Despite these challenges, there is much to be gained from the study and knowledge of social tipping processes in the context of sustainability science. Whether or not these studies identify STPs, their conditions and histories, they always contribute to the existing knowledge base about social change, especially system structures, functions, and identity over time, as well as the barriers and conduits to different types of change.

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