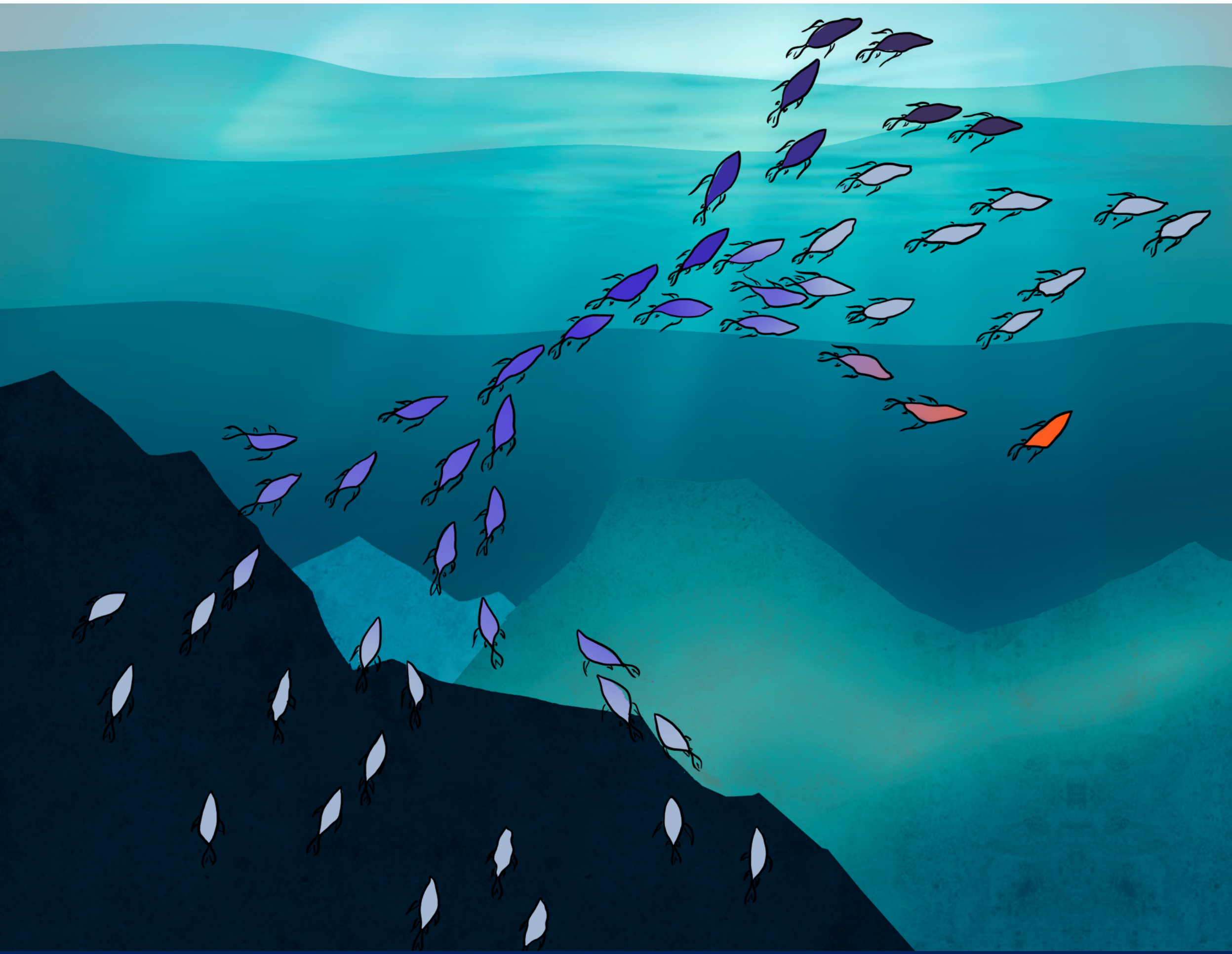
Stockholm University

Novelty in the Anthropocene

Exploring past and future novelty in marine social-ecological systems

Yosr Ammar



Doctoral Thesis in Sustainability Science at Stockholm University, Sweden 2021

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Abstract

Humans have become the major driving force of change, deeply affecting the Earth system and the biosphere. In marine ecosystems specifically, climate-related environmental changes and anthropogenic pressures (e.g., fishing, the introduction of new species, nutrient load) have altered the structures and functioning of social-ecological systems (SES). These changes have created novel, never encountered before, SES dynamics. Novelty, a natural process of SES dynamics, has accelerated due to human activities. On the one hand, novelty allows SES to adapt to change, including maintaining their functions and resilience. On the other hand, the fast-emerging novelty in the Anthropocene epoch is unpredictable and increases the uncertainty related to management and predicting models. Despite consensus on the need for acknowledging novelty in SES, there is much confusion associated with this concept. This thesis provides a unifying conceptualization of novelty in SES by linking Complex Adaptive Systems theories and ecological novelty concepts. The papers that make up this thesis are an empirical contribution to understanding novelty in marine SES in the past and future. Novelty was measured in multiple social and ecological components of the Baltic Sea SES across different temporal and spatial scales. Although novelty is important for SES adaptation to change, it can be a problem or a solution - depending on its rate, drivers, and scale. There is a need to foster novelty that could enhance SES resilience and sustainability, in order to achieve good environmental status in marine ecosystems and for human wellbeing.

Keywords: *Novelty, marine ecosystems, Social-Ecological Systems, Baltic Sea, Complex Adaptive Systems.*

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Stockholm University, 106 91 Stockholm

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Yosr Ammar

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To my family.

Abstract

Humans have become the major driving force of change, deeply affecting the Earth system and the biosphere. In marine ecosystems specifically, climate-related environmental changes and anthropogenic pressures (e.g., fishing, the introduction of new species, nutrient load) have altered the structures and functioning of social-ecological systems (SES). These changes have created novel, never encountered before, SES dynamics. Novelty, a natural process of SES dynamics, has accelerated due to human activities. On the one hand, novelty allows SES to adapt to change, including maintaining their functions and resilience. On the other hand, the fast-emerging novelty in the Anthropocene epoch is unpredictable and increases the uncertainty related to management and predicting models. Despite consensus on the need for acknowledging novelty in SES, there is much confusion associated with this concept. This thesis provides a unifying conceptualization of novelty in SES by linking Complex Adaptive Systems theories and ecological novelty concepts. The papers that make up this thesis are an empirical contribution to understand novelty in marine SES in the past and future. Novelty was measured in multiple social and ecological components of the Baltic Sea SES across different temporal and spatial scales. Although novelty is important for SES adaptation to change, it can be a problem or a solution - depending on its rate, drivers, and scale. There is a need to foster novelty that could enhance SES resilience and sustainability, in order to achieve good environmental status in marine ecosystems and for human wellbeing.

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Sammanfattning

Globala miljöförändringar sker idag snabbare än någonsin på grund av mänsklig verksamhet. Dessa förändringar utmanar ekosystems och socialekologiska systems (SES) förmåga att hantera händelser och störningar. Särskilt i marina ekosystem har miljöförändringar (så som fiske, introduktion av nya arter, föroreningar etc.) påverkat SES strukturer och funktioner, och har skapat nya, aldrig tidigare upplevda, förhållanden i dessa system. 'Novelty' är ett begrepp som kan användas för att förstå och förklara dessa nya dynamiska förhållanden inom SES. Novelty är en naturlig process, men dessa processer har accelererat på grund av mänsklig påverkan. Å ena sidan är novelty processer nödvändiga för att bibehålla anpassningsförmåga, funktioner och motståndskraft inom SES. Å andra sidan är accelererande novelty processer ofta oförutsägbara, vilket kan bidra till ökad osäkerhet i samband med förutsägande modeller och förvaltningssystem. Trots att det idag råder konsensus om att novelty är en viktig process i SES, finns det fortfarande stora oklarheter kring begreppet i sig och dess betydelse. Denna avhandling bidrar till att konceptualisera novelty inom SES, genom att koppla samman teorier om komplexa adaptiva system och ekologiska noveltybegrepp. De artiklar som ingår i denna avhandling är empiriska bidrag till att förstå novelty inom marina SES, med fokus på det som tidigare har hänt och det som kommer att hända i framtiden. Novelty studeras inom olika sociala och ekologiska komponenter inom Östersjöns SES. Flera metoder används för att kvantifiera novelty och dess bakomliggande orsaker på flera tidsmässiga och rumsliga skalor. Sammanfattningsvis visar avhandlingen att novelty är viktigt för systemens anpassningskapacitet, men att novelty både kan vara ett problem eller en möjlighet, beroende på dess hastighet, dess bakomliggande orsaker och dess omfattning. Det finns ett stort behov av att främja noveltyprocesser som kan öka SES resiliens och ekosystems bärkraftighet för att skydda ekosystemtjänster för människors välbefinnande.

Nyckelord: Novelty, marina ekosystem, socialekologiska system, Östersjön, komplexa adaptiva system.

تلخيص

أصبح البشر القوة الرئيسية الدافعة للتغيير، مما أثر بعمق على نظام الأرض والمحيط الحيوي. في النظم الإيكولوجية البحرية على وجه التحديد، أدت التغيرات البيئية الناتجة عن التغير المناخي والضغوط البشرية (مثل الصيد البحري وإدخال أنواع جديدة وتحميل المغذيات) إلى تحول هياكل وعمل النظم الاجتماعية - البيئية. خلقت هذه التغييرات ديناميكيات نظم اجتماعية - بيئية جدة، لم تتم مواجهتها من قبل. الجدة، وهي عملية طبيعية لديناميات النظم الاجتماعية - البيئية، تسارعت بسبب الأنشطة البشرية. فمن ناحية أولى، تسمح الجدة للنظم الاجتماعية - البيئية بالتكيف مع التغيير، بما في ذلك الحفاظ على الوظائف والمرونة. لكن من ناحية أخرى، فإن الجدة سريعة الظهور في عصر "الأنثروبوسين" لا يمكن التنبؤ بها وتزيد من أوجه انعدام التيقن المتعلق بنماذج الإدارة والتنبؤ. على الرغم من الإجماع على الحاجة إلى الاعتراف بالجدة في النظم الاجتماعية - البيئية، فهناك الكثير من الخلط المرتبط بمفهومها. تقدم هذه الأطروحة تصورًا موحدًا للجدة في النظم الاجتماعية - البيئية من خلال ربط نظريات "أنظمة التكيف المعقدة" ومفاهيم الجدة البيئية. تمثل المقالات التي تتكون منها هذه الأطروحة مساهمة تجريبية لفهم الجدة في النظم الاجتماعية - البيئية البحرية، في الماضي والمستقبل. تم قياس الجدة في العديد من المكونات الاجتماعية والبيئية للنظام الاجتماعي - البيئي لبحر البلطيق عبر نطاقات زمنية ومكانية مختلفة. على الرغم من أن الجدة تسمح للنظم الاجتماعية - البيئية بالتكيف مع التغيير، إلا أنها قد تكون مشكلة أو حلًا - وذلك حسب معدلها وعوامل ظهورها ونطاقها. هناك حاجة إلى تعزيز الجدة التي تحافظ على مرونة واستدامة النظم الاجتماعية - البيئية من أجل تحقيق "حالة بيئية جيدة" للنظم الإيكولوجية البحرية ورفاه البشر.

الكلمات المفتاحية: الجدة، النظم البيئية البحرية، النظم الاجتماعية البيئية، بحر البلطيق، أنظمة التكيف المعقدة.

Résumé

Les humains sont devenus la principale force motrice du changement, affectant profondément le système terrestre et la biosphère. Dans les systèmes marins en particulier, les changements environnementaux et la pression anthropique (pêche, introduction d'espèces, pollution) ont modifié les structures et fonctions des systèmes socio-écologiques (SSE). De tels changements ont créé « Novelty » dans la dynamique des SSE, c'est-à-dire des dynamiques complètement nouvelles comparé à ce qui est connu au paravent. « Novelty » est un processus naturel de la dynamique des SSE, mais qui a rapidement accéléré en réponse aux activités humaines. « Novelty » est d'autant plus nécessaire pour les SSEs afin de s´adapter aux changements, et pour maintenir leurs fonctions et résilience. Néanmoins, cette augmentation de manière rapide de « Novelty » en réponse à la pression anthropique, est non seulement imprévisible, mais elle est aussi la cause de l'augmentation des incertitudes face aux modèles de gestion et aux prévisions futures à envisager. Malgré le consensus sur la nécessité de prendre en considération la « Novelty » dans les SSE, ce concept demeure l'objet d'une grande confusion. Cette thèse propose une conceptualisation qui unifie la « Novelty » des SSE basée sur les théories des systèmes adaptatifs complexes (CAS) et diffèrent concepts de « Novelty » en écologie. Les articles qui composent cette thèse présentent une contribution empirique à la compréhension de « Novelty » dans les SSE marins dans le passé et le futur. Elle a été quantifiée dans de multiples composantes sociales et écologiques du SSE de la mer Baltique à différentes échelles temporelles et spatiales. Enfin, bien que « Novelty » soit importante pour l´adaptation des SSE aux changements, elle peut être un problème ou une solution en fonction de sa vitesse, ses moteurs et son échelle. Il sera nécessaire de favoriser la « Novelty » qui pourrait équilibrer la résilience des SSE et la durabilité pour atteindre un bon état environnemental et sécuriser les services écosystémiques pour le futur.

Mots-clés: Novelty, écosystèmes marins, systèmes socio-écologiques, mer Baltique, systèmes adaptatifs complexes.

List of papers

1. **Ammar, Y.,** Niiranen, S., Otto, S. A., Möllmann, C., Finsinger, W., & Blenckner, T. (2021). The rise of novelty in marine ecosystems: The Baltic Sea case. *Global Change Biology*, 27 (7), 1485-1499. https://doi.org/10.1111/gcb.15503

2. **Ammar Y.,** Voss R., Niiranen S., & Blenckner T. (2021). Quantifying socio-economic novelty in fisheries social-ecological systems. *Fish and Fisheries*. https://doi.org/10.1111/faf.12626

3. Blenckner, T., **Ammar, Y**., Müller-Karulis, B., Niiranen, S., Arneborg, L., & Li, Q. (2021). The Risk for Novel and Disappearing Environmental Conditions in the Baltic Sea. *Frontiers in Marine Science*, 8, 745722. https://doi.org/10.3389/fmars.2021.745722

4. **Ammar Y.,** Puntila-Dodd R., Tomczak M., Nyström M., & Blenckner T. (*Manuscript*). Exploring future ecosystem novelty and resilience using the adaptive cycle.

Contributions to the papers

Papers 1 and **2**: Idea generation, data collection, data analysis, paper preparation, and writing as lead author. In **Paper 3:** contribution to the idea generation, the data analysis, the preparation and writing. In **Paper 4**: Idea generation, data analysis, paper preparation, and writing as lead author.

Glossary of terms

Adaptive capacity: the ability of systems, individuals, institutions, and other organisms to adjust to potential damage, to take advantage of opportunities, and to cope with the consequences (IPCC, 2014).

Adaptive cycle: a metaphor that describes the patterns of stability and instability in systems (Gunderson & Holling, 2002).

Complex Adaptive Systems (CAS): systems that exhibit nonlinear behavior emerging from the interactions of their different parts, and have the capacity to adapt, evolve, and learn (Holland, 1992; Levin, 2002).

Disappearing environmental conditions: environmental conditions (e.g., temperature and salinity) that together disappear while the system moves beyond its historical range of variation.

Emergence: a concept describing the outcomes and phenomena of the continuous process of interactions between different parts of the system (Schlüter et al., 2019).

Governance: the actions taken by society, organizations, states, etc. to achieve collective decision goals.

Identity of a system: key components and relationships maintained through time and space in a system to be considered the same system, subjectively defined by the properties or characteristics of interest to the observer (Cumming & Peterson, 2017).

Innovation: an action taken by an animal, human, enterprise, etc. as a solution to solve or cope with problems, such as inventions (e.g., social innovation (Westley, 2013) and evolutionary innovation (Erwin, 2021)). Innovation can, but does not necessarily, generate novelty.

Levels of a scale: the units of analysis that are at different positions on a scale (Cash et al., 2006).

Novelty: a dynamic property of the system describing the extent that the system moved beyond its historical range of variation, i.e., the extent of the shift of the system in relation to the past.

Panarchy: a nested set of adaptive cycles operating at a discrete range of scales (Gunderson & Holling, 2002).

Resilience: the capacity of a system to adapt to change, persist disturbance, learn, self-organize, and transform while sustaining its main processes, functions, and structure (Folke et al., 2010, 2016).

Scale: can be either a spatial, temporal, quantitative, or analytical dimension used to measure and study any phenomenon (Cash et al., 2006).

Social-ecological systems: systems of people, communities, economies, society, and culture embedded in the biosphere (Folke et al., 2016)

Transformation: an active and deliberate form of change that is more significant than adaptation by recombining existing elements of a system in a fundamentally novel way (Moore et al., 2014).

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Introduction

Humans have become the major driving force of change, deeply affecting the Earth system and the biosphere, an epoch sometimes referred to as the Anthropocene (Crutzen, 2002, 2006; Jouffray et al., 2020; Steffen et al., 2011, 2015). The scale, speed, spread, and connectivity of human actions have created new complex dynamics, connecting previously unconnected domains (Bai et al., 2016; Biggs et al., 2011; Folke et al., 2016; Homer-Dixon et al., 2015; Jouffray et al., 2020; Nyström et al., 2019; Walker, Barrett, et al., 2009). For example, intensive irrigation in Asia has affected the rainfall patterns globally with consequences on agricultural activities in Africa (de Vrese et al., 2016). These complex interactions with nature have described humans as a higher-order "hyperkeystone" species (Worm & Paine, 2016). Indeed, accelerated technological development, the rapid growth of the human population, and increased consumption of resources have challenged the ability of ecosystems to cope with events and disruptions (Jackson et al., 2001; Paine et al., 1998; Waters et al., 2016). These dynamics have affected human well-being and transformed landscapes and seascapes (Berkes et al., 2006; Fairhead et al., 2012; Lambin & Meyfroidt, 2011; Lazarus, 2014). People have become an embedded part of the biosphere, shaping its resilience, locally and globally, consciously and unconsciously (Folke et al., 2016).

Natural processes can no longer be understood without accounting for human pressure (Ellis, 2015; Levin, 1999; Österblom et al., 2017; Worm & Paine, 2016). Hence, human actions shaping the Earth System have generated novel, never encountered before, Social-Ecological Systems (SES) dynamics (Folke et al., 2016; Steffen et al., 2015). Although ecological novelty has been continuously emerging in the Earth System through geological epochs, the extent and rate of its emergence has accelerated due to human activities (Burke et al., 2018; Finsinger et al., 2017; Pandolfi et al., 2020; Radeloff et al., 2015; Williams et al., 2019). In marine systems specifically, climate-related environmental and ecological changes, the introduction of species, and other anthropogenic disturbances (e.g., fisheries, nutrient load, hazardous substances) have accelerated at an unprecedented rate (e.g., Jouffray et al., 2020; McCauley et al., 2015; Pinsky et al., 2019, 2020; Sunday et al., 2012). The cumulative effect of such changes may have generated novelty in marine SES. In this context, this thesis focuses on the challenges of the Anthropocene related to the emergence of novelty in marine SES.

Novelty in SES emerges as a continuous process through the interaction between people and ecosystems, changing the context of human actions and the dynamics of ecosystems (Allen & Holling, 2010; Schlüter et al., 2019). For example, after deforestation in the early 1900s, changes in the political status and the economy in Puerto Rico allowed increasing the forest cover where nonnative trees have restored many functions of the native forest (Radeloff et al., 2015). In other words, after deforestation (which represents novel conditions compared to pristine forest conditions), novelty in socio-economic dynamics has been a driver of novelty in the ecosystem in terms of species composition but not in terms of function. In this case, novelty does not necessarily emerge abruptly, such as in the case of regime shifts and bifurcation points, but the continuous generation of novelty can, in some cases, lead to shifts in the system.

Novelty is unpredictable and increases the uncertainties associated with predicting future ecological dynamics and informing environmental policy and management (Barnosky et al., 2017; Blois et al., 2013; Silliman et al., 2018). For example, novel climates are unexplored parts of the climate space, where we have no observational data to parameterize and validate ecological predictions and forecasting models (Maguire et al., 2016; Veloz et al., 2012; Williams & Jackson, 2007). As the 21st century climate continues to move to states outside the range of societal and scientific experiences, detailed changes in ecological systems are unlikely to be possible to predict due to the difficulty of predicting relevant features of ecological niches and the complexity of the biosphere, which can enable novel system dynamics (Beckage et al., 2011). On top of that, great uncertainty arises with the future extent of change in human action and intervention on ecosystems (Folke et al., 2004; Steffen et al., 2015). It is a challenge to unravel how dynamic interactions among and between social and ecological components of a SES jointly generate novelty. The wide range of social and ecological processes and the complexity of their interactions make cross-scale interactions in SES difficult to model (Niiranen et al., 2018). Accordingly, we need methods that could help enhance our understanding of the intertwined fast-changing SES in the Anthropocene (Preiser et al., 2018) and the related novelty for future sustainable management.

A challenge for management is that the future will look less and less like the past and historical baselines are more difficult to reach (Radeloff et al., 2015). The unprecedented rate of climate change and novel climate emergence is of high concern (Burke et al., 2018) as it may not allow certain species to adapt to the fast-changing environment. Indeed, species may have limited adaptive capacity to novel environmental conditions that emerge at a high rate relative to their evolutionary baseline (Williams et al., 2021). Besides, a long-term study of Cenozoic marine plankton communities has revealed that the shift to novel communities persist through time and was associated with a high rate of local extinction, origination, and emigration (Pandolfi et al., 2020). In recent decades, novelty has been increasing in multiple marine ecosystems raising concerns about its impact on SES resilience and ecosystem services (Dornelas & Madin, 2020; Graham et al., 2014; Mora et al., 2013; Reygondeau et al., 2020). If the global emissions are not kept under the corresponding global 2°C target, future projections estimate novel biogeographical state regions (unique regional environment that shapes biodiversity and constrains ecosystem structure and functions) in the oceans may affect 19% of the total number of fish stocks by 2050 (8% of global fisheries) and 59% by 2100 (30% of global fisheries) (Reygondeau et al., 2020). Therefore, a growing challenge is to reduce the rate of change and the rapid emergence of novelty while safeguarding SES resilience to sustain ecosystem services.

Nonetheless, the generation of novelty is critical to maintain the adaptive capacity of SES, including their dynamics, functionality, and resilience (Allen & Holling, 2010). Novelty allows SES to explore alternative dynamics and structures to adapt to changing environments (Allen & Holling, 2010). Novelty can support the transition and transformation to more sustainable trajectories (Folke et al., 2016). Despite consensus on the need for acknowledging novelty in SES (e.g., Allen et al., 2014; Allen & Holling, 2010; Folke et al., 2010; Holling, 1996; Standish et al., 2014), there is much confusion linked to the concept of novelty. In addition, depending on the scale of the study, its context, and applications, novelty may be understood differently and therefore has been used in conflicting terminologies and meanings depending on the discipline. Hence, novelty is a cornerstone of SES, it requires further exploration of its empirical and theoretical underpinnings.

This thesis aims to advance the understanding of novelty in marine SES by

- *providing a unifying conceptualization of novelty for SES by linking different theoretical foundations and related novelty concepts,*
- *empirically contributing to understanding novelty in marine SES in the past and future, and*
- *applying different methods to quantify novelty and its drivers at different scales in marine SES.*

In the next sections, I present an overview of different theories and frameworks about novelty. Then, I frame the conceptualization of novelty and the research approach adopted in this thesis. I illustrate the gaps addressed and the methodologies used. Next, I provide an overview of the Baltic Sea SES, methods, and a summary of the papers. Finally, I end with the thesis contributions and reflections.

Theoretical framework

1. Novelty in Complex Adaptive Systems (CAS)

SES are commonly studied as complex adaptive systems (CAS) to unpack and describe the complex features in the real world (e.g., Cilliers, 2002; Poli, 2013; Preiser et al., 2018; Tengö et al., 2014). Many CAS characteristics were uncovered with research from different disciplinary fields, including physics, genetics, economy, linguistics, and evolutionary biology. For instance, CAS exhibit nonlinear behavior that emerge from the interactions of their parts and have the ability to adapt, evolve, anticipate, and learn (Holland, 1992; Levin, 2002). For example, as an adaptive response to eutrophication in the Black Sea, communities have exhibited nonlinear dynamics and have crossed two thresholds: from phytobenthic algal regime towards a phytoplankton and bivalve-dominated regime, then an endobenthic organisms regime (Blenckner, Kannen, et al., 2015). CAS are characterized by limited predictability, heterogeneity, and historical dependence (Levin, 2002). For example, case studies of complex fisheries systems showed that fished species are more likely to display nonlinear dynamics than unfished species, which limits the predictability of fisheries landing (Glaser et al., 2014). Historical dependence was described in examples of processes of entrapment over time, such as overfishing and collapse of predatory finfish in Maine in the 1990s which forced fishers to switch to a lobster fishery with limited alternative income (Boonstra & de Boer, 2014). CAS experience regularity and at the same time randomness across different scales and levels (Gell-Mann, 1994). These systems continually revise their interaction dynamics so that each part is embedded in perpetual novelty (Holland, 1992). In addition, CAS are contextually determined: if the context changes, the system changes and its element will take a different role or function, resulting in multiple context-dependent identities (Chu et al., 2003; Zellmer et al., 2006). For example, invasive species can adapt to a new environmental context, by taking a different function in the food web. In addition, the same species could be seen as keystone species from an ecological context, but as competition for fishers in a fisheries context.

Many studies have researched multiples CAS characteristics and dynamic properties in SES. However, there is a wealth of research opportunities about novelty in SES that might increase our understanding of SES dynamics and resilience. In CAS, novelty continuously emerges as a response to change in social and ecological components. It emerges through complex interactions, and the same starting conditions can lead to different trajectories (Preiser et al., 2018). Novelty is attributed to the system as a whole rather than its individual components, and the response of the system cannot be understood by its individual components (Hammond, 2017; Heylighen et al., 2017; Preiser et al., 2018; Preiser & Cilliers, 2010; Wells, 2012). For example, ecological systems can maintain the diversity and at the same time the individuality of components as well as the specific effects of this dynamic interaction on the generation of novelty and the development of the system (Levin, 1998; Milne, 1998).

1.1. The adaptive cycle

The adaptive cycle is a metaphor used to describe patterns of stability and instability over time in CAS. It comprises four phases: rapid growth or exploitation (r); slow growth and conservation (K); collapse or release (Ω); and reorganization (α) (Holling, 1986; Figure 1A). For example, in ecosystems, change is episodic as it is characterized by periods of slow accumulation of capital (e.g., accumulation of biomass or nutrients) punctuated by sudden release and reorganization, resulting from internal or external natural or anthropogenic disturbances (Franklin & MacMahon, 2000; Gunderson & Holling, 2002). For instance, Angeler et al. (2015) described adaptive cycles of phytoplankton recurring spring and summer blooms in the Baltic Sea by phases of reorganization, conservation, and adaptation. The adaptive cycle was also often employed as a tool to describe the social responses to environmental and economic changes (e.g., Burkhard & Gee, 2012; Pelling & Manuel-Navarrete, 2011; Santos-Martín et al., 2019), and management interventions on ecosystems (e.g., Auad et al., 2018; Fath et al., 2015; Pérez-Orellana et al., 2020; Soto & Puettmann, 2020). Yet, based on network indicators emerging from thermodynamics and information theory, Sundstrom & Allen (2019) suggest that the adaptive cycle can be considered as more than a metaphor and is a generic and ubiquitous feature of CAS.

The adaptive cycle phases vary within the three axes (Figure 1A): (i) Potential: sets limits to what is possible and the alternation of future options, (ii) Connectedness: the degree of rigidity of internal control over the external forces, (iii) Resilience: determines how vulnerable the system is to unexpected disturbances and surprises that can exceed or break that control (Gunderson & Holling, 2002). The rapid growth phase (r) and the slow growth and conservation phase (K) make the system increasingly overconnected and lose resilience, which fosters the collapse phase (Ω), with conditions of low connectedness, high resilience, and high potential for the reorganization phase (α) of novelty and experiment (Gunderson and Holling, 2002; Figure 1A). The reorganization phase (α) is a phase of great uncertainty, change of unexpected forms, and unexpected crises (Holling, 1986), but offers high potential for a new cycle (Gunderson & Holling, 2002).

A system state can be defined by its function, structure (e.g., composition and biomass), identity (e.g., same species dominance; see glossary), and feedbacks (Gunderson et al., 2006). When a system state is disrupted, it can reorganize with the same elements thereby keeping the identity, feedbacks, and functions (Gunderson et al., 2006) or it can reorganize into a novel configuration by the combination of old and new elements referred to as bricolage (Gunderson & Holling, 2002). Thus, the reorganization generates either a novel reassortment of the existing element or a novel combination of existing and new elements.

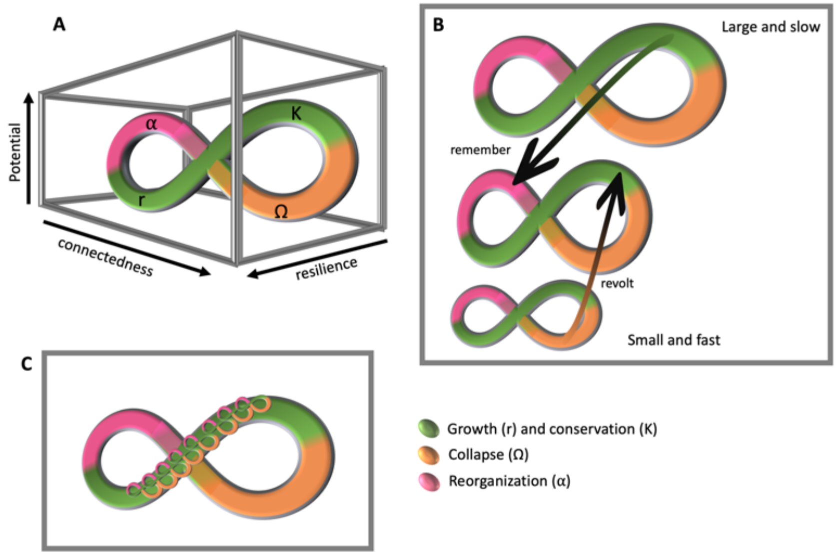

Figure 1: A) Adaptive cycle phases (Gunderson & Holling, 2002; Holling, 1986): rapid growth or exploitation (r); slow growth and conservation (K); collapse or release (Ω); and reorganization (α). The adaptive cycle phases are described over three axes: "Potential sets limits to what is possible – it determines the number of alternative options for the future. Connectedness determines the degree to which a system can control its own destiny, as distinct from being caught by the whims of external variability. Resilience determines how vulnerable the system is to unexpected disturbances and surprises that can exceed or break that control" (Gunderson & Holling, 2002). B) A nested set of adaptive cycles operating at a discrete range of scales, i.e., the Panarchy (Gunderson & Holling, 2002). During a collapse phase with low potential for the creation of novelty, "revolt" connection can cascade up from a vulnerable stage to a larger and slower one to create novelty at a larger level. The "remember" connection can facilitate the reorganization by drawing on the potential and context from the system memory that has been accumulated and stored in a larger and slower cycle. C) Through the (r) to (K) phase, incremental novelty comes from adding complexity via new connections of new adaptive cycle levels, adapted from Burkhard et al. (2011).

1.2. The Panarchy

A nested set of adaptive cycles operating at a discrete range of scales is referred to as Panarchy (Gunderson and Holling, 2002; Figure 1B) and has been used to describe the dynamics and processes of CAS within and across spatial and temporal scales (Allen et al., 2014; Garmestani et al., 2020). The within-scales dynamics affect the processes at other scales (Gunderson & Holling, 2002). For example, multilevel (local to global levels) processes at ecological, social, and governance scales in the Arctic fisheries sub-systems and the interactions across scales showed that cross-scales interactions create uncertainties for blue growth (Niiranen et al., 2018).

In the Panarchy, novelty can emerge at the edge of scale break, where the production of novelty cascades up the level and catastrophic events cascade down

(Allen et al., 2014; Gunderson & Holling, 2002; Figure 1B). Scale breaks are discontinuities between levels of a scale such as gaps in animal body masses across an ecosystem (Garmestani et al., 2009). The response and trajectories of CAS are influenced by the system memory (remember connection in Figure 1B) and the capacity to learn from previous responses and configurations (Allen & Holling, 2010; Cilliers, 2002; Gunderson & Holling, 2002; Preiser et al., 2018).

As stated by Allen and Holling (2010), three types of novelty can be identified in the adaptive cycle: (i) Punctuated novelty introduced at the reorganization phase (Figure 1A); (ii) Background novelty as the result of the dynamics of CAS, at the edge of scale break in the Panarchy, which is critical to maintaining the adaptive capacity and serves as a reservoir of functions as the system evolves or transforms (Figure 1B); (iii) Incremental novelty comes from adding complexity during the (r) and (K) phases via new connections of new adaptive cycle levels (Figure 1C). In this thesis, the main focus will be on punctuated novelty.

1.3. Resilience

Resilience thinking is a lens and integrative approach for dealing with the challenges of the Anthropocene (Folke, 2016). Here, I focus on the resilience approach that emphasizes system nonlinearity, uncertainty, and surprises, phases of rapid and slow changes, and cross-scales dynamics (Folke, 2006). This approach is in line with the adaptive cycle metaphor. The recognition of resilience varying with the adaptive cycle provides a way to reconcile the paradoxes of conservative nature versus creative nature and of sustainability versus creative change (Gunderson & Holling, 2002).

Here, I consider SES Resilience (general resilience) as the capacity to adapt to change, persist disturbances, learn, self-organize, and transform from unsustainable social-ecological pathways while sustaining the identity (Folke et al., 2010, 2016). The specified resilience refers to the resilience of a part of the system, e.g., ecosystem resilience (Walker, Abel, et al., 2009). It is the capacity to adapt to change and reorganize while sustaining the major functions and identity (Folke et al., 2010).

2. Ecological novelty concepts

In CAS theories, much of the thinking and wording come from evolutionary biology. Indeed, mutations are the origin of species adaptation with novel proteins and novel DNAs; for example, Darwin's theory was built on species adaptation to their environment through novel mutations and "natural selection" (Darwin, 1859). Novelty could emerge at different levels, e.g., genes within the genome, physiological traits, phenotypic characters, behaviors, as a result of diverse processes and ecological interactions (Erwin, 2021). For example, the emergence of novel functionally-integrated forms (e.g., novel proteins and genes) can be a mechanism behind adaptation and coevolving at the edge of chaos: "This may be just the conceptual scheme we need: a law, accident, design, selection, even unfolding and transforming in novel functionally integrated forms" (Kauffman, 1993).

In recent decades, ecological novelty has gained great attention. As interpreted by Heger et al. (2019), ecological novelty comprises novel organisms, novel communities, novel ecosystems, and novel selection of pressures (such as novel interactions and novel environmental conditions). These conditions have been referred to as novel, emerging, or no-analog (Chapin & Starfield, 1997; Hobbs et al., 2006; Milton, 2003; Williams & Jackson, 2007). Two schools of thought have defined and identified ecological novelty: (i) novelty as a continuous process of ecosystems dynamics and (ii) novel ecosystems as a concept for biodiversity conservation. Three qualifiers could make the distinction between these lines of ideas (Heger et al., 2019): thresholds (categorical or continuum), reference conditions (baseline influenced by people's background), and intentionality (natural process or related to anthropogenic activities and management).

2.1. Novelty as a continuous process of ecological systems dynamics

In paleoecology, biogeography, and climatology, novelty is considered as a *continuous process of ecological dynamics* of the Earth System through all known geological epochs (referred to here as the *continuous novelty concept*). However, human influence has increased the rate of its emergence (Finsinger et al., 2017). Yet, human agency is not the only criterion for novelty. Novelty emerges in a system when it has been moved beyond its historical range of variations, for example, by natural climate change before the Holocene (Mora et al., 2013). In this context, novelty offers a scientific concept linking many changes that make ecosystems uniquely different from the past (Radeloff et al., 2015). This concept is in line with the CAS theories.

In the *continuous novelty concept*, novelty emerges in a continuum and has been quantified based on dissimilarities associated with high or low novelty, where it is only meaningful to talk about by referring to a specific temporal and spatial baseline (Radeloff et al., 2015; Williams et al., 2007). It can be a nonlinear function of time and emerges at different abiotic and biotic dimensions (Radeloff et al., 2015). Backward cycling (i.e., increase and decrease of novelty over time) has been documented (Finsinger et al., 2017; Jackson, 2013). This quantitative approach has been applied to a large range of physical and ecological systems (e.g., climate, pollen record, and agriculture) at different spatial and temporal (geological epochs) scales (e.g., Finsinger et al., 2017; Fitzpatrick et al., 2018; Mahony et al., 2017; Radeloff et al., 2015; Williams et al., 2007, 2019).

The choice of dissimilarity methods and spatial and temporal baseline boundaries allow novelty metrics to flexibly target the problem, the management context, and the system of interest (Williams et al., 2019). For example, Finsinger et al. (2017) in a study of the emergent patterns of novelty in European vegetation assemblages over the past 15 000 years, found that human activities in the last centuries have significantly contributed to a faster emergence of novelty. Burke et al. (2018) identified the closest past climate to future climate pathways by measuring novelty. They found that keeping the novel climate within the safe operating space similar to that of the Holocene seems increasingly unlikely, novel climate stabilization pathways such as RCP4.5 seem to resemble the mid-Pliocene, and the RCP8.5 is more likely to resemble the Eocene climate (Burke et al., 2018). Williams et al. (2019), in a study of the land use and climate-related environmental novelty in Wisconsin since 1890, identified how to utilize novelty measures in the management of Wisconsin counties. These are a few examples of the use and identification of the continuous novelty in multiple contexts, for different purposes, and at different scales.

2.2. Novel ecosystems as a concept for biodiversity conservation

In the field of conservation biology, it has been argued that *novel ecosystems* are a concept for biodiversity conservation (here referred to as the *novel ecosystem concept*) created by individuals and societal norms and values (Backstrom et al., 2018). In this discipline, the focus is on novel ecosystems typically stemming from human intervention through the introduction of species and land use (Hobbs et al., 2013). Novel ecosystems refer to non-historical and non-analogous ecological assemblages that emerged in anthropogenic landscapes and can no longer be restored to the historical state (i.e., prior to human influence) (Collier & Devitt, 2016; Hallett et al., 2013; Hobbs et al., 2013). Ecosystems are considered novel when they have crossed an irreversible ecological (e.g., climatic changes) or social-ecological (e.g., cost and knowledge gaps) threshold and can no longer be restored to their historical state (Backstrom et al., 2018; Francis, 2014; Hallett et al., 2013; Higgs, 2017; Hobbs et al., 2006, 2009, 2013). An ecosystem that is different from the historical state but has not crossed an irreversible threshold and therefore can be restored to its historical state has been referred to as "hybrid" (Hobbs et al., 2009, 2013). For example, the novel ecosystem concept has been used to describe options for rehabilitating former mine sites towards their historical state or towards a novel state within feasible management regimes acceptable to all stakeholders (Doley & Audet, 2013).

This approach may allow establishing a categorical difference between the systems that are possible to restore to a historical state and those that cannot be restored where alternative solutions towards an alternative stable state may be considered (Schläppy & Hobbs, 2019). Actions would be taken at the sites where the needs or threats are largest, and at the ecosystems that would benefit the most and have the best chance of recovery (Bottrill et al., 2008). Schläppy and Hobbs (2019) suggest that for ecosystems that cannot be restored to their historical state, the focus has to be on the value of novelty or to be restored to a state with a greater value. In this case, the perception of baseline and system identity are important and could differ from the pristine conditions, difficult to restore in some current SES.

The *novel ecosystem concept* has been mainly conceptual and has been strongly criticized. Indeed, the irreversible thresholds have not been well defined, the distinction between hybrid and novel ecosystems in the real world is difficult, and some criteria such as self-perpetuation are hard to identify (Aronson et al., 2014; Murcia et al., 2014; Radeloff et al., 2015; Simberloff et al., 2015). In addition, the term novel has been used in a normative meaning and the categorization of novel and non-novel can send the wrong message about traditional conservation and restoration methods. It may provide a "license to trash" or a "get out of jail" card for companies and a ''Trojan horse'' for conservation, where no attempt of restoration action of degraded ecosystems will be performed (Aronson et al., 2014; Murcia et al., 2014; Simberloff et al., 2015).

3. Novelty in other disciplines

There are numerous and sometimes conflicting meanings for the term novelty. For example, in evolutionary economics, novelty is something that has not been encountered or discovered until a particular time, emerging from generative or interpretative processes, endogenous (man-made) or exogenous (external drivers, e.g., natural disaster) causes (Witt, 2009, 2016). This interpretation of novelty is close to the *continuous novelty concept*, where novelty is outside the known range of historical variation.

In recommender systems (prediction algorithms of consumers behavior), novelty refers to the difference between the present experience in comparison to what has been seen or experienced previously by a consumer and is quantified in prediction algorithms for consumer behaviors (Castells et al., 2015; Sanz-Cruzado et al., 2018). These algorithms are based on dissimilarity methods, similar to the *continuous novelty concept*, in machine learning algorithms to predict consumer choices.

In innovation and new technology studies, novelty and innovation are commonly used in combination or interchangeably. For example, Tria et al. (2015) defined novelty as something new to a particular agent, whereas innovation is something new to the world. The dynamics of correlated novelties, which is based on the evolutionary theory of "adjacent possible" (Kauffman, 1996), are measured in dynamical systems (Tria et al., 2015). In the same field, Hutter et al. (2015) defined the creation or generation of novelty as innovation. In this thesis, novelty and innovation are different concepts. Innovation is understood to be a process used to outstand and solve a potential or actual problem, and novelty is understood to be a dynamic property of systems and will be detailed in the next section.

Research approach and methodology

In this thesis, I draw on multiple strands of the above-mentioned concepts and theories to study novelty in marine SES. I consider SES as CAS, where one of the characteristics is the generation of novelty.

1. What is novelty?

Here, I regard novelty as a dynamic property of SES, which defines conditions that have never been experienced before within the considered scale. Novelty emerges along a continuum and can be nonlinear. It is attributed to the whole CAS rather than to its individual components. The CAS in this case includes an ensemble of elements (e.g., species) within entities (e.g., Baltic basins) described by variables/dimensions (e.g., biomass, composition) in a selected temporal and spatial boundaries. For example, for fisheries in the Baltic SES as elements, the Baltic countries are entities, socio-economic factors are characteristics, and the amount of catch per species can be variables. Elements are described in the multidimensional space of all variables in these entities. Novelty emerges when the multidimensional space moves beyond the past range of variation (Figure 2A). I account for certain CAS features to define novelty in SES as described below.

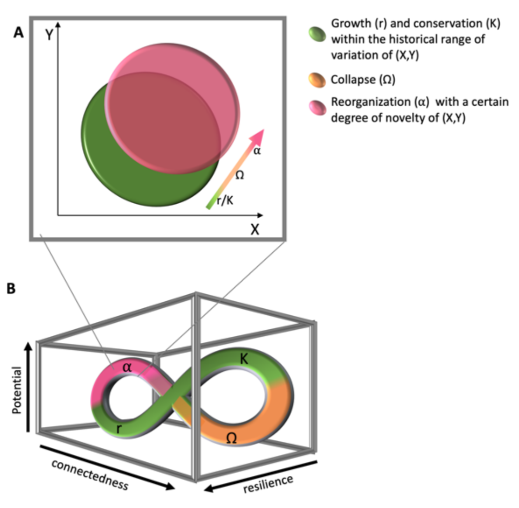

Figure 2: A) Novelty is described by a shift (from the space within the green circle to the space within the pink circle) of the system beyond its historical range of variation of (X, Y) over time. (X, Y) represent two dimensions (e.g., salinity and temperature or abiotic and biotic or social and ecological). B) Adaptive cycle phases: rapid growth and exploitation (r), slow growth and conservation (K), release or collapse phase (Ω), and reorganization (α). The three first phases can be within the historical range of variation of the system (X, Y). During the reorganization phase into novel configurations (α), novel conditions emerge that can be outside the historical range of variation, while some historical conditions can disappear. This can occur in all (α) phases across different levels and scales (Figure 1).

CAS are characterized by their context-dependent identities. The multidimensional characteristics used to identify novelty vary depending on what has been considered as characteristics of the SES in the study, such as structure, function, and interactions between components. For example, novelty could be identified in species biomass but not species composition.

Punctuated novelty is generated at the reorganization phase of the adaptive cycle (Figure 2). During the reorganization phase, the multidimensional space within which all the systems varied in the past deviates (Figure 2A). In this process, other conditions could disappear (Figure 3).

The dynamic processes in CAS could lead to novelty. Novelty can result from innovation, transformation, feedbacks, regime shifts, and other dynamic processes and phenomena (see glossary for definitions). For example, species may have to innovate when environmental conditions change to survive (e.g., new gene or new adaptation strategy) but may also disappear. The resulting species composition counts a certain degree of novelty (Figure 3).

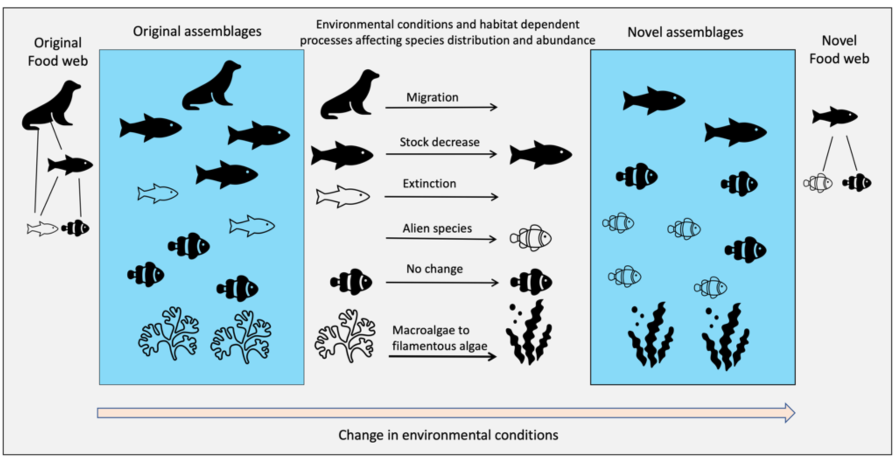

Figure 3: Illustration of the change to a novel assemblage in a marine food web. Complex factors influence the response of species assemblages to change in environmental conditions, including the effect on individual species, the interactions and feedbacks within the food web, and of species with their environment. Adapted from Harborne and Mumby (2011).

2. Novelty qualifiers

Baseline. The perception of baseline can be linked to human perception of the identity and shifts in the system (Papworth et al., 2009; Pauly, 1995; Rodrigues et al., 2019). The baseline also depends on the context of the study, the time scale, and the characteristics considered. For example, some studies suggest using palaeoecological data to define baselines for future models (Barnosky et al., 2017; Fitzpatrick et al., 2018; Jackson & Hobbs, 2009) because considering short time span baselines may ignore and underestimate the evolutionary adaptive capacity of species to future novel climates (Burke et al., 2018). Others suggest that a fixed historical baseline of a community should not be a conservation goal for novel communities based on the ground that novelty persisted through time in fossil marine planktonic communities (Pandolfi et al., 2020). A recent baseline, in this case, may be better suited for organisms that rapidly track their climate niches and have good monitoring data (i.e., data from recent decades) (Fitzpatrick et al., 2018). Therefore, the term historical baseline is a past reference state that could be useful in specific contexts. Here, I use baselines from recent decades rather than a comparison to the pristine conditions.

Threshold. Identifying a threshold for novel conditions that cannot recover to a historical state such as suggested in the *novel ecosystem concept* may require identifying a shift to a different regime after crossing an irreversible threshold, which is not necessary for the emergence of novelty in a CAS. Indeed, such regime shift may require the collapse of all levels of the Panarchy in the system (Allen & Holling, 2010). The generation of novelty at the reorganization phase of the adaptive cycle can happen at a scale or a level (species) and not happen at a larger one (ecosystem). Therefore, I do not consider a threshold as a measure for defining novelty. Instead, I talk about novelty that emerges over a continuum or degree of novelty relative to a specific baseline to illustrate a change beyond the historically known range of variation considering the scale of the study. This novelty represents the magnitude of unprecedented conditions accumulated during a period of time compared to a certain baseline (Figure 2). Accordingly, the *continuous novelty concept* provides a ground for assessing a continuously emerging novelty in SES.

3. Research gaps

There is a lack of mathematical formalization to measure novelty in SES. While the literature around the *continuous novelty concept* is mainly quantitative and measures novelty as the degree of dissimilarity of a system relative to a specific temporal and spatial baseline (Radeloff et al., 2015; Williams et al., 2007), it has focused on ecological novelty rather than novelty in SES (although Radeloff et al. 2015, Williams et al. 2019 have considered the human population). Nevertheless, as dissimilarity methods are flexible and value-neutral, they can measure ecological, socio-economic, and social-ecological novelty of the SES. Hence, I address the gap of quantification of novelty in SES using the methodology from the *continuous novelty concept* literature. The method presented below is deeply linked to this methodological approach and will detail the quantification of novelty.

The concept of novelty has mainly been developed and applied to terrestrial systems and more recently in marine ecosystems (Graham et al., 2014; Harborne & Mumby, 2011; Mora et al., 2013; Perring & Ellis, 2013; Reygondeau et al., 2020; Schläppy & Hobbs, 2019). Most studies addressing novelty in marine ecosystems have been conceptual. A few notable exceptions are novelty in future climate in Mora et al. (2013; referred to as unprecedented climate), future oceanic biogeographical state region in Reygondeau et al. (2020), and Cenozoic marine plankton in Pandolfi et al. (2020) at a global scale. This presents an important gap in the application of novelty research. Major differences exist between terrestrial and marine systems. For example, marine organisms and populations have been adapting to climate change with their strong capacity to colonize new territories, unlike terrestrial species, which have less colonization capacity but greater behavioral adaptation and less physiological sensitivity (Kinlan & Gaines, 2003; Pinsky et al., 2019, 2020; Robinson et al., 2011). Climate-driven range extensions in marine ecosystems are expected to be more common and change at a faster rate than terrestrial ecosystems (Pinsky et al., 2020). This can be challenging in estuary ecosystems because opportunities for species range shifts are limited by the enclosed characteristics restricting the poleward distributions. Salinity may further constrain this distribution. The characteristics of marine ecosystems make the identification of a threshold difficult, and the methodology chosen can be fitted to marine ecosystems and their characteristics.

I chose to study the Baltic Sea SES for the following reasons. The Baltic Sea is one of the most studied seas in the world: long-term monitoring data have been collected, future model scenarios have been developed, and multiple changes in the social and ecological dynamics have been reported. This estuary has been suggested to be a 'time machine' for understanding climate-induced changes in the global coastal ocean (Reusch et al., 2018). Future estimations of the global ocean biogeographical provinces predict that the Baltic Sea will be a novel biogeographical province worldwide in the mid 21st century compared to the late 20th century (Reygondeau et al., 2020). In the next chapter, I describe the Baltic Sea as a SES.

4. Identifying adaptive cycles

The adaptive cycle has been used to describe variability (patterns of stability and instability) in different social, ecological, and social-ecological systems (e.g., Angeler et al., 2015; Auad et al., 2018; Fath et al., 2015; Pelling & Manuel-Navarrete, 2011; Pérez-Orellana et al., 2020). But recently, Castell & Schrenk (2020) have quantitatively identified the adaptive cycle's three axes–Potential, Connectedness, and Resilience (Figures 1 and 2)–using network indicators from information theory applied to a genome, a plant system, and the economic crisis in Europe. Such indicators are commonly used in marine food web model scenarios to describe a food web, its status, and its flow (e.g., Heymans et al., 2007, 2014; Heymans & Tomczak, 2016). The phases of the cycle in Castell & Schrenk (2020), however, have been qualitatively identified following the described definition in Gunderson & Holling (2002). The reorganization phase is characterized by the generation of novelty (Figure 2), thus could be quantitatively identified. Hence, I apply the methodology of Castell & Schrenk (2020) to a future food web model scenario and quantitatively identify the reorganization phase.

5. Research questions

The four papers within this thesis contribute with an empirical understanding of the emergence of novelty and associated drivers in the Baltic Sea SES in the past (**Papers 1** and **2**) and future (**Papers 3** and **4**) across different SES components (Figure 4). I focus on ecological novelty in **Papers 1, 3,** and **4** to contribute to filling the gap of quantifying ecological novelty in a marine SES. In **Paper 2**, I address the gap of quantifying socio-economic novelty in a SES using the Baltic Sea fisheries case study. **Paper 4** builds on the adaptive cycle metaphor to bridge the gaps of novelty and resilience in marine ecosystems. The individual research questions (RQ) of the papers (Figure 4) are as follows:

RQ1: What is the resulting ecological novelty from climate- and anthropogenic-related changes in the last 35 years and what are the potential drivers?

Paper 1 addresses this question by using long-term monitoring data across the Baltic Sea basins for abiotic conditions, phytoplankton, zooplankton, and fish.

RQ2: How much have fishery management and governance actions influenced the emergence of socio-economic novelty in the Baltic SES over the last 40 years?

Paper 2 uses indicators of governance at national, regional, and international levels (i.e., the catch by fishing gear, catch by commercial groups, and trade respectively) to understand how management interventions and governance actions influence socio-economic novelty in the SES.

RQ3: What are the compound risks of the occurrence of future novel and disappearing environmental conditions in different climate and nutrient load scenarios for the fundamental niches of species?

Paper 3 makes use of future biogeochemical model projections of the Baltic Sea to explore the trends of local change, novel and disappearing environmental conditions under the compound effect of climate and nutrient management scenarios, and their potential effect on the fundamental niche of seagrass, starfish, and cod.

RQ4: What is the impact of novelty emerging as a result of the compound effect of climate, nutrient load, and fishing scenarios on ecosystem resilience?

Paper 4 makes use of the Finnish Archipelago Sea food web model under the compound effect of climate, nutrient, and fisheries scenarios and the associated Ecological Network Analysis (ENA) indicators to identify the potential impact of novelty on resilience and the reorganization phase of the adaptive cycles.

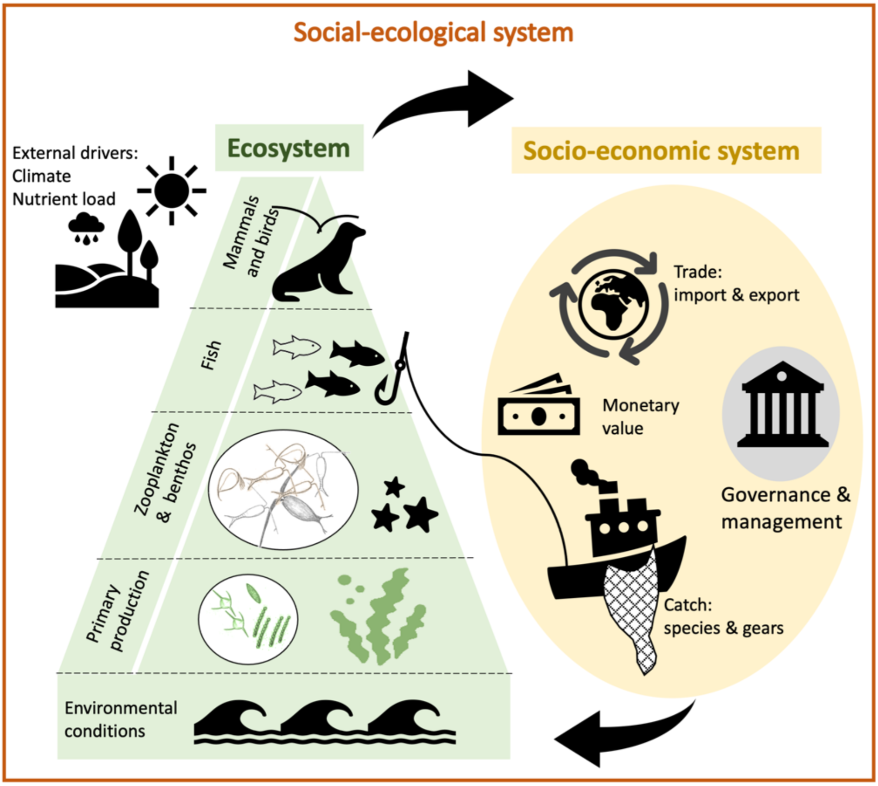

Figure 4: Conceptual framework presenting the social-ecological system components covered by the four papers included in this thesis. **Paper 1**: environmental conditions, phytoplankton, zooplankton, and fish. **Paper 2**: catch by species and gears, trade, their quantities and monetary value, and their link to governance and management interventions. **Paper 3**: environmental conditions under the compound effect of different climate and nutrient load management scenarios and the effect on the fundamental niche of seagrass, starfish, and cod. **Paper 4**: food web (primary production to birds and mammals) under the compound effect of different climate, nutrient load, and fisheries management scenarios.

Case study and methods

1. The Baltic Sea – a human-dominated system

The Baltic Sea (Figure 5), a brackish estuary ecosystem, is one of the most stressed marine ecosystems in the world (Elmgren et al., 2015) due to its enclosed bathymetry combined with the effects of multiple and cumulative drivers such as climate change, overexploitation of fishery resources, hazardous substances, and eutrophication. The perception of pristine conditions of the Baltic Sea can differ between those that consider prior to the 1900s to be pristine oligotrophic clear water conditions (Österblom et al., 2007) and those that argue that the human impact has a much longer history (Zillén & Conley, 2010). Yet, the onset of eutrophication was identified in the 1940s and 1950s (Gustafsson et al., 2012).

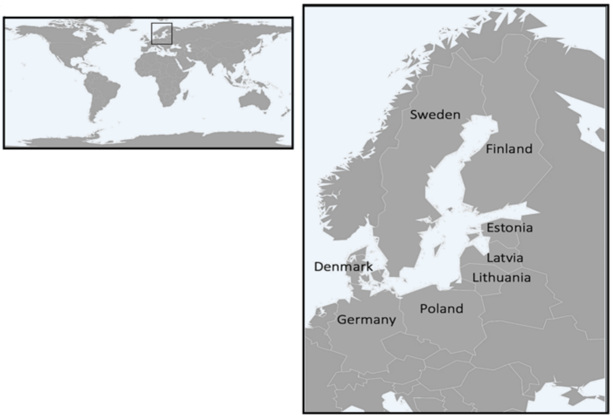

Figure 5: Map of the Baltic Sea and the surrounding countries.

The Baltic Sea has a strong salinity and temperature gradient, decreasing from south to north. It is one of the marine areas that during the past decades has experienced the highest increases in temperature in the world in addition to changes in salinity, which have strongly affected the species dynamics (Belkin, 2009; Rutgersson et al., 2014; The BACC II Author Team, 2015). In fact, the salinity and temperature gradient determine species distribution in the Baltic Sea (Möllmann et al., 2000; Pecuchet et al., 2016; Viitasalo et al., 2015; Vuorinen et al., 1998). The cumulative effects of multiple pressures have impaired the resilience of the Baltic Sea ecosystem (Korpinen et al., 2012) and substantially changed ecosystem structure and function, where many regime shifts have been documented (Casini et al., 2008; Dippner et al., 2012; Eklöf et al., 2020; Lindegren et al., 2012; Ljunggren et al., 2010; Möllmann et al., 2009). The impact of cumulative drivers is different across the Baltic Sea.

The Baltic Sea Action Plan (BSAP; *HELCOM*, 2007), a science-based adaptive management plan started in 2007, takes into account EU directives–e.g., the marine strategy framework directive (MSFD), the water framework directive (WFD), and Habitat Directive (HD)–to achieve a good environmental status and blue growth. Success (e.g., nutrient load reductions and top predator recovery) and failures (e.g., cod stock decrease and hypoxia) of these management interventions have been documented (see Blenckner et al., 2015; Elmgren et al., 2015).

In addition to ecological changes, multiple social, economic, and political changes have taken place in countries bordering the Baltic Sea within the past decades. Most of these countries have encountered political changes in the late 1980s and the beginning of the 1990s, after the collapse of the Soviet Union (USSR). During the 1990s, there was a shift from a centralized economic system to a market economy (Pascual-Fernández et al., 2020). The enlargement of the EU has also changed the socio-economic dynamics and governance structure because countries had to adapt to the EU regulations. Management of the Baltic Sea by the International Baltic Sea Fisheries Commission (IBSFC) was taken over by the EU in 2005 when all of the bordering countries (except Russia) joined the EU (Sellke et al., 2016).

EU policies related to fisheries management (i.e., the Common Fisheries Policy (CFP) and its reforms[1]) have changed the SES dynamics. Furthermore, country-specific governance actions, such as the introduction of Individual Transferable Quotas (ITQs), have prompted Baltic fishers to adapt to changes in society in terms of size of vessel, target species, type of gears, geographical mobility, and number of days spent at sea (Christensen & Raakjær, 2006). Therefore, the fishing industry has adapted, transformed, and innovated in response to changes in environmental and governance systems. Recently, following the trade liberalization policy and the global trend, worldwide trade of fish and fishery products has increased in quantity and diversity of species, especially in terms of imports in the Baltic Sea countries (COM, 2019). A detailed description of the historical development of the Baltic Sea countries is found in **Paper 2.**

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[1] *Council Regulation (EC) No 2371/2002 of 20 December 2002 on the conservation and sustainable exploitation of fisheries resources under the Common Fisheries Policy*, 2002; *Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC*, 2013; *Council Regulation (EEC) No 170/83 of 25 January 1983 establishing a Community system for the conservation and management of fishery resources*, 1983; *Council Regulation (EEC) No 3760/92 of 20 December 1992 establishing a Community system for fisheries and aquaculture*, 1992

Clearly, the Baltic Sea is a SES that has undergone multiple social-ecological changes over the past decades across different scales. These characteristics make the Baltic Sea an interesting case study to empirically analyze novelty in marine SES in the past and the future.

2. Data

In **Papers 1** and **2**, open-access data have been extracted from different research bodies, institutes, and databases. In **Papers 3** and **4**, modeled scenarios data were obtained from collaborators in the BLUEWEBS project and other institutes. The chosen data capture different characteristics and changes in the Baltic Sea SES as described above (Figure 4). Information about data sources and processing are found in respective papers. Details about the data, the geographical distribution, and the time range are found in Table 1.

No ethical dilemmas have been identified in **Papers 1** and **2 (**no use of personal data or experiments with live animals). In **Papers 3** and **4**, the collaborators from the BLUEWEBS project and other institutes are co-authors involved in these papers. An ethics review was approved for the whole PhD project.

3. Measuring novelty

Following the research approach and methodology described, I chose methods linked to the *continuous novelty concept* to enable the description of novelty in the SES over time. These methods account for the spatial and temporal scales of novelty in a relatively closed system such as the Baltic Sea SES, allowing for the exploration of different characteristics of a multidimensional novelty.

Novelty in **all Papers** was measured as the minimum degree of dissimilarity of a system relative to a specific temporal and spatial baseline (Radeloff et al., 2015; Williams et al., 2007). Novelty measures the degree of shift to new conditions of the whole system, compared to the baseline of all elements and entities of the system. It was measured as the minimum dissimilarity of the variables at an entity (e.g., one Baltic basin) of the system to all entities (e.g., all Baltic basins) of the system in the past baseline. The system can stay within the same range of past variation of the baseline (i.e., the range of variation of all the entities of the system in the past) or shift to relatively novel conditions by a certain degree (Figure 2A). The entities of the system are here Baltic Sea HELCOM sub-basins in **Paper 1**, the Baltic countries in **Paper 2**, and grid points in **Paper 3** (Table 1). **Paper 4** uses the same approach over time only for the Finnish Archipelago Sea.

Depending on the type of data and on the research question, dissimilarity methods were computed to quantify novelty in multiple components of the Baltic Sea SES and to answer different purposes (Table 1). All dissimilarities are variants of the Euclidean distance to make use of its isometric properties in the Euclidean space: Standard Euclidean Distance (SED) for environmental variables (**Papers 1** and

3); Normalized Euclidean Distance (NED or ED) for biomass change and socio-economic data (**Papers 1**, **2**, and **4**); and Hellinger distance (HD) for species composition turnover (**Papers 1** and **4**).

Baseline. The baseline, a reference point within a range of variation, is used to compare the emergence of novelty over time. The earliest available temporal baseline was used in **Papers 1** and **2** to capture novelty for the longest period with available data and within a range of variation (i.e., 1980–1984 and 1975–1979). This was supported by the knowledge that many changes have occurred in the Baltic Sea SES since the 1980s (**Paper 2**). Modeled data, however, provide a longer time span and more homogeneous datasets. In **Paper 3**, it was possible to use a 20-year baseline (1980–1999), which provided a large range for comparing the future. In **Paper 4**, modeled data started from 2000 and the calibration period (all Monte Carlo (MC) runs between 2000 and 2018) of the model were used as a measure of the baseline.

Target years. Changes in composition and turnovers are always expected even in relatively stable periods (Dornelas & Madin, 2020; Pandolfi et al., 2020). Therefore, in **Papers 1 and 2**, the time-series data were binned into 5-year bins to reduce the interannual variability and the biases that could be related to monitoring and missing data. In **Paper 3**, 20-year bins of the future biogeochemical model of the Baltic Sea give a perspective on what could be the close future (2030–2049) and the far future (2080–2099) under different scenarios. Novelty for all MC runs per year in **Paper 4** allows a conservative measure of novelty in the future food web model.

4. Identifying the adaptive cycle

In **Paper 4**, Ecological Network Analysis (ENA) indicators calculated from the Finnish Archipelago Sea food web model scenarios were used to identify the adaptive cycles axes. The ENA capacity and ascendency were used as indicators of the two axes potential and connectedness (Castell & Schrenk, 2020; Ulanowicz, 2000), and the overhead flow was used as an indicator of resilience (Heymans et al., 2007; Ulanowicz, 2018).

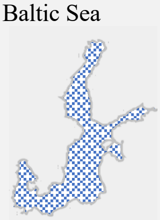
The reorganization phase of the adaptive cycle is characterized by the generation of novelty. A “change point” method applied to novelty timeseries allowed the assessment of significant shifts in mean novelty over time. These shifts were used to identify the reorganization phase. The collapse phase (Ω) and the fast and slow growth phases (r) and (K) were qualitatively identified following the definition in Gunderson & Holling (2002).

5. Identifying drivers of novelty

Although the dissimilarity methods are useful in identifying shifts in the system, they do not allow for the identification of drivers. In this case, combining a set of methods allowed the identification of drivers of novelty:

- **Paper 1**: generalized additive model (GAM) to test whether single or multiple environmental variables could explain the resulting novelty for the three biotic components: phytoplankton, zooplankton, and fish.
- **Paper 2**: cluster analysis (and heatmap) to understand the contribution of countries to the emergence of socio-economic novelty.
- **Paper 2**: qualitative analysis to link socio-political events at different levels and different changes in governance from the literature to the emergence of novelty.
- **Paper 3**: contribution maps to novelty for three variable classes–a) salinity-related factors, b) temperature-related factors, and c) eutrophication-related factors–for each scenario for mid- and far-future periods.
- **Paper 3**: changes in the key variables representing a niche space to explore the impact of novel and disappearing environmental conditions on the fundamental niches of Baltic Sea species, i.e., cod (*Gadus morhua*), eelgrass (*Zostera marina* L.), and starfish (*Asterias rubens*).
- **Paper 4**: model-based clustering to distinguish different regimes based on the studied scenarios.

Table 1: Summary of papers: research questions, data, spatial and temporal scales, methods, and key results.

	Paper 1	***Paper 2***	***Paper 3***	***Paper 4***
Research questions	What is the resulting ecological novelty from climate- and anthropogenic-related changes in the last 35 years and what are the potential drivers?	How much have fishery management and governance actions influenced the emergence of socio-economic novelty in the Baltic SES over the last 40 years?	What are the compound risks of the occurrence of future novel and disappearing environmental conditions in different climate and nutrient load scenarios for the fundamental niches of species?	What is the impact of novelty emerging as a result of the compound effect of climate, nutrient load and fishing scenarios on ecosystem resilience?
Data	Abiotic conditions, phytoplankton, zooplankton, and fish assemblages	Catch by gear type, catch by commercial group, import, and export, all in terms of quantity and value	Biogeochemical model data, species	Food web biomass model data and ENA indicators
Temporal and spatial scales	1980–2014 Baltic Basins 	1975–2014 Baltic Countries 	1980–2099 Baltic Sea 	2000–2090 Archipelago Sea 
Methods	Dissimilarity methods: SED, NED, HD; Generalized Additive Model (GAM)	Dissimilarity methods: ED; Cluster analysis; Qualitative analysis and literature review	Dissimilarity methods: SED; Contribution metrics	Dissimilarity methods: ED, HD; Change point analysis; Model-based clustering
Key Results	Ecological novelty increased over time across environmental conditions and different biotic assemblages, mainly due to temperature and salinity changes.	Socio-economic novelty shifted from a dominance of gears and commercial groups to import and export, mainly driven by Sweden, Denmark, and Poland.	Local change, novelty and disappearing biogeochemical conditions depend on the compound effect of drivers and affect species ecological niches.	Resilience decreased with the high and fast novelty in warmer climate pathways (RCP8.5).

Summary of Papers

Paper 1: ***The rise of novelty in marine ecosystems: the Baltic Sea case.***

Paper 1 contributes to quantifying novelty across multiple components in a marine ecosystem: environmental conditions, phytoplankton, zooplankton, and fish assemblages. Novelty was analyzed along the Baltic Sea spatial environmental gradient through 35 years. **Paper 1** shows that novelty emerged in complex patterns varying in time and space, depending on the baseline conditions. Abiotic novelty was larger in the northern enclosed basins (Gulf of Bothnia, Gulf of Riga, and Gulf of Finland) and the southern Kattegat than in the Central Baltic Sea. A similar spatial pattern has been described for phytoplankton and zooplankton assemblages as the result of changes in composition and stock size. Temperature and salinity were identified as key drivers of novelty in the Baltic biotic communities. Salinity was a driver of summer phytoplankton novelty, where higher novelty was found in northern basins where surface salinity is already low and has decreased further in recent decades. Changes (increases) in spring temperature, which may have altered the dynamics of the food web, were drivers of zooplankton and fish novelty. Future climate change affecting the environmental conditions of the Baltic Sea may favor the increase of biotic novelty. Phytoplankton and zooplankton communities in the northern enclosed basins, especially Bothnian Bay, may be more susceptible to further rise of biotic novelty than in other Baltic basins. This paper highlights the need for further research on novelty in marine ecosystems, including interactions between trophic levels and ecosystem function under novel environmental conditions.

Paper 2: ***Quantifying socio-economic novelty in fisheries social-ecological systems.***

Paper 2 contributes to assessing novelty in marine SES with a focus on socio-economic characteristics. Novelty was quantified over 40 years for catch by gear type, catch by commercial group, and trade (import and export), which can be considered indicators of novelty at national, regional (EU-wide), and international governance levels, respectively. The Baltic socio-economic conditions experienced a continuous but nonlinear increase in socio-economic novelty following baseline-specific trajectories. The total socio-economic novelty has shifted in contribution from factors “gears” and “commercial groups” to “import” and “export”– i.e., from a major influence of national and regional management levels to the international level. The largest difference between countries in the emergence of novelty was identified before the shift. It occurred with a significant increase in catch quantities in the Swedish fishery in the late 1990s and with the introduction of the ITQ system affecting the catch by gears monetary value in Denmark in the early 2000s. The fastest increase in novelty was identified after the shift (2005–2015) mainly due to import and export increase linked to the trade liberalization policies. Sweden, Denmark, and Poland were the major contributors to this trade increase. After the shift, novelty was mainly related to changes in monetary value of catch and trade rather than quantity. The shift from national and regional levels to the international level may be caused by the reduced variability and increased stability due to national and regional fisheries management interventions and may have decreased the SES resilience to shocks. The current novelty emerged from the international level, outside the legislation of a single state. **Paper 2** shows that quantifying novelty, understanding shifts in the system, and the interlinkage between levels could enhance the understanding of SES' complexity and improve the plannability for ecosystem-based management nationally and at higher levels. This is urgently needed for the adaptation and transformation towards more sustainable trajectories.

Paper 3: ***The risk for novel and disappearing environmental conditions in the Baltic Sea.***

Paper 3 contributes to assessing the future risk for novel and disappearing environmental conditions in a marine system under the compound effects of climate and nutrient load management scenarios. As expected, the future projections show an increase in novelty and disappearing conditions over time asymmetrically between Baltic regions. The future nutrient reduction management BSAP improves the eutrophication status of the Baltic Sea but at the same time contributes to highly novel and disappearing environmental conditions relative to the 1980–1999 baseline. This is due to the improvement of oxygen conditions associated with not experienced climate conditions in the baseline period. **Paper 3** also exemplifies the potential consequences of novel and disappearing conditions on the functional niche of three charismatic species: the highly valued commercial fish species cod (*Gadus morhua*), the macrophyte eelgrass (*Zostera marina L.*), and the benthic species Starfish (*Asterias rubens*) under different scenarios. A massive decline may be expected under higher climate emission scenarios (RCP8.5). This first step toward comprehensively analyzing environmental novelty and disappearing conditions for a marine system illustrates the urgent need to include novelty and disappearing projection outputs in Earth System Models. Adaptive management is needed to account for the emergence of novelty related to the interplay of multiple drivers. This analysis provides strong support for the expectation of novel ecological communities in marine systems, which may affect ecosystem services, and needs to be accounted for in future sustainable oceans management plans.

Paper 4: ***Exploring future ecosystem novelty and resilience using the adaptive cycle.***

Paper 4 explores the impact of novelty emerging from the combined effect of drivers on ecosystem resilience using the adaptive cycle. ENA indices ascendancy, capacity, and overhead flow were used as respective indicators of connectedness, potential, and resilience axes of the adaptive cycle. These indicators derive from the Finnish Archipelago Sea (FAS) future food web model under the compound effects of climate, nutrient load, and fisheries management scenarios. Four regimes were distinguished from the baseline regime determined by the impact of the nutrient load and climate with the current fishing pressure on the bottom-up dynamic of the FAS food web. Only the reduced nutrient loads scenario BSAP and a less warm climate (RCP4.5) led to a regime with a good environmental status as according to the Marine Strategy Framework Directive (MSFD). Resilience decreased in regimes with the higher and faster novelty, which was mainly driven by warmer climate conditions (RCP8.5). Hence, there is a need for climate-adaptive management. Regimes under the lower nutrient load management scenario BSAP had more reorganization phases than in the case of reference nutrient load, which may have contributed to a slower decrease in resilience under the warmer climate conditions. The management of local stressors may contribute to break connectedness and reduce the probability of exhibiting nonlinear dynamics. The length of the adaptive cycle phases was irregular between and within regimes. **Paper 4** highlights the importance of understanding the variability (phases of stability and instability) and resilience in the growing Anthropogenic novelty to inform future management.

Contributions and reflections

This thesis contributes to linking theory and empirical evidence in relation to novelty in SES. The papers that make up this thesis can be seen as empirical support to the applicability and feasibility of quantifying novelty, identifying some of its drivers, and exploring its potential impact on ecosystem resilience in a marine SES. The key contributions from each paper can be summarized as follows:

- **Paper 1** measures ecological novelty in the Baltic Sea SES, in environmental conditions and different trophic levels, and identifies environmental drivers of biotic novelty.
- **Paper 2** focuses on the socio-economic novelty, and contributes to showing the impact of management actions and governance decisions on the emergence of novelty in a fisheries SES and the drivers at different governance levels.
- **Paper 3** gives insights on future novel and disappearing environmental conditions in the Baltic Sea in particular and estuary in general and the potential impact on species fundamental niches.
- **Paper 4** investigates the impact of novelty on ecosystem resilience based on the adaptive cycle and suggests a methodology to quantitatively identify the reorganization phase of the generation of novelty.

1. Contribution to SES: novelty dynamics within CAS

Novelty is defined as a continuous dynamical process of SES. Multiple characteristics of CAS have been empirically identified. First, novelty is contextually determined by the system identity and the variables/dimensions included to characterize the system. A certain degree of novelty can be found using certain variables and not found using others (e.g., biomass vs. composition in **Paper 4** or the aggregate measure of all factors and separately in **Paper 2**). The perception of what is novel can differ depending on what is considered the identity of the system. Second, the emergence of novelty is nonlinear. The contribution of variables or group of variables to the emergence of novelty over time can change–e.g., the contribution of temperature, salinity, and eutrophication-related factors, which have changed between the 2030–2049 and 2080–2099 periods relative to the 1980–1999 baseline–depending on the scenarios (**Paper 3**). In addition, novelty can show backward cycling (**Papers 1, 2,** and **4)** (Finsinger et al., 2017; Jackson, 2013). Fourth, the degree of novelty depends on the baseline chosen (historical dependence) and follows baseline-specific trajectories. Finally, punctuated novelty can be generated and identified at the reorganization phase of the adaptive cycle (**Paper 4**) **(**Allen & Holling, 2010**)**. These patterns reflect the complex dynamics of SES, where novelty can be a nonlinear function of time, and follows baseline-specific trajectories.

2. Lessons learned from the Baltic Sea SES

Combining the past emergence of ecological novelty with the socio-economic novelty induced by management actions and governance decisions of the Baltic Sea SES (**Papers 1** and **2)** was not feasible due to scale differences. This challenge highlights the difficulty of accounting for social and ecological interactions in the system. Indeed, governance scales rarely match those of ecosystems, which is one of the fundamental reasons why management often fails (Berkes, 2010; Folke et al., 2007; Galaz et al., 2008). Managing a specific level/scale (specific resilience) while ignoring the complexity of interactions of the SES (general resilience) generates new problems and unintended consequences of management (Poli, 2013; Preiser et al., 2018; Walker, Abel, et al., 2009). For example, ignoring the signs of nonlinear dynamics caused by climate change and other drivers in natural resource planning, such as the case of the eastern Baltic cod, had severe ecological, economic, and cultural consequences (Möllmann et al., 2021). The resilience of SES needs to be addressed across all levels and scales (Folke, 2016; Gunderson & Holling, 2002). Therefore, there is a need for a better understanding of novelty emerging from the interactions between social and ecological parts of the SES at all scales and levels for future management interventions (**Paper 2**).

In the future, novel and disappearing conditions will have consequences on ecosystem services and biodiversity because species composition and interactions will lack current analogs (**Paper 3**). Conservation and management need to be nuanced along the novelty continuum considering the great uncertainty in future ecosystem behavior, human action, and management interventions (Folke et al., 2004; Radeloff et al., 2015; Steffen et al., 2015). **Papers 3** and **4** illustrate examples of climate, nutrient load, and fishing management scenarios that show potential pathways under the compound impact of human action. For example, the combined effect of nutrient reduction management (BSAP), higher temperature, and changing salinity will result in novel environmental conditions and species assemblages, not experienced before (**Papers 3** and **4**). This is important to consider in ecosystem services planning because improved conditions (e.g., less anoxic) do not necessarily mean going back to the historical state. Adaptive management needs to consider the emergence of novelty related to the interplay of multiple drivers. Understanding the variability (patterns of stability and instability) of SES related to growing novelty could provide learning on the windows of opportunity for adaptive management to act and the phases when most uncertainty and surprises could be expected.

In recent years, relative to the used baselines (1980–1984 and 1975–1979 in **Papers 1** and **2**, respectively), novelty has emerged at a faster pace in the Baltic Sea as a result of global drivers. Temperature and salinity changing globally as a consequence of climate change were the main drivers of ecological novelty in the past abiotic and biotic conditions in the Baltic Sea (**Paper 1**). Faster ecological novelty is likely to be expected with the higher emission RCP8.5 scenarios and may affect the SES resilience (**Papers 3** and **4**). Indeed, the rate of climate change caused by anthropogenic pressure has never been experienced before through all geological epochs (Burke et al., 2018). Species adapt differently to environmental changes. Some species can benefit from changes such as climate warming by increasing their abundance and expanding their geographical ranges (Antão et al., 2020; Bates et al., 2014; Pinsky et al., 2020). Others may not survive especially when environmental novelty is higher than certain species' adaptation potential (e.g., low salinity, prey mismatch). It is more worrying in estuary ecosystems where the northward shift may not be an option (**Paper 3**). On the other hand, higher and faster socio-economic novelty resulted from international trade and increased imports of fishery products (**Paper 2**). The highly connected and homogenized systems worldwide have weakened internal feedbacks and increased the chance of novel pervasive risks (Nyström et al., 2019). Future management practices need to aim at preventing the fast and global emergence of novelty increasing homogenization and decreasing sustainability. Management focusing on the rate rather than the state may provide a more realistic foundation for proactive and pragmatic management of fast, slow, and abrupt changes in the fast-changing conditions of the Anthropocene (Williams et al., 2021).

3. Is novelty a problem or a solution?

Novelty will always be generated as part of the dynamics of systems and is necessary for their adaptive capacity. However, novelty stemming from human actions and interventions could have altered the variability and the dynamics of systems with impacts on SES resilience. The higher and faster novelty at larger scales might be a problem rather than a solution. For example, the increase of anthropogenic novelty under the compound effect of different drivers could increase the irregularity of adaptive cycles frequency and phases duration (**Paper 4**). Such altered variability was found in the summer phytoplankton adaptive cycles in the Baltic Sea as an adaptive response to environmental changes (Angeler et al., 2015). These changes could have consequences on higher trophic levels. Nonetheless, the lack of novelty can decrease the variability and compromise the resilience of the SES such as found in the socio-economic novelty related to the management interventions of fisheries (**Paper 2**). Management that decreases short-term variability increases long-term variability, shifts the location of critical thresholds, suppresses learning of the ecosystem behavior, and compromises the SES resilience (Carpenter et al., 2015). Hence, whether novelty is a solution or a problem depends on its drivers, rate, scales and impact on the SES resilience. All are important to consider in the management of SES. Fostering novelty that could balance systems variability and sustainability and increase SES resilience is needed. Such novelty requires innovation and transformation toward sustainable solutions and trajectories.

Novelty that has been identified in the regional case study of the Baltic Sea may not be novel from a global perspective (i.e., a different baseline) as similar conditions may occur in other estuaries or coastal oceans. Estimating novelty at national, regional, and international levels and at different scales can provide (i) learning on managing a system that has occurred before (i.e., low degree of novelty compared to the baseline conditions), (ii) learning at which scale different types of novelty (depending on the characteristics) may arise that will help inform how to manage at the appropriate scale and level, and (iii) identifying the processes of the emergence of novelty in a CAS across different scales and levels. Additionally, considering an adaptive cycle perspective may provide an understanding of variability, novelty, and resilience. This may reduce the risk of missing opportunities for biodiversity conservation and of unintended management outcomes to secure ecosystem services for human wellbeing and long-term sustainability.

4. Alternate views of the *novel ecosystem concept*

The recovery from the impact of climate change will take millennia (Blois et al., 2013), yet it is possible. In all climate change events, species assemblages transformed into more generalist species and interactions (Blois et al., 2013), which we may expect in the future. The availability of geological analogs to future climate offers some evidence of the eco-evolutionary adaptive capacity of species, where all species today have an ancestor that survived the hothouse climate of the Eocene and Pliocene (Burke et al., 2018). Although species have adapted through all geological epochs, human action has accelerated these movements, which may have challenged the adaptation potential of species.

Novel ecosystems typically originate from human intervention through the introduction of species and land use (Hobbs et al., 2013). Ecosystems are considered hybrid if they are different from the historical state but did not cross an irreversible threshold and can be restored to their historical state (Hobbs et al., 2009, 2013). However, ecosystems have always changed, novelty has always emerged in the past, and will continue to emerge in the future. Assuming categorically the existence of novel ecosystems can ignore the complexity of SES and the Earth System dynamics. The restoration of ecosystems to a greater value if they have crossed a threshold such as suggested in Schläppy & Hobbs (2019) could increase the risk of unintended management intervention in the short and long term. This is especially true as evidence of backward cycling was found over different time scales (**Papers 1**, **2**, and **4**; Finsinger et al., 2017; Jackson, 2013). Additionally, as stated by previous critics, irreversible thresholds have not been well defined, the distinction between hybrid and novel ecosystems in the real world is difficult, and some criteria such as self-perpetuation are difficult to identify (Aronson et al., 2014; Murcia et al., 2014; Radeloff et al., 2015; Simberloff et al., 2015). The identification of such threshold usually requires identifying a shift to a different regime characterized by large, abrupt, and persistent changes in the structure and function of the system (Andersen et al., 2009; Folke et al., 2004; Scheffer et al., 2001). This type of regime happens after the collapse of all levels of the Panarchy in the system (Allen & Holling, 2010). This is difficult to identify as it involves acknowledging different functions, characteristics, and dynamics at different scales or levels. Hence, the concept could create confusion if it is misinterpreted and used as a tool to change ecosystems that are thought to have crossed an irreversible threshold. It ignores the identity and complexity of SES, which could increase the risk of mismanagement of natural resources.

In some cases, embracing novel ecosystems as a perspective for human adaptation rather than a categorical threshold could improve the management of ecosystems in a fast-changing environment. Anthropogenic climate change is not a disturbance after which conditions will return to their previous state but is a combination of directional changes from baseline conditions and changes in frequency and intensity of extreme events (Fisichelli et al., 2016). For example, many coral reef ecosystems are changing at an unprecedented rate and probably will not recover to pristine conditions. In such cases, the novel ecosystem as a perspective can reveal new management approaches and change human behavior to adapt to changing environments (Graham et al., 2014). In addition, it is unrealistic to eradicate all non-indigenous invasive species. However, preventing further transfer and establishment of invasive species is needed, i.e., to prevent further human impact. In most cases, invasive species are associated with the loss of resilience and extinction of other species (Chaffin et al., 2016). In general, there is a need to slow down the changing path (Williams et al., 2021) and to stimulate novelty that decreases anthropogenic impacts on ecosystems rather than causing further anthropogenic change. Stabilizing the Earth System will require the management of humanity's relationship with the Earth System through fundamental orientation of human values, equity, behavior, institutions, economies, and technologies (Steffen et al., 2018).

5. Methodological contributions and limitations

Although the ecological effects of certain single global-change factors such as climate change are well studied, knowledge about their cumulative effects and complexity remains limited (Heger et al., 2019; Kueffer, 2015). However, novelty analysis, a multidimensional measure of change across scales, quantifies the extent that a system has shifted from the historically known range of variation under the cumulative impact of different drivers. This approach gave a perspective of the resulting cumulative effects of drivers on a marine SES in the past and the future.

Dissimilarity methods are useful in their ability and flexibility to combine multiple variables, which captures the emergence of novelty in a multidimensional CAS. They allowed for computing the degree of multidimensional change in relation to the closest multidimensional conditions in a past baseline, which could inform how much is known or unknown compared to different past dynamical states for management. Furthermore, the wide range of dissimilarity methods available makes it possible to target different characteristics of the system (environmental conditions in **Papers 1** and **3**, species composition and biomass in **Papers 1** and **4**, and socio-economic conditions in

Paper 2). However, dissimilarities do not allow the distinction of specific pathways and variables that contribute to the emergence of novelty. Combining a set of different methods, quantitative and qualitative, is important for uncovering the complexity of SES and the drivers of novelty at different scales. Future studies that include other methods could advance the research of novelty and the impact of the interactions between social and ecological components at different scales.

Using open access data has multiple advantages with respect to, for example, visibility, reproducibility, and accessibility. However, these data are usually heterogeneous over time, over sampling areas or countries, and over monitoring schemes and come with gaps over time and space (e.g., Mihoub et al., 2017). Handling these data to produce homogenous datasets is often challenging. Although these challenges are mastered with model data, other challenges arise. In general, models do not reflect the natural variability because there is no opportunity for bricolage (e.g., the arrival of invasive species and the creation of new functions). This suggests that opportunities for novelty in nature might be higher. Long-term future model scenarios are usually linear, with future projections based on what is known today. Extreme events such as heatwaves, which are expected to increase in the future and highly affect marine ecosystems, cannot be modeled. Consequently, long-term model scenarios could indicate general trends under different possible scenarios and help evaluate the vulnerability of fixed policy (e.g., fisheries management) to changing environmental and social conditions (Holsman et al., 2019) rather than exact patterns in the future. There is, however, a need to include novelty projection outputs in Earth System Models (**Paper 3**) and consider species' nonlinear responses to environmental changes.

Conclusion and next steps

This PhD thesis is a contribution to linking theoretical foundations with empirical evidence about novelty in SES from a CAS perspective. The case study of the Baltic Sea SES provided an empirical understanding of the emergence of novelty in marine SES in the past and of what could be expected in the future. This case study permitted the application of methodologies related to the *continuous novelty concept* and the adaptive cycle metaphor and revealed some characteristics of novelty in SES. Considering that novelty can be a problem or a solution - depending on its rate, drivers, and scale, there is a need to foster novelty that could promote SES resilience and increase sustainability.

Worldwide, the rate of emergence of novel climate and environmental conditions (Kloor, 2009; Mora et al., 2013; Reygondeau et al., 2020) will determine the impacts on the economy, the competition for natural resources, and conflicts and geopolitical instability (Díaz et al., 2006; Spijkers et al., 2021). Therefore, I hope this thesis has contributed to understanding novelty in marine SES and uncovering some of its drivers and characteristics to improve life below water (Sustainable Development Goal 14) for future sustainability.

Novelty studied across different scales has revealed many CAS characteristics such as nonlinear dynamics, context-dependent identities, and historically-dependent trajectories. The punctuated novelty introduced at the reorganization phase of the adaptive cycle was identified at the ecosystem level (**Paper 4**). Yet, the background novelty and incremental novelty, which were introduced in this thesis, need more empirical underpinning. Novelty across scales and levels of the Panarchy and the increased complexity during the (r) to (K) phases could be an interesting future research direction.

While novelty is important for the adaptive capacity of systems, it can increase or decrease SES resilience and sustainability. Multiple questions remain, which offers opportunities for future research on novelty. For example, how much novelty, in which direction, and at which rate could it sustain the system within the safe operating space? What is the rate of novelty that could promote SES resilience and sustainability? New methodologies such as the algorithms used for predicting consumer behaviors could be interesting if used to refine the predictions of human behavior in a SES context. They can improve the prediction of future novel environmental changes, species adaptations, and human actions, including interactions and feedbacks. This method may advance the understanding of novelty and contribute to achieving good environmental status in marine ecosystems and sustaining ecosystem services for human wellbeing.

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