



# To tip or not to tip: The Window of Tipping Point Analysis for social-ecological systems

Marie-Catherine Riekhof<sup>1</sup>  | Lotta Clara Kluger<sup>1</sup> |  
Renato Salvattecchi<sup>1,2</sup> | Lotta Siebert<sup>1</sup> | Rudi Voss<sup>1,3</sup>

<sup>1</sup>Department of Agricultural Economics, Center for Ocean and Society (CeOS), Kiel University, Kiel, Germany

<sup>2</sup>Laboratorios de Investigación y Desarrollo (LID), Centro de Investigación para el Desarrollo Integral y Sostenible (CIDIS), Facultad de Ciencias y Filosofía, Universidad Peruana Cayetano Heredia, Lima, Peru

<sup>3</sup>Biodiversity Economics, German Centre for Integrative Biodiversity Research (iDiv), Leipzig, Germany

## Correspondence

Marie-Catherine Riekhof, Center for Ocean and Society & Agricultural Economics Kiel University, Neufeldtstr. 10, 24118 Kiel, Germany.  
Email: [mcriekhof@ae.uni-kiel.de](mailto:mcriekhof@ae.uni-kiel.de)

## Funding information

Bundesministerium für Bildung und Forschung, Grant/Award Numbers: 01LC1823A, 01LC1826A; European Union's Horizon 2020 research and innovation programme, Grant/Award Number: 773713

## Abstract

We introduce six steps to define a “Window of Tipping Point Analysis” which serves as a framework to increase the understanding of processes and tipping points in social-ecological systems. We apply the Window of Tipping Point Analysis to a mathematical model and two case studies (i.e., Baltic Sea and the Humboldt Current Upwelling system), focusing on three aspects. In “to tip or be tipped” we look at agency in preventing (or driving) tipping. In “to be tipped or not to be tipped” we discuss intertemporal developments and chosen time periods for delineating regime shifts. In “to tip or not to tip” we discuss the desirability of states and their relation to the elements included. We argue that agency in tipping-point management, the occurrence of tipping points, and desirable states depend on the window chosen for the analysis.

## KEYWORDS

ecosystem management, regime shift, social-ecological system, tipping point

## Recommendations for Resource Managers

- “Setting the stage” for a tipping point analysis in social-ecological systems matters and can be done

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2022 The Authors. *Natural Resource Modeling* published by Wiley Periodicals LLC.



with the introduced “Window of Tipping Point Analysis” that consists of six steps.

- It is a tool to regulate the complexity of the analysis that supports the discussion on the desirability of outcomes and the agency in tipping point management.
- Looking through different windows at the same social-ecological system will help to move to a deeper understanding of the social-ecological system, its tipping-points, and its management.

## 1 | INTRODUCTION

Tipping points are all over: in scientific journals (in the past few years, the number of publications on the topic “tipping point” has been increasing according to Web of Science), in popular books (e.g., Gladwell, 2000), and in climate science, among others. While Malcolm Gladwell defines a tipping point as “that magic moment when an idea, trend or social behavior crosses a threshold, tips, and spreads like wildfire...” (back cover), the IPCC definition refers with the term tipping points to “critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible” (Hoegh-Guldberg et al., 2018) (for defining elements based on a literature review see Milkoreit et al., 2018). As “tipping” rarely happens isolated in a system - a term that needs precise definition to begin with—, but may stipulate cascading effects to and within neighboring systems, there is an ongoing scientific discourse on tipping points in interrelated systems, ranging from connected lake systems (e.g., Scheffer, 1989; Scheffer & van Nes, 2007) to social-ecological systems (SES)<sup>1</sup> as connected subsystems (e.g., Lauerburg et al., 2020). Interestingly, the majority of studies locates the tipping point in the ecological subsystem (see e.g., Lauerburg et al., 2020 for a review on marine case studies as well as Filatova et al., 2015), with potential cascading effects on other subsystems. Lauerburg et al. (2020) report a cascading to other subsystems only in 47% of the cases. Both aspects—location of tipping in the ecological subsystem and relatively little cascading—could be interpreted as evidence for buffering behavior in the social realm, showing the need to discuss the role of agency in driving or preventing tipping points or its cascading effects in SES. Tipping points may also be created by the introduction of resource use regulation, and the type of regulation may determine whether cascading occurs (see Noack et al., 2018).

We add to this discussion by asking “to tip or to be tipped?,” “to be tipped or not to be tipped?,” and “to tip or not to tip?”; with the questions relating to whether there is agency in preventing or fostering tipping, whether a phenomenon in an SES should be classified as crossing a tipping point, and whether tipping to a new or back to the old state is desirable, respectively. As we will argue, the answers to these questions relate to the boundary of the examined system such that we introduce a “Window of Tipping Point Analysis” detailed further down.



“To tip or to be tipped” relates to the notion of “tipping point management,” that is of having the choice of actively tipping the system or preventing its tipping, that is sometimes used in recent literature (e.g., Voss & Quaas, 2022). In some occasions, it might not even be possible to prevent a tipping, because the tipping is rather caused by exogenous factors that are hard to manage, and the possibilities to act on tipping often relate to the boundaries drawn to the system considered, or to its institutional constraints (Horan et al., 2011).

“To be tipped or not to be tipped” relates to the question whether an observed phenomenon should be classified as tipping point. Based on an interdisciplinary literature review, Milkoreit et al. (2018) identify “multiple stable states,” “abruptness,” “feedbacks,” and “limited reversibility” as necessary elements for tipping point definitions. Whether an observed alteration in the system state can be considered reversible depends on the time period considered, and the relevant period depends on the question at hand. 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. Whether the system is truly reversed to its old state depends on the elements included in the analysis, as we will argue and illustrate by our examples.

In “to tip or not to tip” we argue that the process of crossing a tipping point (and reaching a different “stable” state) in a SES is not necessarily negative for a system at question, but that this evaluation rather depends on the respective perspective on the system and on the elements included in the analysis. The decision on whether the crossing of a tipping point should be fostered or prevented may thus also differ depending on the chosen perspective.

The complexity of tipping point analysis in SES is apparent, and new approaches to reduce the complexity in SES are warranted (see also Lauerburg et al., 2020) and adaptive frameworks needed (Schlüter et al., 2011). We introduce a “Window of Tipping Point Analysis” as an adaptive framework that allows for complexity reduction for an examination at hand, while preserving the consideration of complexity through the combination of different windows. Within a Window of Tipping Point Analysis (WTPA) the questions raised above can be answered and different (potential) states of the system’s elements can be discussed.

The “Window of Tipping Point Analysis” that we suggest consists of six steps to define the scope of the analysis of tipping points in SES. This becomes especially important when discussing policy options and models (and their components) for the analysis of consequences of crossing tipping points. We argue that it is important to also consider “zooming out” of that window, that is, broadening the view to discuss interlinkages with other subsystems outside of the analysis window, and of lying different windows next to each other to reach a deeper understanding of the SES, its tipping points, and management options. Especially with shifts in ecosystems, but also in the social subsystems, driven by climate change, the suitable WTPA may change, and lying different windows next to each other may give us a more comprehensive view of the system. The WTPA also serves as a mean to bring different approaches together, for example, case studies, modeling and mental models.

In contrast to frameworks like Ostrom (2009) that aim at developing common elements—that is, a common window—when looking at different SESs, we suggest to use different windows when looking at the same SES, and to explicitly include different (potential) states in the analysis, as crossing of tipping points is a feature of SES (Stockholm Resilience Center, 2016). The WTPA is one way of dealing with the complexities inherent in SES and thus with its tipping points and regime shifts.

Next, we will present the WTPA before we present three applications. We end with a discussion.



## 2 | THEORETICAL FRAMEWORK: DEFINING A WTPA IN SOCIAL-ECOLOGICAL SYSTEMS

Interactions within and between society and the environment are complex, usually including nonlinear relations. The interactions between the society and the environment are often analyzed through the theoretical lens of a “social-ecological system” (e.g., Ostrom, 2009) that consists of one ecological and one social or socioeconomic subsystem with many interrelated elements. The nonlinear elements are often referred to as “tipping elements” with crossing of a tipping point leading to a different (stable) state. An example for an element in the ecological subsystem may relate to the abundance of a particular species, while an element in the social realm may relate to a certain industry. The combination of different states of the SES's elements forms a regime.<sup>2</sup> Largely following the interdisciplinary literature review by Milkoreit et al. (2018) already referred to above, we relate to tipping points in SES when there are “multiple stable states” and “feedbacks,” and when there is “limited reversibility” in the period considered.

When aiming at understanding, for example, through modeling, the tipping of SESs it is important to consider—as it is in the case for any model—that the choice of (model) elements will very much determine the outcome of the (modeling) exercise and its potential applicability with respect to management and policy discussions. For example, in the context of resource management, the inclusion of formal fishers as the sole element of “resource users” in a setting where informally or illegally operating resource users play an important role for resource dynamics and thereby sometimes even for ecological tipping will necessarily miss the chance to estimate the true impacts of intervention actions on the resource. On the one hand, an inclusion of too few elements may reduce the degree to representativeness of the analysis. On the other hand, selecting too many elements increases the chance to over-complicate the model, to miss describing the actually important dynamics or to blur the modeling outcome. Taking into account different potential states of the elements in a SES adds an additional layer that needs to be dealt with.

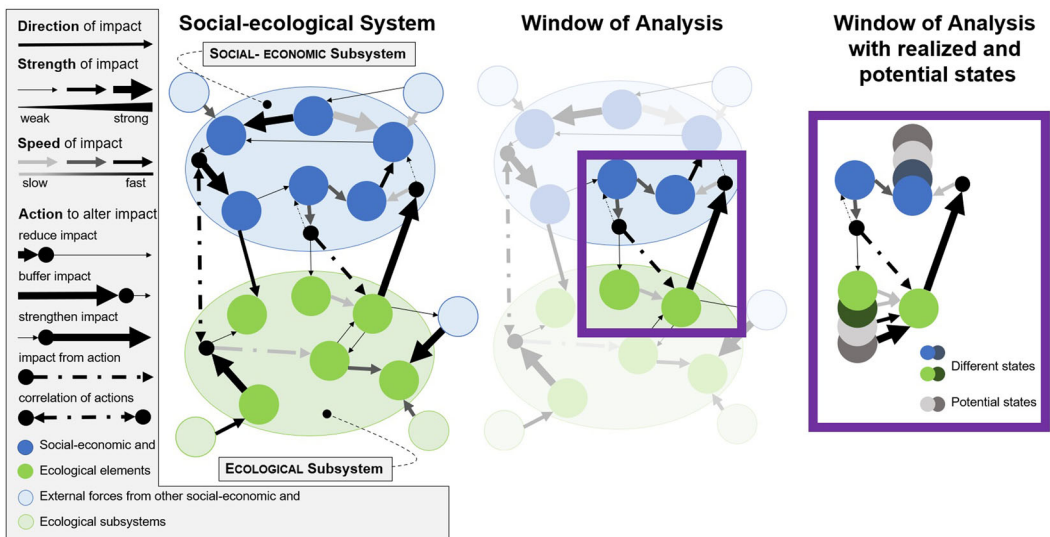
Thus, for a profound analysis, the complexity of the SES needs to be reduced to its core elements related to the question at hand. While this is implicitly done in most studies, we suggest to explicitly define what we term a “Window of Tipping Point Analysis,” as this window may determine whether one detects a tipping point in the first place and as it explicitly takes “time” into account. In addition, the window helps to clearly show how derived results and policy options relate to the elements included in the analysis and the time period considered, which may foster overall knowledge generation related to a SES when different windows can be put next to each other, for example, for different periods of time.

The definition of a Window of Tipping Point Analysis (WTPA) itself related to the research question to be examined encompasses the following six steps:

1. Describe the elements included in the analysis. This may relate to specifying which species are considered (ecological subsystem) and which human actors or sectors (social realm). We define elements as a relevant unit that may change its state. Its exact dimension depends on the analysis at hand.
2. Describe the period considered and the speed of adjustment (years vs decades).
3. Describe the relations between the different elements. The relation may be uni- or bidirectional, with different speeds between the elements.

4. Describe which exogenous impacts—impacts from outside the window—may be relevant and are considered; and ideally, also describe which exogenous impacts are excluded from the analysis and how elements within the window impact elements outside of the window.
5. Describe the potential states of the different elements. This is especially relevant when conducting a temporal analysis. Relations between elements may change depending on their specific states.
6. Describe intervention possibilities and how these intervention possibilities may relate to the different elements and their potential states.

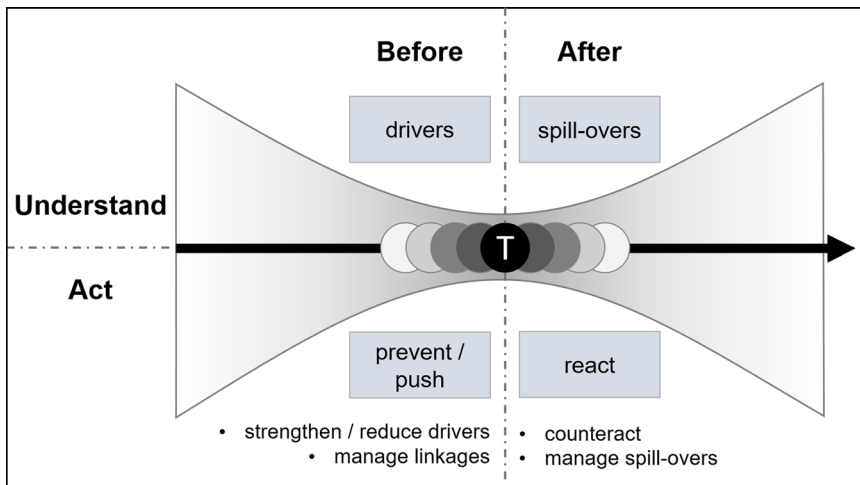
We illustrate the different steps of the WTPA with the help of Figure 1: The left panel shows the current understanding of a SES, with all its complexities, different elements and dynamics, possibly with different speeds but excluding different potential states. The middle and the right panel show the WTPA, including potential states on the right. Once the major analysis is done within the well-defined tipping-analysis window, one can zoom out and discuss the broader view and relate it back to the overall system.



**FIGURE 1** Introducing the concept of the Window of Tipping Point Analysis (WTPA). The left panel shows the current understanding of a SES, with all its complexities, different elements and dynamics, possibly with different speeds but excluding different potential states, while the middle and the right panel show the WTPA, including potential states on the right. To build the WTPA, one first has to describe the elements (circles in the figure) that should be included in the analysis (Step 1). Step 3 relates to the arrows included in the window, taking Step 2 into account, as only those interrelations relevant for the time period considered will be listed. Obviously, the speed of impact considered (shade of the interlinkages) has to be a subgroup of the dynamics observed in the SES. Step 4 aims to make explicit that certain drivers become exogenous, and certain side-effects from interventions may not necessarily be considered. Arrows come from "nowhere," that is, outside the window, and may go to nowhere, that is, outside the window. One may miss cascading effects if they work via an element not included. Step 5 describes potential states of the elements that are included in the analysis (see the right panel). They are likely to depend on the time period considered, that is, a certain state may be relevant in 10 years from now, but not next year. Step 6 relates to setting the blackballs that show possible actions and resulting impacts on the system.

Two remarks are in order. First, we do not explicitly include the specification of thresholds for tipping. While this is important, these thresholds themselves are subject to uncertainty and different types of drivers, such that we focus on the different states and the interaction between elements, and not on the exact thresholds. Second, we focus on the uncertainty relevant for management decisions while leaving the uncertainty surrounding depicted relationships aside. We argue that using different WTPA on the same SES will lead to a better understanding of the system.

The WTPA therefore does not claim to reduce uncertainties, but rather increases understanding of highly complex SES. It follows the same principle as a magnifier. By setting the focus on relevant factors, while disregarding others, the complexity can be reduced. The gained understanding of the interactions and processes within the WTPA help to make more reliable predictions and to choose appropriate policy interventions to either prevent or push tipping points. Surely, uncertainties about the timing and consequences of a tipping point remain. So far, it is not possible to predict tipping points with 100% certainty, but research rather tries to determine time frames in which a tipping is more likely. This is visualized in Figure 2, where the different shaded circles show possible crossings of a tipping point, colored according to their probability or occurrence. The uncertainty related to the drivers of the tipping and the impacts from the tipping are depicted by the area surrounding the arrow that depicts the passage of time: when getting closer to a tipping event, predictions may be more reliable and precise. Further, there is a higher understanding of direct consequences from crossing a tipping-point than for long-term effects and possible spill-overs. Obviously, the described and depicted situation is one possible scenario for a tipping point; the situation may look different for other tipping points.



**FIGURE 2** Classification of management options related to tipping points. The arrow relates to the passage of time and “T” specifies the crossing of the tipping point. The uncertainty related to the timing of the crossing is indicated by different shaded circles, corresponding to their likelihood of occurrence, with dark colors indicating a higher probability. It illustrates a sooner or later crossing due to chances in drivers, for example, due to management action. The area around the timeline shows the time dependent uncertainty range related to the tipping point, the processes leading up to the tipping point and resulting impacts. In the depicted graph, the understanding around the actual tipping point is larger than further apart



The Window of a Tipping Point Analysis is also helpful when thinking of management options. First, it characterizes the scope of action—which elements can (and should) be influenced, what is exogenous to the considered system? Different (sub-)system come with different agency determining policy options (reduce drivers, focus on reaction). Second, the WTPA may also influence which regimes are desirable, as impacts on elements outside of the window may be ignored. This may especially be related to future states of an element which are difficult to imagine.

If one aims at discussing different management options, one has to differentiate whether one looks at the time before a tipping occurred—or after. If the crossing of a tipping point is yet to be expected, management should focus on (i) identifying and understanding drivers of change, (ii) depending on the desirability of the new state preventing or pushing for the tipping, and (iii) possibly “breaking” linkages to stop potential cascading effects and (iv) defining actions for the reaction to the tipped system. After the tipping point has been crossed, one should focus on (i) understanding the enfolding dynamics and (ii) reacting by managing the transition and possible cascading effects (see Figure 2 for an illustration).

Still, a manager has to look at overall costs: it may be easier to focus on reactions to tipped systems, especially, it has to be examined whether the tipping of a SES can actually be prevented by any action that is to be formulated at a reasonable cost. Depending on the moment of time at which the tipping point analysis is conducted, only a mere reaction may be possible. In the case of climate change, exogenous drivers of a locally defined SES, its resources and resource users, may be “unmanageable” for local managers and policy makers because the time and spatial scale of those drivers’ is simply too large. International market dynamics may continue to drive local resource over-exploitation (and render local management options difficult, see e.g., Riekhof et al., 2019), if the locally extracted resource is solely subject to international demand, or international prices continue to out-compete alternative livelihood option. Here, the WTPA clearly shows which elements lie inside and outside of the influence of local managers.

The choice between prevention versus reaction, or adaptation versus mitigation, relates to agency, but also to the desirability of different states. Uncertainty and irreversibility might lead to a bias for or against the implementation of mitigation policy—with the well-documented endowment effect may lead to a status-quo bias (Kahneman et al., 1991). Cooperation between stakeholders—and thus agency—might be higher if there is a high risk of a catastrophic shift, increasing the incentives to mitigate (Tavoni & İriş, 2020). Uncertainty about a catastrophic shift and the irreversibility of environmental damage, lead to earlier and stronger intervention. But mitigation policy produces sunk costs (irreversible expenditures) which would deter early action (Pindyck, 2020). These costs include costs of adaptation, but also the increase in risk in other systems, that might be affected by the shift (Fenichel & Abbott, 2014). Thus, a good understanding of the SES, related uncertainties, and the different options is warranted and we think the WTPA can be of help.

In the following, we illustrate the working of our WTPA by applying it to a mathematical model and two cases studies related to our questions whether there is agency in preventing or fostering tipping (“to tip or to be tipped?”), whether a phenomenon in a SES should be classified as tipping point and how this relates to time (“to be tipped or not to be tipped?”), and whether tipping to a new or back to the old state is desirable (“to tip or not to tip?”).



### 3 | APPLICATIONS

#### 3.1 | To tip or to be tipped: The WTPA and a mathematical model

Modeling may be a way forward to explore different management options, so next, we discuss how our WTPA and the questions around agency can be related to existing mathematical representations of tipping points. Note that the WTAP can stand on its own and does not need a mathematical model as base. Here, we rather apply the WTPA to a mathematical model. To do so, we take the model by Klose et al. (2020) and add elements related to management. Klose et al. (2020) examine interacting tipping elements with the help of cusp bifurcation, and especially how in the case of one-directional coupling of strength  $\delta$  the tipping of a "master"-subsystem may lead to the tipping of its "slave"-subsystems, as for example, in the case of a shallow lake system.

As in Klose et al. (2020), our set-up is a continuous dynamical system  $\dot{x}_i(t) = f_i(x_1, x_2, \dots, x_n)$  with  $n$  elements  $x_i$ ,  $i = 1, \dots, n$  that may tip, each represented by a cusp bifurcation such that dynamics for each element can be represented by

$$f_i(x_1, x_2, \dots, x_n) = \alpha_i x_i(t) - \beta_i x_i^3(t) + \gamma_i + \sum_{j \neq i} g_{ij}(x_j(t)), \quad (1)$$

with  $g_{ij}(x_j(t))$  displaying the (possible nonlinear) interaction between the different elements. For expository purpose, we specify  $g_{ij}(x_j(t)) = \delta_{ij} x_j(t)$ , with  $\delta_{ij}$  displaying the (linear) interaction between the different elements, that is, the impact from the state of element  $j$  and element  $i$ , related to the one-directional coupling of strength  $\delta$  mentioned above. For each element, two branches with stable equilibria and a range with unstable equilibria exist such that one can speak of a "normal" and an "alternate" state. Parameters  $\alpha_i, \beta_i > 0$  indicate the distance between the two branches and the strength of nonlinearity, respectively. When  $g_{ij}(x_j) = 0$ , the parameter  $\gamma_i$ , in turn, relates to the threshold when dynamics lead to either one or the other state, that is, it determines whether the system is in its bistable range. When  $g_{ij}(x_j) \neq 0$ , the state of element  $j$  influences the state of element  $i$ . A change in the state of  $j$  may have cascading effects to element  $i$ .

In terms of our WTPA, setting up the model covers Step 1 (the inclusion of the elements, here termed  $x_i$ ) and Step 3 (the relation between the elements, here represented by  $\delta_{ij}$ , for  $\delta_{ij} = 0$ , one would have independent elements and potentially subsystems). Step 2, which relates to the speed of adjustment, is implicitly covered by the units of  $t$ . It should be stated explicitly whether  $t$  relates to days, years, or centuries. Furthermore, one should state explicitly which time period is represented when setting up the model. Step 4 relates to the role of  $\gamma_i$ . If  $\alpha_i$  and  $\beta_i$  are kept constant—as in Klose et al. (2020)—the size of the control parameter  $\gamma_i$  then indicates whether the element is in its bistable range or not, such that we interpret  $\gamma_i$  as some exogenous driver. This driver could also include stochastic elements. In an accompanying discussion, relevant drivers not included in the model should also be discussed. The different states (Step 5) are indirectly depicted by the choice of  $\alpha_i$  that determines the distance between the two stable branches of the system.

Relating to Step 6, we enlarge the model to include intervention possibilities and to describe how these intervention possibilities may relate to the different elements. Especially, we enlarge (1) by introducing management elements  $y_i$  and  $z_i$ , obtaining



$$\begin{aligned} \dot{x}_i(t) = f_i(x_1, x_2, \dots, x_n) = & \alpha_i x_i(t) - \beta_i x_i^3(t) + (\gamma_i - y_i) + \sum_{j \neq i} (\delta_{ij} - z_i) x_j(t) + \sum_j \sigma_{ij} y_j \\ & + \sum_j \epsilon_{ij} z_j. \end{aligned} \quad (2)$$

The idea is that measures can be undertaken that, first, impact the control parameter  $\gamma_i$ , that is, reducing (or increasing) the driver, and, second, can reduce (or increase) the impact from other elements on the current element,  $\delta_{ij}$ , that is, potentially breaking linkages. These actions  $y_i$  and  $z_i$ , in turn, may have repercussions on the element itself as well as on other elements, that is, actions  $y_j$  and  $z_j$  may impact the state of element  $x_i$  (see Figure 1: Arrows indicate the size and direction of  $\delta_{ij}$ , while the black balls represent  $y_i$  and  $z_i$ . Arrows originating from the black balls represent  $\sigma_{ij}$  and  $\epsilon_{ij}$ ). When  $\gamma_i$  has stochastic elements, the impact of the management action cannot be stated with certainty.

If the change of a state would be achieved by management actions, we would term this “to tip” the element, while if the exogenous drivers causes the change of state, we would term it “to be tipped.” Depending on the relative strengths of the forces and the available margin, the manager would or would not be in a position to being able to tip the element or to prevent tipping, and may only be able to react (see also Figure 2). As a next step, one could define preferred states and add cost and benefit estimates and then examine how the inclusion of different elements impacts the optimal management strategy and desired states, for example. Also, one could consider different types of uncertainty and how they influence management decisions.

### 3.2 | To be tipped or not to be tipped: The WTPA applied to the Humboldt Current Upwelling system

One SES famous for discussion on different regimes and possible crossing of tipping points centers around the Humboldt Current Upwelling system in front of Peru, usually focusing on anchovy and sardine landings (see Figure 3b,c). Here, we take advantage of an exceptional long time period, as the usual landing data covering the last decades can be combined with historical and high-resolution paleoceanographic data to get a better overview of trends and decadal-scale changes in fish populations. We illustrate with the help of the WTPA that “to be tipped or not to be tipped?” relates to the choice of different windows with respect to the time period. Also, the case study allows to discuss “to tip or to be tipped?” related to agency, and to touch upon “to tip or not to tip?” related to beneficiaries from different shifts and management actions. We start with giving some background information before we apply the WTPA.

Over time, different sea related natural resources have been important for Peru. After the independence from Spain in 1821, Peru experienced an economic boom as a result of global demand for guano (bird droppings) as a fertilizer. In the 19th century the major sources of nitrate and ammonia were saltpeter and guano, the latter is a highly effective fertilizer due to the high contents of nitrogen, phosphate, and potassium. Guano birds are historically the most conspicuous predators on Peruvian anchoveta and the populations of guano birds exceeded 20 million birds in the 1950s. The guano birds consumed an estimated 1.3–2.1 million metric tons of anchoveta per year, before the inception of the fishery (Jahncke et al., 2004). From 1840 to 1880, Peru exported huge amounts of guano, which consisted in the exploitation of centuries-old deposits of droppings (see Figure 3a). This period is known as Peru’s “Guano Age”

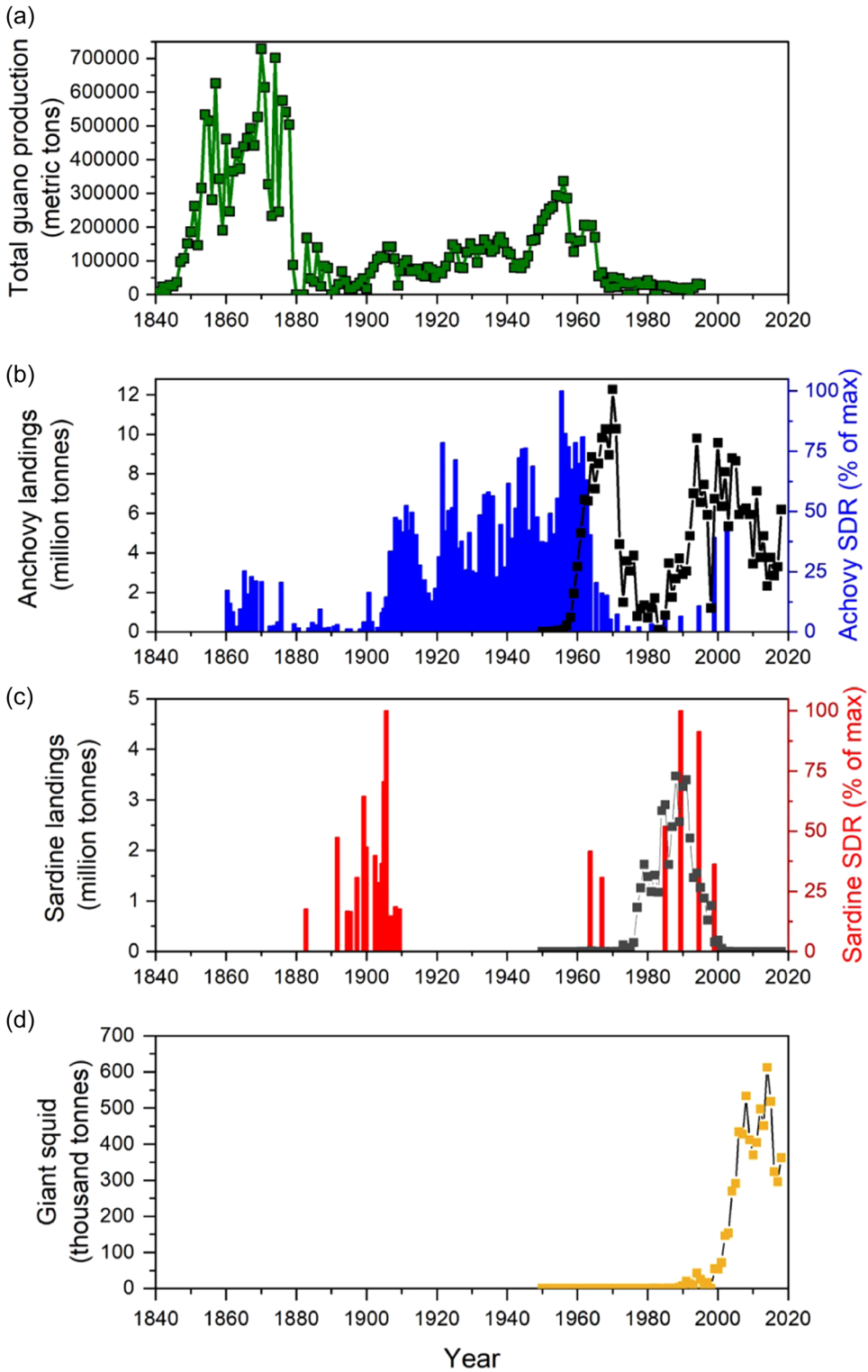


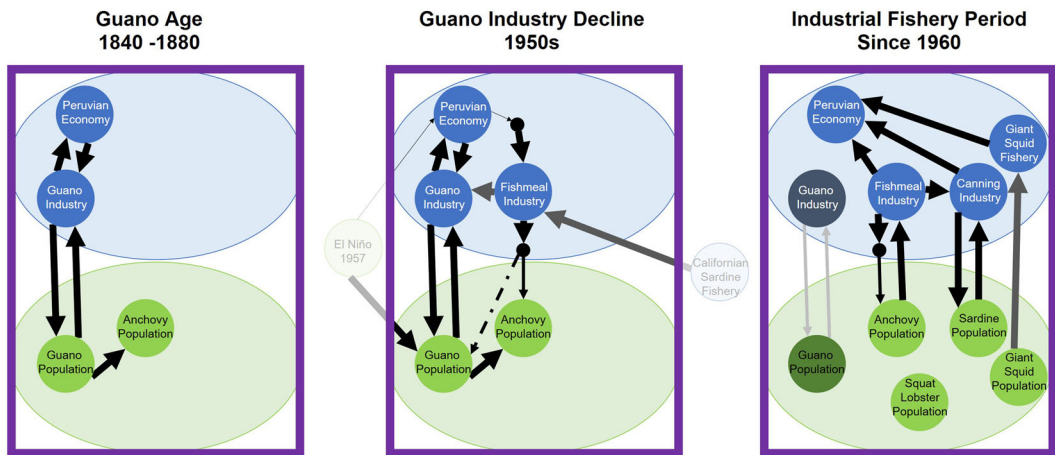
FIGURE 3 (See caption on next page)



(Figure 4, left panel). In 1879 Peru exhausted its major guano deposits. However, in 1909 environmental experts implemented a program that led to dramatic increases in the guano bird population and the production of guano for human benefit (Cushman, 2005). Unlike the Guano Age (which depended on the exploitation of old-deposits), this new period relied on a sustained yield of excrement from Peru's marine bird population existing at that time. The guano harvest increased from the start of the 20th century to mid-1950 when the guano industry started its decline due to a new industry in the Humboldt Current.

A major threat to the guano industry in the 1950s was the rapid development of an industrial fishery based on Peruvian anchoveta (*Engraulis ringens*) and a very strong El Niño event. The California sardine fishery in the 40s produced high-protein feed for industrial animal husbandry, an economic activity of rising international importance after the Second World War, but collapsed in the 1940s due to a combination of overfishing and adverse climatic and oceanographic conditions. The same industrial participants who were responsible for the collapse of the California sardine fishery shifted focus to the anchovy fishery in Peru (Field et al., 2011). The guano administrators in Peru realized the ecological threat this posed to the guano birds and their business (Cushman, 2005). The Peruvian government adopted several

### Different Regimes in the Humboldt Current Upwelling system during the last 150 years



**FIGURE 4** The Window of Tipping Point Analysis applied to the Humboldt Current Upwelling system. Different Windows illustrate the development over time, that is, describing the elements included in the analysis in the “guano age” (left panel), during the decline of the guano industry (central panel) and the rise of the small-pelagic fisheries (right panel). Direction and strength of impacts between elements is described (cf. legend of Figure 1).

**FIGURE 3** Time series of guano production, marine resources landings and anchovy and sardine population reconstruction in the Humboldt Current Upwelling system. (a) Guano production (metric tonnes), data from Cushman (2005). (b) Anchovy landings (lines) and anchovy scale deposition rates (bars) as a proxy for anchovy abundance (Salvatteci et al., 2018). (c) Sardine landings (lines) and sardine scale deposition rates (bars) as a proxy for sardine abundance (Salvatteci et al., 2018). (d) Landings of giant squid (*Dosidicus gigas*). Anchovy, sardine and giant squid landings from FishStatJ (FAO, 2022).



experimental fishery regulations designed to protect the guano birds but a strong El Niño event in 1957 decimated the guano bird's population (Figure 4, central panel). This El Niño event contributed to an economic crisis affecting the entire country. First some rigorous fishery regulations were issued to protect the guano industry, but a later change in the Peruvian economy toward free market policies boosted the fishery industry. The extraordinary growth of the Peruvian fishmeal industry produced a rapid economic recovery. During the 1960s the highly abundant anchovy led to enormous investments in fishing vessels and processing plants (Figure 4, right panel). In turn, the guano bird population dramatically decreased due to lack of food and another El Niño event in 1964.

The golden age of the Peruvian fishmeal industry had a shorter time span than that of the Guano age (Figure 3b). Anchovy fishery collapsed at the start of the 1970s due to a combination of unfavorable conditions and overfishing, similar to what had been observed in California in the 1940s. It was decades later when scientists discovered that in the Humboldt and California Current Upwelling systems, anchovy and sardine populations are characterized by strong fluctuations in abundance as paleoceanographic records revealed (Baumgartner et al., 1992; Salvattecchi et al., 2019; Figure 3b,c). Anchovy landings remained persistently low for almost 20 years and the Peruvian fishmeal industry was strongly depressed. During the 1980s, factories and fishing vessels subsisted on another small pelagic fish that was abundant during the 80s and early 90s: the Peruvian sardine. Sardines are less abundant than anchovy (Figure 3c) and are mainly used in the canning industry. Thus, the apparent minor shift from one small pelagic fish to another small pelagic fish changed the fishery industry boosting the canning industry in Peru.

Anchovy population started to recover while sardine population declined in the late 1990s, boosting again the fishmeal industry (Figure 3b). During the last two decades, Peru was responsible for 30%–40% of the worldwide production of fishmeal and fish oil, but the steady decline in anchovy landings during the last 10 years let scientists and stakeholders to believe that another regime shift is to be observed in the near future.

While the two anchovy periods, inferred from the historical record, could suggest that both periods are similar, a more careful look on the marine ecosystem suggests marked differences between these two periods. The most evident difference is the presence of species from the late 90s to the date that were not abundant during the 60s and 70s. For example, the squat lobster (*Pleuroncodes monodon*) and the giant squid (*Dosidicus gigas*) have become highly abundant along the Humboldt Current since the mid-1990s (Figure 3d). Specifically, the giant squid fishery has become extremely important in Peru during the last decade.

Paleoceanographic studies have also indicated that there are multiple modes of variability in anchovy and sardine states (Salvattecchi et al., 2018, 2019). For example, periods characterized by high abundance of both species and others of low abundance of both species were recorded making the evident the multidimensionality of the system. The combined observations from the paleoceanographic and the historical records suggest that the Humboldt Current Upwelling system (HCUS) had continuously changed from one small-pelagic fish regime to the other, and also that there are multiple timescales of variability in anchovy and sardine states.

The HCUS case provides an excellent opportunity to apply the WTPA. The long-time period allows to see different states of elements, and how interrelations may depend on the states. We delineate three regimes, in which the elements have potentially different states, and argue that between the different regimes, tipping points have been crossed. The choice of different (shorter) time periods and different (fewer) elements may lead to different regimes and, respectively, different tippings (relating to "to be tipped or not to be tipped"). The WTPA makes



choices explicit. Also, having three windows next to each other may help to better understand the HCUS.

Related to Step 1 of the WTPA, the ecological subsystem is defined as the anchovy, sardine, seabirds and the giant squid populations, while the social realm is defined as the guano, fishing, fishmeal, and canning industry (Figure 4).

As already discussed, the period considered can be expanded from the usual landing data covering the last decades to the last 150 years with the addition of historical and high-resolution paleoceanographic data to get a better overview of trends and decadal-scale changes in fish population by looking through different windows. Accordingly, we chose three periods as subsamples to be depicted in three WTPA (Step 2): the “guano age” period (1840–1880), the “guano industry decline” (1950s), and the “industrial fishery period” (1960 to the date), all depicted in Figure 4. Based on the previous discussion, we chose the WTPA of the industrial fishery period to include the different states of the elements (anchovy, sardine, giant squid) as one overall regime with fluctuations.

For Step 3, the relationships between the different elements in each of the time periods considered needs to be described (see Figure 4). In some cases, the strong link between the ecological subsystem and the social realm change radically with time as is the case of the guano industry that was important during the “Guano age” and during the “Guano Industry decline” (left and central panels in Figure 4) but stopped being an important economic source during the “industrial fishery period” (right panel in Figure 4).

The two major exogenous impacts identified for the emergence of the subsequent element states (i.e., central and right panel in Figure 4) were (a) the need for guano as a fertilizer in the early 19th century that boosted the Peruvian economy and (b) the collapse of the Californian sardine fishery in the 1940s that served as a trigger for the initiation of the industrial fishery in Peru (Step 4). Another exogenous impact, related to climate-ocean interactions, is the multidecadal change in ocean properties that produced the fluctuations of anchovy and sardine (Salvatteci et al., 2018), and ultimately impacted the fishmeal and canning industries (right panel in Figure 4).

Step 5 relates to the different states of the elements. The focus here was on historical data and thus on realized states of the different elements. The different windows show how certain elements are only relevant during certain periods, that their states have changed over time (most prominently related to Guano), and that the interlinkages between the elements have changes as well. Their states and their relationships may change in the future again, in particular with increased human pressure and global warming. For example, anchovy populations are expected to decline in a warmer world (Salvatteci et al., 2022), and this would very likely affect, yet again, the fishmeal industry and perhaps produce another tipping point (and a potential new regime), calling for an additional WTPA that looks into the future and potential states.

Finally, related to Step 6, it became clear that measures related to the Guano industry were implemented, but that there was little agency to act on the fluctuations in sardine and anchovy stocks (“to tip or to be tipped”). In addition, initial management action was focus on the “old” guano industry, trying to prevent the crossing of a tipping point and the establishment of a new industry (“to tip or not to tip”).

In the future, intervention possibilities for potential tipping may be applied (e.g., trying to prevent the collapse of anchovy through fisheries management strategies), but are likely not to stop the decline of anchovy given that it is climate-driven and thus exogenous to the WTPA. Rather, adaptation strategies for the fishing industry may be promoted to foster direct human



consumption of small pelagic fishes. For example, the use of anchovy, or any other small pelagic fish that a future warmer ocean could bring into the HCUS, in the canning industry as to foster an increased resilience of this industry.

For this future examination and different examinations in general, shorter periods may be considered and other conclusions reached related to different regimes. Thus, related to “be tipped or not to be tipped,” it shows that the time period considered matters and accordingly, the WTPA is a suitable approach to bring different studies together.

### 3.3 | To tip or not to tip: The WTPA applied to the Central Baltic Sea fishery

One question arising also for the Baltic Sea Fishery is to “To tip or not to tip,” or rather “To tip back—or to tip to where?” as tipping points have been crossed (Möllmann et al., 2009). The “old” state may not be desirable, for example, as it was vulnerable in the first place. Is there an even “better” state? From whose perspective? A new state may offer opportunities that were not foreseeable before, for example, new species entering a setting with warming waters, allowing for a more diverse fisheries portfolio or new income opportunities. In the following, we examine the Central Baltic Sea fishery and its tipping points with the help of different Windows of Tipping Point Analysis and discuss what we can derive from looking at different windows. Again, we start with giving some background information before we apply the WTPA.

The Central Baltic Sea comprises the area to the east of the island of Bornholm up to the Archipelago. In the north-east (ICES Sub-division 25–29 and 32). The Sea is bordered by eight countries and provides numerous ecosystem services, including provisioning of food via fisheries. It is a brackish water body with a comparatively low biodiversity (HELCOM, 2018). Historically, the major fisheries resources are cod, herring, and sprat. Cod and herring stocks show only little exchange with the bordering Western Baltic (SD 22–24), and are managed within their distributional area. The sprat stock is distributed in both areas, however with highest abundance recorded in the Central Baltic. As the Baltic is an almost enclosed sea, distributional shifts, for example, due to climate change, are restricted to movements within the area. Fisheries use a large variety of gears, with trawl fisheries being the most important technique. Quantitative stock assessment and catch data are available since the 1970s, monitoring of other ecosystem indicators started more recently, and socioeconomic data are mostly restricted to the last 25–30 years. The stocks show partly pronounced interannual fluctuations in productivity (ICES, 2020), with almost immediate ecological impacts, and management acts on a yearly basis with setting total allowable catches as a major measure. In principle, different management options are perceivable, see Figure 5.

To discuss “To tip back—or to tip to where?,” we define different WTPA. The smallest window of analysis comprises one element each in the ecological as well as socioeconomic system (Figure 6, left panel): the cod stock dynamics are analyzed in combination with the cod trawling fleet (Figure 5a). Bio-economic optimization models (Quaas et al., 2013; Tahvonen et al., 2013; Voss & Quaas, 2022) suggest that the cod stock should be built up to large levels, enabling a highly profitable fishery (Figure 5b). At the same time, however, the fishing effort (number of boats, individual effort or a combination of both) would decrease (Voss et al., 2017). Starting at low spawning stock biomass, as currently observed (Figure 5a), management actions would aim to reduced fishing until the stock has been built up.

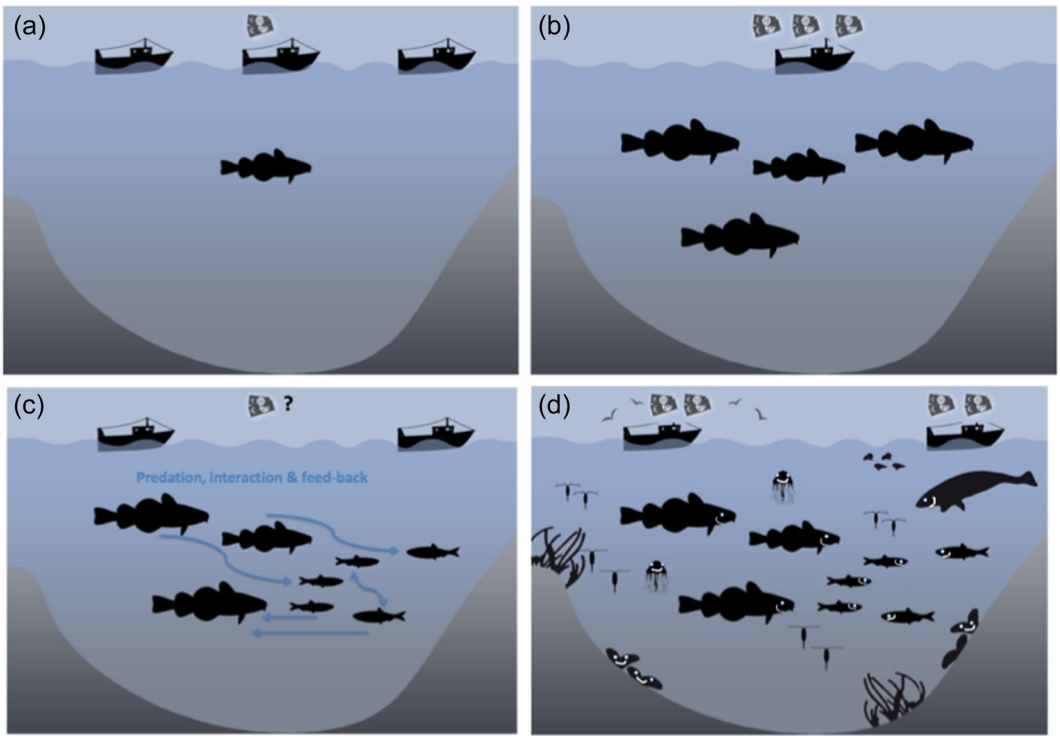


FIGURE 5 Fisheries management options. From (a) open access to (b) single species optimization to (c) multispecies optimization to (d) ecosystem-based management.

Different Windows of Analysis for the Central Baltic Sea

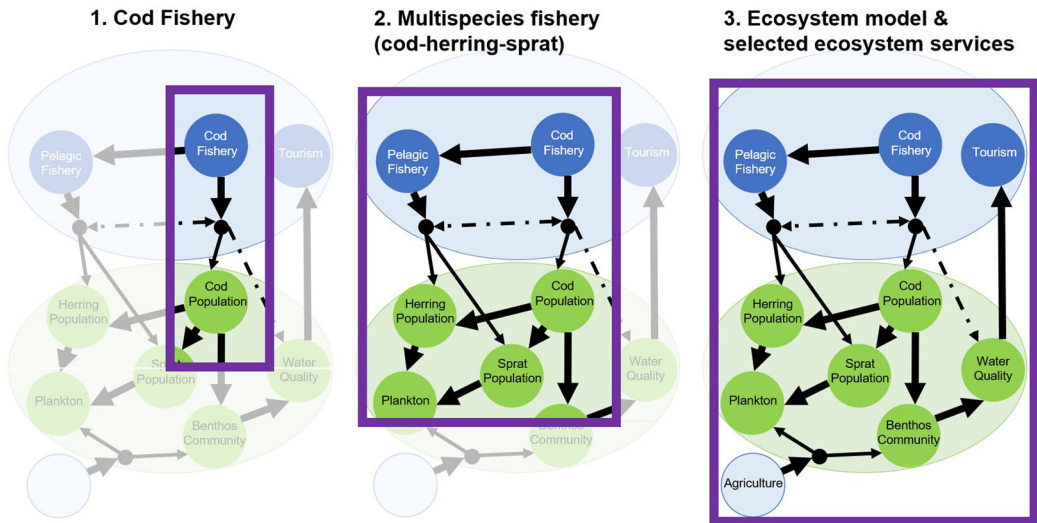
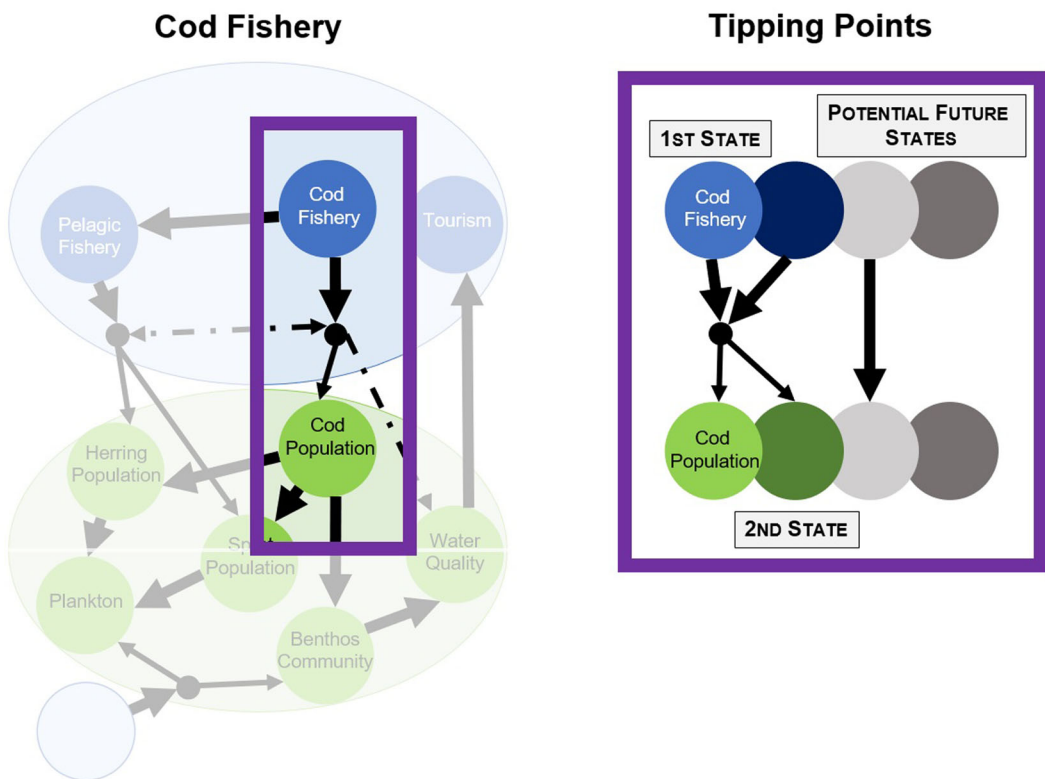


FIGURE 6 The Window of Tipping Point Analysis applied to the Central Baltic Sea ishery. Different Windows illustrate the inclusion of different elements. Direction and strength of impacts between elements is described (cf. legend of Figure 1).

In principle, different future states can be imagined (see Figure 7), that is, from current low to future high cod stocks and from a bigger to a smaller, more profitable, fleet. Besides these management induced changes, other drivers are present and past regime shifts may entail information for future developments. For example, a regime shift in the Central Baltic in the late 1980s involved a tipping point toward a lower cod stock productivity (Möllmann et al., 2009). The tipping resulted in reduced optimal cod stock size and fishing opportunities as well as in reduced optimal profits (Voss & Quaas, 2022). From this narrow window of analysis perspective (Figure 6, left panel), tipping was purely negative and a back-tipping would have been beneficial. However, even after crossing that tipping point, a rebuilding of the cod stock to high stock sizes remained the management target to yield highest profits for the fishery. Since 2019 the perception of the Central Baltic cod stock productivity changed again, and a potential passing of another tipping point is discussed, which further worsened the situation (Voss et al., 2022). If this would hold true, a rebuilding of the stock might not any longer be manageable or profitable, respectively.

The fish species show strong interactions (Figure 5c). Cod is a major predator on sprat and juvenile herring. At the same time, cod shows cannibalistic behavior, especially at large stock size. Sprat and herring, in turn, prey on pelagic cod eggs, diminishing cod recruitment. Furthermore, herring and sprat stocks compete for pelagic copepods as prey. Fisheries usually target one of the species, as fishers don't have the same share of quota for the different stocks.



**FIGURE 7** The Window of Tipping Point Analysis (WTPA) applied to the Central Baltic Cod Fishery. The left panel shows the WTPA for the cod fishery; the right panel adds different potential states. Direction and strength of impacts between elements is described (cf. legend of Figure 1).





Any management action regulating one of the stocks will therefore also affect the other stocks via ecological interaction as well as change the distribution of profits within the fisheries segment (Voss, Quaas, Schmidt, & Hoffmann, 2014). Due to the principle of “relative stability” this carries through up to the national level (Voss, Quaas, Schmidt, Tahvonen, et al., 2014). These strong interactions call for a multi-species, multi-fleet model and a larger window of analysis is warranted (Figure 5c).

The second, larger window of analysis comprises three fish stocks (cod, herring, sprat), their interaction, as well as two fishing fleets (Figure 6, central panel): A pelagic fishery for herring and sprat and the cod fishery. Enlarging the window of analysis opens the discussion of trade-offs and winners and losers of changes in cod stock productivity as a result of crossing a tipping point (Rindorf et al., 2017; Voss, Quaas, Schmidt, & Hoffmann, 2014). Sprat and herring stocks will profit from a reduced cod stock size as they are suffering from less predation. Clupeid stock sizes and harvest of the fisheries targeting these fish might be higher at a smaller cod stock. This involves a discussion on fairness and equity (Voss, Quaas, Schmidt, & Hoffmann, 2014), as management actions directed to restore the cod stock size will harm herring and sprat fishers.

While the smallest window of analysis, without a doubt, suggested that it would be beneficial to tip-back the system if possible, the larger window of analysis opens the view for conflicting interests.

The fish stocks are embedded in the Central Baltic Sea ecosystem, and provisioning of food is just one of the ecosystem services which managers might be concerned about. Sustainable environmental management will need to consider multiple ecological and societal objectives simultaneously. Accordingly, the currently developed ecosystem approach to (fisheries) management considers not only individual ecosystem components but also their interconnections, which introduces new challenges for both scientists and managers (Levin et al., 2009; Linke et al., 2014). For the case of the Central Baltic Sea, recreation and tourism, which are linked to water quality, offer additional important ecosystem services to the people in the surrounding countries (Ahtiainen et al., 2019; Heckwolf et al., 2021).

The largest window of analysis in our example (Figure 6, right panel) therefore includes the interaction of fish species with plankton and benthos communities. These impact water quality, being itself an important factor for tourism. Evaluation of interaction, uncertainties, and trade-offs becomes increasingly complicated. Especially, as plankton and benthos are strongly impacted by eutrophication (mainly caused by agriculture), and different options of eutrophication management will alter the ecological system. One option of informing decision makers in face of such complex networks is the use of decision support tools. For example, Uusitalo et al. (2022) constructed a Bayesian Network which allows the simultaneous evaluation of the fisheries economics and the attainment of various environmental management objectives, therefore facilitating discussion on the trade-offs and synergies between goals and across sectors. Still, even with a larger window, spill-overs to elements not included or from drivers not considered matter and a WTPA makes this explicit.

Summarizing this case with respect to our six-step definition of the WTPA approach, yields a range of potentially included elements, from single ecological and economic components in the smallest window, up to a complex, interacting and interlinked socioeconomic system in the largest window (Steps 1 and 3). Quantitative data are available on a yearly basis since approximately 50 years (Step 2), thereby defining a temporally much narrower window as compared to the Peruvian Upwelling system case study. Major exogenous impacts are, for example, the impact of eutrophication on the Central Baltic ecosystem, as well as climate



change effects on fish stock productivity (Step 4). While cod and herring seem to be climate losers, the sprat population currently still profits from temperature increase. These environmental changes can, at least partly, trigger different productivity states of the fish stocks (Step 5), what has been shown for the cod (e.g., Möllmann et al., 2021; Voss & Quaas, 2022), and is assumed for herring. Intervention possibilities (Step 6) are numerous and range from measures directly affecting stock abundance (e.g., setting Total Allowable Catches), to eutrophication management, or interventions in the socioeconomic realm, like, for example, subsidies or fostering of direct marketing. Which one to favor depends on the choice of WTPA.

## 4 | DISCUSSION AND CONCLUSION

We argued that the detection of crossing a tipping point largely depends on the time period considered, and on the elements included in the analysis such that a WTPA is useful to better understand the SES and the potential states of its elements. We also argue that the WTPA is useful to define the agency of the people involved and to determine policy options (e.g., reduce drivers, focus on adaptation) as well as to define desirable states of individual elements and the entire system.

After crossing a tipping point, actors may prefer to return to the previous regime of the system. Still, should one aim to tip back to the original system state (in case tipping already occurred) if that original state has been somewhat vulnerable to tipping in the first place? In general, crossing a tipping point may not be a bad thing. Depending on the context (of the SES and the tipping point at hand), the new system state may offer opportunities for system elements, may create a ground for further development previously unforeseeable. In the context of fishery, as an example, global warming is often discussed as a necessarily negative process everywhere. But this discourse does not always relate to the reality of (fishery) resource users, because warming waters or changing environmental conditions may also lead to the opportunity to target species that did previously not exist in the area (climate change may alter species distribution) but that by chance be high-priced species (on international markets). Even though the process of environmental change will always, in any SES, lead to the distinction of (ecologically) important species, the change in species composition and resulting economic opportunities for human actors may lead to a positive evaluation of the achieved new system state.

One major challenge in the analysis of tipping points relates to knowledge of effects of crossing a tipping point and on effects of management interventions. Tipping point management will necessarily require the weighing of costs and benefits of each possible action—and of not reacting at all. One major reason why many people want to prevent tipping relates to the consequences of crossing such a point which are often unknown or at least uncertain. There is not only uncertainty concerning the effects of crossing, but also when and whether it occurs in the first place. This may cause stakeholders to misjudge the situation and consider a tipping point as inevitable, which can in turn accelerate or enable the tipping of the system. Identifying tipping points and their consequences, reduces the uncertainty and can therefore prevent regime shifts (Maas et al., 2017). Using different models to look at what-if scenarios and putting several Windows of Tipping Point Analysis next to each other fosters a deeper understanding of the SES, its potential tipping points and their development, and policy options or options to act of different groups of people.



A connected and remaining challenge is also the inclusion of agency of the modeled actors. The resilience of a "bad" current state might even be considered to be stronger when considering the agency (of human actors) and their status-quo bias.

The above-mentioned uncertainty and the reaction of different actors is crucial to consider in tipping point management strategies (i.e., in related intervention options): only if such management is designed in an adaptive manner, if the behavior of the system and its elements in such a new, resulting state is evaluated critically and management strategies altered, if needed, can one assume that such management will achieve a plural, multidimensional benefit for the SES. Here, the WTPA is also useful as the selection of elements for the model and indicators for the discussion of system state influence policy outcome and should be made explicit and discussed in a broader view. For the broader view, a connection to concepts like the "safe operating space" may be interesting to explore to ensure a desirability of a system state beyond the WTPA at hand.

## ACKNOWLEDGMENTS

M.-C. R. and R. S. acknowledge funding from the research project Humboldt-Tipping (Social-Ecological Tipping Points of the Northern Humboldt Current Upwelling System, Economic Repercussions and Governance Strategies) from the German Federal Ministry of Education and Research under grant agreement number 01LC1823A. R. V. acknowledges funding from the European Union's Horizon 2020 research and innovation programme under the grant agreement No. 773713 "PANDORA" and the German Federal Ministry of Education and Research under Grant 01LC1826A "marEEshift." Open Access funding enabled and organized by Projekt DEAL.

## AUTHOR CONTRIBUTIONS

**Marie-Catherine Riekhof:** Conceptualization (lead); funding acquisition (equal); Investigation (equal); supervision (lead); visualization (equal); writing – original draft (equal); writing – review & editing (lead). **Lotta Clara Kluger:** Conceptualization (equal); investigation (equal); visualization (supporting); writing – review & editing (equal). **Renato Salvattecì:** Conceptualization (equal); data curation (lead); investigation (equal); visualization (supporting); writing – original draft (equal); writing – review & editing (equal). **Lotta Siebert:** Conceptualization (supporting); investigation (equal); Visualization (equal); writing – original draft (supporting); writing – review & editing (supporting). **Rudi Voss:** Conceptualization (supporting); funding acquisition (equal); investigation (equal); visualization (supporting); writing – original draft (equal).

## DATA AVAILABILITY STATEMENT

The data employed to plot Figure 3 are openly available from FAO Fishery and Aquaculture Statistics, from Salvattecì et al. (2018), and the guano data from The University of Texas at Austin Repository at <https://repositories.lib.utexas.edu/handle/2152/531?show=full>.

## ORCID

Marie-Catherine Riekhof  <http://orcid.org/0000-0001-6565-8661>

## ENDNOTES

<sup>1</sup> We understand SES as socioeconomic ecological systems.



<sup>2</sup> Knowing that elements can have different states, the question arises when a (sub-)system is to be considered "tipped" and a regime shift occurred. We will not discuss this question here in general but leave this to the different application.

## REFERENCES

- Ahtiainen, H., Liski, E., Pouta, E., Soini, K., Bertram, C., Rehdanz, K., Pakalnieta, K., & Meyerhof, J. (2019). Cultural ecosystem services provided by the Baltic Sea marine environment. *Ambio*, 48(11), 1350–1361.
- Baumgartner, T., Soutar, A., & Ferreira-Bartrina, V. (1992). Reconstruction of the history of pacific sardine and northern anchovy populations over the past two millennia from sediments of the Santa Barbara Basin, California. *CalCOFI Rep*, 33, 24–40.
- Cushman, G. T. (2005). *The Lords of Guano: Science and the Management of Peru's Marine Environment, 1800-1973* (PhD thesis). University of Texas at Austin, Texas, 762pp.
- FAO. (2022). *Fishery and Aquaculture Statistics. Global capture production 1950-2019 (FishstatJ)*. FAO Fisheries Division. Updated 2021. Retrieved May 2022, from [www.fao.org/fishery/statistics/software/fishstatj/en](http://www.fao.org/fishery/statistics/software/fishstatj/en)
- Fenichel, E. P., & Abbott, J. K. (2014). Natural capital: From metaphor to measurement. *Journal of the Association of Environmental and Resource Economists*, 1(1/2), 1–27.
- Field, D. B., Chavez, F., Lange, C. B., & Smith, P. E. (2011). *Shifting baselines: The past and the future of ocean fisheries*. Variations in Fisheries and Complex Ocean Environments (pp. 59–76). Island Press.
- Filatova, T., Polhill, J. G., & van Ewijk, S. (2015). Regime shifts in coupled socio-environmental systems: Review of modelling challenges and approaches. *Environmental Modelling & Software*, 75, 333–347.
- Gladwell, M. (2000). *The tipping point: How little things can make a big difference*. Little, Brown.
- Heckwolf, M. J., Peterson, A., Jänes, H., Horne, P., Künne, J., Liversage, K., Sajeve, M., Reusch, T. B. H., & Kotta, J. (2021). From ecosystems to socio-economic benefits: A systematic review of coastal ecosystem services in the Baltic Sea. *Science of The Total Environment*, 755, 142565.
- HELCOM. (2018). HELCOM thematic assessment of biodiversity 2011-2016. Supplementary report to the HELCOM 'State of the Baltic Sea' report. *Baltic Sea Environment Proceedings No. 158*. 88. Available at: <http://stateofthebalticsea.helcom.fi/wp-content/uploads/2019/09/BSEP158-Biodiversity.pdf>
- Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K., Engelbrecht, F., Guiot, J., Hijjoka, Y., Mehrotra, S., Payne, A., Seneviratne, S. I., Thomas, A., Warren, R., & Zhou, G. (2018). Chapter: Impacts of 1.5°C global warming on natural and human systems. In V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield (Eds.), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*, World Meteorological Organization Technical Document (pp. 177–284). In Press. Available at: [https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15\\_Chapter3\\_Low\\_Res.pdf](https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter3_Low_Res.pdf)
- Horan, R. D., Fenichel, E. P., Drury, K. L. S., & Lodge, D. M. (2011). Managing ecological thresholds in coupled environmental-human systems. *Proceedings of the National Academy of Sciences*, 108(18), 7333–7338.
- ICES. (2020). Baltic fisheries assessment working group. *ICES Scientific Reports*, 2(45).
- Jahncke, J., Checkley, D. M., & Hunt, G. L. (2004). Trends in carbon flux to seabirds in the Peruvian upwelling system: Effects of wind and fisheries on population regulation. *Fisheries Oceanography*, 13(3), 208–223.
- Kahneman, D., Knetsch, J. L., & Thaler, R. H. (1991). Anomalies: The endowment effect, loss aversion, and status quo bias. *Journal of Economic Perspectives*, 5(1), 193–206.
- Klose, A. K., Karle, V., Winkelmann, R., & Donges, J. F. (2020). Emergence of cascading dynamics in interacting tipping elements of ecology and climate. *Royal Society Open Science*, 7(6), 200599.
- Lauerburg, R., Diekmann, R., Blanz, B., Gee, K., Held, H., Kannen, A., Möllmann, C., Probst, W., Rambo, H., Cormier, R., & Stelzenmüller, V. (2020). Socio-ecological vulnerability to tipping points: A review of empirical approaches and their use for marine management. *Science of the Total Environment*, 705, 135838.
- Levin, P. S., Fogarty, M. J., Murawski, S. A., & Fluharty, D. (2009). Integrated ecosystem assessments: Developing the scientific basis for ecosystem-based management of the ocean. *PLoS Biology*, 7(1), e1000014.



- Linke, S., Gilek, M., Karlsson, M., & Udovyk, O. (2014). Unravelling science-policy interactions in environmental risk governance of the Baltic Sea: Comparing fisheries and eutrophication. *Journal of Risk Research*, 17(4), 505–523.
- Maas, A., Goemans, C., Manning, D., Kroll, S., & Brown, T. (2017). Dilemmas, coordination and defection: How uncertain tipping points induce common pool resource destruction. *Games and Economic Behavior*, 104, 760–774.
- Milkoreit, M., Hodbod, J., Baggio, J., Benessaiah, K., Calderón-Contreras, R., Donges, J., Mathias, J.-D., Rocha, J. C., Schoon, M., & Werners, S. (2018). Defining tipping points for social-ecological systems scholarship—An interdisciplinary literature review. *Environmental Research Letters*, 13(3), 033005.
- Möllmann, C., Cormon, X., Funk, S., Otto, S. A., Schmidt, J. O., Schwermer, H., Sguotti, C., Voss, R., & Quaas, M. (2021). Tipping point realized in cod fishery. *Scientific Reports*, 11(14259). <https://doi.org/10.1038/s41598-021-93843-z>
- Möllmann, C., Diekmann, T., Müller-Karulis, B., Kornilovs, G., Plikshs, M., & Axe, P. (2009). Reorganization of a large marine ecosystem due to atmospheric and anthropogenic pressure: A discontinuous regime shift in the Central Baltic sea. *Global Change Biology*, 15(6), 1377–1393.
- Noack, F., Riekhof, M.-C., & Quaas, M. (2018). Development in a dual economy: The importance of resource-use regulation. *Journal of the Association of Environmental and Resource Economists*, 5(1), 233–263.
- Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, 325(5939), 419–422.
- Pindyck, R. (2020). *What we know and don't know about climate change, and implications for policy* (Technical report).
- Quaas, M., Requate, T., Ruckes, K., Skonhofs, A., Vestergaard, N., & Voss, R. (2013). Incentives for optimal management of age-structured fish populations. *Resource and Energy Economics*, 35(2), 113–134.
- Riekhof, M.-C., Regnier, E., & Quaas, M. F. (2019). Economic growth, international trade, and the depletion or conservation of renewable natural resources. *Journal of Environmental Economics and Management*, 97, 116–133.
- Rindorf, A., Dichmont, C. M., Thorson, J., Charles, A., Clausen, L. W., Degnbol, P., Garcia, D., Hintzen, N. T., Kempf, A., Levin, P., Mace, P., Maravelias, C., Minto, C., Mumford, J., Pascoe, S., Prellezo, R., Punt, A. E., Reid, D. G., Röckmann, C., ... Voss, R. (2017). Inclusion of ecological, economic, social, and institutional considerations when setting targets and limits for multispecies fisheries. *ICES Journal of Marine Science*, 74(2), 453–463.
- Salvatteci, R., Field, D., Gutiérrez, D., Baumgartner, T., Ferreira, V., Ortlieb, L., Sifeddine, A., Grados, D., & Bertrand, A. (2018). Multifarious anchovy and sardine regimes in the Humboldt current system during the last 150 years. *Global Change Biology*, 24(3), 1055–1068.
- Salvatteci, R., Gutierrez, D., Field, D., Sifeddine, A., Ortlieb, L., Caquineau, S., Baumgartner, T., Ferreira, V., & Bertrand, A. (2019). Fish debris in sediments from the last 25 kyr in the Humboldt current reveal the role of productivity and oxygen on small pelagic fishes. *Progress in Oceanography*, 176, 102114.
- Salvatteci, R., Schneider, R. R., Galbraith, E., Field, D. B., Blanz, T., Bauersachs, T., Crosta, X., Martinez, P., Echevin, V., Scholz, F., & Bertrand, A. (2022). Smaller fish species in a warm and oxygen-poor Humboldt current system. *Science*, 375, 101–104.
- Scheffer, M. (1989). Alternative stable states in eutrophic, shallow freshwater systems: A minimal model. *Hydrobiological Bulletin*, 23(1), 73–83.
- Scheffer, M., & van Nes, E. H. (2007). Shallow lakes theory revisited: Various alternative regimes driven by climate, nutrients, depth and lake size. *Hydrobiologia*, 584(1), 455–466.
- Schlüter, M., McCallister, R. R. J., Arlinghaus, R., Bunnfeld, N., Eisenack, K., Hölker, F., Milner-Gulland, E. J., Müller, B., Nicholson, E., Quaas, M., & Stöven, M. (2011). New horizons for managing the environment: A review of coupled social-ecological systems modeling. *Natural Resource Modeling*, 25(1), 219–272.
- Stockholm Resilience Center. (2016). *Insight #2 Regime Shifts*. <https://www.stockholmresilience.org/research/insights/2016-11-16-insight-2-regime-shifts.html>
- Tahvonen, O., Quaas, M. F., Schmidt, J. O., & Voss, R. (2013). Optimal harvesting of an age-structured schooling fishery. *Environmental and Resource Economics*, 54(1), 21–39.
- Tavoni, A., & Irıř, D. (2020). Tipping and reference points in climate change games. In G. Chichilnisky & A. Rezai (Eds.), *Handbook on the Economics of Climate Change* (pp. 239–258). Edward Elgar Publishing.



- Uusitalo, L., Blenckner, T., Puntilla-Dodd, R., Skyttä, A., Jernberg, S., Voss, R., Müller-Karulis, B., Tomczak, M. T., Möllmann, C., & Peltonen, H. (2022). Integrating diverse model results into decision support for good environmental status and blue growth. *Science of The Total Environment*, 806, 150450.
- Voss, R., Neuenfeldt, S., & Quaas, M. (2022). Robust, ecological-economic multispecies management of central baltic fishery resources. *ICES Journal of Marine Sciences*. 79(1), 169–181. <https://doi.org/10.1093/icesjms/fsab251>
- Voss, R., & Quaas, M. (2022). Fisheries management and tipping points: Seeking optimal management of eastern Baltic cod under conditions of uncertainty about the future productivity regime. *Natural Resource Modeling*. 35, e12336.
- Voss, R., Quaas, M. F., Schmidt, J. O., & Hoffmann, J. (2014). Regional trade-offs from multi-species maximum sustainable yield (MMSY) management options. *Marine Ecology Progress Series*, 498, 1–12.
- Voss, R., Quaas, M. F., Schmidt, J. O., Tahvonen, O., Lindegren, M., & Möllmann, C. (2014). Assessing social—Ecological trade-offs to advance ecosystem-based fisheries management. *PLoS ONE*, 9(9), e107811.
- Voss, R., Quaas, M. F., Stoeven, M. T., Schmidt, J. O., Tomczak, M. T., & Möllmann, C. (2017). Ecological-economic fisheries management advice—Quantification of potential benefits for the case of the eastern baltic cod fishery. *Frontiers in Marine Science*, 4, 209. <https://doi.org/10.3389/fmars.2017.00209>

**How to cite this article:** Riekhof, M.-C., Kluger, L. C., Salvattecchi, R., Siebert, L., & Voss, R. (2022). To tip or not to tip: The Window of Tipping Point Analysis for social-ecological systems. *Natural Resource Modeling*, 35, e12357. <https://doi.org/10.1111/nrm.12357>