Synthesis of applying frameworks and tipping point concepts to Learning Sites
Deliverable 5.3

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1 GES4SEAS Project Summary

Human activities at sea (e.g., maritime transport, extraction of living and non-living resources, etc.) and in coastal areas (e.g., agriculture, leisure and recreation, etc.) have expanded considerably, leading to an increased level of pressures and subsequent degradation of ocean health and, ultimately, human health. Single and cumulative impacts of these activities are likely to increase, driven by human demands and enhanced by climate change.

Human activities evolve following socio-economic drivers leading to pressures, which often are studied in isolation from each other even though their impacts on marine ecosystems can interact, making the effects cumulative (e.g., synergistic, antagonistic or a combination). Knowledge on these interactions and their cumulative effects in the marine environment has increased in recent years, but huge challenges still remain to be solved. Thus, there is little predictability with which to inform decision-making processes, especially on ecological tipping points, which, if exceeded, could lead to a point of no-return for the system. In this context, an ecosystem-based management (EBM) approach to the management of human activities at sea and on land should ensure that the combined pressure of such activities is kept within levels compatible with the achieving Good Environmental Status (GES) (requirements of the Marine Strategy Framework Directive – MSFD), against a background of climate change. This means that the capacity of marine and coastal ecosystems to respond to human-induced changes is not compromised, enabling the sustainable use of marine goods and services by present and future generations.

Thus, the main objective of GES4SEAS is to inform and guide marine governance in minimizing human pressures and their impacts on marine biodiversity and ecosystem functioning, while maintaining the sustainable delivery of ecosystem services. This will be achieved through developing an innovative and flexible toolbox, tested, validated, demonstrated and upscaled, in the context of adaptive EBM approach. The toolbox will allow competent authorities to assess and predict the effect of multiple stressors (including climate change) and pressures from human activities, at the national, sub-regional, regional and European level. Ultimately, this will ensure they achieve GES, and support different policies at national, European and global levels (e.g. Birds and Habitats Directives (BHD), Biodiversity Strategy 2030, United Nations Sustainable Development Goals (SDG)).

Stakeholders and the key competent authorities (including national, regional and European levels) are integrated in a Practitioner Advisory Board (PAB) to co-create and validate the toolbox and the EBM approach. This will result on a real problem-solving approach with iterative and incremental development steps.

GES4SEAS will also rely on existing multi-actor networks to involve and engage with stakeholders. This multi-actor approach will ensure that the research and deliverables are relevant to marine managers all around the world. Lastly, it is important to highlight that the toolbox will be tested and demonstrated at 11 Learning Sites (LSs) covering all European regional seas (and also overseas), and environments. Thus, it is expected that GES4SEAS will achieve Technological and Societal Readiness Levels 6. This will be achieved by the participation of 20 partners, covering the four European regional seas and Canada.

It is expected that GES4SEAS will:

- Operationalize integrative and holistic solutions for EBM, based upon a software toolbox for analyzing, assessing and mapping cumulative pressures, GES and ecosystem services.
- Provide evidence (and training) to key stakeholders of the benefits of using the toolbox that will be developed in GES4SEAS for assessing the environmental status of marine waters and the ecosystem services considering the effects of multiple pressures so opt for using it.
- Ensure the EBM approach and guidelines for the management of Invasive Alien Species (IAS), harmful algal blooms (HABs) and jellyfish, the approach for monitoring top predators are used by end-users.
- Investigate, using models, the best ways to obtain thresholds of GES/non-GES status and tipping points (system breaking points).
- Reach and engage a wider society, and specifically young people and educators, on key messages steaming from this project, so GES4SEAS contributes to societal ocean literacy and responsible behaviours.

2 Deliverable 5.3. Summary and objectives

Environmental and anthropogenic pressures drive directional responses in marine ecosystems. Past a certain intensity of pressure, that is a threshold, the ecosystem response may change drastically. Once such a tipping point is reached, returning the ecosystem to its previous functional state is complex and generally takes a long time (or even, sometimes, impossible). Additionally, the multiple feedback loops and cascading effects that drive ecosystems can either increase resilience or trigger pressure propagation across the ecosystem. Therefore, there is a need to assess ecosystems status in a more comprehensive manner, that is including as many ecosystem components and pressures as possible to incorporate most if not all the feedback loops and cascading effects in the ecosystem that either increase resilience or cause propagation of pressures in the ecosystem.

This deliverable (D5.3.) aims to synthesise previous tipping point assessment results from D3.2 (Lynam et al., 2025) to develop or point towards major improvements or solutions to improve upon the incorporation of tipping points in ecosystem assessments. Therefore we:

1. Developed a system to help Tikta[1] users to incorporate threshold assessments in their Cumulative Effects Assessment (CEA) analyses and environmental status assessment, using Nested Environmental status Assessment Tool (NEAT).
2. Develop a perspective that moves towards ecosystem-based tipping point assessment.
3. Identify what improvements in monitoring could help towards achieving better tipping point assessments.
4. Discuss some key considerations that will improve tipping point identification and recovery of ecosystems, such as early warning signals, positive tipping points, and safe operating space.
5. Develop a framework that combines the use of these potential solutions in a meaning full manner to guide decision makers to identify where they need to improve to achieve better incorporation of tipping points in environmental and cumulative impact assessments.

[1] Tikta is an open source software, developed by GES4SEAS, allowing users to make Cumulative Effects Assessments (CEA) and evaluate the environmental status of the sea, using Nested Environmental status Assessment Tool (NEAT). More information can be found here: https://www.ges4seas.eu/toolbox/#toggle-id-1

3 Introduction

Environmental and cumulative anthropogenic pressures drive directional responses in marine ecosystems (Borja et al., 2024). Past a certain intensity of pressure, that is a threshold, the ecosystem response may change drastically (Andersen et al., 2009). Similarly, interactions between multiple pressures may sway the directional response of the ecosystem, often to the detriment of the ecosystem. It is often difficult to identify exactly what combinations of pressures in a given ecosystem cause potential shifts in its response and what thresholds of these pressures will likely limit such shifts (Korpinen et al., 2021). Even if such a threshold for each pressure was to be identified based on the best possible assessment of the ecology, from a marine spatial use and socio-economic perspective, implementing measures to limit pressures reaching the threshold remains even more difficult (Hillebrand et al., 2021; Gorjanc et al., 2022). The implementation of pressure thresholds through policy often then results in compromise and trade-off discussions around moving a pressure threshold to strike a fit within the socio-economic scheme. The question is whether such efforts are effective for managing marine ecosystems?

One of the major issues with marine spatial use, it that it creates situations where multiple pressures can act together on ecosystems (Kirkfeldt and Andersen, 2021). Cumulatively, these pressures drive changes in the ecosystem, until there reaches a point where there is a sudden shift in how the ecosystem functions, that is a tipping point is reached (Heinze et al., 2021). Once such a tipping point is reached, returning the ecosystem to its previous functional state is complex and generally takes a long time (decades) (Zhang et al., 2022). During this time multiple stochastic events (environmental or anthropogenic) may further drive changes in the ecosystem, limiting or speeding the recovery. Meanwhile, directional climate change mean that in several instances, recovery to the previous functional state (baseline) is undesirable or not feasible (Halpern et al., 2025). Given completely limiting marine spatial use is unrealistic, the focus remains on how best to use marine space while limiting ecological impact, that is, what thresholds of pressures to avoid. The problem is that, as depicted through the literature (Nikolaou et al., 2025) and the case studies in D3.2 (Lynam et al., 2025), multiple ecosystems across Europe have passed a tipping point or are already in a poor environmental status. For example, on the eastern Spanish coast, changes in fishing regulations and practice have largely changed sardine populations and their impact on their ecosystem. Similarly, in the Bothnian bay, changing environmental parameters due to human activity and climate change has shifted the food web structure three times over 40 years through a series of cascading events and impacts.

However, overall, the case studies assessed in GES4SEAS show that while some tipping points were detected for specific ecosystem components and pressure combinations, multiple other ecosystems have changed broadly and tipping points were not quite clearly detected, meaning that there is a need to shift the focus from assessing specific ecosystem components, but move towards broader ecosystem-based tipping point assessments (Lynam et al., 2025).

Given the deteriorated or poor environmental status of some marine ecosystems across Europe, retrospective assessment and identification of pressure thresholds can inform some level of avoidance of further ecosystem degradation and the processes that have caused degradation and shifts. For ecosystems that have not been majorly degraded, it is imperative to assess what components of the ecosystem are under threat from pressures, how these influence feedback loops in the ecosystem, and what are the risks (e.g., low, moderate, high) of that ecosystem to shift into a degraded state. A major part of the focus and efforts also need to go towards improving current environmental status. In that regard, it is clear that an understanding of what threshold of pressures cause major impacts is needed (Borja et al., 2024). Additionally, it is fundamental to understand how the ecosystem as a whole is responding and what early indicators can help assess the risks of further degradation or shifting ecosystem state. Finally, there is a need to determine what pressure thresholds can help ecosystem recovery (e.g., through positive tipping points). While it is understandable that an identified pressure threshold can provide a pressure reduction target and therefore a much clearer goal for policy and actions, identifying such thresholds that enhance recovery of ecosystems, where tipping points have often been passed already, resides in the assessment of how ecosystems recover given changes in the combinations of pressures that impact them. This is currently very complex and has not been done to the extent of retrospective ecosystem shift assessments, even if some concepts such as positive tipping point, adaptive envelope and safe operating space can help defining some pressure limits.

Throughout this deliverable D5.3, **the aim is to describe how pressure threshold assessments will be incorporated in Tikta to facilitate the assessment of how such thresholds increase or decrease cumulative impact in the ecosystem.** Secondly, following the tipping point analyses made on multiple ecosystems in D3.2 (Lynam et al., 2025), **we will discuss the gaps in policy regarding ecosystem assessment for identifying, mitigating or avoiding ecosystem shifts**. Importantly, **we will delve into considerations of how policy can help enhancing the implementation of tipping point risk assessments, taking both a degradation avoidance and a recovery enhancement perspective**.

4 Incorporation of tipping point concepts and analysis in Tikta

When considering thresholds in the context of ecosystem response to a pressure, we are referring to a pressure that has limited effect below a certain level, and whereby the effect increases as the pressure increases until we approach the threshold pressure level. At that threshold, we could consider that a maximum effect is reached. Beyond this, any further increases in pressure do not cause the response to increase any further. The response to a pressure as outlined here, with a threshold pressure level and maximum response, can be described using a logistic function. The generalized logistic function can be written:

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}}$$

For the case where, the function varies between 0 and 1. Figure 1 shows the function for X0 = 0.5 and for 3 different values of k.

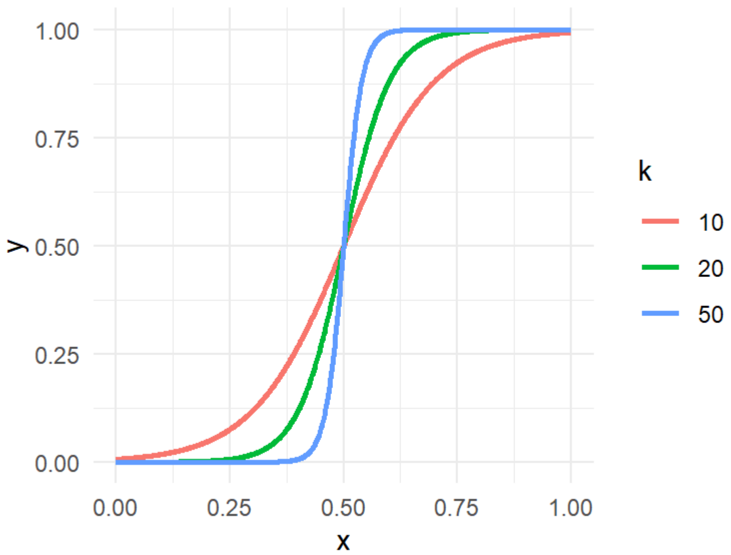

Figure 1: A general logistic function with different slopes (K: steepness parameter).

Other non-linear responses

There are many other non-linear functions which could be relevant for representing ecosystem responses to pressures. Some of the more common ones are outlined briefly here. Others not shown, include power functions, Weibull functions.

Log functions with the general form $f(x) = a + b \cdot \log(x)$ denote an increasing response of ecosystem component y from pressure x (can be rapid or more gradual) followed by a plateau effect with maintained maximum response (Figure 2A). **Exponential functions** with the general form of $f(x) = Ae^{kx}$ show limited response of ecosystem component y from pressure x until a level of pressure x where y starts to respond rapidly (Figure 2B).

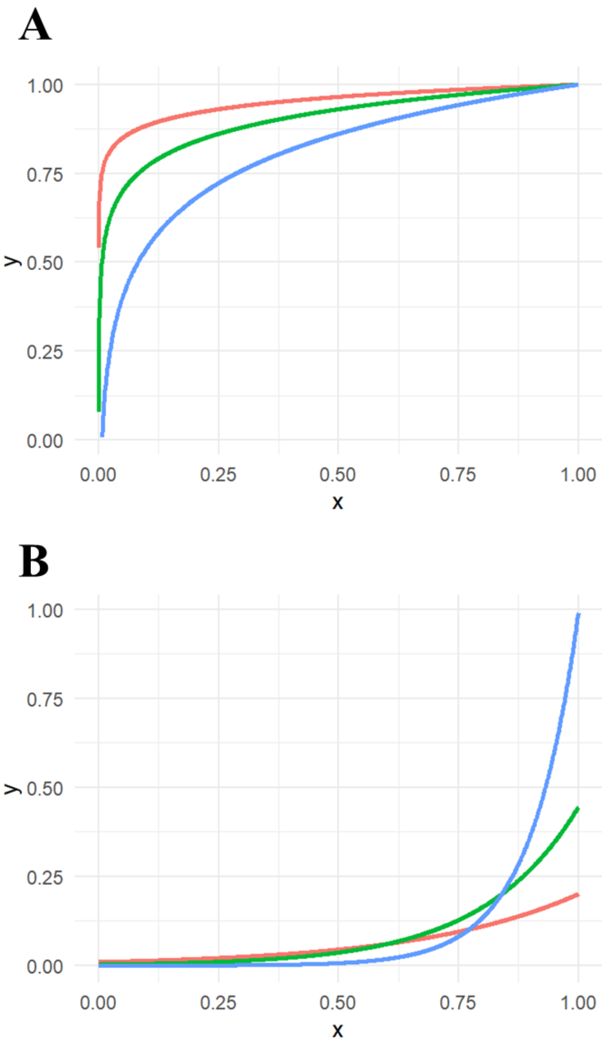

Figure 2: General shape of log (A) and exponential (B) response curves that show potential thresholds where the response of an ecosystem component y can shift in relation to increasing pressure x.

Multivariate responses

In the current implementation of Tikta, the effect of pressures on ecosystem components is calculated separately for each unique combination of pressure and ecosystem component. The combined result is then calculated by simple addition of individual contributions. For the Halpern mean method

(Halpern et al., 2008), the sum is then normalised to the quantity or number of ecosystem components but there is no interaction between pressures. The EcoImpact Mapper tool allows for testing if the effects of interactions between stressors are potentially important for the results of a cumulative effect assessment (Stock & Micheli, 2016).

Figure 3 illustrates how the separate responses of two different pressures *left* can be combined by interaction *right*. An antagonistic interaction where the effect of one pressure is counteracted or reduced by the other pressure is shown by the blue curve $f_{12}(x) = f_1(x) * (1 - f_2(x))$ whilst the red curve illustrates how the combined response is greater than either of the individual responses the $f_{12}(x) = 1 - (1 - f_1(x)) * (1 - f_2(x))$.

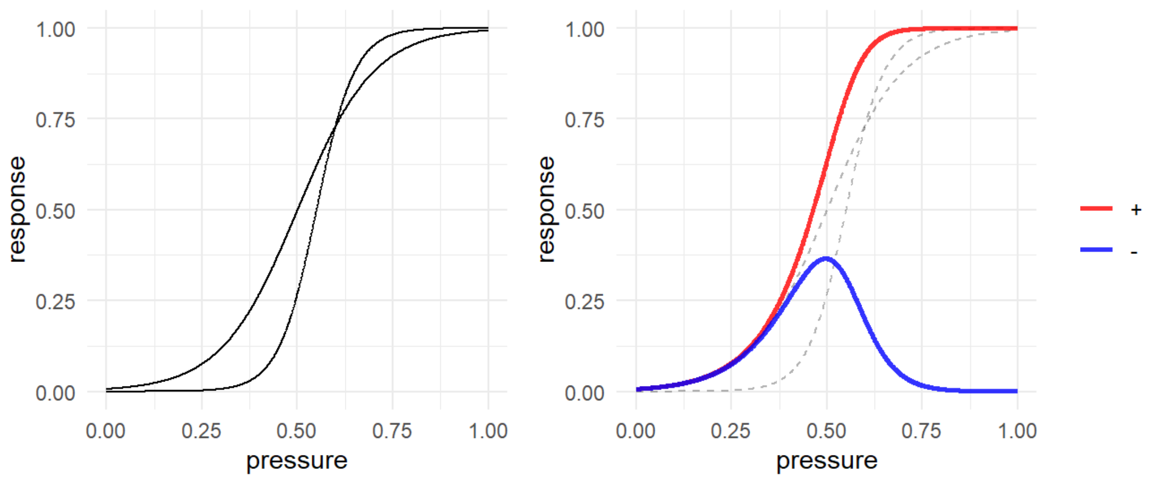

Figure 3: Two pressure response curves (left) and potential interactions (right)

Fitting pressure-response functions

We need to find the function which best describes the response of an ecosystem component to increasing intensity of a pressure.

Threshold functions

This example (Figure 4) shows observations of abundance of a species at different pressure intensities. By fitting a logistic function to the observations, we can estimate the response of the species to the pressure.

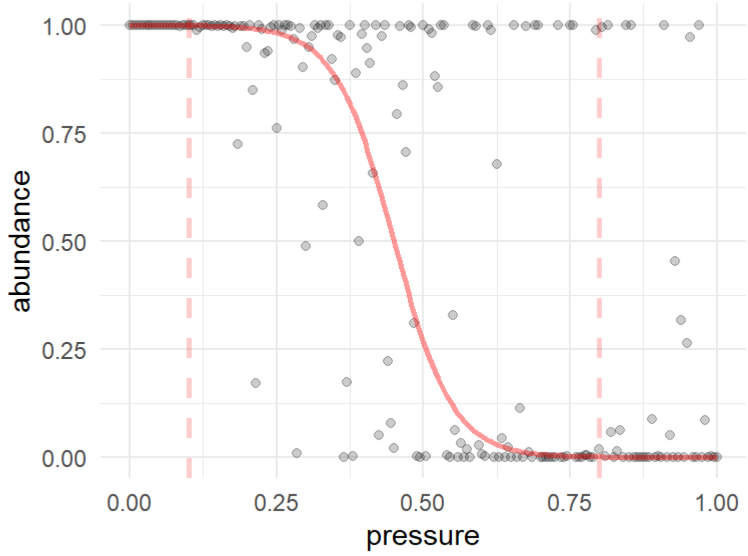

Figure 4: Abundance of a species versus pressure intensity.

Given the knowledge about the range of pressure values where the species shows a response, we can formulate a pressure-response function to describe how the impact on the species varies (Figure 5).

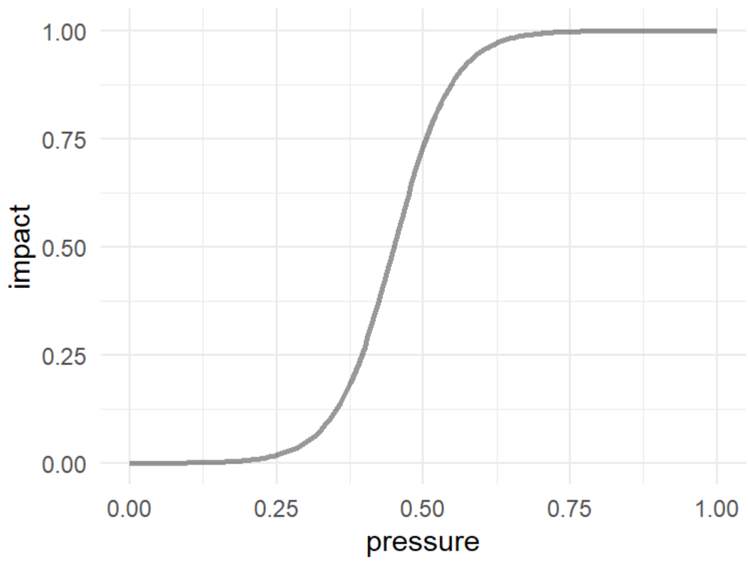

Figure 5: Impact on species in relation to pressure intensity.

Threshold function - a piecewise linear approximation

The logistic function can be approximated by a piece-wise linear function with two fixed points. For general case where y can vary outside the range 0-1, the equation can be written:

$$f(x) = \begin{cases} y_0, & x \leq x_0 \\ y_0 + \left(y_1 - y_0\right)\left(\frac{x - x_0}{x_1 - x_0}\right), & x_0 < x \leq x_1 \\ y_1, & x > x_1 \end{cases}$$

For the case where y varies in the range 0-1:

$$f(x) = \begin{cases} 0, & x \leq x_0 \\ \frac{x - x_0}{x_1 - x_0}, & x_0 < x \leq x_1 \\ 1, & x > x_1 \end{cases}$$

Figure 6 shows how the logistic function for k=20 can be approximated by a piece-wise linear function.

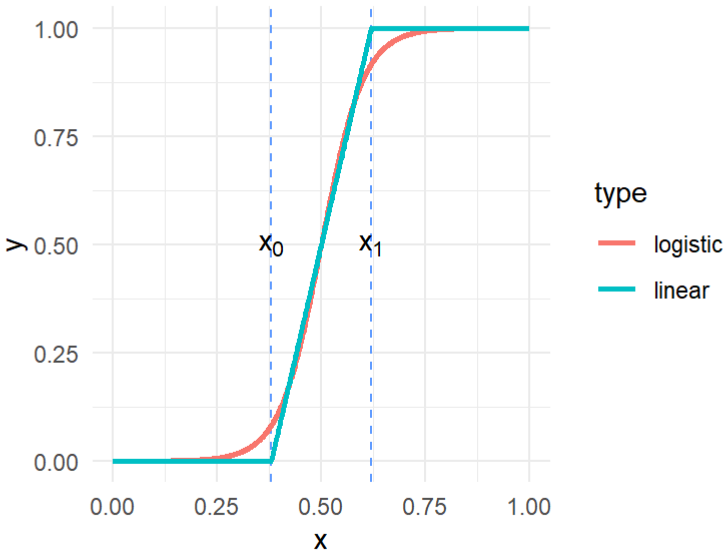

Figure 6: A piece-wise linear approximation of a logistic function.

By selecting the appropriate parameters, piece-wise linear functions can be used to represent other functional relationship, including thresholds, where a pressure has no effect below a certain intensity or where its effect does not increase above a certain limit:

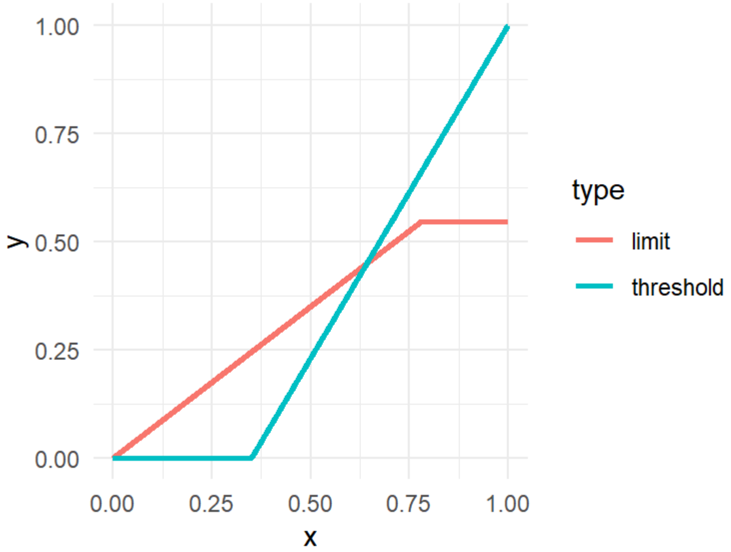

Figure 7: Piece-wise linear threshold functions.

A generalized piecewise linear function

In many cases the functions can be approximated by linear piece-wise functions. The number of segments in the piece-wise function can be increased to give a closer fit to the original function:

$$f(x) = \begin{cases} y_0, & x \le x_0 \\ y_0 + \left(y_1 - y_0\right)\left(\frac{x - x_0}{x_1 - x_0}\right), & x_0 < x \le x_1 \\ y_1 + \left(y_2 - y_1\right)\left(\frac{x - x_1}{x_2 - x_1}\right), & x_1 < x \le x_2 \\ \cdots & \\ y_{n-1} + \left(y_n - y_{n-1}\right)\left(\frac{x - x_{n-1}}{x_n - x_{n-1}}\right), & x_{n-1} < x \le x_n \\ y_n, & x > x_n \end{cases}$$

Implementation and usage of threshold assessment in Tikta

The implementation of tipping point concepts will be done by using multiple thresholds of pressure and ecosystem component interactions, that is, the user will have the option to compute threshold values for any combinations of pressures and ecosystem components they choose. The computation will be based on linear piecewise regression and logistic regression as described above. More practically, first, within Tikta, the user will be able to choose a new analysis and go to the detect threshold analysis template. There, the user will have the option of selecting the pressures and ecosystem components for which they require threshold detection (Figure 8). Once the parameter selections are made, the user will run the analysis and Tikta will calculate the X0 and X1 boundaries of pressure limits where a large shift in ecosystem component can be detected through the logistic regression and piecewise linear regression (Figure 9). These values for X0 and X1 can then be saved as text file for input into CEA analysis later.

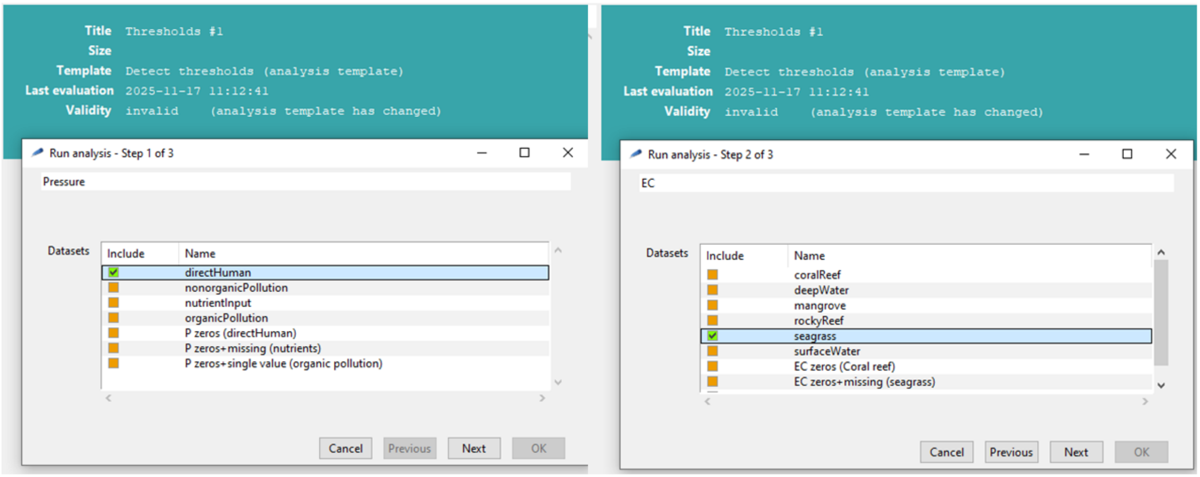

Figure 8: Parameter selection for threshold calculations with Tikta. Here, the user selected direct human impact as pressure and seagrass as ecosystem component to calculate potential thresholds.

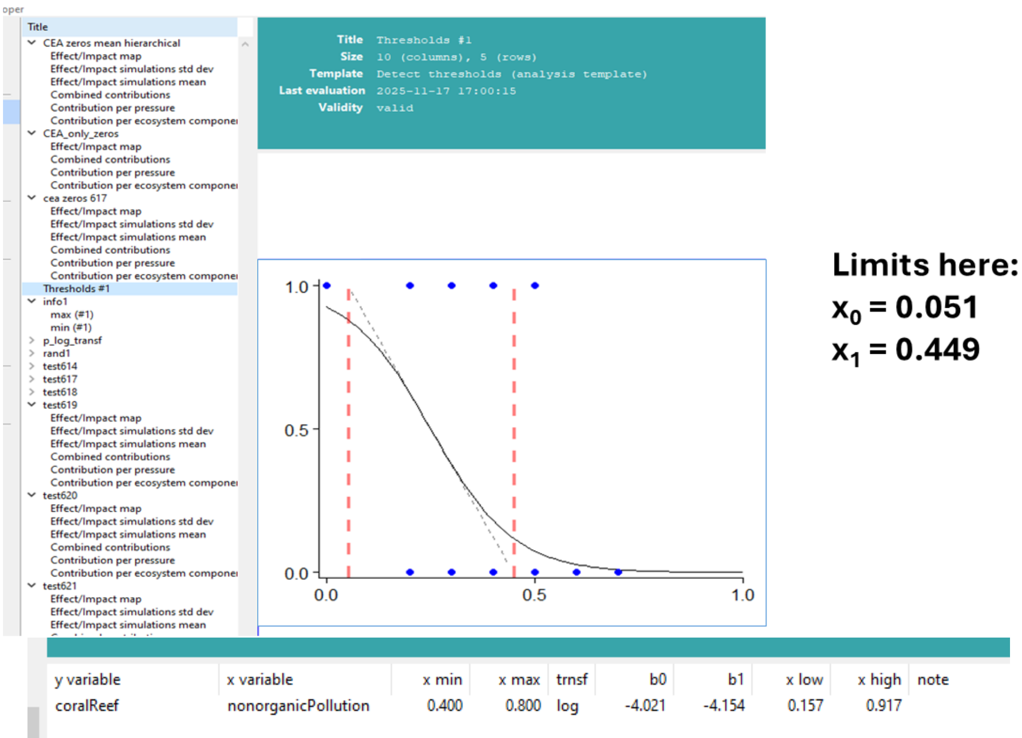

Figure 9: Example of thresholds detection ran through Tikta. Here, pressure values less than 0.051 do not cause major impact on the ecosystem component whereas a between thresholds of 0.051 to 0.449 a major decrease in ecosystem component occurs. Beyond the pressure threshold of 0.449, the ecosystem component remains strongly impacted. The currently implemented functionality returns the parameters of the logistic function b0 and b1 as well as the estimated lower and upper threshold values x0 and x1. While the analysis is currently fully implemented, the graph generation is still to be incorporated, but this screenshot shows functionality which is developed, giving the results of logistic regression.

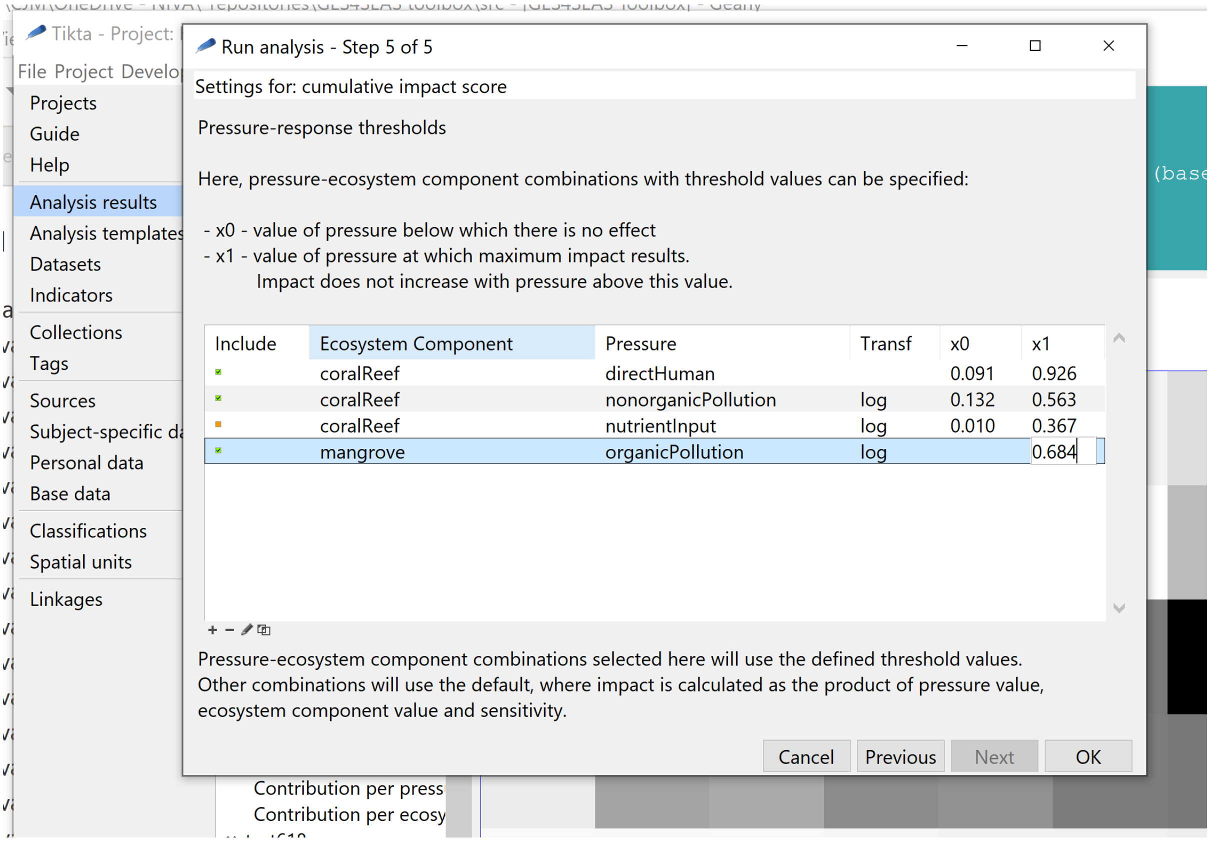

Figure 10: Manually defining upper and lower threshold values for pressures in a pressure-ecosystem component combination, implementing a piece-wise linear approximation of a logistic function response (as shown in Figure 6)

To incorporate thresholds into CEA analysis, the user will be able to manually input the desired pressure thresholds in the pressure normalisation section. More precisely, currently, before the CEA assessment, as default, all pressure values are normalised from 0 to 1 based on the minimum and maximum pressure values. Now the user will be given the option to select “default” normalisation or “threshold” normalisation (Figure 10). The “threshold” normalisation option will allow the user to specify what threshold value (e.g., X0 or X1) to normalise the pressure data with, essentially replacing either minimum or maximum by either X0 or X1 or both. Pressure values lower than the low threshold will be directly converted to 0 and pressure values larger than the high threshold will be directly converted to 1. By doing so, the user can expect that pressure values beyond selected thresholds would be where the maximum effect has been reached.

5 Policy framework for enhancing tipping point assessments and integration in decision making

5.1 Introduction

Integrating thresholds or tipping points in policy and decision making can be a complex balance between appropriate assessments of such tipping points and socioeconomic considerations (Van Ginkel et al., 2020, Melanidis et al., 2023; Pereira et al., 2025). Past policies and decisions related to ecosystem management (especially decisions that have led to limited outcomes) influence the level of conservatism in new policy, especially when implementing strong thresholds (Sims and Finnoff, 2016). Navigating through the multiple perspectives at play requires much information about the ecosystem in question, that is the ecological and climate processes that drive the ecosystem, and current or future developments in socio-economic activities around the ecosystem. Often, one or more of these components remain missing or compromised to some extent to allow for prioritisation of another. For example, ecosystem assessments regarding tipping points are often focused on few, often more economically valuable, ecosystem components and pressures (Hemraj and Carstensen, 2025), or climate-impact cost-benefit models downplay the relevance of climate tipping points in socio-economic cost-benefit assessments (Cai et al., 2015, Rising et al., 2022). These make decision making regarding implementation of thresholds inefficient. Therefore, we aim to define a more comprehensive assessment of ecosystem tipping points and how to integrate it in decision making.

On a global scale, climate tipping points have become a key feature of major international congress and conventions regarding policy and directions for global environmental conservation. However, often climate tipping points have been left out of climate economics, which has resulted in an underestimation of economic risks and losses in almost 180 countries (Dietz et al., 2021), albeit climate tipping points being important ecologically and for future ecosystem services (Marsden et al., 2024). This means that the urgency of implementing tipping points into climate policy has been downplayed because of a lack of modelled economic risks. From a local ecosystem perspective, implementation of thresholds in decision making regarding environmental conservation and socioeconomics tend to focus on targeted ecosystem components or services (e.g., those associated to fisheries). While multiple techniques for tipping points detection or prediction across ecosystems are available, currently most regional or local monitoring programs are not particularly designed to identify approaching tipping points across the ecosystem (Hewitt and Thrush, 2019). These are rather more designed towards monitoring specific economically important ecosystem components (exceptions do exist where a much broader suite of ecosystem components is monitored such as in the Baltic Sea). This means that, even if the intention is of understanding mechanisms behind tipping points and integrating these into policy, the ability for broader ecosystem assessment and identification of potential issues before they lead to severe tipping points can be limited (Hewitt and Thrush, 2019), and thus not well integrated in decision making. The lack of broader ecosystem assessment regarding tipping points is a major drawback to the state of incorporation of tipping points and thresholds in ecosystem conservation and policy. This is because ecosystems have multiple feedback loops through which impacts propagate and damage the structure of the ecosystem network (all interacting ecosystem components). Additionally, recovery of the ecosystem may mean rehabilitating multiple ecosystem components at the same time, again focusing on the ecosystem network structure, rather than focusing on some ecosystem components that are primarily impacted.

Discussions to limit the inclusion of tipping points in environmental decision making, especially concerning biodiversity loss, point out that thresholds are difficult to identify with high certainty in empirical data (Hillebrand et al., 2020). Additionally, even past a pressure threshold, biodiversity change tends to keep accumulating gradually and there are important lags and feedback loops in biodiversity change in relation to environmental and pressure change, driven by population dynamics and demography (Hillebrand et al., 2023). These point out that major improvements are needed on retrospective or predictive tipping point assessments, especially through integrating ecosystem-wide assessments that account for multiple feedback loops and cascading effects that drive processes and eventual shifts in ecosystems. On a more practical implementation perspective, there are multiple cases where enforcement of threshold values for pressures lead to such thresholds becoming the target limits, which thus do not prevent pressures from strongly degrading ecosystems even if the threshold has not been passed (e.g., fisheries operating close to a maximum catch allowance still maintains high fishing pressure). This can also potentially increase the acceptance of smaller pressure effects that cumulate slowly and gradually, and that nonetheless produce significant harm to ecosystem (Hillebrand et al., 2023). More importantly, focussing on thresholds and tipping point behaviour of few important ecosystems components likely disregards other non-linear dynamics, feedback mechanisms, or random events (stochasticity) that may drive ecosystem state shifts. Therefore, there remains a need to develop a system where safe limits for multiple ecosystem components and feedback loops can be defined in relation to multiple pressures that potentially can lead to ecosystem collapse or shift through tipping points.

Given the importance of tipping points ecologically and economically, it is imperative that any decision-making framework including tipping points and thresholds is founded on the best possible monitoring, identification, and implementation practice. This is even more important in marine spatial planning where use and exploitation of marine resources are increasing and the suite of pressures on marine ecosystems is changing fast. In Europe, most regional water bodies is currently in unfavourable environmental status with the Mediterranean, North Sea, Black Sea, and Baltic Sea under most cumulative pressure (Nikolau et al., 2025). This means that two approaches are needed, including a preventive approach and a limiting approach, that is a focus on limiting further degradation and enhancing ecosystem resilience. One of the main factors that remain in the way of both approaches is the important need of maintaining positive socioeconomics. Hence, understanding the socioeconomic dimensions that drive decision making towards the implementation of tipping points in policy is also important. Therefore, here, we will discuss the potential goal for broader ecosystem assessment, including developing a safe operating space through multiple pressure threshold boundaries. We will then delve into three considerations that can be enforced by policy to help towards achieving such goal. These include (1) conservationist decision making in relation to economic irreversibility, (2) monitoring improvements and (3) positive tipping points.

5.2 The goal: ecosystem-based safe operating space with threshold boundaries

The overall structure of an ecosystem, whether it is at a local or global scale, is determined by the interactions of the ecosystem components with the activities and pressures that are exerted on them (Mele et al., 2020; Santana-Falcon et al., 2022; Gomes et al., 2024). The interaction between ecosystem components, or between pressures and ecosystem components, are composed of multiple feedback loops (Nystrom et al., 2012; van Breugel et al., 2024) that, overall, keep together the structure of the ecosystem network. The maintenance of such feedback loops in the ecosystem conserves the state of the ecosystem. Deviation of some ecosystem components (for example through multiple pressure impact) can be brought back if the feedback mechanisms are not damaged, that is the ecosystem is resilient to some level of disturbances and impacts on some ecosystem components. Such an ecosystem is structured within a multidimensional space, bounded by thresholds of different combinations of pressures, where deviation of any ecosystem component within the bounds can be managed by the ecosystem itself, that is the structural network re-mains within a safe operating multidimensional space (Figure11, green box). The problem is when combinations of pressures become excessive and their impact pushes an ecosystem component over the thresholds bounds. In such cases, the ecosystem component can no longer be maintained solely by the ecosystem's own feedback loops box). More importantly, when multiple ecosystem components pass different thresholds of cumulative pressures, the structural network and feedback loops of the ecosystem may shift strongly (Figure 11, red box) and therefore the ecosystem becomes degraded.

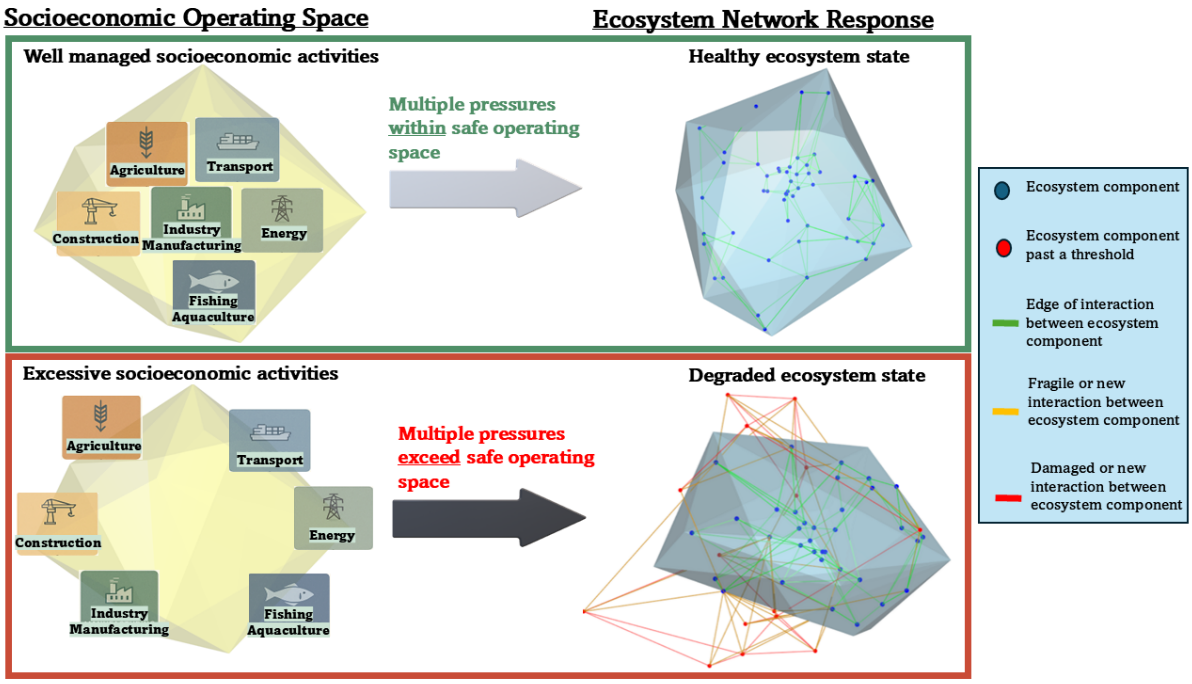

Figure 11: Comparison of ecosystem safe operating space based on socioeconomic-derived pressures (yellow multidimensional space) and ecosystem structural network response to pressure thresholds (blue multidimensional space). The socioeconomic multidimensional space is shaped by thresholds of activity intensities in the ecosystem, and the ecosystem multidimensional space is shaped by the threshold of different combinations of pressures that can lead to ecosystem components (blue nodes) to shift through a non-linear response. In the green box, activities are within safe operating space and the pressures enforced onto the ecosystem network do not push any ecosystem component (blue nodes) beyond the pressure thresholds. In the red box, activities are beyond the acceptable limits, and the ecosystem network is disrupted with some nodes having passed beyond the pressure threshold (red nodes) while other nodes are at the limit and can tip over (yellow nodes). Here the ecosystem network shows that the regulating feedback loops of the eco-system may have been disrupted severely as many nodes and interaction edges are beyond the safe operating space.

The concept of safe operating space is not new (Rockstrom et al., 2009; Scheffer et al., 2015; Halpern, 2017); however, the appropriate parameterisation of such safe operating space for ecosystems remains to be developed. Parameterisation of safe operating space boundaries can be done through tipping point analysis whereby thresholds of non-linear pressure effects on ecosystem components can be identified. It is important to assess the overall ecosystem structural network to determine which ecosystem components are impacted beyond acceptable thresholds (e.g., ecosystem component will lose function in the network or go extinct from the network), and which nodes are key to maintaining the structure of the network. Like most tipping point analyses, threshold boundaries of safe operating space have mostly been analysed using few pressures and few ecosystem components (Hemraj and Carstensen, 2025). For example, in the Mediterranean Sea, a workflow to determine potential safe operating space for sardine and anchovy fishery in relation to fisheries pressure and climate change was developed and potential thresholds identified (Ramirez et al., 2021). Similarly, a workflow for salmon fisheries safe operating space was developed for North American watersheds by integrating potential interactive pressure effects on salmon populations (Moore et al., 2025). While these studies provide evidence-based potential safe operating space for specific fisheries or other ecosystem components, they remain partly conceptual or based on few pressures and ecosystem components. A more empirical definition of safe operating space was defined for walleye populations through parameterisation of thermal and optical habitat limits (Hansen et al., 2019). This shows that more detailed parameterisation using thresholds of safe harvest based on temporal variations in environmental parameters is possible, albeit being on one species. Additionally, in deliverable 3.2, multiple case studies identify thresholds that could formulate safe operating spaces for specific ecosystem components and based on specific pressures (Table 1).

Table 1: Case studies derived from Deliverable 3.2 (Lynam et al., 2025) that identify thresholds that would consolidate specific safe operating spaces in different contexts.

Case study	Country	Area	Ecosystem	Main Ecosystem Component	Main pressures	Main findings
Gelidium corneum macroalga biomass decline across the Basque coast	Spain	Basque coast	Bay of Biscay	Gelidium corneum macroalgae	Wave intensity, Harvest	**1.** A sharp decline in macroalgae biomass in the 2010-2015 period. **2**. Decline due to the cumulative effect of increased wave flux energy and harvesting. **3.** Potentially transitioning the G. corneum ecosystem to a new regime. **4.** The G. corneum ecosystem will likely not recover within the next years even if the environmental conditions return to the healthier conditions or the human activities are minimized.
Sardine and Anchovy fisheries of the Ebro Delta	Spain	NW Mediterranean	Ebro Delta	sardine and anchovy	fishing	**1.** The changes in regulation implemented in 2007 lead to a continuous increase in bottom trawling in important sardine nursery areas. **2.** Study on the discards of bottom-trawlers in the area indicates that sardine and anchovy account for 50% of discards of bottom trawling activity in this area. **3.** Therefore, the changed regulations may have caused a cascading effect through the increased capture

						and discard of sardines including juveniles.
Macroalgal Forests to Barrens	Greece	Eastern Mediterranean	North Aegean, South Aegean & Levantine Sea	Macroalgae cover	sea urchins and Sarpa salpa	**1.** A barren state in the North Aegean is primarily driven by sea urchins and Sarpa salpa. **2.** In contrast, in the South Aegean & Levantine Sea, *Siganus* spp. are the main drivers pushing macroalgal forests toward a barren state. **3.** A high abundance of both invasive fish species in the warmer sites (South) **4.** a significant breakpoint was identified at a grazing index value of 3. **5.** Invasive species limit the recovery of macroalgae.
Biogeochemical shift	Finland	Northern Baltic Sea	Åland Sea and the Bothnian Sea	geochemical components	Limited inflow of saline water and substantial freshwater input from rivers	**1.** Due to limited inflow of saline water and substantial freshwater input from rivers, the salinity is lower and vertical stratification of the water column is weaker in the Bothnian Sea than in the Baltic main basin. **2.** Clear trends and tipping points in salinity were found. **3.** The salinity tipping points in the early 1990's coincided with the dynamics of saline water inflow to the Baltic Sea via the Danish straits.
Open sea trophic guild	Finland	Baltic Sea	Bothnian Bay	trophic guilds	environmental change	**1.** The Bothnian bay food web has shifted three times over 40 years. **2.** These shifts were linked to several environmental parameters. **3.** Decreasing Redfield ratio indicates change from phosphorus limited conditions towards more favourable conditions for phytoplankton. **4.** Decreasing winter salinity trends might indicate changes in freshwater inputs from rivers or precipitation patterns. **5.** Increasing summer bottom temperatures seem to favour benthic predators, potentially influencing their food sources and distribution. **6.** Understanding these trends is crucial for developing effective management strategies.
Sea turtle sex ratio	Greece	Mediterranean	Marathonisi, Laganas, Gerakas	loggerhead turtle	increasing sand temperature	**1.** Increasing air temperature is drastically increasing the sand temperature. **2.** In Marathonisi and Laganas, a shift toward predominantly female hatchlings is anticipated later in the century. **3.** Gerakas has already surpassed 60% female hatchling rate as early as 2020.

To improve on the implementation of tipping points and thresholds in ecosystem assessments and policy, there remains a strong need to determine the overall ecological impact of multiple pressures on an ecosystem's multiple components (Kefi et al., 2022). This is important because it removes the focus on few species but recentres it on the overall structural network of the ecosystem. Such broader assessment is important because it gives the opportunity to build a multidimensional safe operating boundary for the ecosystem based on the potential response of different ecosystem components. And how their impact can propagate and affect other ecosystem components through direct interaction or feedback loops. Most importantly, such a multidimensional operating space can be developed based on thresholds of multiple combinations of interacting pressures and interacting ecosystem components. Therefore, the goal for better implementation of tipping points in ecosystem assessments and integration in decision making is to focus more efforts on the development of such threshold-based safe operating space that define when ecosystem components might cross given thresholds and what the repercussions on the overall ecosystem structural network may be.

5.3 Conservationist decision making in relation to economic irreversibility

A major driver in decision making regarding environmental policy is the balance between environmental impact and socio-economic developments (Barbier, 2025). Marine spatial use, species harvesting and other human activities force impacts on ecosystems driving potential shifts. Since the socioeconomic activities precede the impact on and response of ecosystems, we seek to address the socio-economics drivers of tip-ping points implementation in decision making first. Socioeconomics become important when factoring in the cost-benefit assessments of irreversible environmental impacts and their implementation in policy. The problem is that most environmental economics models remain basic, compared to ecological models, and cannot properly implement ecological effects (Cai et al., 2015, Rising et al., 2022). For example, integration of climate irreversible impacts on market and non-market goods and services caused by tipping points in ecosystems show that previous climate impact cost-benefit models have largely downplayed the importance and relevance of climate change in socio-economic cost-benefit assessments (Cai et al., 2015; Rising et al., 2022). Additionally, a major impediment related to large-scale socio-economics assessments (global, regional) is the difficulty of separating confounding effects of pressures (e.g., climate change-related pressures and other pressures) (van Ginkel et al., 2020), meaning that the inferred impact on socioeconomics, such as economic substitution effects, is blurred and minimalised. Therefore, the appropriate policy response is difficult to identify and implement. This means that large-scale (global, regional) socio-economic evaluations, even with tipping point considerations currently is not efficient to promote conservationism in environmental decision making, even if it can help limit undesirable tipping points (Barbier, 2025).

Local assessments, on the other hand, more clearly relate environmental tipping points to socio-economic impacts (van Ginkel et al., 2020), suggesting that assessments, decision making, and policy implementation can be better developed from the local perspectives then upscaled. Nonetheless, challenges also exist in assessment and policy implementation at local levels. For example, pressure thresholds based on assessment of tipping points and their enforcement in policy may be interpreted as targets rather than thresholds for avoiding irreversible shifts (Hillebrand et al., 2025). Additionally, tipping point assessments and implementation in decision making at local scale often remain reactive, that is they are acted upon when thresholds have been passed or environmental degradation is clear (Serrao-Neumann et al., 2016). Such reactiveness often arises from different aspects; for example, when (1) socio-economic cost-benefits are still mostly positive even if pressures amount on the ecosystem but the ecosystem is not well degraded yet, meaning that a “wait and see” approach is used. The reaction only occurs when the ecosystem becomes degraded from the pressures or economic impacts are clear. Second, (2) sunk costs and economic irreversibility (sunk cost from investing in environmental protection without certainty of preservation, or previous conservation costs that were less successful) lead to less conservative decision making than what would be optimum whereby the balance between the threat of irreversible environmental damage and the certainty of economic irreversibility often tends towards avoiding economic irreversibility (Sims and Finnoff, 2016).

Altogether, currently, it seems that the best implementation strategy for tipping points in marine policy should help with balancing environmental and socioeconomic irreversible effects through two points. First, it should improve on preventive approach, rather than reactive, which include better monitoring of changes in the ecosystem, especially ecosystem-based indicators that are detected well before the occurrence of tipping points. Second, implementation should be made starting from local level where economic and ecological models can be coupled better. Importantly, there needs to be much improvement on deter-mining how socio-economic activities translate to environmental impact (not just pressures) and where such impact is likely to drive tipping points (Figure 11). Additionally, it is imperative that ecosystem tipping points and safe operating space are more strongly integrated with socioeconomic safe operating space, guiding decision making for socio-economic progress and environmental conservation.

5.4 Improving monitoring for tipping point early detection and ecosystem-based safe operating space

Monitoring for tipping point detection requires an understanding of the ecosystem's behaviour prior to a shift, that is assessing indicators or shifts in the ecosystem leading to tipping points. Such indicators often lean on early warning signals (EWS) of tipping points in the ecosystem. EWS can advise on the potential risk of reaching a tipping point and provide thresholds of pressure that do not comprise the actual pressure level at which the tipping point occurs (Figure 12). The question is what EWS most reliably inform on risk of reaching tipping points (e.g., shift in specific indicator species, changes in variance in species abundances, variability in ecosystem stability, ecosystem network indicators, etc.), how can we facilitate monitoring them, and how can we implement them in policy? Multiple EWS exist that effectively predict potential shifts in ecosystems (Dakos et al., 2024). For example, currently, approximately 65 EWS are commonly used globally, and these effectively predict shifts in 70% of cases (Dakos et al., 2024). However, generally reliable and informative EWSs should be at relevant complexity scale to represent the state of the broader ecosystem (including shifts in species community and pressures interactions) (Kefi et al., 2022), rather than focus on some specific components or pressures in the ecosystem (Hemraj and Carstensen, 2025), and preferably be applicable across different ecosystems (even if ecosystem-specific EWS should be considered for ecosystems with very specific environmental conditions). This is often not the case as most EWS tend to be applied on individual combinations of ecosystem components and pressures, and few account for multiple parameters and high dimensionality (Dakos et al., 2024).

Current marine monitoring practice in Europe, driven by the Marine Strategy Framework Directive (MSFD) and Water Framework Directive, focuses on species distribution and on distribution of pressures. The MSFD also currently promotes the use of indicators to determine how these populations, communities, or pressures are changing on a spatiotemporal basis. This is extremely important for understanding shifting trends in populations, communities or habitats, and how changes in pressures can relate to biodiversity shifts and environmental status. However, two important gaps in the monitoring system remain. (1) There is a major lack of monitoring for EWS of ecosystem tipping point. (2) There is also a lack of ecosystem-wide EWS (e.g., broader ecosystem functioning network indicators and indicators of changes in feedback loops across different ecosystem components) that strongly inform on the state of the overall ecosystem. These gaps mean that much of the complex interactions that underpin resilience, stability or tipping point risks are not specifically monitored. Currently, the MSFD descriptors tend to operate individually and the only descriptor that seeks to combine multiple species across an ecosystem is Descriptor 4 (food webs). Even then, Criteria 2 (balance of abundances between trophic guilds) in Descriptor 4, for which specific assessment methods are not clear, is the only one that seeks to combine multiple species interactions across the ecosystem. In relation to tipping points, this means that the current monitoring setup favours detection of tipping points specifically within groups of organisms rather than across the ecosystem. Currently, the setup seems to favour assessing how specific ecosystem components or descriptors are shifting in relation to activities and pressures and then to what extent they may be impacting the whole ecosystem. That does not mean that researchers cannot combine data from multiple Descriptors to perform ecosystem-wide analyses, but it means that since the descriptors target different assessment types, it is difficult to combine them for broad ecosystem-wide assessments. Tipping points thus are only examined or predicted for some ecosystem components, that is only part of the ecosystem. Additionally, the lack of focus on EWS means that most assessments of tipping point are retrospective rather than predictive.

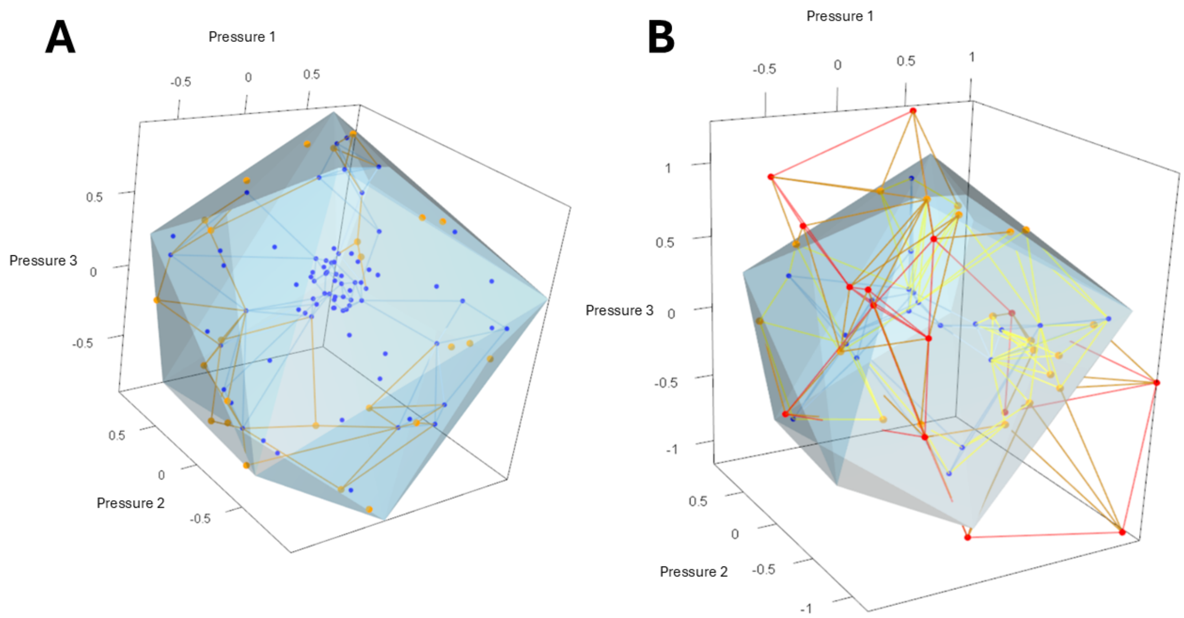

Figure 12: Assessing and monitoring ecosystem-wide response to combinations of multiple stressors to identify the risk of ecosystem state shift through a tipping point. In A, the network of ecosystem component interactions remains within the limits of the multiple pressure boundaries. Some nodes (yellow) are on the edge of tipping beyond the threshold and their interaction with other nodes have changed (yellow edges). There-fore, these can potentially serve as early warning signals (EWS) of tipping point of the network structure. In B, multiple nodes have passed beyond the pressure thresholds (red nodes). Their interaction edges have either disappeared or can have a negative effect on other nodes to which they are connected. This can then prop-agate through the network and disrupt its structure (degradation of the ecosystem).

For improving detection or prediction of ecosystem-wide tipping points in the current monitoring system, it is first important to promote synergies between MSFD descriptors or develop a specific descriptor targeting ecosystem-wide EWS (e.g., those that target ecosystem structural change; Figure 12), while maintaining the current long-term monitoring programmes. It is also important that such monitoring covers a broad range of environmental parameters, organisms and habitats, whether they are economically important, iconic, or charismatic, to facilitate better ecosystem overview (Figure 12). The necessity of monitoring across the ecosystem is to facilitate early identification of changes in the ecosystem before more specific assessment, that is a more adaptive or tiered monitoring approach (Figure 13) that focuses on standardised surveillance monitoring of ecosystems for identifying the current state of the ecosystem, the components that are changing, the magnitude of change, and what pressures are causing such changes. Information from surveillance monitoring can then be used for the development of EWS for the ecosystem (e.g., indicators of structural shifts in the ecosystem's network), which will facilitate early detection of changes in the ecosystem. Targeted monitoring, with increased focus on specific ecosystem components and pressures, and more detailed assessments can then be used to more clearly identify the processes that are driving shifts in specific ecosystem components and how these changes are, or will, drive potential further shifts and tipping points in the ecosystem. Such tiered assessment may facilitate risk assessment of ecosystem tipping points and help manage parts of the ecosystem that are most impacted. Overall, while the monitoring system and assessment of ecosystems, based on the MSFD, provide important indications of ecosystem state, adaptive monitoring through standardised surveillance followed by targeted monitoring across eco-systems and regions can help with improving synergies between Descriptors and across different regions. This in turn will facilitate the development, application and comparison of EWS of tipping points.

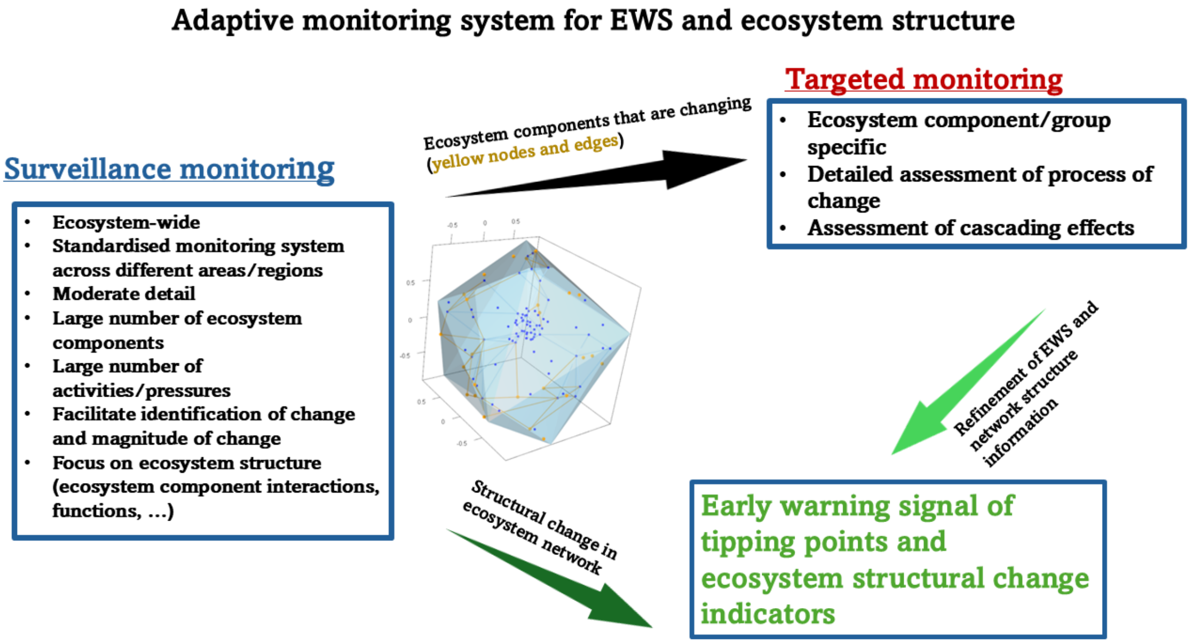

Figure 13: Using surveillance and targeted monitoring to develop and refine network-based early warning signals (EWS) of ecosystem tipping points by identifying ecosystem components that are vulnerable to passing the safe operating space. The network shows ecosystem components that are unaffected (blue) and those that are vulnerable (yellow). Yellow lines show potential cascading negative effects in the networks structure should the vulnerable nodes pass outside of the safe operating space (blue shape).

5.5 Tipping points from an ecosystem recovery perspective

With the large extent of marine ecosystem that is under pressure or in a degraded state, there is a major push for investing in the recovery of ecosystems. Such investments include restoration, cumulative impact assessment for pressure management, socio-ecological shifts towards better environmental stewardship, and others. While such efforts are increasing exponentially, the recovery process of marine ecosystems, thresholds of maximum pressures to promote recovery, and the definition of recovered state still require underpinning. Given shifting baselines and the general long process of recovery, whether an ecosystem has recovered often depends on the definition of recovery, which itself can be very broad. However, a sudden shift from degraded state to an alternate state can define a state of recovery given there is improvement in the ecosystem and its functions (Figure 14). The theory of tipping points and bifurcation in ecology suggest that to promote the recovery of ecosystems, pressures are required to be reduced to a level well below the tipping point threshold (Scheffer et al., 2001; Boettiger and Batt, 2019). However, two questions remain unanswered; (1) what are the thresholds of different pressures that can support recovery, and (2) can such reduction of pressure be realistically achieved given the necessity of marine spatial use?

Retrospectively determining the thresholds of pressure reduction, driven by changes in human activities and socio-economic changes, is difficult, especially because it requires data from case studies whereby large reductions of pressure have led to ecosystem recovery (examples exist but are far less common and data poor compared to examples of ecosystem degradation due to human activities and pressures). Nonetheless, information on such "positive" tipping points (i.e., accumulation of small recovery steps or actions that cause a sudden increase in recovery; Figure 14; Lenton, 2020; Lenton et al., 2022) can provide important insights on how to balance pressures on ecosystems, that is what would formulate an "optimum pressure range" depending on the state of the ecosystem. For example, in a non-degraded ecosystem, the optimum pressure can be one that maximises the use of the ecosystem while keeping the risk of ecosystem shifts within a safe operating space. On the other hand, for a degraded ecosystem, the optimum pressure can be one that supports recovery, either by maintaining only necessary ecosystem use or completely stop-ping ecosystem use (e.g., strongly protected areas). In the latter, accumulation of small ecosystem enhancement steps can manifest into a positive tipping point for the ecosystem's recovery.

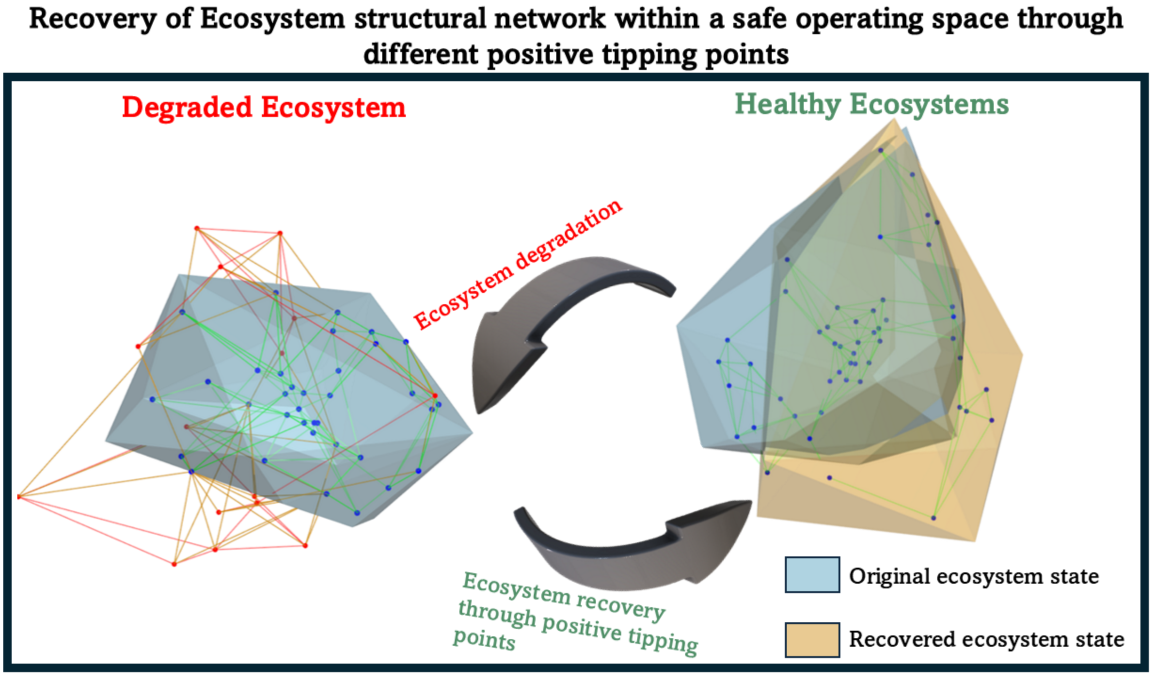

Figure 14: Example of ecosystem recovery where key impacted nodes are restored within the safe operating space. Such restoration will require rehabilitation of the degraded nodes but also strengthening of key nodes in the ecosystem that maintain the structure of the network, whether they are themselves degraded or not. Focusing on both degraded and non-degraded, but key, nodes can help leverage on positive tipping points because build-up of the whole ecosystem network integrity is focused on rather than specific nodes. Importantly, the pathways of recovery can be diverse (depending on how the multiple pressures are dealt with) and the final recovered ecosystem (yellow) may deviate from the original (blue) in terms of structure but be in a healthy state.

Harnessing the potential of positive tipping points to increase recovery of degraded ecosystems, or partially impacted ecosystems, can provide a good avenue to promote recovery or avoid degradation. However, currently, major gaps remain in the research related to positive tipping points and its implementation in policy and ecosystem management. First the ecological aspects of positive tipping points (e.g., thresholds of pressures in relation to ecosystem components, methods of analysis, indicators of positive tipping points) need to be underpinned (Lenton, 2020; Lenton et al., 2025). Theoretically, similar models as regular tipping points and EWS assessments can provide good indications of thresholds and EWS of positive tipping points. However, given the relative scarcity of appropriate data to test such models, it is still difficult to develop well defined pressure thresholds for different ecosystem components that supports ecosystem recovery or formulate an "optimum pressure range". Therefore, assessment of the overall ecosystem structural network may provide important information on the gradual or shift in build-up of functions, resilience or stability in the ecosystem (Figure 15). Second, there are still multiple socioeconomic and political barriers that prevent the implementation of positive tipping points (Fesenfeld et al., 2022; Tabara, 2022). For example, multiple transformative change in socioeconomics (beyond modelling economical risks as described above) and policy are required, first, to generate positive ecosystem and sustainability-centric actions and, second, to improve monitoring and assessment of positive feedback of socioeconomic changes into ecosystem state. Such change can be driven by improving efficiency (better gains from current ecological and socioeconomic solutions), sufficiency (behavioural change towards sustainability rather than extractivism or consumerism), and substitution (replacement by technological or behavioural change that promote positive feedback) (see Fesenfeld et al., 2022). Nonetheless, this provides a major opportunity for policy to enforce positive changes in socioeconomics, socio-ecological, and environmental conservation practice, from which positive cascading effects and feedback can then be assessed and monitored (Figure 15). Such improvement can be driven by surveillance and adaptive monitoring that are used to assess ecosystem-based tipping points, EWS, or positive tipping points. Such assessment can then for the basis for tightening or loosening socioeconomics that depend on the ecosystem. An optimum pressure range that operates within the safe operating space for the ecosystem can then be developed (Figure 15). The monitoring and assessment of ecosystem safe operating space should be done regularly.

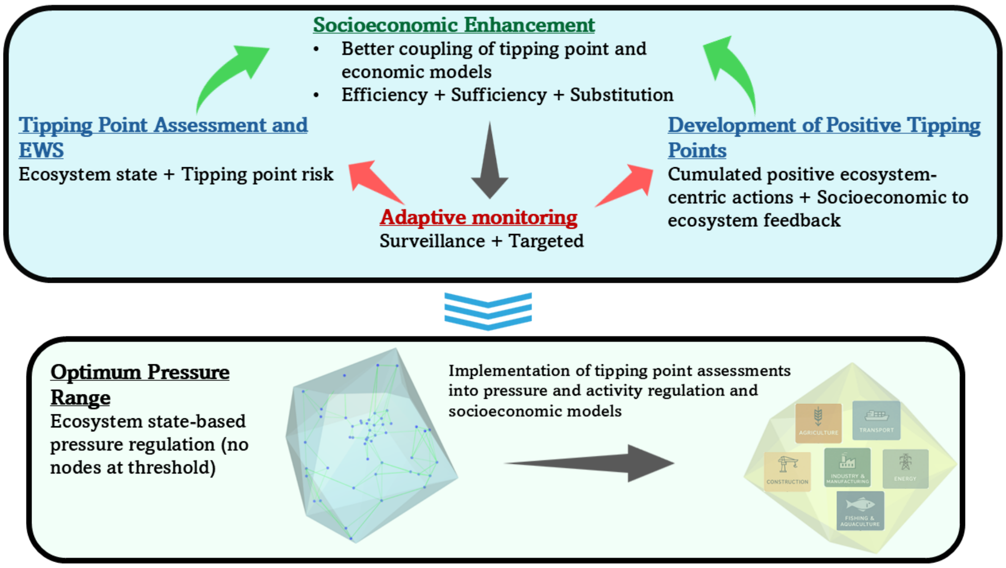

Figure 15: Framework of key aspects that policy can focus on for enhancing the use of tipping points in decision making and ecosystem management. Here, we can use adaptive ecosystem monitoring to assess ecosystem-based tipping point, EWS, and positive tipping points (red arrows). These then feedback into improving socioeconomic activities to identify which activities require better regulation and adjustments (green arrows). Post socioeconomic enhancement efforts, the cycle continues through continued adaptive monitoring and ecosystem assessment. From this cycle, we can define optimum cumulative pressure levels that do not disrupt the ecosystem resilience but also provides sustains socioeconomic benefits

6 Overall conclusion

In GES4SEAS, we assessed tipping points in various contexts and various learning sites. The results, published in Deliverable 3.2 (Lynam et al., 2025), show that multiple marine ecosystems across Europe are in an unfavourable state. In some ecosystems, we were able to approximate when or through which pressures a tipping point has occurred and shifted the state of the ecosystems. In other instances, identifying such tipping point proved much more complex, even if it was clear that the ecosystem had changed drastically due to multiple cumulative pressures. By synthesising the results, we identified that there are major improvements to be done in the way we examine ecosystem state shifts and tipping points.

Among the most important improvements, is the need to assess ecosystems in a more comprehensive manner, that is including as many ecosystem components and pressures as possible to incorporate most if not all the feedback loops and cascading effects in the ecosystem that either increase resilience or cause propagation of pressures in the ecosystem. This is important to uncover processes and ecosystem components within the ecosystem that are most vulnerable or key to the functioning of the ecosystem. The current deliverable tackles this in two ways. First, (1) it provides an overview of the system that can be used in Tikta to investigate the occurrence of thresholds across multiple combinations of pressures and ecosystem components and incorporate these in CEA assessment. Second, (2) it seeks to provide new frameworks for decision makers to understand why examining ecosystem structural networks is important, how to potentially to this and which line of research regarding tipping points are key to pursue in the future.

The incorporation of threshold assessments in Tikta is based on simple but well defined and trusted regression methods. While the identification of thresholds cannot be undertaken through interactive multiple pressures and ecosystem components interactions, it still provides the user with the ability to assess their data for potential presence of important thresholds and incorporate these thresholds in their CEA assessment. With these thresholds analyses embedded within Tikta, it facilitates users to explore their data further to understand dynamics that may be driving cumulative impacts in their ecosystem, before running the actual CEA. Importantly, users can now test multiple threshold scenarios and identify most, or less conservative analysis scenarios based on the threshold choices.

Regarding the frameworks developed in this deliverable, the goal was to help decision makers to picture the problem with assessing only part of an ecosystem to define tipping points, but, more importantly, also picture how broader ecosystem structural network assessment can strongly improve how we identify shifts in ecosystems. Here, we stress that it is imperative that there is much better coupling between socioeconomic and ecological assessments to identify safe operating spaces where both are in balance. We understand that this is difficult to achieve, however, by analysing the ecosystem structural network, it becomes clearer which ecosystem components become vulnerable or are central for the ecosystem not to degrade. These can be used as EWS of ecosystem shifts or even indicators of positive tipping points helping ecosystem to recover. More importantly, what we point out is a need to improve on how ecosystems are monitored and how to combine ecosystem assessment, EWS, positive tipping points and adaptive monitoring to circularly and continuously assess how cumulative human and climate pressures impact marine ecosystems and what feedback in socioeconomics may help improve marine ecosystems.

Overall, by using results from assessments in multiple learning sites (Deliverable 3.2; Lynam et al., 2025), we have now synthesised findings and developed a potential solution for Tikta users to assess thresholds within their CEA analyses and developed future avenues for more comprehensive tipping point assessments that can guide decision makers in terms of their own assessments of ecosystems but also where efforts are needed to improve tipping point assessment and incorporation in environmental assessments.

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