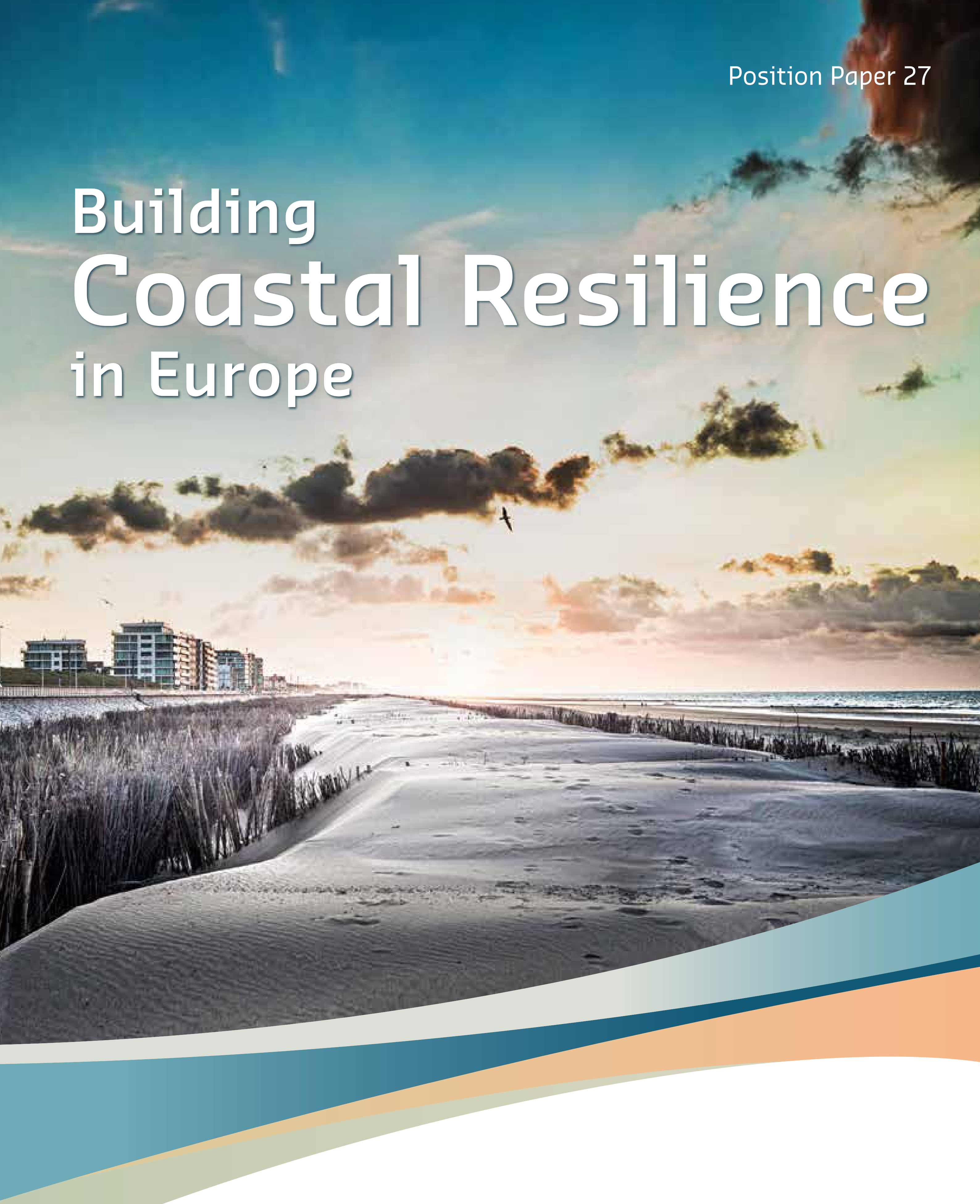

Position Paper 27

Building
Coastal Resilience
in Europe

European
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European Marine Board IVZW

The European Marine Board provides a pan-European platform for its Member organisations to develop common priorities, advance marine research, and to bridge the gap between science and policy in order to meet future marine science challenges and opportunities.

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Building Coastal Resilience in Europe

European Marine Board IVZW – Position Paper 27

This Position Paper is a result of the work of the European Marine Board Working Group on Coastal Resilience. See Annex 1 for the list of Working Group Members and affiliations.

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Foreword

Coasts are particularly attractive and subject to significant cumulative anthropogenic pressures linked to increasing demographic growth and a high concentration of socio-economic issues. Rich in exceptional ecological and landscape diversity, they are also exposed to erosion leading to a retreat of the coastline, to which may be added the risk of flooding. This fragility of coastal areas is accentuated by the impacts of climate change, with coasts standing at the forefront of the climate and biodiversity crises.

Building resilience to coastal pressures is a journey we must embrace to ensure that coastal communities and ecosystems can persist, adapt or transform when faced with disturbances, while maintaining essential functions. Resilience is becoming ubiquitous in many research programs and government strategies, including the UN Ocean Decade for Sustainable Development, launched in 2021, which aims for "a healthy and resilient" Ocean and and the objectives of the EU Mission: Restore our Ocean and Waters by 2030. However, more ambition is needed. In 2021, ahead the COP26 in Glasgow during the World cities day, António Guterres, the UN Secretary General, warned that: "while sea-level rise could directly endanger more than 800 million people in coastal cities by 2050, only 9% of climate action funding is spent on adaptation, mitigation and resilience of cities".

Building coastal resilience requires improved standardisation in its definition and practice. Solutions should benefit both nature and people and take a holistic approach across the land-sea boundary. Adaptive capacity of human societies and the engagement of local communities are critical, and the multiple values of nature should be included in public policies and decision-making. Governments can put in place the mechanisms needed through their Nationally Determined Contributions towards the Paris Agreement, as well as national adaptation plans, maritime spatial plans and other national plans.

This Position Paper aims to inform and inspire policy-makers, coastal communities and the scientific community on journeys to build coastal resilience. It provides an overview of frameworks to address coastal resilience in a site-specific manner, and challenges and opportunities provided by observations, data, modelling and science at large. It draws on the natural and social sciences and selected case-studies from various coasts in Europe to describe tools, barriers and enablers to building coastal resilience.

The European Marine Board chose to pursue a Position Paper on coastal resilience in spring 2020. The Working Group (see Annex 1) includes diverse and interdisciplinary expertise and kicked off with an online meeting in January 2021. I would like to thank them on behalf of the EMB membership for their hard work and collaboration during the writing of this document, in particular the chapter leads: Remi Mongruel, Karen Timmermann, Thorsten Bleckner, Eugene Farrell and Jennifer Bailey. I would also like to thank the external reviewers for their valuable insights and critical comments that contributed to strengthening this Position Paper. Finally, I would like to thank the EMB Secretariat, in particular Britt Alexander, for the coordination of the Working Group and supporting the writing, editing and publication of this document.

Gilles Lericolais
Chair, European Marine Board
October 2023

Table of Contents

Executive Summary

European coasts face multiple, interacting and cumulative pressures including those resulting from increasing greenhouse gas emissions (e.g. sea-level rise, Ocean warming, Ocean acidification, extreme events) and localised activities such as fishing, aquaculture, waste disposal and coastal urbanisation. These create a unique set of context-specific issues that need to be addressed holistically, considering the dynamics between both coastal societies and ecosystems as part of interconnected social-ecological systems. Building and enhancing resilience to these pressures requires coastal social-ecological systems that can persist, adapt or transform while maintaining their essential functions to deliver ecosystem services for both nature and people. This Position Paper presents key policy and scientific recommendations on how to build coastal resilience and enhance capacity to cope with impacts from climate change and other pressures. While this Position Paper focuses on the European continent, including the United Kingdom and other non-European Union countries, and does not specifically include the European Union outermost regions, the conclusions and recommendations may also be applied to other regions.

Chapter 1 sets the scene by providing an overview of European coasts, resilience and the governance context. Chapter 2 gives an overview of concepts and frameworks for building coastal resilience, along with a six-step approach for their use in coastal management. The key pressures facing European coastal social-ecological systems and their impacts are described in Chapter 3, including knowledge gaps for individual pressures, their combined effects, and tipping points at which a transition to a new state is triggered. Chapter 4 presents tools for building coastal resilience, with a specific focus on coastal protection and Nature-based Solutions, as well as barriers and enablers to the implementation of these tools. Chapter 5 provides practical context for the concepts, frameworks, pressures, tools, barriers and enablers, and recommendations through three case-studies across Europe: the Maharees Peninsula, Ireland; the Venice Lagoon, Italy; and the Belgian Coast. Chapter 6 presents recommendations for policymakers, scientists and communities to work towards resilient coastal systems. This document is primarily targeted at policymakers, programme managers, research funders and the wider science-policy and scientific communities who are making decisions that will influence the future resilience of European coasts.

Building Coastal Resilience

European Marine Board Position Paper No. 27

POLICY RECOMMENDATIONS

I. Adopt a systems approach to coastal management

This should be based on adaptive, cross-sectoral and coherent policies. All aspects of the land-sea interface should be included in the Integrated Maritime Policy and links between marine- and land-based policies should be improved.

II. Include nature and people from the beginning of the design process

An ecosystem-based management approach should be adopted and an inventory developed of coastal management solutions and their impacts.

III. Build adaptive capacity at multiple scales

This should be across local communities, and national, regional and EU governance.

IV. Reflect the values of natural capital

The multiple social and economic values of natural capital should be reflected in our public policies and decision-making processes.

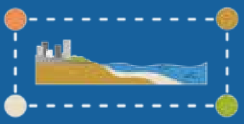
V. Follow the six-step approach

1. Conceive the management process as long-lasting and adaptive.

2. Co-produce with stakeholders throughout the process.

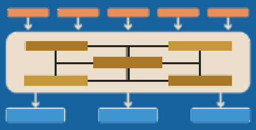
3. Define the resilience issue(s) to be addressed and select framework(s) to use.

4. Define coastal social-ecological system boundaries, structure and dynamics.



5. Identify, pilot and provide training on tools.

6. Sort and refine possible solutions and identify realistic scenarios.



Credit: Amy Dozier (CC BY-NC-ND 4.0)

Building Coastal Resilience

European Marine Board Position Paper No. 27

SCIENTIFIC RECOMMENDATIONS

I

Establish integrated transdisciplinary research on coastal social-ecological systems

This should address knowledge gaps for single pressure and site-specific multiple, cumulative pressure-response relationships, and tipping points.

II

Develop sufficient observational, monitoring and data capacity

Increased investment in observations, monitoring, Big Data and artificial intelligence is needed. Data should be integrated into an interdisciplinary platform with resilience indicators.

III

Develop and operationalise standardised coastal resilience indicators for Europe

A pan-European framework to develop clarity and standardisation in the definition and practice of coastal resilience is needed to operationalise indicators in practice.

IV

Improve model prediction capacity

This is needed to forecast and develop future scenarios on the magnitude, timing, location and impacts of multiple, cumulative pressures.

V

Invest in research on nature-based and hybrid solutions

The environmental and socio-economic co-benefits, site specific feasibility, and impacts of various combinations of seaward and landward Nature-based Solutions should be identified.

Examples of Nature-based Solutions

HYBRID Marsh-levee systems; artificial beaches in front of seawalls; dune-dyke systems.

SEAWARD Conservation and restoration of marine coastal habitats; vertical ocean farming; marine protected areas; low trophic aquaculture.

LANDWARD Conservation and restoration of landward coastal habitats; vegetated dunes and marshes; 'green' structural engineering.

Credit: Amy Dozier (CC BY-NC-ND 4.0)

2021 United Nations Decade
2030 of Ocean Science
for Sustainable Development

Contribution to the UN Ocean Decade Challenges and Outcomes

This Position Paper and its recommendations support the UN Decade of Ocean Science for Sustainable Development’s (Ocean Decade) societal outcomes (O1 – O7) and challenges (C1 – C7) in the following ways:

- **‘A clean Ocean’** (O1) where sources of pollution are identified, reduced and removed and **'understand and beat marine pollution'** (C1) by providing recommendations on research needed to better understand the impact of pollutants and their interaction with other coastal pressures so that they can be better managed. The recommended systems approach to coastal management and research, which considers all aspects of the land-sea interface, is important to reduce and manage impacts of pollutants in coastal zones.
- **'A healthy and resilient Ocean’** (O2) where marine ecosystems are understood, protected, restored and managed and **'Protect and restore ecosystems and biodiversity'** (C2) by highlighting knowledge and policy gaps that need to be filled in order to scale-up Nature-based Solutions.
- **‘A productive Ocean’** (O3) supporting a sustainable Ocean economy, **'Sustainably feed the global population'** (C3) and **'Develop a sustainable and equitable Ocean economy'** (C4) by highlighting knowledge gaps relating to social-ecological impacts of fisheries, and the need for cross-sectoral, coherent, adaptive and well implemented policies that allow a safe operating space for a sustainable Blue Economy.
- **‘A predicted Ocean’** (O4) where society understands and can respond to changing Ocean conditions by providing recommendations on the observations, data and modelling capacities needed to understand and predict changes in the coastal zone linked to multiple and cumulative pressures.
- **‘A safe Ocean'** (O5) where life and livelihoods are protected from Ocean-related hazards by identifying the knowledge and tools needed to prepare for and respond to extreme climatic events such as coastal flooding, storm surges, marine heatwaves and other coastal pressures including sea-level rise.
- **‘An inspiring and engaging Ocean'** (O7) outcome where society understands and values the Ocean in relation to human wellbeing and sustainable development and **'Change humanity's relationship with the Ocean'** (C10) by making recommendations on how to engage local communities in enhancing coastal resilience, and educating the public to promote wider acceptance of Nature-based Solutions.
- **‘Unlock Ocean-based solutions to climate change'** (C5) by identifying knowledge gaps on how to scale-up Nature-based Solutions, which have the potential to support the mitigation of and adaptation to climate change.
- **‘Increase community resilience to Ocean hazards'** (C6) by providing recommendations to enhance the adaptive capacity of human communities.
- **‘Skills, knowledge and technology for all'** (C9) by identifying the knowledge gaps that need to be addressed in order to enhance coastal resilience.

Contribution to the EU Mission: Restore our Ocean and Waters

This Position Paper and its recommendations support the three EU Mission Restore our Ocean and Seas actions in the following ways:

- **‘Protect and restore marine and freshwater ecosystems and biodiversity’** by highlighting knowledge gaps and policy recommendations to scale-up Nature-based Solutions and include nature in the design process of coastal resilience solutions.
- **‘Prevent and eliminate pollution of our Ocean, seas and waters’** by recommending a holistic approach to coastal management considering all aspects of the land-sea interface and the need to connect land and marine policies, and research communities.
- **‘Make the Blue Economy carbon neutral and circular**' by highlighting the need to reduce pressures on the coastal zone, including climate-induced pressures.

EMB acknowledges that while the Working Group members writing this document and its recommendations represent some diversity in terms of European geographical location (see Annex 1), professional background, and career level, their views do not represent ideas from all forms of diversity. This document has a European focus, but its messages and recommendations are relevant to coastal stakeholders globally.


Credit: Wikimedia Commons (CC BY-SA 2.0)

Ria Formosa Lagoon in Portugal.

1

Introduction

Credit: Anjelina Potin

The coast is a critical interface between land, sea and atmosphere, and is facing increasingly intense threats due to growing human populations, climate and other environmental changes and resource overexploitation. Resilience of both coastal communities and ecosystems is essential for the persistence of human-natural coastal systems today and into the future. Humans have a unique relationship with the coast. The archaeological record suggests that humans were originally coastal dwellers and spread from our possible origins along the coast of southern Africa via coastlines (Gillis, 2016). Population density is on average higher along the coast than elsewhere, and most of the world's megacities are located in the coastal zone (Neumann et al., 2015).

The European coastline is highly diverse in its geophysical characteristics (e.g. geology, tides, waves, sediment budget, landforms), coastal habitats (including kelp and seagrass beds, coral and oyster reefs, wetlands, beaches and dunes), and socio-economic-political contexts (e.g. economic activities, governance and political structures, resource management, international relations). In Europe over 500 million people, or almost half of the European population, live in coastal regions (see Figure 1.1) and this number is increasing[1]. Human communities along the European coast vary dramatically in their sensitivity to change and adaptive capacity, from declining and isolated to thriving and integrated. Their varying geographic conditions mean their exposure to change also varies greatly.

1.1 Why are coasts important?

Coastal Social-Ecological Systems (CSESs) occupy dynamic spaces with interactions between coastal societies and ecosystems, and have unique problems that need to be considered holistically. Commercial interests in the Ocean have increased exponentially as land-based resources become fully exploited or exhausted due to continued population growth, and as global per capita production and consumption increase (Jouffray et al., 2020). Coastal zones can be heavily urbanised, host a range of Blue Economy activities and have growing economic significance. The worldwide Blue Economy is estimated to reach three trillion USD per year (OECD, 2016).

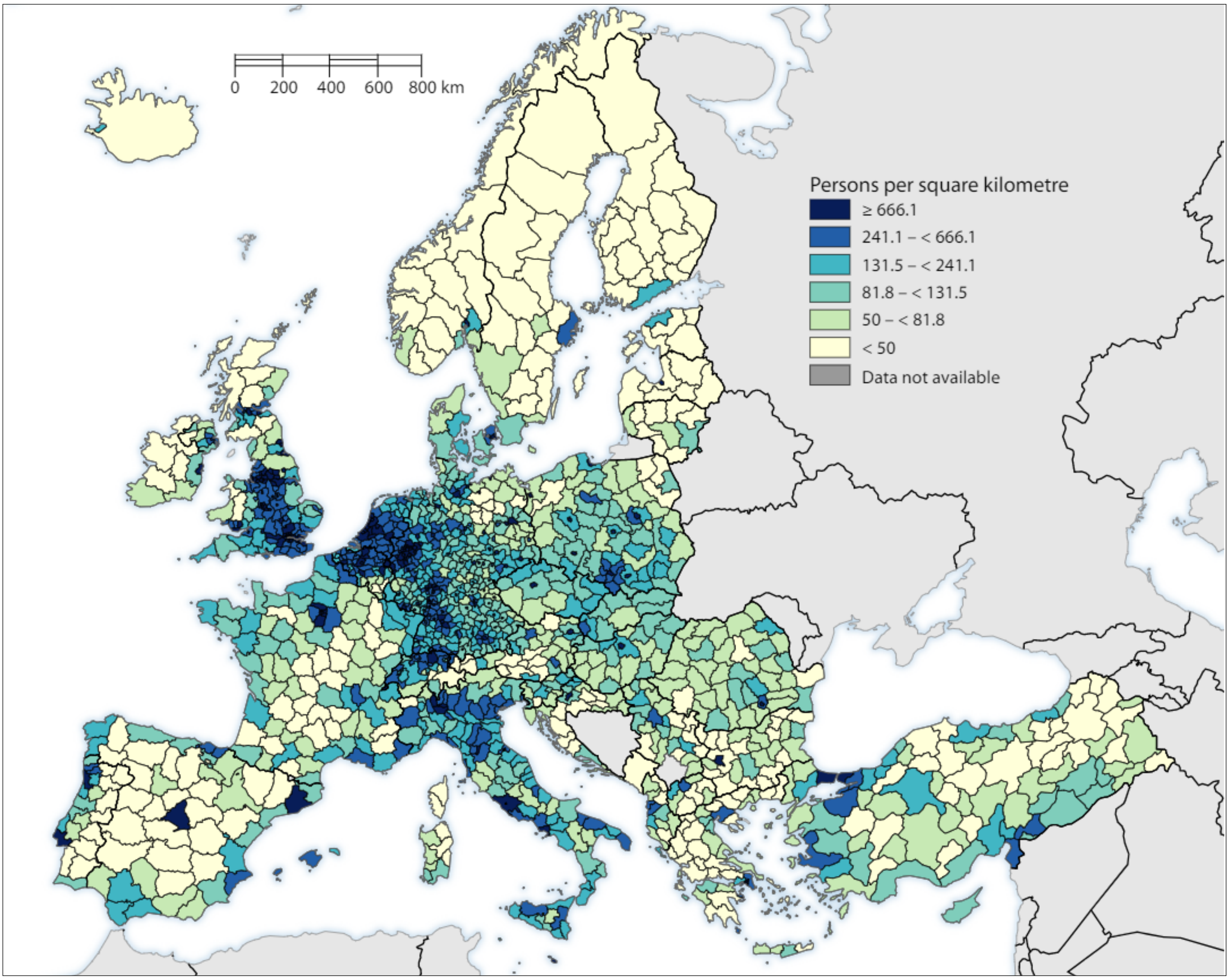


Figure 1.1 European population density (persons per km²) in 2018 given by Nomenclature of Territorial Units for Statistics (NUTS3).

Credit: Administrative Boundaries: © EuroGeographics © UN-FAO © Turkstat. Cartography: Eurostat - IMAGE, 07/2022. Source: Eurostat (dataset code demo_r_d3dens)

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[1] https://ec.europa.eu/futurium/en/system/files/ged/eprs-briefing-633160-demographic-trends-eu-regions-final.pdf

BOX 1: KEY TERMINOLOGY

Coastal resilience: The capacity of coastal natural and socio-economic systems to persist, adapt or transform when faced with disturbances induced by factors such as sea-level rise, extreme events and human impacts, whilst maintaining their essential functions (Folke, 2006: Masselink & Lazarus, 2019).

Coastal Social-Ecological System (CSES): A concept for understanding the highly connected interactions between coastal societies and ecosystems.

Building resilience: Actions towards more resilient CSESs starting from a deteriorated state.

Enhancing resilience: Actions towards improving the resilience of CSESs.

Coastal zone: The interface between land, sea and atmosphere, i.e. anywhere on land that lies within reach of the influence of the sea, and anywhere offshore that is affected by what happens on land. The seaward limit of the coastal zone is defined depending on the issue at hand and varies in policies.

Coastal regions: A socio-economic term for a region with either a sea border or with more than 50% of its population living within 50 km of the sea[2]. The generic term used throughout this report is coastal zone, but coastal area, coast, coastal space and coastal systems are also used as synonyms.

Socio-economic community: A human community inhabiting a particular place such as a coastal zone, their interpersonal relationships, cultural patterns, economic and governance structures, and shared memories and aspirations.

Ecosystem services: The social and economic benefits obtained by society from its use of the ecological functions of ecosystems (Millennium Ecosystem Assessment, 2005).

Pressures: Mechanisms of change of state on the natural system and subsequently the social system. Pressures are caused by human activities. Pressures may have positive or negative impacts, however this document focuses on mitigation and adaptation of the negative impacts of pressures on CSESs. Pressures are therefore considered “the cause of the problem” (Elliott et al., 2017).

Tools: Management measures to enhance the resilience of CSESs, ecosystems and ecosystem services. For example, beach nourishment enhances resilience of CSESs to coastal flooding and coastal erosion by increasing the protection of the beach.

Enablers to coastal resilience: Any changeable element of a CSES that enhances its resilience. For example, policy shifts that prioritise Nature-based Solutions could be an enabler. Enablers of one function can also act as barriers to other functions.

Barriers to coastal resilience: Any changeable element of a CSES that hinders or constrains its resilience. For example, a governance barrier could be legal objections by local property owners to beach replenishment projects, or lack of jurisdiction and resources.

Nature-based Solutions (NbS): Actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human wellbeing, ecosystem services, resilience and biodiversity benefits (UNEA, 2022).

Adaptation: In human systems, adaptation is the process of adjustment to existing or expected disturbances and their effects in order to moderate harm or exploit beneficial opportunities. In natural systems, it is the process of adjustment to existing disturbances and their effects, which can be facilitated by human intervention (adapted from IPCC, 2022).

Mitigation: A human intervention to reduce pressures (adapted from IPCC, 2022).

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[2] https://ec.europa.eu/eurostat/web/coastal-island-outermost-regions/background

Credit: Erich Westendarp (Pixabay)

European coasts play a significant role in tourism and maritime trading.

Given this growth potential, governments, political entities and international agencies are eager to boost economies through the development of the Blue Economy.

European coasts are constantly changing, influenced by new emerging economies to take advantage of European environmental and economic goals and the untapped potential of the marine environment. European coasts play a significant role in tourism and host most of the European Union (EU)'s fisheries and fishing ports, aquaculture, and maritime trading ports that service half of the EU's trade[3]. Coasts are also important for energy production i.e. offshore renewable energy (Soukissian et al., 2023).

The coastal population in Europe overlaps with some of the world's most productive and diverse ecosystems. Coastal ecosystems are critical providers of wide-ranging ecosystem services to human society including provisioning, regulating and cultural services. Provisioning services provide tangible, harvestable goods such as fish, shellfish and seaweed; regulating services include coastal protection, prevention of erosion, water purification, heat and carbon storage (i.e. blue carbon); and cultural services include recreation and tourism, aesthetic, spiritual, intellectual and cultural benefits (Austen et al., 2019). Coasts are also a therapeutic landscape for human health and wellbeing (Bell et al., 2015). These services influence human wellbeing both directly, through human use, and indirectly, via impacts on supporting and regulating services in other environments. The potential benefits from coastal provisioning services include taxation opportunities for governments, payments for access to fishing grounds, financial, social and employment benefits for national economies and local communities, and opportunities for coastal tourists.

Coastal ecosystems also provide non-monetary benefits in the form of advances in scientific knowledge, sense of place (Ainsworth et al., 2019), connectedness (Mayer et al., 2009), feelings of wonder, worship, spirituality (Heintzman, 2009), emotional restoration (Severin et al., 2022) and a free place to play or gather with family and friends (Garcia Rodrigues et al., 2017). Being in nature enables experiences through aesthetic appreciation (Fletcher et al., 2014), inspiration (de Oliveira & Berkes, 2014), and opportunities for solitude (Borrie & Roggenbuck, 2001). It can also enhance capabilities such as knowledge about nature (Plieninger et al., 2013), cognitive functioning (Berman et al., 2008) and physical and mental health (Hartig et al., 2014).

However, coastal zones are particularly vulnerable to threats from increasing human pressures e.g. urbanisation, tourism, agriculture, fisheries, aquaculture, dredging and waste disposal, as well as increases in greenhouse gas emissions with subsequent effects on sea level, water temperature, Ocean oxygen and Ocean acidification.

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[3] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=International_trade_in_goods_by_mode_of_transport


Credit: Pixabay

Coasts provide non-monetary benefits, for example, feelings of wonder, worship, spirituality, emotional restoration and a free place to play or gather with family and friends.

In addition, the multitude of different activities in the coastal zone can cause conflicts between sectors with different objectives and competing uses of marine resources and space. For example, the need to expand Marine Protected Areas (MPAs) creates conflict with activities including offshore renewable energy installations, fishing and shipping.

Most land-based activities (notably agriculture and urban/industrial/tourist settlements) cause a range of pressures across freshwater resources, the Ocean and seas. Pressures from human activities on marine habitats and species are found in 93% of Europe's Exclusive Economic Zone (European Commission, 2021). The highest potential of combined effects from multiple pressures in Europe are found along the coasts of the North Sea, Southern Baltic Sea, Adriatic Sea and Western Mediterranean regions (European Commission, 2021). In addition, biodiversity in European seas is declining; the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) regional assessment shows negative biodiversity trends for all available marine indicators for all European sea basins (IPBES, 2019).

1.2 Resilience as a journey

In practice there are multiple and diverse meanings of the term resilience (see Box 1. for the definition of coastal resilience used within the context of this document) and this varies between disciplines such as engineering, ecology and social science (see section 4.2.4 on resilience indicators). Coastal resilience comprises several dimensions of wellbeing, including political, social, economic and environmental (Chaigneau et al., 2022).

Resilience is not something that we can 'achieve', or indeed, may not be a desirable outcome in some circumstances. For example, some ecosystems persist in a poor state of health regardless of management interventions, requiring existing ecological thresholds to be exceeded to allow new healthier ecosystem functions and conditions to occur. The properties of social-ecological resilience usually include at least three main characteristics — resistance, recovery and robustness (Grafton et al., 2019). In general, resistance refers to a system's ability to actively change while retaining its identity or to passively maintain system performance following one or more adverse events; recovery refers to the time it takes for a system's performance to recover to a desired functionality following one or more adverse events, and robustness means the probability of a system to maintain its identity and not cross an undesirable (possibly irreversible) threshold following one or more adverse events (Grafton et al., 2019).

This document describes advances to build and enhance resilience to sustain essential functions provided by CSESs. Resilience is not a destination and should not be interpreted as a binary term i.e., that something is either resilient or not resilient. The use of the term resilience can also be a barrier in itself for engaging local stakeholders in climate change adaptation due to its vague and ambiguous interpretations. Therefore, resilience is not an outcome or a destination, and is best perceived as a relational journey, or a non-linear and dynamic process (Farrell et al., 2023) that is influenced by the interacting components of complex CSESs (Faulkner et al., 2018). Resilience requires coherence across organisations, their practices and behaviours, embracing social, economic and environmental elements, and strengthening adaptation responses at sectoral and local levels.

1.3 European and International governance context

The EU legislative landscape relevant for coastal resilience is complex (see Figure 1.2 for an overview of key legislative frameworks discussed within this document). The main legal instruments that are relevant to the coast, such as the Habitats Directive (Council Directive 92/43/EEC, 1992), Marine Spatial Planning Directive (MSP, Directive 2014/89/EU, 2014), Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC, 2008) are coordinated through the Integrated Maritime Policy (IMP, COM/2007/575 final, 2007). In addition, the European Green Deal (COM/2019/640 final, 2019), European Climate Law (Regulation (EU) 2021/1119, 2021) and 2030 Biodiversity Strategy (COM/2020/380 final, 2020), are relevant for coastal resilience and link to international legislation. All EU legislation discussed in this report is also relevant to non-EU countries who share sea-basins with EU countries and who use EU legislation as guidance for developing their own national legislation.

Internationally, the United Nations Convention on the Law of the Sea (UNCLOS[4]) states that coastal nations have exclusive exploitation rights in their Exclusive Economic Zones (up to 200 nautical miles from their coasts), and may set laws, regulate and use any resources in their internal (landward side of territorial baseline) and territorial waters (12 nautical miles from territorial baseline). The international legally binding agreement on climate change, the Paris Agreement[5], is also very important for coastal resilience as nations must act to build resilience to the impacts of climate change, and mitigate greenhouse gas emissions. The Kunming-Montreal Global Biodiversity Framework[6], another international policy instrument to consider when addressing coastal resilience, includes measures to protect and restore nature, and the RAMSAR Convention on Wetlands[7] is important for coastal zones as it provides the international framework for the conservation and use of wetlands and their resources. Finally, the United Nations (UN) has declared 2021-2030 as the UN Decade of Ocean Science for Sustainable Development[8] and the UN Decade of Ecosystem Restoration[9], which both provide significant opportunity to scale-up ecosystem conservation and restoration in support of the UN 2030 Agenda and the Sustainable Development Goals. During these Decades there are targets for scientists, policymakers, industry and society to work together to find solutions to sustain the ecosystem services provided by coastal habitats.

Credit: Sébastien Hervé (UBO)

Marine pollution is an ecological issue for coastal resilience.

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[4] https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf

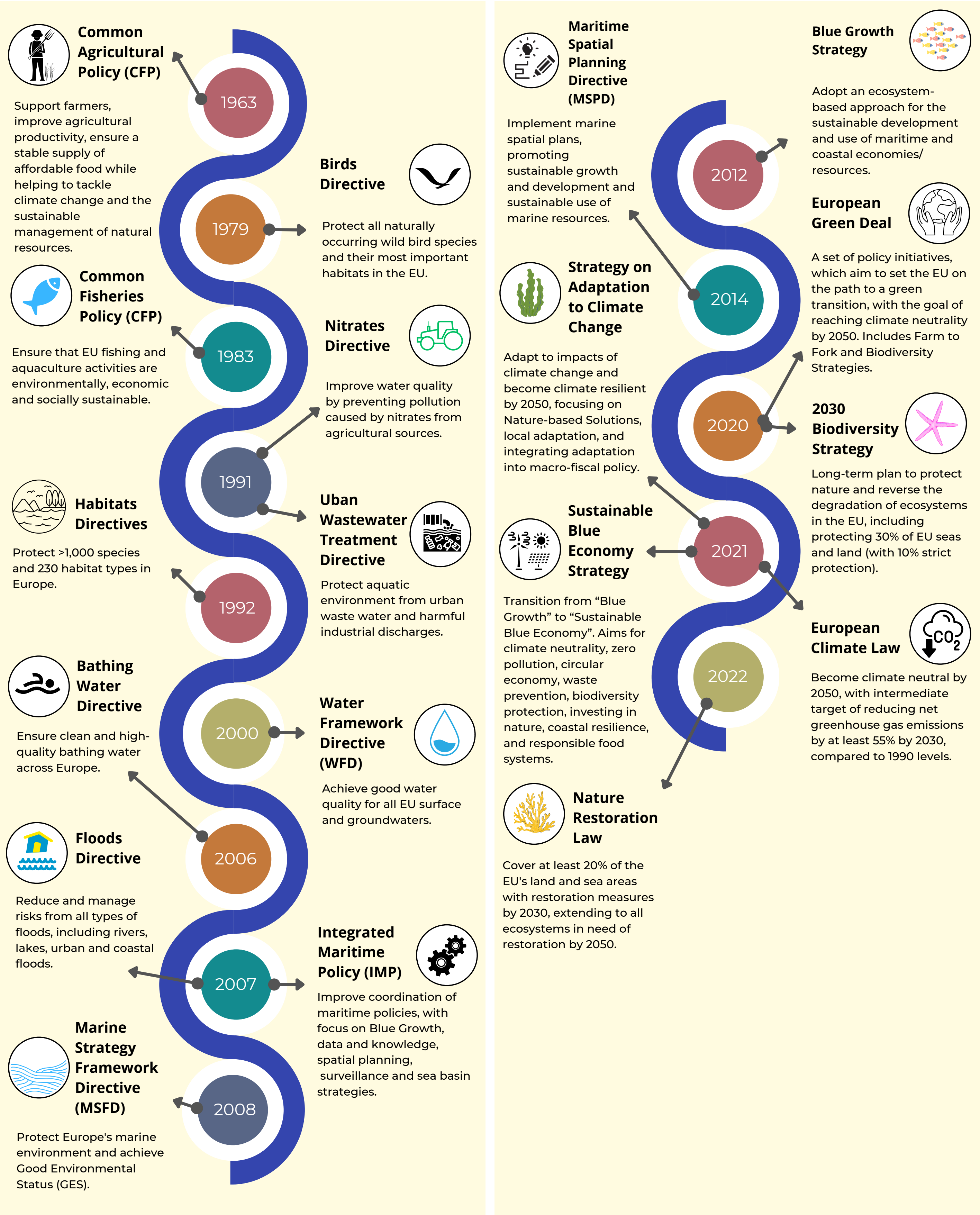
[5] https://www.un.org/en/climatechange/paris-agreement

[6] https://www.cbd.int/article/cop15-final-text-kunming-montreal-gbf-221222

[7] https://www.ramsar.org/

[8] https://oceandecade.org/

[9] https://www.decadeonrestoration.org/



1963

Common Agricultural Policy (CFP)

Support farmers, improve agricultural productivity, ensure a stable supply of affordable food while helping to tackle climate change and the sustainable management of natural resources.

1979

Birds Directive

Protect all naturally occurring wild bird species and their most important habitats in the EU.

1983

Common Fisheries Policy (CFP)

Ensure that EU fishing and aquaculture activities are environmentally, economic and socially sustainable.

1991

Nitrates Directive

Improve water quality by preventing pollution caused by nitrates from agricultural sources.

Uban Wastewater Treatment Directive

Protect aquatic environment from urban waste water and harmful industrial discharges.

1992

Habitats Directives

Protect >1,000 species and 230 habitat types in Europe.

2000

Water Framework Directive (WFD)

Achieve good water quality for all EU surface and groundwaters.

2006

Bathing Water Directive

Ensure clean and high-quality bathing water across Europe.

2007

Floods Directive

Reduce and manage risks from all types of floods, including rivers, lakes, urban and coastal floods.

Integrated Maritime Policy (IMP)

Improve coordination of maritime policies, with focus on Blue Growth, data and knowledge, spatial planning, surveillance and sea basin strategies.

2008

Marine Strategy Framework Directive (MSFD)

Protect Europe's marine environment and achieve Good Environmental Status (GES).

2012

Blue Growth Strategy

Adopt an ecosystem-based approach for the sustainable development and use of maritime and coastal economies/ resources.

2014

Maritime Spatial Planning Directive (MSPD)

Implement marine spatial plans, promoting sustainable growth and development and sustainable use of marine resources.

2020

European Green Deal

A set of policy initiatives, which aim to set the EU on the path to a green transition, with the goal of reaching climate neutrality by 2050. Includes Farm to Fork and Biodiversity Strategies.

2030 Biodiversity Strategy

Long-term plan to protect nature and reverse the degradation of ecosystems in the EU, including protecting 30% of EU seas and land (with 10% strict protection).

2021

Strategy on Adaptation to Climate Change

Adapt to impacts of climate change and become climate resilient by 2050, focusing on Nature-based Solutions, local adaptation, and integrating adaptation into macro-fiscal policy.

Sustainable Blue Economy Strategy

Transition from “Blue Growth” to “Sustainable Blue Economy”. Aims for climate neutrality, zero pollution, circular economy, waste prevention, biodiversity protection, investing in nature, coastal resilience, and responsible food systems.

European Climate Law

Become climate neutral by 2050, with intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels.

2022

Nature Restoration Law

Cover at least 20% of the EU's land and sea areas with restoration measures by 2030, extending to all ecosystems in need of restoration by 2050.

Figure 1.2 Timeline of European legislative frameworks relevant for coastal management and coastal resilience.

Credit: NIOZ

Saltmarshes and farmland separated by a dyke in the Dutch Scheldt delta.

2

Concepts and frameworks to assess coastal resilience

Credit: Marthje Schüler

In ecology, the resilience concept originated in the work of (Holling, 1973) as an application of complex system theory (Lyapunov, 1892) (i.e. systems composed of many components which may interact with each other) to natural systems. It was expanded to economics by the launch of the Beijer Institute of Ecological Economics program[10] on the interface between ecology and economy in 1991, and the founding of the Resilience Alliance[11] in 1999. Through these collaborations between natural and social scientists, resilience expanded from adaptively managing ecosystems to adaptively governing complex Social-Ecological Systems (SESs) (Folke et al., 2016). This entails dealing with uncertainty and changes at all levels and scales while considering the role of institutions (i.e systems for organising standardised patterns of social behavior) and networks, knowledge and social learning (i.e. learning new behaviours by observing and imitating others), local cultures, and political and power dimensions of sustainability. Resilience is an interdisciplinary concept and is linked to sustainability, and the diversity of institutions needed for natural resource governance (Ostrom, 2009).

The increasing popularity and use of resilience contrasts with a lack of clarity about how to implement it in practice, in particular in the context of marine SESs. Even after decades of research and policy engagement to advance understanding of resilience and calls for better inclusion into decision-making, resilience management of SESs is still not widely practiced (Grafton et al., 2019). Therefore, resilience often remains ambiguous and poorly defined within the context of decision-making (Masselink & Lazarus, 2019; see section 1.2). However, it has inspired operational frameworks, such as coastal zone management, to support sustainability policies. This chapter introduces approaches to frame resilience issues, which are important when developing solutions to build and enhance resilience. It provides an overview of selected key concepts and relevant frameworks for assessing and managing the resilience of SESs, and includes historical perspectives, level of operationalisation and limitations. These frameworks are diverse and range from purely conceptual, which have been developed to understand resilience problems, to varying degrees of operationalisation in support of policy-making.

In practice, these frameworks are all part of systems theory and can be used together. For example, the Ecosystem Service Assessment (ESA) framework is often considered necessary for understanding a SES, and the Driver-Pressure-State-Impact-Response (DPSIR) approach includes some processes that explain SES dynamics. These frameworks are not exhaustive, but cover the most well known examples. Other frameworks, such as those to implement transformative change to address the root cause of issues such as climate change (Nightingale et al., 2022), require substantial changes in practices but also views, values and institutional structures. Examples of transformative interventions include de-growth (i.e. shrinking rather than growing economies, using less resources and putting wellbeing ahead of profit) and post-growth (i.e. changing the composition and structure of economic activity to achieve the multiple goals of a more rounded vision of economic and social progress) policies. The EU is making progress in this regard with the European Green Deal which has some transformative narrative. Other transformative interventions include wide-scale Marine Protected Areas (MPAs), the prohibition of fishing by trawling within MPAs (proposed as part of the European Union (EU)'s Biodiversity Strategy and "Action Plan for protecting and restoring marine ecosystems for sustainable and resilient fisheries"[12]) and the inclusion of the social cost of a loss of carbon sequestration capacity in fisheries management (e.g. Prellezo et al., 2023).

The framework(s) needed depends on the issue to be addressed, the stakeholders involved and available knowledge. Due to the diversity and complexity of coastal zone situations, there is no "one size fits all" framework to address coastal resilience issues. This chapter closes by presenting a six-step approach based on basic principles and roadmaps from typical applications of these frameworks, which can be used to understand and address coastal resilience issues.

Credit: Daniela Anahi Asar

The preservation of social heritage, including traditional activities such as fishing, is a social issue relevant for coastal resilience.

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[10] https://beijer.kva.se/

[11] https://www.resalliance.org/

[12] https://oceans-and-fisheries.ec.europa.eu/system/files/2023-02/COM-2023-102_en.pdf

2.1 The Sustainable Development (SD) concept

The sustainable development concept can be used to help understand the inherent tension between basic human needs and the preservation of natural capital, which is a typical coastal resilience issue. The main reasons for this tension are increases in population density in coastal areas, technological progress which has historically been synonymous with environmental damage, and rising standards of living which may create new demands for resource use. It should be noted that recently, in some countries, rising living standards have stimulated a demand for higher environmental quality and technological progress has also led to more environmentally-friendly practices. The Brundtland Commission Report (United Nations, 1987) defined sustainability as *“meeting the needs of present without compromising the ability of future generations to meet their own needs*[13]*”*. This definition includes the feedback that occurs due to the interdependence of human and environmental systems.

2.1.1 Weak vs. strong sustainability

The idea that human capital (i.e. the monetary value of skills, knowledge, competences of humans and the technologies they produce) can substitute natural capital (i.e. the stock of natural resources) is referred to as "weak sustainability" and assumes that most environmental damage can be reversed. Weak sustainability considers it possible to put a monetary value on natural assets and to use cost-benefit analysis to choose between development or conservation policy options. In contrast, "strong sustainability" requires that both man-made and natural capital remain intact separately, considering that they are not substitutes but rather complement each other and that most environmental damage is irreversible (Daly, 1990). The use of weak sustainability economic methods to support strong sustainability policies is the root of many of the barriers to enhancing coastal resilience. We advocate strong sustainability as the preferred approach, which focuses on critical thresholds that should not be reached, especially regarding environment and ecosystem dynamics, and favours multi-criteria assessments and cost-effectiveness analyses for developing multi-objective policies, which always include an environmental dimension.

In practice, when ecological stability is not threatened, the assumptions of the weak sustainability approach remain valid, and standard economic assessment tools such as monetary valuation or cost-benefit analysis can be used to support decisions. In such situations, any change in the state of the ecosystem remains marginal, which is compatible with the use of standard monetary valuation methods, since these methods are based on the concept of marginal unity[14] (Hueting et al., 1998). However, when the preservation of critical ecological thresholds is at stake, the benefits of preserving natural capital tend to become infinite and the question is no longer whether it is worth preserving nature, but how and at what cost. Cost-effectiveness or multi-criteria analyses should therefore be favoured. For instance, in critical ecological situations, although the costs of ecological restoration can be evaluated using monetary expenditure, the same does not apply when valuing all the benefits of this restoration. Most of these benefits are invaluable, or have no monetary value, thus costs may seem disproportionate and the cost-benefit analysis would conclude that ecological restoration is not worthwhile (Feuillette et al., 2016). In contrast, using cost-effectiveness or multi-criteria analyses would ensure that the ecological objective is achieved, while minimising the economic or social costs of environmental preservation.

2.1.2 The sustainable development concept in practice

The sustainable development concept provides the rationale for the EU’s Integrated Maritime Policy (IMP). Implicitly, strong sustainability is referred to when sustainable development is used by environmental advocates or decision-makers in the context of the IMP or other nature conservation policies. However, the multiple definitions of "sustainable development" (i.e. weak and strong sustainability) feed ambiguities. The vision of the Ocean and seas as a place of many opportunities has expanded in the wake of the EC’s Blue Growth Strategies, creating internal tensions within the IMP and two of its constituent Directives i.e. Maritime Spatial Planning (MSP), and Marine Strategy Framework Directive (MSFD), whose objectives are difficult to reconcile (Trouillet, 2020). This could lead to weak sustainability in practice, with possible negative consequences for coastal resilience. This is because the priority given to the development of new economic activities can result in the changes they bring to the marine and coastal environment being considered marginal, although they could in fact be critical. Even in the context of marine environmental policies, such as the Water Framework Directive (Directive 2000/60/EC, 2000) or the MSFD, a temptation may persist to promote the use of “standard” economic assessment tools, like monetary valuation of ecosystems or cost-benefit analysis of management options, which are based on the assumptions of weak sustainability. This is exemplified when the MSFD states that to achieve or maintain Good Environmental Status (GES), impact assessments, including cost-benefit analyses, should be carried out prior to the introduction of any new measure (European Commission, 2018). The recent recommendation by the EC to transition from “Blue Growth” to “Sustainable Blue Economy” (COM/2021/240 final, 2021) attempts to overcome these conflicts and to reconcile nature conservation with economic development and gets closer to strong sustainability. Efforts to reconcile economic development and nature preservation at the global level now insist on the search for triple win solutions aiming to make development bearable, viable and equitable (UNDP, 2012).

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[13] https://www.un.org/en/academic-impact/sustainability

[14] Applied to natural capital, marginal unity involves estimating the benefits we would lose if we decided to remove a unit from an ecosystem. But when the ecosystem is under threat, removing one unit of the ecosystem could have critical rather than marginal consequences, and the benefits lost would become immeasurable. This is because the benefits of critical natural capital are infinite (economists refer to this as "infra-marginal" utility), which means that there is a "monetisation frontier", i.e. situations in which the methods of monetary valuation of nature are no longer valid.

2.2 Social-Ecological Systems (SES) frameworks

The SES framework is based on the concept of explicitly coupling the dynamics of ecological and social systems and can be applied to address resilience by analysing how ecological and social processes interact at different spatial and temporal scales (Folke, 2006). This approach can be used to develop policy-relevant scenarios based on an in-depth empirical understanding from both the natural and the social sciences, thereby contributing to adaptive stewardship of CSESs (Österblom et al., 2013). This is particularly relevant as many problems in natural resource management stem from not recognising the dynamics and inextricable link between ecosystems and social systems[15].

SESs are considered complex adaptive systems i.e. they are capable of self-organisation, continual adaptation, composed of a large number of interacting components each with complex behaviour changing in space (spatial thresholds) and time (time thresholds), have non-linear and unpredictable dynamics, exhibit feedback between social and ecological processes, and have the impossibility to extrapolate information from one SES to another (Delgado-Serrano et al., 2015). Resilience, along with transformability, adaptability and vulnerability, are critical properties of SESs that govern their dynamics and future trajectories, and these properties should be considered in combination (Walker et al., 2004). Transformability is the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system unable to persist. Adaptability is the capacity of actors in a SES to influence resilience (i.e. to manage it), while vulnerability refers to exposure to, sensitivity to, and ability to adapt to disturbances (Villasante et al., 2022a). The many characteristics of complex SESs need to be considered before addressing resilience and dealing with these characteristics simultaneously is very challenging. This is why different representations of SESs have been proposed. For example, (Binder et al., 2013) identified up to 10 SES frameworks, which include the DPSIR and the Ecosystem Services frameworks described in sections 2.3 and 2.5, and the adaptive cycles concept and Ostrom framework described in this section are also SES frameworks.

The adaptive cycles theory can best be used to understand biophysical processes (Gunderson & Holling, 2002), while the Ostrom framework is best suited to social, political and governance processes (Ostrom, 2009). For coastal management, Ostrom's SES framework has been used in the Baltic Sea to identify social-ecological actions, such as responding to reduced cod availability by changing investment in fishing fleets or time spent fishing, which may have caused the ecological regime shift (i.e. drastic changes in the structure and functioning of ecosystems caused by amplified feedbacks) leading to the cod fishery collapse (Schlüter et al., 2019), while the adaptive cycle theory has been used to investigate regime shifts in the central Baltic Sea, with implications for environmental legislation i.e. setting targets for restoration (Tomczak et al., 2022). An example of the use of both the SES approach and adaptive cycles to understand regime shifts and investigate resilience of a CSES in the German part of the Baltic Sea to the installation of offshore wind farms (Burkhard & Gee, 2012). It was found that the trajectory of the system was dependent on social willingness to change and internal socio-political shifts.


Credit: Dugornay Olivier (CC BY 4.0)

The production crisis and re-organisation of the oyster farming industry in France is an example of adaptive cycles of coastal social-ecological systems.

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[15] https://whatisresilience.org/wp-content/uploads/2016/04/What_is_resilience_ENG_aktiv.pdf

2.2.1 Adaptive cycles and panarchy

The adaptive cycles concept provides opportunities for the sustainable management of SESs, through better understanding of the behaviour of the system and by estimating and tracking the position of the system within the adaptive cycle, in order to plan effective and adaptive interventions (Castell & Schrenk, 2020). The adaptive cycles concept explains the natural dynamics of change over time, and can help understand the complex adaptive systems of SESs, including Coastal Social-Ecological Systems (CSESs). This theory assumes that adaptive systems cycle through four phases: rapid growth due to the exploitation of resources, conservation of resources, release of resources, and reorganisation (Gunderson & Holling, 2002; Figure 2.1). Systems tend to spend most time in the exploitation phase, in which there is an accumulation of resources and the multiplication of relationships. The conservation phase is often referred to as the equilibrium state into which the system settles until it is disrupted. As the system moves from exploitation to conservation, the potential (i.e. the range of possible future responses) and connectedness (i.e. relationships between the elements) of the system increases. However, resilience shrinks as the high connectedness amongst system elements makes the system vulnerable to cascading disturbances. This is when a system reaches its tipping point (i.e. the critical point at which a transition to a new state is triggered). The release phase is characterised by the rapid release of accumulated resources due to disturbances such as extreme or accidental events, or human-induced changes such as over-exploitation or commercial collapse. This is followed by the reorganisation phase and a new phase of exploitation.

An example of adaptive cycles of a CSES is the oyster farming industry in France. Its development was made possible by the mastery of larvae collection. Young oysters were placed in oyster growing beds in coastal areas where their living biomass increased. This attracted new producers, and created more and more complex supply chains, including the use of oysters from different production basins, corresponding to the multiplication of socio-economic relationships. However, both the attractiveness of the activity, which stimulated overexploitation, and the openness of the supply chains, which exposed the industry to diseases or invasive species, lead to production crises (e.g. in the early 19th century). These crises correspond to the “release” phase and were followed by re-organisation phases, during which oyster production started again with new species, new techniques and changes in the political support of the industry and the sociological profile of producers (Mariojouls & Prou, 2015).

SESs and their adaptive cycles occur within a broader system of systems known as panarchy. This is the hierarchical set of adaptive cycles of SESs and emphasises the role of processes and scale, and the interlinkages between different adaptive cycles. Interactions and adaptation can occur across all scales, i.e. top-down driven by changes in large-scale SESs (e.g. an entire nation), or bottom-up driven by changes in small-scale SESs (e.g. a fishing community) (Gunderson & Holling, 2002). The alternative stable states of an ecosystem is an example of an adaptive system that periodically flips from one state to another, influenced by other SESs (see section 3.3).

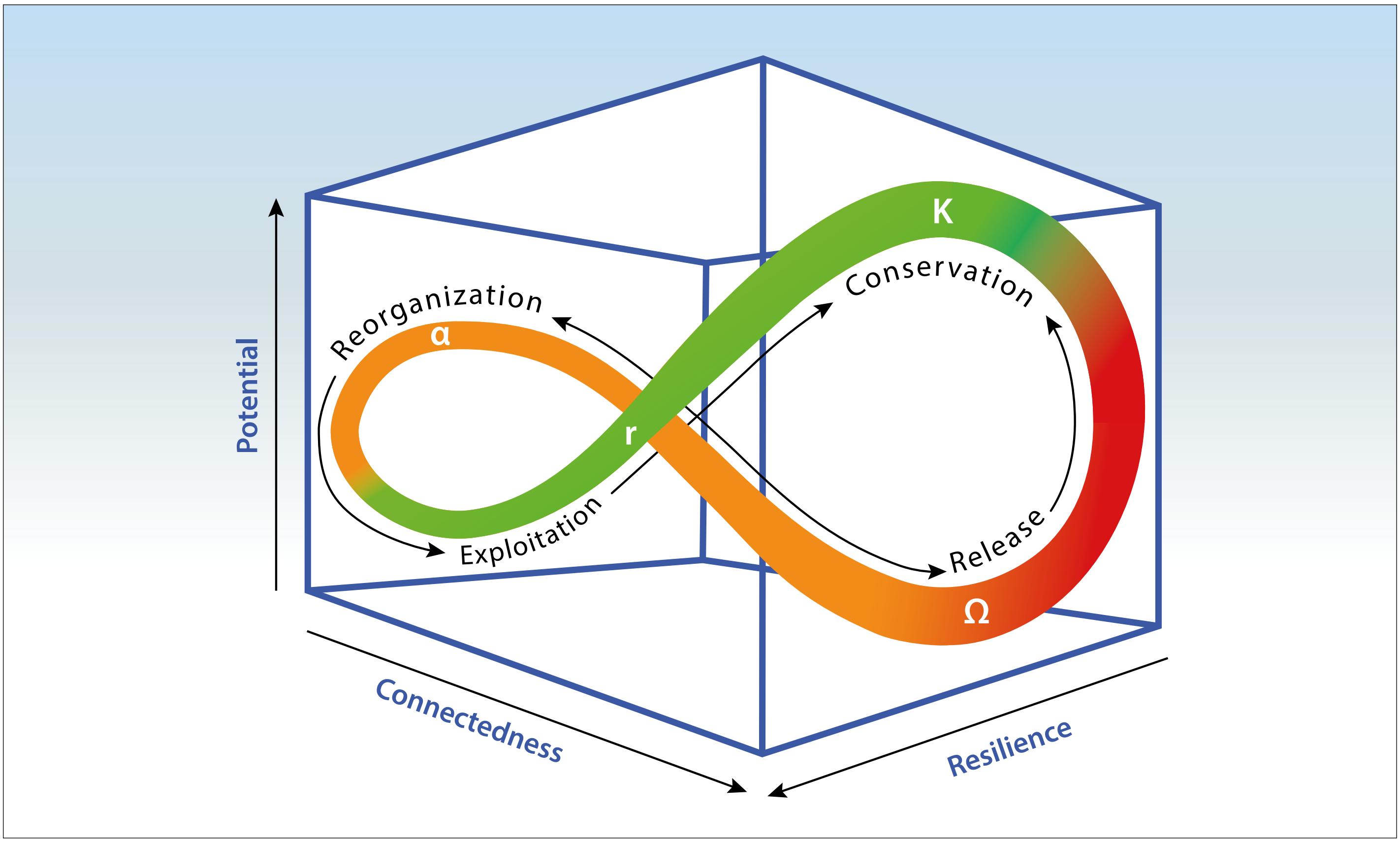


Figure 2.1 Gunderson and Holling’s adaptive cycles within a SES, according to its potential, internal level of connectedness and resilience. The four phases of a complex adaptive cycle are shown: exploitation (r), conservation (k), release (Ω) and reorganisation (α).

Credit: Adapted from Castell & Schrenk, 2020 (CC BY 4.0)

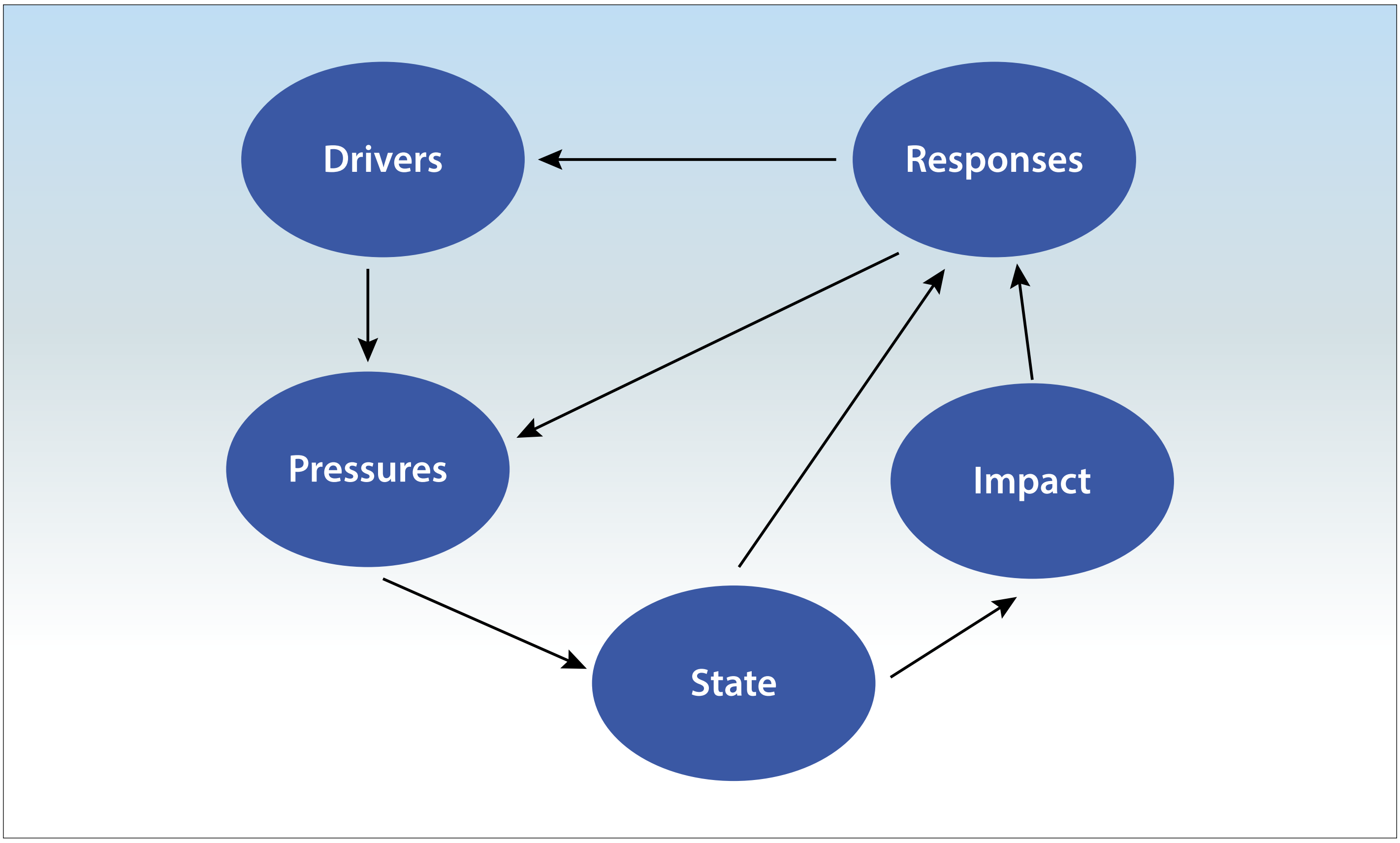
2.2.2 Ostrom framework

A framework particularly suitable for coastal zones is the Ostrom framework (Ostrom, 2005; Ostrom, 2009). It originated in social science and focuses on the governance factors that enable collective action to ensure sustainable use of local resources. These governance factors relate to: the ability to designate legitimate resource users and exclude others and to separate the managed resource from other resources; the inclusivity in determining usage rules; how suitable the rules are to the context; the degree and way rules are monitored and enforced; how the benefits generated by the resource are distributed; the recognition of rights; and the recognition as to how the resource system is nested within other systems (Ostrom, 1990). This framework was originally suitable for natural common-pool resources, like water and fisheries, used by well-identified social groups. However, it can also be applied to broader issues, applying lessons from various social science topics, for instance governance and institutional dynamics (Biesbroek et al., 2017), social relationships (Nkhata et al., 2008), social learning (de Kraker, 2017), and finally cultural and community resilience (Faulkner et al., 2018) and the factors of adaptive capacity which are required to enhance social resilience (Cinner & Barnes, 2019; see section 4.1.1).

2.3 The Driver-Pressure-State-Impact-Response (DPSIR) framework

The DPSIR framework (Figure 2.2) has been developed to help structure complex environmental problems and connect conceptual exploration across social and natural sciences. It started as a simple stress-response model in the 1970's and was later adapted to the Pressure–State–Response model (OECD, 1993), and the European Environment Agency (EEA) added Drivers and Impacts to clarify the cause–effect relationships between human and natural systems and to assist in assessing progress towards sustainable development (Lewison et al., 2016). The categories of the DPSIR framework are defined as (Gabrielsen & Bosch, 2003):

- **Driving forces,** which describe social, demographic and economic developments and the corresponding lifestyle changes, levels of consumption, and production patterns;
- **Pressure indicators,** which describe the mechanisms of state change, or the 'cause of the problem' resulting from anthropogenic activities e.g. the use of resources and land by human activities, or the release of substances (e.g. emissions), physical or biological agents;
- **State indicators,** which describe the quantity and quality of physical phenomena (e.g. temperature), biological phenomena (e.g. fish stocks) and chemical phenomena (e.g. atmospheric CO_2 concentrations) in an area;
- **Impacts,** which are produced by changes in the state of the SES and affect the functioning of the environment, such as human and ecosystem health, resource availability, loss of manufactured capital, and biodiversity; and
- **Responses,** which are the actions taken by society (groups or individuals) and government to prevent, compensate for, improve or adapt to changes in the environment to mitigate impacts.



Source: Adapted from European Environment Agency, 1997 (CC BY 4.0)

Figure 2.2 The DPSIR Framework.

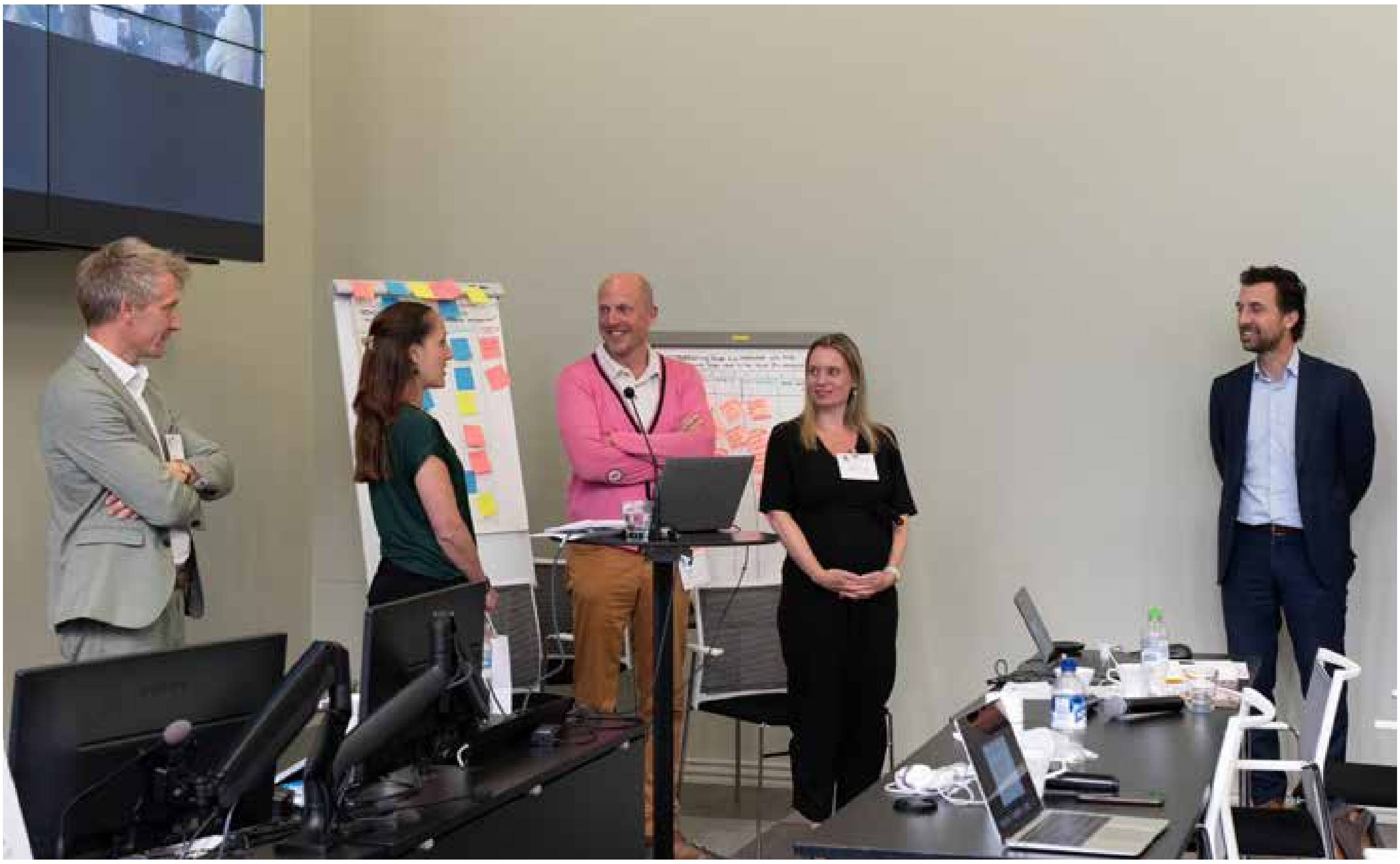
The causal links start with driving forces, pass through pressures to the state of the environment and impacts on ecosystem functions and human wellbeing, while responses can apply to all four other categories (Smeets & Weterings, 1999). Discrepancies in categorisation can occur, as it depends on the issue at stake and the scale of the analysis: each human activity (i.e. aquaculture or urbanisation) can be either a driver or a pressure, and environmental problems such as eutrophication (i.e. the process of nutrient enrichment of water bodies) can be seen either as a state or an impact.

The DPSIR framework has been widely used in coastal zone management to depict cause-effect relationships, as a problem structuring method (Elliott et al., 2017), to design sustainability indicators and to design forecasting models (Patrício et al., 2016). It can be combined with other frameworks, like spatial approaches or Ecosystem Service Assessments (Gari et al., 2015), and can be an efficient tool to organise sophisticated empirical scientific research and transdisciplinary knowledge at a level appropriate for developing understanding about coastal SESs (Lewison et al., 2016). The DPSIR framework is useful in an operational decision context, as it can cope with uncertainty and knowledge gaps if there is a lack of scientific evidence, to demonstrate causal relationships between all its categories. It emphasises the necessity to consider social dynamics, environmental issues and management solutions in an integrated way through a problem-oriented approach. Key lessons learnt from the application of the DPSIR framework to marine and coastal management include the need for nested models to assess links between pressures and state (Patrício et al., 2016). See section 5.2 for a case-study on the Venice Lagoon Coastal System in which the DPSIR framework was used for investigating changes in the Lagoon.

More recently, the Drivers, Exchanges, State of the environment, Consequences and Responses (DESCR) framework has been proposed as a variant of the DPSIR framework. This framework considers the interrelationships between the natural systems and the forces of change that alter the performance of the natural environment, in order to provide an overview of actions that may reduce negative consequences (Chacón Abarca et al., 2021). Instead of analysing pressures as in the DPSIR framework, the bidirectional exchanges of fluxes of matter and energy with the environment are considered simultaneously, evaluating their natural dynamics and connectivity.

2.4 Integrated Coastal Zone Management (ICZM)

ICZM is a dynamic, multidisciplinary and iterative approach that promotes sustainable management of coastal zones. It aims to balance environmental, economic, social, cultural and recreational objectives, while remaining within the limits of the ecological system. It also aims to integrate these objectives with the instruments needed to meet them; all relevant policy areas, sectors, and levels of administration; and terrestrial and marine components in time and space. In practice, ICZM requires the collaboration of all coastal zone stakeholders in the conception and implementation of a development model of mutual interest (COM/2000/0547 final, 2000).



Credit: Allahyar Valiyev (CoP meeting on sustainable Blue Economy of the eMSP NBSR project)

Integrated Coastal Zone Management (ICZM) requires the collaboration of all coastal zone stakeholders in the conception and implementation of a development model of mutual interest.

ICZM was formalised in Chapter 17 of "Agenda 21[16]", adopted in 1992 following the Rio Conference, which recognised the cascading effects of terrestrial pollution on coastal areas and the need for a holistic approach to protection. ICZM can be used to plan multi-sectoral development, provided that the approved mix of uses and economic activities would generate the smallest amount of foreseeable harm to the environment in order to balance development and environmental protection. To achieve such a multi-objective policy requires a five-stage approach, based on scientific knowledge at every stage (GESAMP, 1996). The first stage is to define the context within which ICZM will be implemented, which requires rapid assessments using available data and prioritising concerns. The second stage is planning, during which all possible actions should be considered, alternative options tested and knowledge on the structures and processes that regulate the coastal ecosystem used to guide decision-making and compliance. The third stage seeks institutional acceptance and funding of the ICZM plan with stakeholder participation in a political negotiation process, which may necessitate several cycles. The fourth stage corresponds to the operational implementation of the ICZM plan and includes monitoring to ensure that the effect of the plan can be evaluated. The fifth stage is dedicated to evaluation and to the search for ever more sustainable regulations for coastal development that will ensure that the whole ICZM protocol is revised in a new cycle.

ICZM was proposed as an EU legal requirement in the first proposal for a Directive for MSP and integrated coastal management (COM/2013/0133 final, 2013). However, the integrated coastal management element was dropped from the proposed Directive during the negotiation process. The agreed Directive on MSP requires Member States to draw up maritime spatial plans, but only mentions ICZM as one of the "formal or informal processes" that will allow the land-sea interface to be considered, and the extent to which the MSP Directive currently covers inland coastal regions is minimal. Integrated management practices have two major difficulties: 1) many coastal zone resilience problems originate from land (i.e. watershed pollution or urban growth) so management solutions concern land as much as marine management bodies, and 2) better integration of the objectives and practices of land and marine management bodies can only be obtained with a Directive or a Decree to enforce this approach. In practice, ICZM requires long-term investment in local management involving stakeholders from both land and sea.

In Europe, ICZM currently takes place predominantly at a local level including agency-led initiatives, bottom-up approaches, local pilot projects and local government involvement (O'Hagan & Ballinger, 2010). For instance, the French government launched 25 ICZM pilot projects in 2005 that addressed environmental issues and user conflicts through an inter-municipal planning approach based on territorial cohesion schemes or urban master plans (Deboudt, 2012). In the Thau Lagoon (South of France), a local management agency was created in order to implement both the territorial cohesion scheme and the Water Law aimed at addressing the objectives of the Water Framework Directive. This ICZM approach, which attempts to reconcile environment preservation, maintenance of traditional activities like fisheries and shellfish farming, the support of growing economic sectors like tourism and the development of new recreational activities, is still in force today (Derolez et al., 2023).

2.5 Ecosystem Service Assessment (ESA) framework

Ecosystem services (see Box 1 in Chapter 1 for definition) describe, in a systematic way, the links between an ecosystem and the society that it depends on. Ecosystem services provide benefits to human societies, who attribute a value to the contribution of these services to human wellbeing. The ESA framework argues for the conservation of ecosystems and biodiversity and was popularised through the UN's Millennium Ecosystem Assessment in 2005. Its conceptual framework links ecosystem functions with the services they provide and the resulting contributions to human wellbeing (Gómez-Baggethun et al., 2010). The Economics of Ecosystem Services and Biodiversity (TEEB[17]) initiative complemented this framework with the role of institutions and proposed an agenda to operationalise the ecosystem services approach.

TEEB advocates a three-step approach to operationalise ESA (Braat & de Groot, 2012): 1) identify and characterise ecosystem services and assess the capacity of ecosystems to provide them; 2) value ecosystem services first in biophysical units and then in monetary units; and 3) use these values to develop new management instruments, which can enhance the resilience of SESs. However, monetary valuations are not feasible for all services and even not desirable in some cases. Some ecosystem services are valuable for their own sake and not for any benefits they deliver and therefore have intrinsic values (Austen et al., 2019). Most ecosystem services should be considered irreplaceable and therefore not equal (Hueting et al., 1998). Thus, applying only monetary valuation methods is ethically problematic and misleading (Austen et al., 2019). In practice, monetary valuation of ecosystem services is often used to implement cost-benefit analyses of management options, but these should not be used to make trade-offs in situations where ecosystems represent a source of complex non-instrumental values for society. Alternative valuation methods, without monetisation, such as multi-criteria analysis, integrated valuation or participatory multi-criteria analysis (Gómez-Baggethun & Martín-López, 2015; Austen et al., 2019) are better suited for this type of valuation.

Other approaches that can be used to assess ecosystem services include biophysical indicators and their mapping, which can be used regionally or nationally, or experts producing relevant semi-quantitative assessments through scoring at local scales. Biophysical approaches to ecosystem services are more likely to consider connectivity between ecosystems and the impacts this has on the provision of services. The ESA approach is thus useful for organising debates about the trade-offs between different uses, practices or management options in the coastal zone. Marine and coastal ESA assessments have been used to: 1) address multiple policy objectives simultaneously; 2) interpret EU-wide policies to smaller scales; and 3) inform local decision-making (Drakou et al., 2016).

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[16] https://sdgs.un.org/publications/agenda21

[17] https://teebweb.org/

Credit: Sheila Heymans

Vegetated dunes contribute to coastal protection as an ecosystem service.

The most global use of the ESA approach is by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES[18]). IPBES implements a demand-driven approach to provide international, regional and local decision-makers with the most accurate science-based information on biodiversity, ecosystem services, and more globally, nature's contributions to people and the diverse values and valuation of nature including non-monetary value such as sense of belonging or cultural heritage (IPBES, 2022). Nature's contributions to people represents an evolution of the concept of ecosystem services with a more inclusive and diverse interpretation of human-nature relations, reflecting the increasing involvement of social sciences, humanities and other knowledge systems (e.g. Indigenous peoples and local communities) in global environmental science-policy interfaces (Díaz et al., 2018).

In the coastal zone, the ESA approach emphasises the services of coastal protection, which includes limiting erosion and the protection against extreme events such as storms and tsunamis. The supply potential of these services is concentrated in seagrass beds, kelp forests, offshore reefs, mussel beds, beaches, dunes, salt marshes and lagoons. The social importance of these kinds of service calls for the use of Nature-based Solutions (NbS). However, most of the services provided by coastal ecosystems have no monetary value, which is why ecosystem service assessment should focus on multidisciplinary and multi-criteria approaches providing biophysical as well as social indicators.

SESs that provide a wide range of diversified services are more likely to be resilient. Identifying the services delivered by coastal ecosystems and demonstrating their multiple values highlights the dependency of coastal communities on their natural capital. The perception of the contribution of ecosystem services to wellbeing, and the sustainability of their use, can create institutional changes to modify the way ecosystem services are used, or to restore or protect ecosystems (Braat & de Groot, 2012). The ESA framework has been applied in practice to assess services supplied by the Venice Lagoon (see case-study in section 5.2.) from environmental, economic and social perspectives (D'Alpaos & D'Alpaos, 2021), and in relation to the human activities which allow for the provision of ecosystem services and the management strategies that ensure their maintenance (Rova & Pranovi, 2017). For more on marine ecosystem services evaluation methodologies and recommendations see Austen et al. (2019).

2.6 Risk, Vulnerability and Adaptive capacity (RVA)

An efficient operational way to represent a SES is to focus on risks, vulnerability and the adaptive capacity that may impair or reinforce its resilience. This reduces the complexity of the SES analysis by searching for those components that can or should be managed, namely the pressures that need to be reduced and the enablers of positive feedback that should be increased. In some cases, responses to risks must also be considered in adaptive management, as these responses can have unexpected effects and even increase the risks they were intended to reduce (Simpson et al., 2021). Vulnerability involves both the ecological and social components of SESs. In

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[18] https://ipbes.net/

general, vulnerability is defined as the result of the exposure to a risk combined with the sensitivity to the risk (both of which increase vulnerability) and adaptive capacity (which reduces vulnerability) (Adger, 2006). While the risk can be estimated through global statistical analyses, sensitivity is specific to each component of the social-ecological system, depending on its own features and also its preferences when humans are concerned. Nevertheless, managing vulnerability ensures resilience by reversing the problem of searching for resilience in SESs. From this perspective, resilience can be replaced by the more operational target of minimising exposure to risk and strengthening capacity to adapt in order to reduce the vulnerability of SESs.

Sea-level rise, extreme events and issues relating to human safety are typical problems which call for an adaptive management approach to vulnerability. The adaptive management approach is also suitable to address chronic events that modify SESs in the long-run and can exceed tipping points (i.e. a threshold after which a system rapidly changes its state). Adaptive management was first envisaged by Holling in 1978 as a way to manage complex SESs. The adaptive management approach consists of: “adaptive policymaking”, which provides a stepwise approach for developing a basic plan and contingency planning to adapt to new information over time; and/or “adaptation pathways”, which provide insight into how to sequence actions over time, potential lock-ins (i.e. limited openness to change and the use of sub-optimal policies even though better alternatives are present), and path dependencies (i.e. basing outcomes on previous decisions, habits and actions) (Haasnoot et al., 2013). Adaptive management has been extensively used to cope with flood risk in coastal zones (Bednar-Freidl et al., 2022), including in developing recommended strategies such as retreat of human communities (Haasnoot et al., 2021). Adaptive management aims to achieve the highest societal benefit while minimising conflicts and is needed in the coastal zone (Schupp et al., 2019). It helps to take deep uncertainty (i.e. uncertainty for which probability and possible outcomes are unknown or not agreed upon by experts) into account in planning decisions and suggests that planners should create a strategic vision for the future, commit to short-term actions, and establish a framework to guide future actions. As long as deep uncertainty remains, increased frequency and/or larger increments of a step-wise approach to adaptation measures are recommended. Adaptive policy-making should guarantee that the policy process will adapt in line with changes in the SES to be managed e.g. when new circumstances or new knowledge arise. Examples include the 2013 reform of the EU Common Fisheries Policy (Regulation EU 1380/2013, 2013), the current revision of the MSFD, and the MSP Directive which includes constant monitoring and evaluation (Schupp et al., 2019). However, Directives are not always able to adapt at the same pace as ecosystem change. The policy cycle of assessment and reform can take up to 10 years or more, while changes in ecosystems could happen from one year to the next. The adaptation pathway approach is particularly well-suited for capturing various stakeholder perspectives and therefore the complexity of resilience issues for coastal communities (Townend et al., 2021). As an example, the Netherlands has adopted an adaptive pathway plan to be able to deal with deep uncertainty in ice mass-loss from Antarctica that may have high-impact, low-likelihood scenarios of sea-level rise (Haasnoot et al., 2020) and therefore for coastal inundation. Another practical example of the use of adaptive management for the Belgian coast is described in section 5.3.

Credit: Matt Palmer (Unsplash)

The Netherlands has adopted an adaptive pathway plan to be able to deal with deep uncertainty in ice mass-loss from Antarctica that may have high-impact, low-likelihood scenarios of sea-level rise.

The risk management approach relies on risk analysis, which consists of characterising the threats, vulnerabilities and consequences of adverse events to determine the expected loss of critical functionality. Risk analysis and risk management based on probabilistic quantitative methods (i.e. methods that estimate the likelihood that a given risk will occur) have been widely adopted for dealing with foreseeable and calculable stress situations (Linkov et al., 2014). In the coastal zone, risk management has often been used to address sea-level rise and flooding. The standard approach against flood risk is to control flood threats with infrastructure, and behaviour with laws and regulations. These are known as resistance-based strategies and aim to remove, as far as possible, the threat of extreme variations and to minimise the potential for adverse impacts on society (Morrison et al., 2018). The focus on risk management implies a narrower definition of resilience, which could be seen as “the stability near an equilibrium steady state, where resistance to disturbance and speed of return to the equilibrium are used to measure the property” (Gunderson & Holling, 2002). However, in practice much is known about how an ecosystem or man-made structure responds to an extreme event, but much less is known about how these systems recover over time and space. This favours engineering strategies when risk determination can be done based on *a priori* evidence of earlier hazards and associated damages (Smith & Fischbacher, 2009), such as building a dyke based on likelihood of future storm occurrence. However, in isolation this approach fails to cope efficiently with uncertainty and the diversity of risks perceived by coastal communities. Most risk management frameworks consider a single hazard type, while community resilience is inherently multidimensional (Almutairi et al., 2020). For this reason, risk management and vulnerability approaches need to be enhanced with adaptive management (Morrison et al., 2017), which can cope with unpredictable natural hazards or unexpected results of the interactions between ecosystems and humans (Adger, 2006).

2.7 Climate Resilient Pathways (CRP) framework

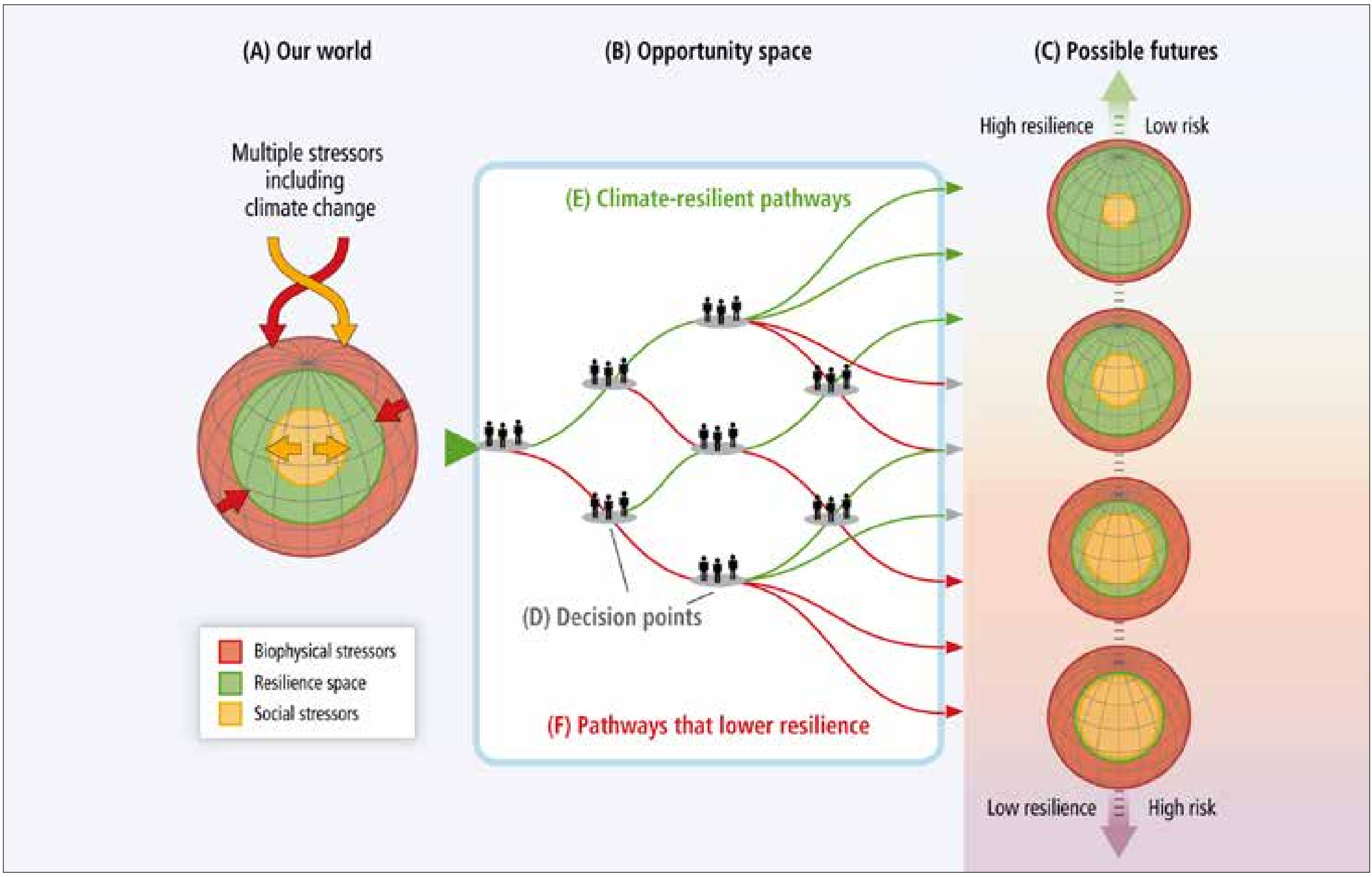
As part of the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Denton et al. (2015) reviewed the transformational changes (e.g. human institutions; technological and biological systems; social processes) required for climate-resilient pathways for society to achieve sustainable development, stressing the urgent need to act now rather than postponing responses. They stated that “the pursuit of climate-resilient pathways involves identifying vulnerabilities to climate change impacts; assessing opportunities for reducing risks; and taking actions that are consistent with the goals of sustainable development". They emphasised the role of society and our capacity to manage risk and to decrease vulnerability through mitigation, adaptation and decision-making. They also proposed that developing resilient pathways could provide iterative, continually evolving processes for managing change within complex, multi-faceted systems to contribute to the goal of sustainable development. Resilience is described as a journey or a process, with an opportunity space where decisions can be made for different climate-resilient pathways (Figure 2.3). Enabling conditions for climate resilient development pathways are described in Chapter 18 of the IPCC report on impacts, adaptation and vulnerability (IPCC, 2022b).

The climate resilient pathways framework can be used to help coastal communities understand the pathway to their current situation, how it relates to the resilience of the SES of which they are a part, what future resilience would look like, and what decisions they would need to make to achieve a resilient system in the future (Farrell et al., 2023). Through an adaptation of the IPCC opportunity space (i.e. decision points and pathways that lead to a range of possible futures; see Figure 2.3) and climate resilient pathways approach, the “Building Coastal and Marine Resilience in Ireland” project in Ireland (see the Maharees Peninsula Case Study, section 5.1) demonstrated a collaborative framework for coastal communities to engage in a process for enhancing their resilience and to identify barriers to their participation in climate actions. The framework supports engagement and discussion with and between stakeholders so they can analyse decisions made (or not made) and the pathways that have led to more (or less) climate resilient states. This is useful to scrutinise mistakes that were made or opportunities that were missed, as well as actions that proved decisive and beneficial (Farrell et al., 2023). The pathways approach can lead to roadmaps to build the capacity of local SESs by providing a structure to discuss knowledge gaps in coastal science, policy, governance and management, and to place these in the context of a process and decisions required to enhance local-scale resilience.

2.8 Community Resilience (CR) frameworks

Extensive research has been conducted to understand what constitutes “resilient” communities, i.e. those that have the adaptive capacity to respond to climate and socio-economic challenges. Although there is no universally accepted model or framework for the assessment of “resilience”, a number of community resilience frameworks relate specifically to coastal areas including, but not limited to, Coastal Community Resilience (Courtney et al., 2007); the Coastal Community Hazard Protection Resilience index (Ewing, 2015); the Rural Coastal Community Resilience Framework (Jurjonas & Seekamp, 2018); and the Community Resilience Index[19]. Patel et al. (2017) found that the term “community resilience” remains a fluid concept that is understood and applied differently and identified nine core elements that are widely proposed as important for community resilience: 1) local knowledge, 2) community networks and relationships, 3) communication, 4) health, 5) governance and leadership, 6) resources, 7) economic investment, 8) preparedness, and 9) mental outlook.

These frameworks facilitate coordination and discourse to organise the actions of people, who fall into different groups, some with shared interests and others with independent or conflicting interests. Community resilience frameworks are very useful to assess what structures or processes facilitate action by different actors (individual, household, social group, community, national) and, equally, the circumstances that might impede action. These frameworks can be used to understand the enablers and barriers to actions that might enhance or reduce resilience along the coast (see Chapter 4) while understanding that any case-study will have its own regional context with specific stakeholders.



Source: European Environment Agency, 1997 (CC BY 4.0)

Figure 2.3 Opportunity space and climate-resilient pathways. (A) Our world is threatened by multiple stressors that impinge on resilience from many directions, represented here as biophysical and social stressors, such as climate change, climate variability, land use change, degradation of ecosystems, poverty and inequality, and cultural factors. (B) Opportunity space refers to decision points and pathways that lead to a range of (C) possible futures with differing levels of resilience and risk. (D) Decision points result in actions or failures-to-act throughout the opportunity space, and together they constitute the process of managing or failing to manage risks related to climate change. (E) Climate resilient pathways (in green) within the opportunity space lead to a more resilient world through adaptive learning, increasing scientific knowledge, effective adaptation and mitigation measures, and other choices that reduce risks. (F) Pathways that lower resilience (in red) can involve insufficient mitigation, maladaptation, failure to learn and use knowledge, and they can be irreversible in terms of possible futures (IPCC, 2014).

Credit: Allahyar Valiyev (CoP meeting on sustainable Blue Economy of the eMSP NBSR project)

Community resilience frameworks help to facilitate coordination and discourse to organise the actions of people.

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[19] https://cdrp.jibc.ca/resources/hazard-and-resiliency-tools-resources/community-resilience-index-cri/

2.9 How does one frame resilience issues in the coastal zone?

Resilience of exisiting CSES states can be described as a "wicked problem" i.e one that is difficult or impossible to solve because of its complex and interconnected nature. This makes consensus building more difficult across divergent views about the nature of the issues, their relative importance and appropriate responses. An “issue” within this context is a topic that matters for people. For instance, exposure of people to risk, the degradation of water quality or the inefficiency of conservation measures. This acts as a “social warning” indicating that people feel that a CSES is vulnerable, suggesting that conditions for resilience are not fulfilled. It also shows that key stakeholders’ viewpoints are anchored in different assumptions, values, interests and capacities. While some problems are relatively well-defined and well-structured, with agreed technical parameters and a solid knowledge base, this is not the case for wicked problems, which are typically less structured or “ill-structured” (Head, 2019). Framing, or the way a complex reality is selected, organised or interpreted to provide guidelines on how to act or analyse (Rein & Schön, 1996), is then needed to deal with wicked problems. The way the problem is framed in terms of content (problem definition) and process (social debates regarding the issues at stake) is crucial as it will strongly influence the analytical frameworks that will be used and the solutions that may be envisaged. In certain circumstances, the framing process can be driven by some stakeholders at the expense of others. For instance, interests from the agricultural industry contributed to framing the Water Framework Directive to ensure that water quality issues were dominant and issues of water access and supply were minimised (Morrison et al., 2019).

The lack of resilience of many CSESs is a wicked problem because resilience issues are complex. Resilience involves often unpredictable dynamics of complex CSESs and arises from interacting ecological, economic and social characteristics. To reduce complexity, it is useful to identify the major issue affecting coastal resilience, and then to identify secondary issues. Further explanation of the links between resilience issues and their causes are explained in Chapter 3, however, general issues that affect coastal resilience include:

- Ecological issues, including natural resource overexploitation, ecosystem disturbance and environmental damage, such as accidental spills or pollution, in a context of increasing and interacting human pressures;
- Hazards and risk issues, encompassing exposure of the coasts and its inhabitants to floods, sea-level rise and extreme events in the context of climate change;
- Economic development issues, including the needs for economic growth, job creation and business’ viability in the context of growing environmental pressures impacting human activities;
- Social issues concerning equity, community cohesion, and the preservation of social heritage including traditional activities. Equity may be endangered when access to resources or nature is constrained or limited. Cohesion and heritage are at threat when the dynamic of the whole SES leads to (ecological or economic) regime shifts, which may affect people’s values; and
- Management issues relating to the ability of coastal governance to ensure ecological and social resilience in a context of incomplete knowledge and to design efficient solutions when there is unequal bargaining power between stakeholders with conflicting social, economic or political interests. Management issues arise when resilience problems are not considered, are incorporated into management plans but without any operational measures, or when inefficient operational measures are implemented.

Resilience is often difficult to maintain or enhance because of unpredictable changes in ecological processes and human activities, or the ineffectiveness of previously considered solutions. For this reason, performing an initial diagnosis of the problems that affect the maintainance or enhancement of resilience will enable selecting relevant components and processes of the CSES that need to be considered and the resilience framework to be used for further analysis. This initial diagnosis involves specifying the multiple issues at stake. Table 2.1. provides a summary of some selected resilience issues that could be included in such a diagnosis, the concrete pressures from which they arise (see Chapter 3 for descriptions of coastal pressures) and the possible uses of existing resilience frameworks to address each issue. Some frameworks are mainly analytical and better suited to assess the situation, provide an initial diagnosis and eventually recommend possible measures (DPSIR, ESA, SES, SD), while others are more operational and can make a more concrete contribution to improving management and governance (CR, CRP, ICZM, RVA).

Table 2.1 Selected examples of the potential uses of frameworks to address coastal resilience issues.

CATEGORY OF ISSUE AFFECTING RESILIENCE	SPECIFIC ISSUE	EXAMPLE OF POSSIBLE CAUSES OF THE ISSUE	EXAMPLES OF POSSIBLE USES OF FRAMEWORKS TO ADDRESS THE ISSUE
Ecological issues	Habitat destruction	Urbanisation Human overcrowding	ICZM[*] for land planning adaptation to coastal carrying capacity ESA[*] for enhancing public awareness
	Resource overexploitation[**]	User conflict	SES[*] for coping with user interactions and the resulting emergent properties
	Water quality	Pollution	DPSIR[*] for identifying pollution sources ESA[*] for demonstrating the diversity of services linked to water quality and for promoting Nature-based Solutions
Hazards and risks issues	Coastal erosion	Flood defence Climate change	RVA[*] for improving adaptive capacity ESA[*] for promoting Nature-based Solutions
	Sea-level rise	Inefficient flood defence Climate change	RVA[*] for identifying vulnerable areas SES[*] for assessing multi-level adaptive capacity CRP[*] for improving management effectiveness
	Extreme events (e.g. storms, flooding)	Climate change	RVA[*] for minimizing exposure to risks CRP[*] for improving capacity to cope with risks
Economic development issues	Economic growth	Attractiveness of coastal resources	SD[*] for ensuring uses compatible with the preservation of natural capital (i.e. stock of natural resources)
	Job creation or maintenance	Coastal population growth	SD[*] for ensuring the social distribution of economic growth benefits CR[*] for dealing with with the social demands for economic investments
	Business' vulnerability	Environmental constraints	RVA[*] for ensuring coastal enterprises' profitability and adaptive capacity
Social issues	Equity	Limited access to resources	SD[*] for ensuring the equitable distribution of opportunities ESA[*] for demonstrating the diversity of social demands related to coastal areas
	Social cohesion	Social transformation	RVA[*] for identifying vulnerable populations SES[*] for exploring social adaptations CR[*] for achieving social appropriation of changes
	Heritage preservation	Regime shifts	ESA[*] for understanding the diversity and importance of cultural services provided by the coasts SES[*] for demonstrating the diversity of mental representations of the coasts
Management issues	Management absence	Ignorance of resilience issue	DPSIR[*] for revealing the resilience issue and its sources
	Management failure	Inefficiency of measures	ICZM[*] to ensure coherence between land and sea management devices ESA[*] for enhancing stakeholder awareness RVA* for reducing unexpected effects and increasing efficiency of management SES[*] for exploring institutional complexity

[*] CR: Community Resilience; CRP: Climate Resilient Pathways; DPSIR: Driver-Pressure-State-Impact-Response; ESA: Ecosystem Service Assessment; ICZM: Integrated Coastal Zone Management; RVA: Risk, Vulnerability and Adaptive capacity; SES: Social-Ecological System; SD: Sustainable Development.

[**] Not only professional fisheries, which have long been managed by dedicated fisheries policies, but also a pool of natural resources used by different user categories, for instance recreational fishers or nature-watchers.

2.10 Six-step approach for enhancing coastal resilience

When facing unsustainable situations, coastal zone managers may be tempted to mobilise a ready-to-use analytical framework or institutional tool to understand and solve the problem. However, CSESs are complex systems and no one methodology will fit all situations and be able to build and enhance resilience. Instead, a pragmatic and wide spectrum approach is recommended, which draws from various sources. Thus, complexity, uncertainty and adaptation, which are at the core of the dynamics of CSESs, should be the keywords of any attempt to govern coastal systems resilience.

Based on the recommendations for implementing the SES and ICZM frameworks, we recommend the following six steps (see Figure 2.4) for practitioners to structure their approach to strategically use the frameworks described in this Chapter to work towards coastal resilience. The first two of these six steps are basic principles that are transversal and should be applied throughout the whole process. Steps three to six should then be carried out in sequence. Due to the multidimensional and dynamic aspects of resilience issues, and the complexity of the resilience frameworks, this six-step approach should be implemented by a core team of managers, experts and researchers who are trained and have experience in both the ecology and socio-economics. Over the long term this should ensure sufficient learning-by-doing experience to gradually achieve effective results.

Step 1: Conceive the management process as long-lasting and adaptive

In order to tackle “problem complexity” and “stakeholder divergence”, a holistic, problem-oriented approach is needed that is adaptive, participatory and transdisciplinary (Xiang, 2013), even if it remains difficult to achieve by public leaders and managers (Head, 2019). This requires new approaches to systems thinking (i.e. making sense of complexity by looking at interactions between parts of a system), co-production and adaptive management (Head & Alford, 2015). Managers need to operate in a long-lasting project mode, so that re-assessments, re-adjustments, adaptations and iterations can be achievable over time.

Step 2: Co-produce with stakeholders throughout the process

Stakeholders should be engaged in co-production in a fair and transparent manner throughout these six steps. Addressing coastal resilience is a social process that involves a diversity of stakeholders with various competencies and visions, including local residents, representatives of professional or citizen organisations, indigenous peoples and stakeholders who live far from the coast but who care deeply about a coastal place (also known as armchair stakeholders) (Gurney et al., 2017). Stakeholders are involved in resilience issues, either as threats, potential victims or both. Thus, stakeholders should be involved in defining the issue and system boundaries (steps three and four), and in refining the resilience issue and system representation using their knowledge. They should also be involved in the identification and choice of possible solutions (steps five and six). Techniques for involving stakeholders depend on the topic to be addressed and include meetings, focus groups and public consultations. All relevant stakeholders should be mapped to be sure that none are missed, and this should continue throughout the process. Stakeholder engagement ensures that different types of knowledge are integrated into the process and improves the social acceptability of management measures. This enhances social organisation and agency (i.e. the ability of individuals or groups of people to choose how to respond to environmental change), which are key elements enabling adaptive capacity in human communities (see section 4.1.1).

Step 3: Define the resilience issue(s) to be addressed and select framework(s) to use

Problem framing and definition influence the type of solution that is proposed (Head, 2019) and this determines the whole resilience management process. Problem framing involves choosing a core issue and sub-issues and methods such as "triage" (Pendleton et al., 2015) are useful in defining these issues. Triage is a structured decision-making approach that involves identifying the key elements by answering questions such as: What is most important to people? What is most likely to change? What enters into our management capacity? Problem definition may lead to changes in the list of stakeholders to be involved. Once the core- and sub-issues have been identified, the next step is selecting the most suitable frameworks.

Step 4: Define CSES boundaries, structure and dynamics

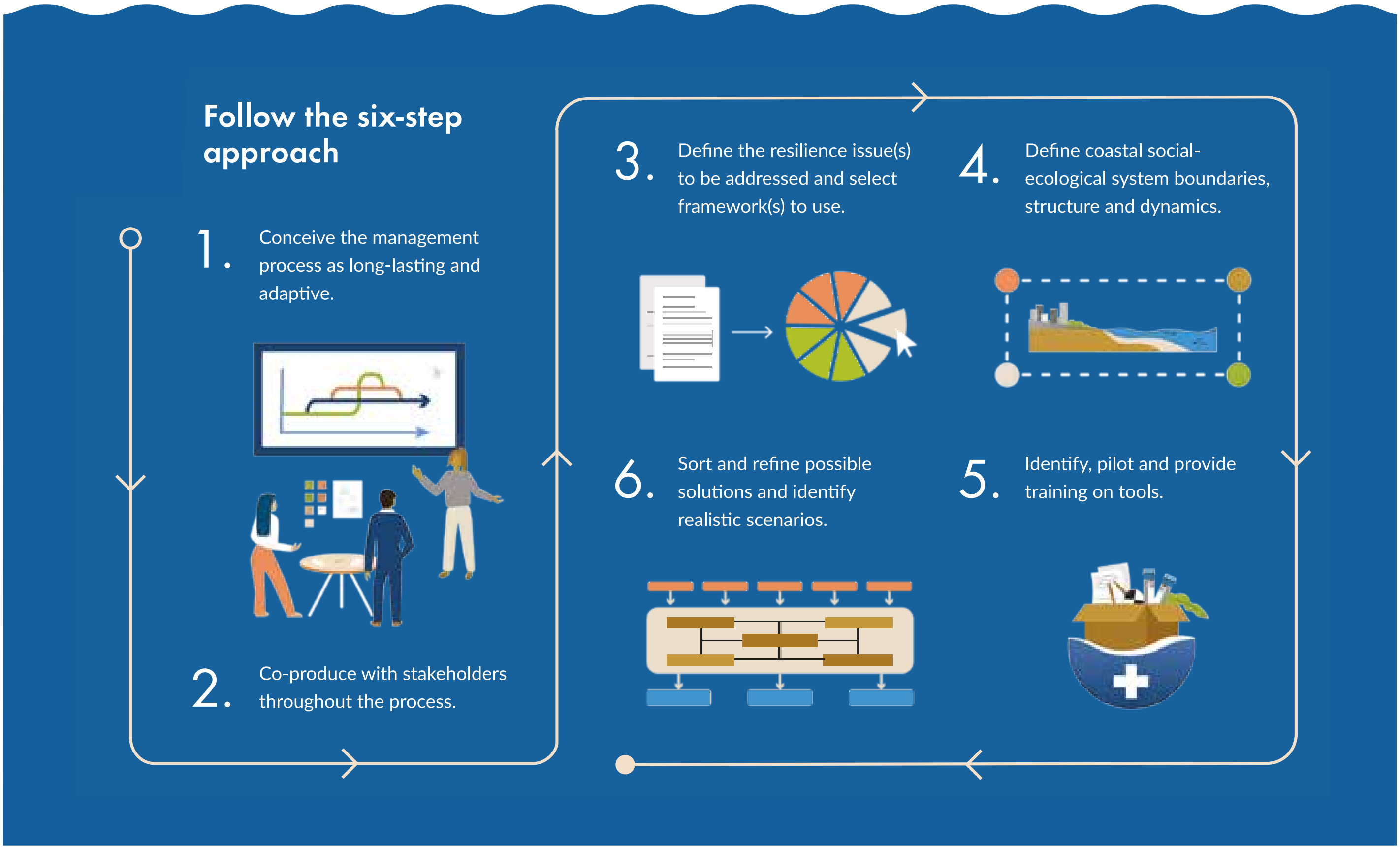
Defining the boundaries, structure and dynamics of the CSES involves identifying the manageable components and processes of the coastal resilience issue, so that the adaptive capacity of the coastal system can be reinforced. This means defining its main components which vary depending on scale; the key processes and how they vary over time; the ecological, social, geographic and economic boundaries; and interactions with external drivers. Components may consist of for example a river basin, habitats, animal and plant communities, species and their traits, individuals, local communities, groups of users, associations, administrative units or institutions. The concept of a “problemshed” (i.e. a spatial unit focused on the issues at stake) rather than a geographic boundary is useful to determine these components (Mollinga et al., 2007). Identifying the relevant key processes and components of the coastal SES requires data mining (e.g. time-series analysis to identify trends or regime shifts) and can be enhanced by numerical or qualitative models. Different time-scales may be relevant for the key processes, and resilience will be compromised if the most threatening changes occur at the fastest rate. Similarly, different spatial scales may be considered depending on the processes at stake. Coastal ecological processes may be affected by external drivers of change, while coastal management bodies generally belong to wider institutional and political systems, which may exert either constraints or incentives on local initiatives towards resilience. Identifying whether components, processes and drivers are local, regional or global will help to determine to what degree they can be managed. This step may also lead to a revision of the list of stakeholders to be involved.

Step 5: Identify, pilot and provide training on tools

Tools to build and enhance coastal resilience constitute NbS, hybrid solutions, grey infrastructure or other technical interventions, and management and policy solutions including adaptive, cross-sectoral and coherent policies, capacity-building, and public awareness (see Chapter 4). The most suitable solutions depend on the issue at stake and the characteristics of the CSES. The most efficient solutions are often a combination of different tools. For instance, a technical solution needs to be adopted by coastal populations and therefore needs to be agreed on by stakeholders and accompanied by social learning or training. Methods for identifying possible tools include technical innovations (such as new infrastructure or changes in user practices), institutional analyses to identify management failures and surveys to identify social demands and assess the conditions for social acceptability. Long-term investments in research, piloting, monitoring as well as co-production and training of key actors and the general public are also imperative.

Step 6: Sort and refine possible solutions and identify realistic scenarios

The last step is choosing the tools that will need to be implemented. Possible management options should be selected according to the following criteria: their expected efficiency for achieving resilience, their technical and financial feasibility, and their social acceptability. Engagement and buy-in of stakeholders are important to increase the acceptance of management options, which should consider the wide range of social goals that may arise from public participation. When several solutions are possible, decision trees or cost-effectiveness analyses can be used to assess or refine technical solutions. The combination of potential solutions should be assessed through scenario modelling and/or multi-criteria analysis.



Credit: Amy Dozier (CC BY-NC-ND 4.0)

Figure 2.4 Six-step approach for building coastal resilience.

3

Pressures and impacts on the coast

Credit: Alain Henaff (UBO)

Coastal areas have suffered severe ecological and social impacts due to growing human occupation, resource exploitation and human-induced climate change. Specifically, European coasts are affected by multiple pressures such as eutrophication, pollution, overexploitation of fish stocks and climate change, with impacts including sea-level rise, habitat loss and degradation (European Environment Agency, 2019). With the growth in Blue Economy activities, including emerging sectors such as renewable energy and blue biotechnology, it is increasingly important to determine to what extent these can be developed while maintaining the resilience of Coastal Social-Ecological Systems (CSESs). European coastal habitats are suffering ongoing decline despite scientific and policy efforts to reverse this trend. Many of these ecosystems are so heavily degraded that they cannot deliver valuable ecosystem services. The most recent report on the state of nature in the European Union (EU) states that only 15% of assessed European marine and terrestrial habitats have a good conservation status, with 81% having poor or bad conservation status (European Environment Agency, 2020). Grasslands, dunes, bog (i.e. freshwater wetland with wet and poorly drained peat-rice soil) and fen (i.e. peat-forming wetlands that rely on groundwater input) habitats show strong deteriorating trends, and can all be found in coastal areas. Marine habitats in general have good status reported less frequently compared to terrestrial habitats. While biodiverse and functionally intact ecosystems can absorb and buffer natural and anthropogenic disturbances, recovering the function of the ecosystem quickly, degraded ecosystems tend to show no, or only small, signs of recovery when pressures are reduced (Duarte et al., 2009).

As described in Chapter 2, the Social-Ecological System (SES) approach shows how social and ecological systems are interconnected and CSESs experience multiple pressures which can affect their resilience. In the Driver-Pressure-State-Impact-Response (DPSIR) framework, pressures are defined as *"mechanisms of change of state on the natural system, and subsequently the social system"* (see Box 1. in Introduction and section 2.3). Pressures impact ecosystem state and subsequent human wellbeing, which can erode the resilience of CSESs (Figure 3.1). Drivers include climate change, human activities, as well as social, demographic, and economic developments such as population and economic growth, and tourism.

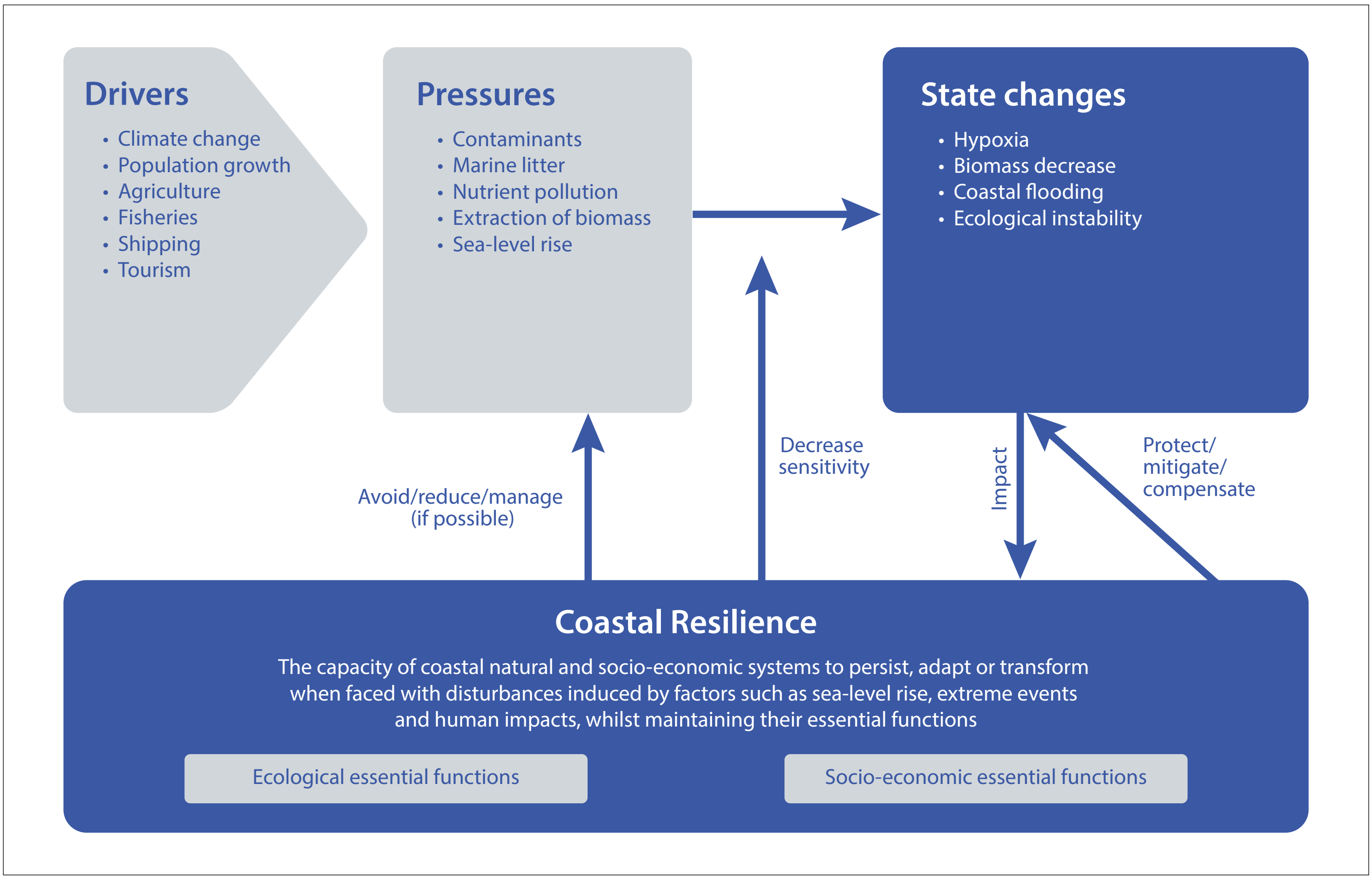
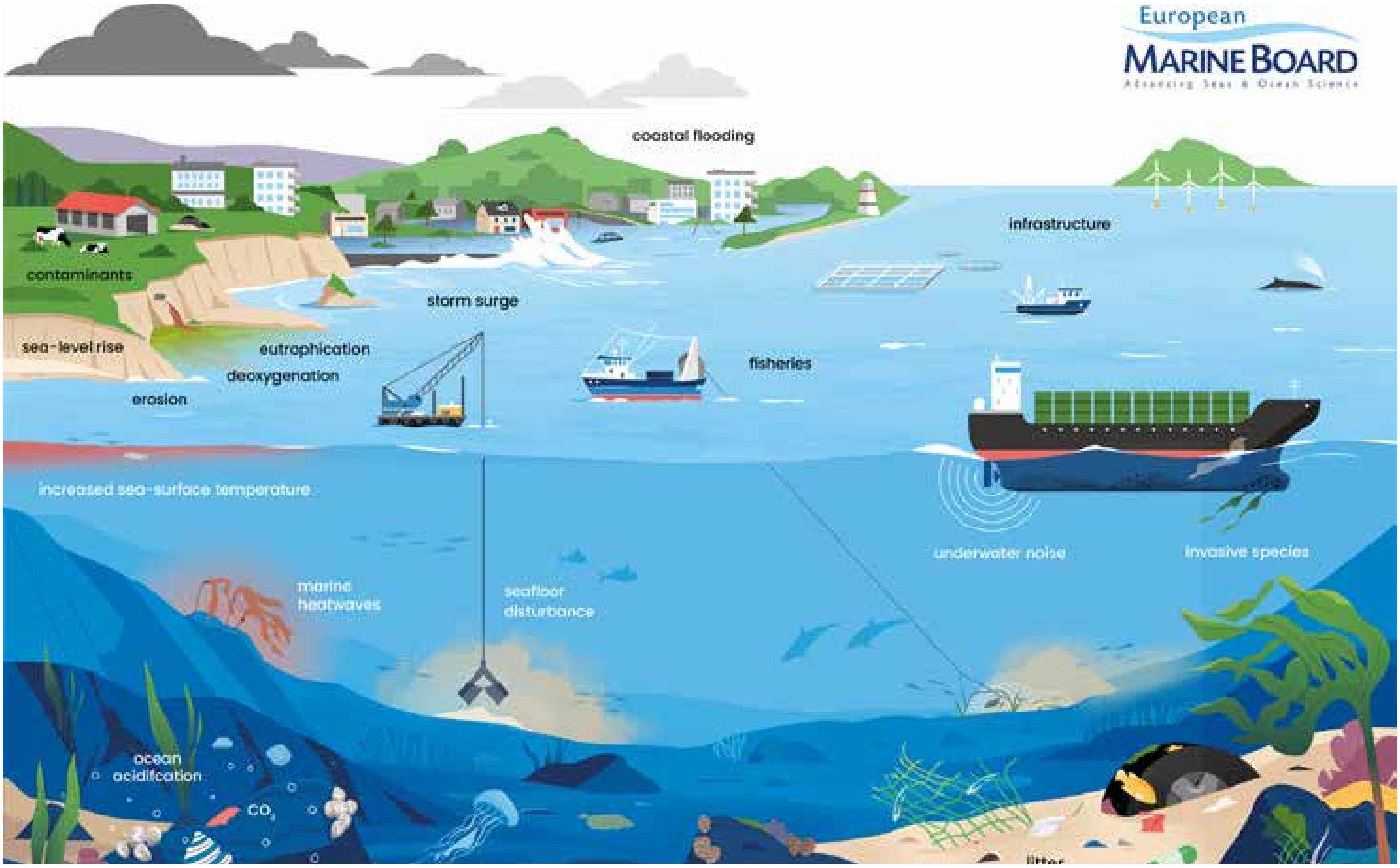


Figure 3.1 Examples of drivers, pressures and state changes, their interactions, and impact on coastal resilience. Pressures result from anthropogenic drivers and affect the state of the ecosystem, eroding the resilience of the Coastal Social-Ecological System (CSES). The pressures reduce the ability of the CSES to absorb additional disturbances and essential functions are lost. Society can reduce the risk of eroding the resilience of CSESs by avoiding or reducing the pressure or by increasing protection and mitigating the impacts.



Credit: Amy Dozier (CC BY-NC-ND 4.0)

Figure 3.2 Overview of coastal pressures.

Pressures can result from one or more anthropogenic activities and can be categorised as Exogenic Unmanageable Pressures (ExUPs) or Endogenic Manageable Pressures (EnMPs). The root drivers of ExUPs arise from outside the coastal zone being managed (i.e. regional or global) and their management therefore demands management and political action at scales beyond CSESs. However, the impacts of such pressures on the CSES can be addressed at a local level through mitigation and adaptation measures. For example, pressures arising from climate change are primarily of global origin. Political instability, unemployment or general population growth drivers may be national issues, but all of these impact specific CSESs in different ways. Climate-induced ExUPs are addressed in this Chapter, although other ExUPs exist such as the degradation of offshore ecosystems, which are coupled to CSESs. The causes of EnMPs are within the management boundary of the CSES and their impacts can be managed within the CSES. Although not exhaustive, this Chapter describes the 13 most important EnMPs and climate-induced ExUPs (Figure 3.2) and how they impact European coastal systems. We highlight their causes and trends from global to local levels, and ways in which these individual pressures and their interactions impact coasts and threaten the resilience of CSESs. The impact of climate-induced pressures on the Global Ocean is explored further in the Ocean and Climate Chapter of Navigating the Future VI[20]. Due to the expertise of the authors, ecological impacts are primarily highlighted, although social impacts are equally important such as the impact of offshore fishing stock collapse on the welfare and wellbeing of coastal communities which, without diversification, would not be resilient to the collapse of the fishing sector.

3.1 Exogenic (climate-induced) pressures

The global increase of greenhouse gas emissions due to the increase in fossil fuel consumption leads to climate-induced pressures on coastal systems, which has negative impacts on the resilience of CSESs. These pressures include increases in sea-surface temperature (SST), sea-level rise (SLR), extreme events including marine heatwaves (MHW), floods and increase in storm intensity and frequency, Ocean acidification (OA) and deoxygenation (see Grégoire et al. (2023) for more information on the impact of climate change on Ocean deoxygenation). This section briefly describes the most important climate-related pressures and their known impacts on coasts. More detailed assessments of the impacts of these climate-induced pressures can be found in the Intergovernmental Panel on Climate Change (IPCC) Report on Impacts, Adaptation and Vulnerability in the 'Europe' Chapter (Bednar-Freidl et al., 2022), the IPCC Special Report on the Ocean and Cryosphere (IPCC, 2019), the World Ocean Assessments I and II (United Nations, 2016; United Nations, 2021), the Intergovernmental Science-Policy Platform on on Biodiversity and Ecosystem Services (IPBES) global and regional assessments (IPBES, 2018; IPBES, 2019), and the Biodiversity and Climate change workshop report (Pörtner et al., 2021). These pressures are broadly addressed at a European level within the European Green Deal and the EU Strategy on Adaptation to Climate Change (COM/2021/82 final, 2021).

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[20] https://www.marineboard.eu/navigating-future-vi

3.1.1 Sea-surface temperature (SST) increase

Global mean SST has changed by 0.88ºC between 1850–1900 and 2011–2020. Since 1980, the increase in SST has been 0.6°C with the rate of change varying regionally (Fox-Kemper et al., 2021). In Europe, SST has risen between 0.2°C per decade in the North Atlantic and 0.5°C per decade in the Black Sea between 1981–2018[21]. This warming affects coastal ecosystems in different ways including changes in species composition i.e. losses and gains. Mobile species change their range or move into cooler and deeper areas (Pinsky et al., 2020) and kelp forests are disappearing at their southern limits in Europe (Araújo et al., 2016). Temperature changes the time of reproduction and migration of species (called phenology), causing ecological mismatches between species that previously co-evolved (e.g. predators and their prey, Wilson et al., 2021). These mismatches have unknown consequences on the functioning of ecosystems as increased temperature will not affect all organisms in the same way. Temperature also impacts species abundance and composition, especially of sessile/immobile animals (Vye et al., 2020), and the carbon sequestration potential of coastal ecosystems (European Marine Board, 2023). Current emission pathways show that global SST will continue to increase throughout the 21st century with increasing negative impacts on marine ecosystems (IPCC, 2021), as well as impacts on multiple ecosystem services such as food production and carbon storage potential. In global fisheries, the benefits of meeting global warming targets are recognised, acknowledging that the increase in mean global temperature may lead to potential decrease in fisheries catches (Prellezo et al., 2023).

Key knowledge gaps related to SST increase include what effect future SST changes will have on food webs and other interactions between species, and how SST increase will interplay with other pressures.

3.1.2 Extreme events: Marine heatwaves (MHWs)

Extreme events in the Ocean are rare but have severe impacts for marine systems (Gruber et al., 2021). Among these, MHWs have increased in intensity and frequency globally and in European seas over the last decades (Oliver et al., 2018). This trend is expected to continue into the future influenced in part by changing climate trends (Frölicher et al., 2018), with the Arctic Ocean being one of the regions to experience the largest increase in frequency of MHWs (Fox-Kemper et al., 2021). MHWs are characterised by discrete periods of anomalously high Ocean temperatures i.e. lasting for more than five days with temperatures more than 90% higher than the 30-year historical baseline (Hobday et al., 2016). For example, in June 2023, the global average SST reached record-breaking levels, with the north Atlantic Ocean experiencing several extreme MHWs at 0.91°C above the monthly average and reaching 4-5°C above average at their peak[22] (Figure 3.3).

Credit: K. Miguel Urquizo Richmond

Kelp forests are disappearing from their southern limits in Europe due to increased sea-surface temperature.

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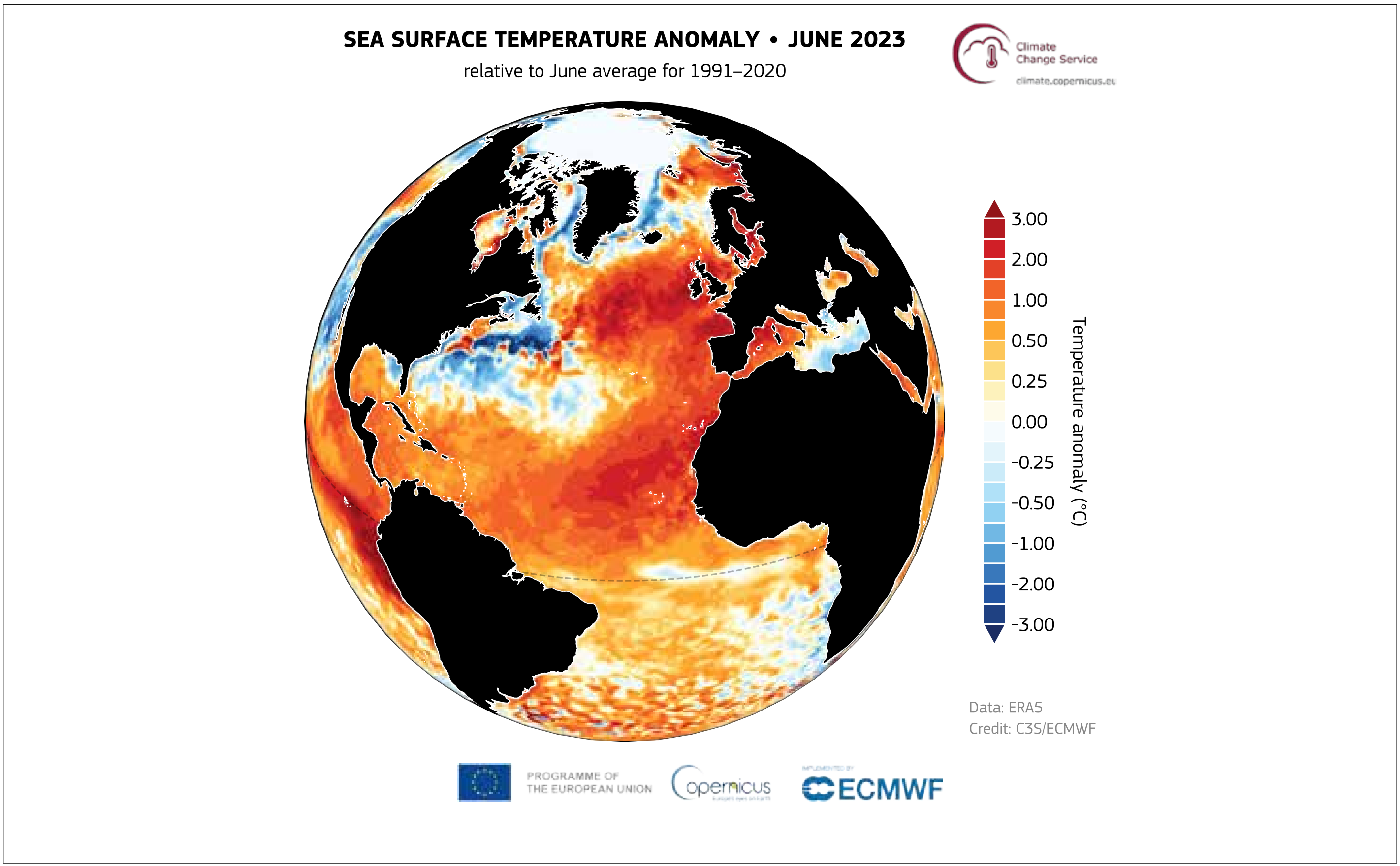
[21] https://www.eea.europa.eu/ims/european-sea-surface-temperature

[22] https://climate.copernicus.eu/record-breaking-north-atlantic-ocean-temperatures-contribute-extreme-marine-heatwaves



Credit: Copernicus Climate Change Service/ECMWF

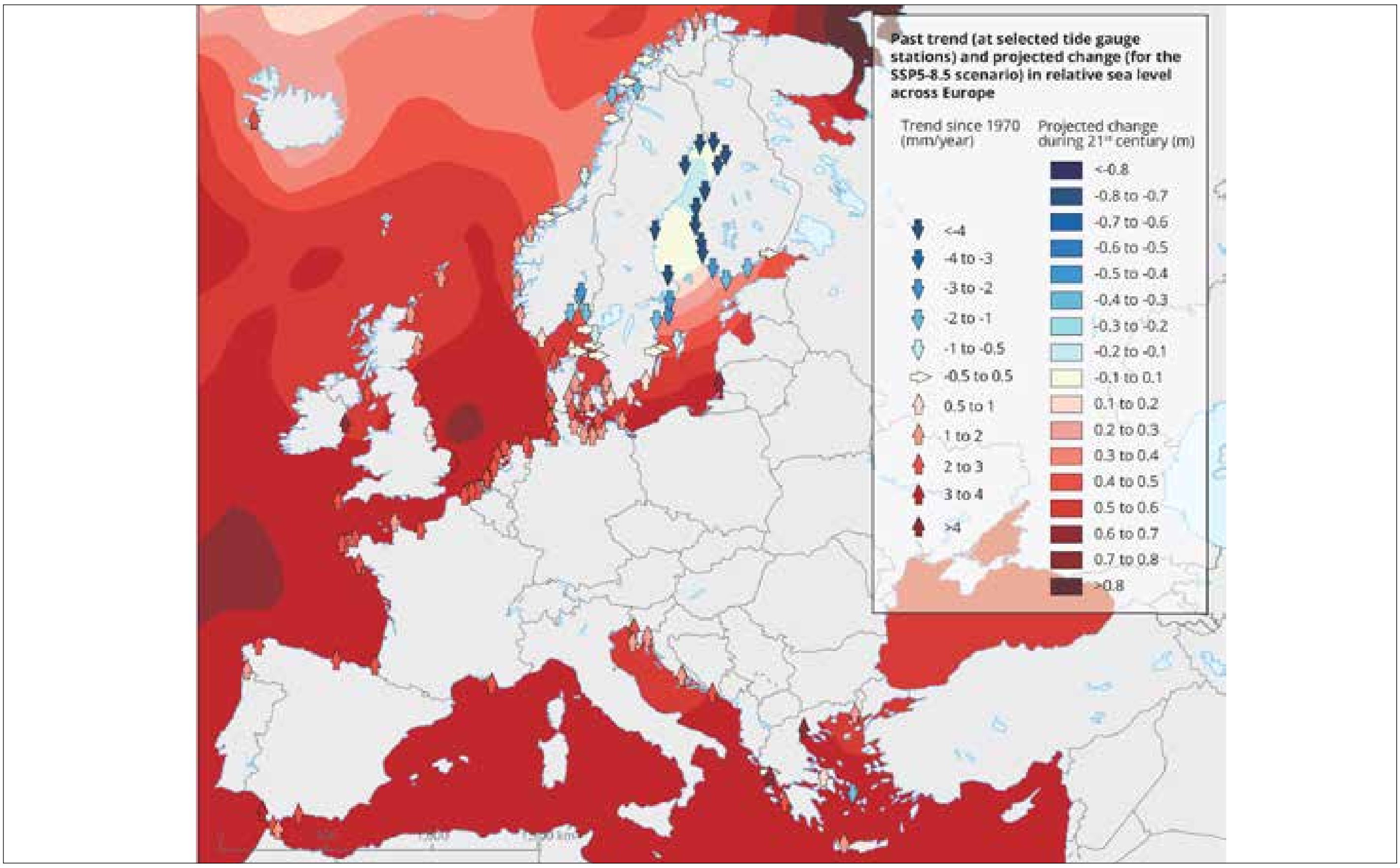
Figure 3.3 Sea-surface temperature anomaly (ºC) for the month of June 2023, relative to the 1991-2020 reference period. Data source: ERA5.

MHWs are coupled to gradual Ocean warming but they pose a greater threat to coastal resilience in the short term. Prolonged SST extremes of only 2-3°C above ambient summer conditions can have detrimental ecological implications, including mass mortalities, harmful algal blooms, shifts in species' range, and altering food webs and species interactions, posing risks to coastal resilience. An example is the loss of habitat forming species such as kelp, which provide services including wave attenuation, carbon storage and nutrient cycling (Filbee-Dexter et al., 2020). The effect of MHWs may also strongly affect intertidal areas (i.e. areas of the coast that are covered at high-tide and uncovered at low-tide) by changing bioturbation patterns (i.e. the disturbance of sediment by infiltrating plants and animals) of benthic organisms, and thereby changing the erodibility of these systems. MHWs may induce species mortality and hence cause shifts in communities (Zhou et al., 2023) and change the behaviour of migratory birds that feed within intertidal areas. Ecological consequences of MHWs can also lead to socio-economic impacts including loss of ecosystem services, loss of fisheries income, loss of iconic species and human conflict (Smith et al., 2021). For example, if tidal flats become more erosive due to changes in bioturbation behaviour, they may become continuously inundated with water and associated species may drown, thereby reducing their wave attenuating capacity and thus providing less coastal protection.

The key knowledge gaps for MHW include an interdisciplinary understanding of the impact of MHWs on individual organisms, at ecosystem level and on ecosystem services, and the combined effects of MHW with other anthropogenic pressures.

Credit: Robert Mlinac

Marine heat waves may change the behaviour of migratory birds that feed within intertidal areas.



Credit: European Environment Agency (CC BY 2.5 DK)

Figure 3.4 Past trends and projected change in relative sea level across Europe[23].

3.1.3 Sea-level rise (SLR)

SLR is caused by thermal expansion due to Ocean warming and the loss of land-based ice from glaciers and ice sheets (Marti et al., 2022). Storage of water in artificial reservoirs, such as dammed lakes, has mitigated this rise slightly but is a one-time contribution and by far too small to balance it. Between 1901 and 2018, global mean sea level increased by 20 ± 5 cm, with increasing rates over the past couple of decades (IPCC, 2021). Most European coasts have experienced SLR, although at different rates (Figure 3.4). In many Mediterranean coastal areas, SLR is strongly enhanced at the local level by subsidence (i.e. gradual shrinking of the land in coastal areas over time) of coastal plains due to stratigraphy architectures (i.e. the arrangement and composition of geological layers of sedimentary rock and deposits) and/or by active tectonic movements (Di Paola et al., 2021). In contrast, along the Northern Baltic Sea and parts of the Norwegian coast, sea level is decreasing as land has risen due to post-glacial rebound since the last ice-age i.e. the uplifting of land after the weight of ice sheets has been removed[24].

Depending on greenhouse gas emissions scenarios, global mean sea level is projected to be between 28 and 101cm higher by the end of the 21st century compared to the mean over the time period 1995-2014. However, due to uncertainty in ice sheet dynamics, a rise of up to 2m by 2100 and 5m by 2150 cannot be ruled out (Fox-Kemper et al., 2021). Dealing with this deep uncertainty poses a huge challenge for coastal planners and decision-makers because it is not clear which scenarios they should anticipate and plan for. SLR in most European coastal areas is projected to be similar to the global average, with the exception of the Northern Baltic Sea and Norwegian coast, where it will be lower due to the land rising. Potential impacts of SLR include flooding, increased coastal erosion, landslides, the submergence of flat regions along continental coastlines and on islands, and the displacement or collapse of intertidal flats, tidal salt marshes, low subtidal foreshores (i.e. between high- and low- water marks) and dune ecosystems. Several of these ecosystems play a key role in creating nature-based or hybrid solutions for flood defence (Zhu et al., 2020). For example, it has been shown that a small increase in water depth on tidal flats causes a small increase in average wave height, which has a drastic effect on salt-marsh establishment and marsh width, which is key to flood safety (Zhu et al., 2020). It is estimated that 20% of Europe's coastlines are already actively eroding despite much of it already being protected (Figure 3.5). Low-lying coastlines with high population densities and small tidal ranges are most vulnerable to SLR due to increased vulnerability to damage caused by flooding and erosion and limited availability of land to relocate people and infrastructure away from the coast. Rising sea level also causes saltwater intrusion into low-lying groundwater aquifers (i.e. layers of rock, sand or gravel that can absorb water and through which water can flow), thus threatening freshwater supplies and endangering coastal ecosystems and wetlands.

A key knowledge gap is that current global climate models used for sea-level projections have a relatively low resolution and it is not clear how well they simulate sea-level changes along complex coastlines and/or on shallow shelf regions that border much of the western European coast. Additionally, it is still unclear how open

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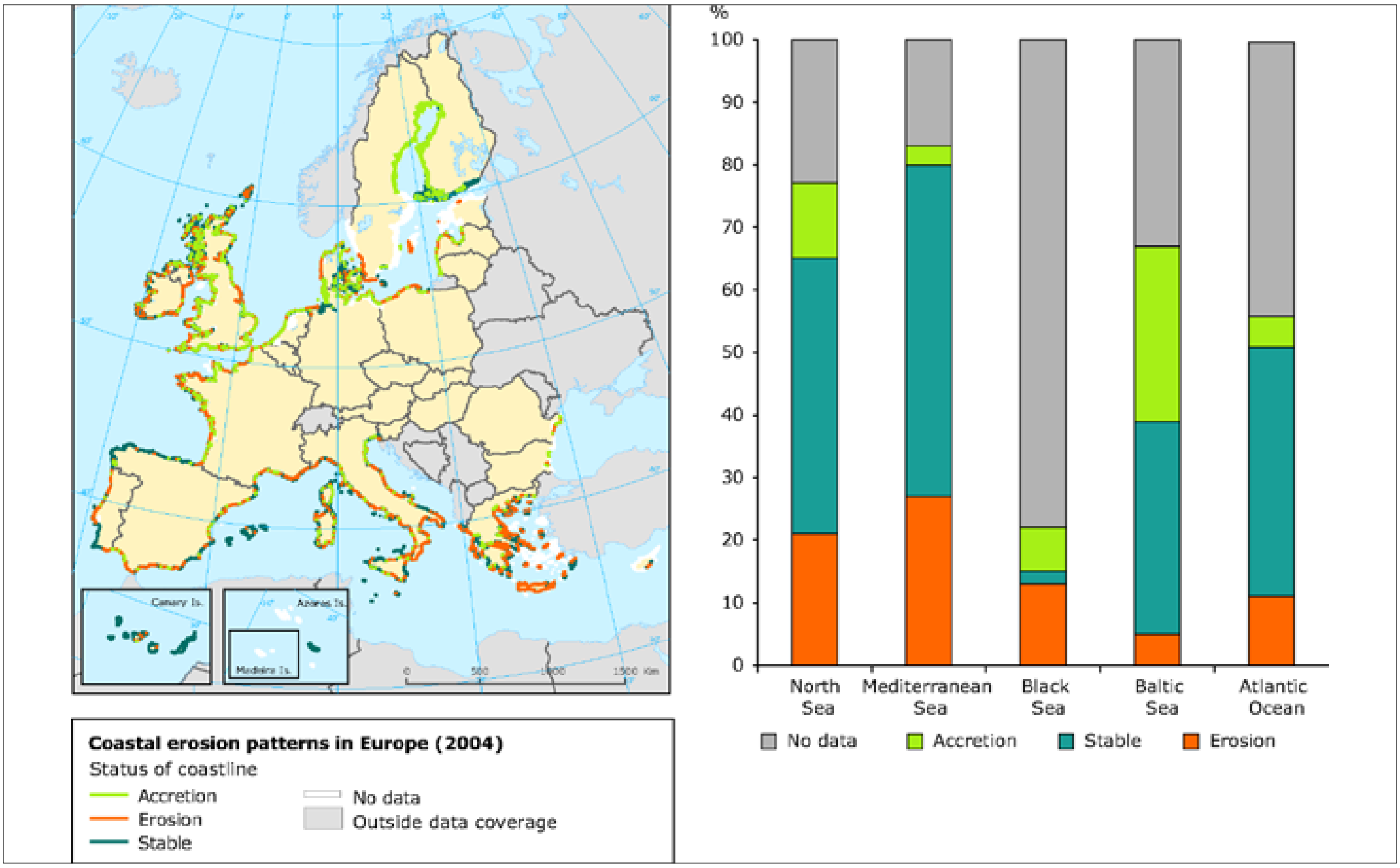
[23] https://www.eea.europa.eu/data-and-maps/figures/past-trend-at-selected-tide-2

[24] https://www.eea.europa.eu/ims/global-and-european-sea-level-rise



Credit: European Environment Agency (CC BY 2.5 DK)

Figure 3.5 Coastal erosion patterns in Europe considering the integrated outcome of natural trends and management measures. Data from 2004[25].

Ocean sea-level changes relate to coastal sea-level changes. Dynamic downscaling of climate models from global to regional scales is one approach to address this (Hermans et al., 2020). Other knowledge gaps include understanding the uncertainties with respect to sea-level change including low-probability, high impact events such as the collapse of the West Antarctic ice sheet; the role of shallow continental shelf regions in connecting open Ocean sea-level changes to the coast; the effect of sea-level rise on the long-term applicability of nature-based and hybrid flood defence solutions; and site-specific tipping points related to saltwater intrusion of groundwater, beyond which small changes in saltwater intrusion caused by sea-level rise leads to full seawater intrusion (Mazi et al., 2013).

3.1.4 Extreme events: coastal flooding, storm surges and waves

Rising mean sea levels increase the exposure of coastal communities to episodic flooding due to increases in rare Extreme Coastal Water Levels (ECWL). Changes in ECWL are driven by changes in mean sea level, tides, and changes in frequency and magnitude of storms, which in turn cause storm surges and changes in waves. They may also be caused by tsunamis (Kopp et al., 2021) and meteotsunamis. The interaction between storm surges, waves and mean sea-level changes are just starting to be explored by scientists. The co-occurrence of other multiple hazards, such as the interaction between storm surges, heavy rain and subsequent river flooding, and increase in terrestrial run-off are also not well studied. The compound effect of these hazards amplifies the risk in exposed areas, such as estuaries, and may lead to greater ECWL than projected from individual climate-related drivers alone.

ECWLs are projected to increase during the 21st century and beyond, and thus flooding will occur more frequently with more severe impacts in many locations (Bevacqua et al., 2019). Sparse sampling (usually only point measurements by tide gauges), scattered historical information, and the influence of local characteristics (e.g. bathymetry), makes it challenging to assess the probability of ECWL at any given point along the coastline. Yet this information is essential for risk management and prevention. Future extreme sea levels and flood risk along European coasts will be strongly impacted by global warming. Based on the highest greenhouse gas emission and warming scenarios, averaged along all European coasts, extreme flooding is projected to occur annually by 2100, although these events were previously only predicted to occur once every 100 years (Vousdoukas et al., 2017). The uncertainty in future projections of ECWLs remains high and is ultimately linked to the uncertainty around future changes in mid-latitude storminess and storm track behaviour. Higher flood levels increase the risk to human lives and property, including risk of damage to sea dykes, homes and other infrastructure, with potential impacts on tourism, recreation and transportation. Coastal protection infrastructure designed to withstand less frequent flood events is likely to be at risk as the frequency of these extreme events increases. Coastal flooding also poses a risk to coastal habitats from estuaries to sandy beaches, which are impacted by storms. The management of impacts from

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[25] https://www.eea.europa.eu/data-and-maps/figures/coastal-erosion-patterns-in-europe-1

coastal flooding, storm surges and waves are specifically addressed in the EU Floods Directive (Directive 2007/60/EC, 2007).

The key knowledge gaps for ECWL include compound effects of multiple hazards e.g. storm surges, heavy rain and related coastal flash floods and river floods; how the frequency, intensity and drivers of such compound events may change in a warmer climate; how to estimate the probability of ECWL at specific points along the coast; and understanding links between the uncertainty of sea-level change and the uncertainty around future changes in mid-latitude storminess and storm track behaviour.

3.1.5 Ocean acidification (OA)

OA is a threat to the Ocean and the services it provides. Globally, Ocean surface pH has declined from 8.2 to below 8.1 since the industrial revolution (Gattuso et al., 2014) as a direct result of an increase in atmospheric CO_2 concentrations which have been taken up by the Ocean. This decline corresponds to an increase in oceanic acidity of about 30%[26]. It is virtually certain that OA will continue to increase in the future (IPCC, 2019). There are local and seasonal variations in OA, particularly in coastal waters, and measurements and predictions of OA and their impacts in highly complex coastal areas are particularly difficult (Gattuso et al., 2014). There are also local causes of OA, including run-off from acidic fertilisers, nutrient loading, eutrophication and upwelling in coastal areas due to water from the deep Ocean being more acidic than surface water (Kelly et al., 2011). OA interacts with other global pressures on the Ocean, including warming and deoxygenation. The combined impact of these stressors on current and future marine ecosystems and the ecosystem services they provide are far-ranging. A decline in pH has wide consequences for marine life such as reduced calcification rates in species with shells such as oysters (Hoppit & Schmidt, 2022) and it can cause a loss of biodiversity and the ecosystem services provided by these species (Zunino et al., 2021). In addition to impaired calcification, OA can impact the metabolism, reproduction (e.g. by impacting larval development of some invertebrates), behaviour and survival of marine organisms, thereby altering food webs, causing biodiversity loss and loss of complexity of marine ecosystems (Doney et al., 2020). This has a negative effect on the societies and economies that rely on Ocean services such as tourism, aquaculture and fisheries. Habitat destruction (i.e. of corals and shellfish reefs) as a result of calcium carbonate dissolution from OA also reduces coastal protection. In addition, OA reduces the future ability of the Ocean to act as a carbon sink (Goodwin et al., 2009).

The Marine Strategy Framework Directive (MSFD) currently does not include any descriptors requiring the monitoring and assessment of OA although there is discussion on whether it could be considered under Descriptor 7, which refers to coastal pressures that are able to permanently change the hydrographic conditions of the coast or seabed. In addition, OA can be reduced by limiting agricultural run-off, organic matter and nutrient pollution, and reducing sulphur and nitrogen oxide emissions, which are all tackled by the Water Framework Directive.

Key knowledge gaps on OA include how to predict the impacts of OA on highly complex coastal areas, different species, and ecosystem function and services; the interaction between OA and other stressors including eutrophication, warming and deoxygenation; genetic adaptation potential of organisms; and understanding the role of primary producers (e.g. algae, seagrass beds) in local protection against OA.

3.2 Endogenic pressures

3.2.1 Eutrophication and deoxygenation

Eutrophication is a process where aquatic environments become progressively enriched with nutrients, which enter from the atmosphere, land, rivers, adjacent marine areas, or from disturbance of contaminated sediment. The main anthropogenic sources of nutrients to coastal waters include agriculture, waste-water and combustion of fossil fuels (Malone & Newton, 2020), while some aquaculture practices and ship discharges also contribute nutrients to the coastal waters. Nutrient enrichment results in increased pelagic primary production (organic matter) initiating a cascade of impacts. These include increased phytoplankton biomass that can cause the development of harmful algal blooms, reduced water clarity, shading of benthic vegetation due to blocking of sunlight, changes in benthic and pelagic food web structures, fish recruitment failures, increased risk of hypoxia (i.e. low oxygen conditions) in bottom waters and associated loss of benthic species, loss of habitats, changes in biogeochemical pathways, and decreased biodiversity (Kemp et al., 2009). The causes and impacts of deoxygenation in coastal zones are described further in EMB Future Science Brief N°. 10 on Ocean oxygen (Grégoire et al., 2023). These changes in ecosystem structure and function have significant implications for the goods and services provided by coastal ecosystems including food provision, recreational activities, nutrient cycling, and carbon storage with direct effects on the fisheries and coastal tourism sectors, among others.

The principal mechanisms of coastal eutrophication are well understood and its main manifestations, i.e. algal blooms, loss of benthic habitats and oxygen depletion, have been documented worldwide (Breitburg et al., 2018). Although the underlying mechanisms of eutrophication are universal, the effects of eutrophication are highly site- and system- specific, making quantitative predictions difficult and the establishment of universal cause and effect relations impossible. Coastal systems vary greatly in their sensitivity and resilience to nutrient input due to the differences in physical, hydro-morphological and biological characteristics as well as the other pressures that the system experiences. In order to guide management actions, nutrient budgets for individual ecosystems can be constructed, as well as indices that measure sensitivity to changes in nutrient input (Cloern, 2001).

The effort to reduce eutrophication at European level as part of the Water Framework Directive, Nitrates Directive (Council Directive 91/676/EEC, 1991), Urban Wastewater Directive (Council Directive 91/271/EEC, 1991), Bathing Water Directive (Directive 2006/7/EC, 2006), Habitats Directive and Descriptor 5 of the MSFD during the past decade has resulted in significant nutrient load reductions in many places. However, Piroddi et al. (2021) showed that the

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[26] https://www.eea.europa.eu/ims/ocean-acidification

Credit: Lesbats Stephane, Ifremer (CC BY 4.0)

Nutrient enrichment of coastal waters results in increased pelagic primary production, initiating a cascade of impacts including deoxygenation and the development of harmful algae blooms.

achieved reductions (and possible future reductions) of nutrients are not sufficient to positively impact the ecological structure and function of most coastal seas, and that not all ecosystem functions are equally well studied regarding eutrophication. Although signs of coastal ecosystem recovery following oligotrophication (i.e. nutrient reduction) are emerging (Riemann et al., 2016), the recovery process is slow and is not a complete reversal of the eutrophication process. This is likely due to time lags, interacting pressures, shifting baselines (i.e. the change in perception over time of what a healthy ecosystem is) and semi-irreversible processes such as (local) extinction of key species. The lack of data and knowledge on ecosystem recovery following nutrient reductions are, however, hampering predictions on if, when and where coastal ecosystems will return to a healthy state.

Although eutrophication has been very well studied, there are still some key knowledge gaps including how to fully represent coastal processes in ecosystem models; the responses of coastal species, ecosystems and their services to eutrophication, reduced nutrient loads and deoxygenation; the impact of changes in primary production when most nutrients are taken up by plants that are not as fully consumed in the ecosystem; how changes in dissolved oxygen impact the recruitment and metabolism of benthic and pelagic organisms; how long an ecosystem takes to recover following nutrient reduction; climate-eutrophication joint effects; and how to predict the large site-specific variability in sensitivity of ecosystems to eutrophication.

3.2.2 Invasive species

The introduction and spread of marine non-indigenous species (NIS), i.e. species that have been introduced outside their previous or present natural range by human activities, are increasing in European coastal waters mainly as a result of shipping and aquaculture activities (Galil et al., 2014), and also due to expansion in the habitable range of marine species due to warming Ocean temperatures (King et al., 2021). Marine transport, via both ballast water and hull fouling, is the largest source of NIS. The Mediterranean Sea has been the most affected by the introduction of NIS, due to its connection with the Red Sea through the Suez Canal, while the Baltic and Celtic Seas have been least affected (United Nations, 2016). Only a small fraction of the NIS establish themselves and proliferate, with negative impacts on the native biodiversity, and these are then referred to as invasive or alien species. An example of NIS is the exotic seaweed *Rugulopteryx okamurae* (Figure 3.6) that in 2015 was first detected on the south side of the Strait of Gibraltar and within one year became an invasive species with an overflowing competitive capacity and growth (García-Gómez et al., 2020). Their impacts can range from changes in the genetic diversity of native species to species extinction, and can alter entire ecosystems and the services they provide (Corrales et al., 2020). Invasive species can be found at all levels of an ecosystem from algae to fish, and their invasion potential, geographic extent, and ecological and economic impacts can vary (Molnar et al., 2008). Ecosystem services that are impacted by invasive species include biomass production and coastal protection with effects on the fisheries and tourism sectors, among others. For example, an invasive seagrass replacing the native species in Bonaire (Caribbean), was found to strongly reduce the erosion resistance of the ecosystem, which is key for coastal protection (James et al., 2020). In addition, in Ireland an invasive oyster parasite has had a significant negative impact on native commercial oyster populations since the 1980's (Culloty & Mulcahy, 2007).

Invasive species have been recognised as a threat to marine and coastal systems in the MSFD, where NIS are addressed in Descriptor 2[27]. They are also addressed in the EU Biodiversity Strategy and the EU Regulation on the prevention and management of the introduction and spread of invasive alien species (Regulation (EU) 1143/2014, 2014). Globally, the International Convention for the Control and Management of Ships' Ballast Water and Sediments[28] helps prevent the spread of potentially harmful aquatic organisms and pathogens in ships' ballast water by introducing restrictions on what water can be discharged where and water treatment needed before it is discharged. Key knowledge gaps to understand the impact of NIS and invasive species on coastal resilience include how to predict which NIS will become invasive species and their impact on ecosystem function; the impact that NIS have in CSESs with less resilience versus more resilience; how NIS contribute to the impact of multiple stressors on CSES resilience; and how to manage NIS.

3.2.3 Extraction of marine biomass: fisheries

Commercial and recreational fishing are some of the oldest and most widespread human activities in the marine environment (Jackson et al., 2001) and the leading cause of biodiversity loss and altered ecosystem functions (Jacquet & Pauly, 2022). According to the State of World Fisheries and Aquaculture (SOFIA) report, marine capture fisheries have remained fairly stable since the late 1980's at around 80 million tonnes per year, with approximately 10% of that being caught in Europe (FAO, 2022). Roughly 35% of global fish populations are overfished, with 63% of the stocks in the Mediterranean and Black Sea not being sustainably fished, while the North Atlantic, North and Baltic Sea stocks are 72% sustainably fished according to the Food and Agricultural Organization of the United Nations (FAO)'s definition (FAO, 2022).

Fishing has a number of different effects, from directly removing animals and therefore food for predators and competitors, to removing specific sized individuals and changing the reproductive ability of a stock, to damaging habitat-forming organisms and

Credit: Jesús Sánchez Lechu

Figure 3.6 Invasive macroalgae *Rugulopteryx okamurae* in southern Spain.

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[27] https://easin.jrc.ec.europa.eu/easin/Document/JRC124136_recommendations_on_marine_non_indigenous_species_eur_30640_en-1.pdf

[28] https://cil.nus.edu.sg/wp-content/uploads/2019/02/2004-International-Convention-for-the-Control-and-Management-of-Ships-ballast-water-and-sediments.pdf

Credit: Dana Ezgeta

A key knowledge gap is the long-term impact that fish trawling gear has on benthic habitats.

benthic ecosystems (e.g. seagrass, mussel beds). Indirect and cascading effects of this removal include changes in predator-prey and competition dynamics, and changes in habitat structure and composition (Crowder et al., 2008). The combination of these effects can influence the structure and functions of coastal ecosystems, and cause fisheries to collapse due to tipping points being crossed (Möllmann et al., 2021). In Europe, some depleted fish populations have been rebuilt through successful implementation of Common Fisheries Policy regulations (Duarte et al., 2020), but challenges remain, as highlighted in FAO's 2022 report. At the EU level, fisheries are addressed in the Common Fisheries Policy and Descriptor 3 of the MSFD. The recent EU "Action Plan for protecting and restoring marine ecosystems for sustainable and resilient fisheries[29]" outlines ambitions to make fisheries management more sustainable in line with the protection and restoration of marine ecosystems by improving the application of an ecosystem-based fisheries management approach, specifically to reduce by-catch and increase seabed integrity. In this approach, all interactions within an ecosystem, including human interactions, are considered holistically.

Key knowledge gaps to understand the impact of fisheries on coastal resilience include understanding the impact that fishing has on the size spectra of populations, and how that can impact predator-prey, recruitment and competition dynamics; understanding the impact of different fishing practices and intensity on ecosystem functioning and services; the long-term impact that fish trawling gear has on benthic habitats; the impact that extraction of prey and predator species has on resilience of coastal ecosystems; the population dynamics of all species caught in fishing gear, not just target species; and the impact that climate change, and other pressures, have on the resilience of CSESs to fisheries.

3.2.4 Contaminants and marine litter

Since the second half of the last century, large industrial areas have developed along the European coast. Many of these sites have been heavily contaminated, have stored this contamination in their sediments, and are now acting as secondary sources of contamination of for example heavy metals, organochlorines (i.e. chemicals that contain carbon, chlorine and, sometimes, several other elements), polychlorinated biphenyls (PCBs), and radioactive waste (Tierney et al., 2016). This topic was covered in detail in EMB Position Paper N°. 16 on "Monitoring chemical pollution in Europe's sea – programmes, practices and priorities for research" (Janssen et al., 2011).

Through the interaction of currents, tides and winds, some coastal areas are prone to the deposition and accumulation of natural and plastic floating debris. The plastic is incorporated in the soil, even

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[29] https://oceans-and-fisheries.ec.europa.eu/system/files/2023-02/COM-2023-102_en.pdf

accelerating soil formation by binding organic matter that would otherwise be transported away by waves or wind, and leading to changes in the coastal landscape as well as altering habitats (Bastesen et al., 2021). Marine litter, of which 85% is plastic[30], poses a risk to marine and coastal systems, through harm to marine life through ingestion and entanglement, food web impacts, release of harmful chemicals, vectors for viruses, etc. Once in the sea, plastics can be degraded into smaller pieces known as micro- and nano-plastics, which can be ingested by a wide range of marine organisms, disrupt marine ecosystems and release attached chemicals. It is a significant pressure for coastal biodiversity, fisheries, tourism and aquaculture, and present-day protection levels are not sufficient to tackle marine litter, even within Marine Protected Areas (MPAs, Soto-Navarro et al., 2021). The topic of marine pollution in general, including from plastics, pharmaceuticals, personal care product compounds, engineered nanoparticles, flame retardants, biocides and synthetic industrial chemicals, will be covered in the Ocean and Fresh Water Chapter of Navigating the Future VI[31].

Many coastal oil refineries are still active and are supplied by oil pipelines and tankers. Although the number and frequency of oil spills in marine and coastal areas has decreased globally within the last decade (ITOPF, 2023), small discharges still occur. The largest environmental impacts in coastal areas are from large oil spills (United Nations, 2016). Shipwrecks and groundings mean that the fuels and chemicals that ships use may leak or leach into surrounding waters (Byrnes & Dunn, 2020). Unrecovered wrecks, several dating back to World War II, also present lingering dangers of oil spills and removing wrecks can result in leaks that removal was meant to prevent (HELCOM, 2021).

Discharge from ships also contribute to the release of contaminants to coastal sea. Discharges include oil and oil waters, sewage, ballast water, antifouling compounds, solid residues (waste and other), operational residues (such as scrubber products i.e. used in exhaust gas cleaning systems to remove harmful substances before gases are emitted to the atmosphere), and other dangerous substances. The International Convention for the Prevention of Pollution from Ships (MARPOL[32]) provides rules on what can be discharged.

Anti-foulants prevent the biofouling of ships' hulls but the chemicals contained within them can leach into surrounding waters. Tributyltin (TBT) was once used extensively as an anti-foulant but has been banned since 2008 due to its toxic nature, and has been replaced by copper- and zinc-based compounds. These compounds are usually boosted by additional biocides which can also be toxic

Credit: W. Carter, Wikimedia Commons (CC0 1.0)

Discharge from ships, including ballast water, contribute to the release of contaminants to coastal seas.

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[30] https://www.eea.europa.eu/publications/european-marine-litter-assessment

[31] https://www.marineboard.eu/navigating-future-vi

[32] https://www.imo.org/en/about/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-%28MARPOL%29.aspx

and may be accumulating in sediments, particularly in ports (Byrnes & Dunn, 2020).

Cruise and passenger ships are also producers of wastewater, both “blackwater” (i.e. sewage) and “greywater” (i.e. wastewater from sinks, showers and washing machines). Blackwater, which if untreated should not be discharged within 12 nautical miles of the coast, is the more contaminated of the two, but both contain bacteria, viruses, parasites, total and suspended solids, and nitrogen. Such discharges are particularly significant in low-water exchange regions such as the Adriatic and the Baltic Seas and can contribute to algal blooms, mucilage and eutrophication (Carić & Mackelworth, 2014). Bilge water, tank cleaning effluents, and cooling water bring with them additional pollutants, including oil, and other lubricants and chemicals.

Maritime traffic also causes atmospheric emissions of various types that affect the sea, including CO_2, nitrogen oxides (known collectively as NOx), sulphur oxides (known collectively as SOx), carbon and particulate matter. These emissions can be mitigated by the use of scrubber systems that remove pollutants from exhaust gas. MARPOL includes regulations for the prevention of pollution by oil, harmful substances, sewage and sulphur and nitrogen oxides. Contaminants can cause reduction in function or ecosystem collapse and can impact sectors including fisheries, tourism and aquaculture. Contaminants and marine litter are addressed in the EU’s Nitrates Directive, Urban Wastewater Treatment Directive, Water Framework Directive, and MSFD Descriptor 8 covering hazardous substances and Descriptor 10 on litter.

Key knowledge gaps to understand how contaminants influence coastal resilience include site-specific ecosystem impacts from shipping pollution; a holistic understanding of the origins, pathways, amounts and impacts of micro- and nano-plastics on CSESs to be able to tackle marine litter at its source; social-ecological impacts of chemical leaching from plastics; and the effects of the combined accumulation of plastic and organic materials on coastal landscapes and vegetation.

3.2.5. Anthropogenic disturbance of the seafloor

Marine sediments such as sand and gravel, also called aggregates, are used for a variety of industrial and building applications including for the production of concrete and for beach nourishment. With increasing coastal erosion and urbanisation,


Marine sediments such as sand are used for a variety of industrial and building applications, and for beach nourishment.

Credit: Callistemon (CC BY-SA 4.0)

including the development of coastal defences, global aggregate demand has increased three-fold (up to 40 billion tonnes per year) over the last three decades (Oberle et al., 2019). As this demand is increasing, existing aggregate resources are depleted and there is an increase in illegal and unsustainable sand extraction in the marine environment (Torres et al., 2017). Conversely, due to the high sedimentation rates in some parts of the coast, dredging and dumping of sediments are done to maintain harbours and shipping lanes (e.g. the Scheldt Estuary and the Wadden Sea).

Extracting, dredging and dumping of marine sediments affect the integrity of marine and coastal environments. These activities impact the seafloor by disturbing benthic habitats and communities, and by directly removing benthic fauna and flora associated with the sediment. This often results in serious local reductions in population size, species diversity and community biomass (Cooper et al., 2011). These changes in marine sediments also impact fish, birds and marine mammals through the food web and it can take between a few years and decades for the seafloor to recover (Walker et al., 2016). Keeping parts of the original seafloor untouched is a way to increase the repopulation and the recovery of benthic communities in the affected areas (Schultze & Nehls, 2017). At EU level this is managed through MSFD Descriptor 6 on seafloor integrity, which aims to ensure that the structure and functions of ecosystems are safeguarded and benthic ecosystems are not adversely affected (Vasilakopoulos et al., 2022). Sand and gravel mining are additionally considered in the Water Framework Directive, the Habitats Directive and the Birds Directive.

Additionally, sediments from harbours and estuaries are often heavily contaminated with heavy metals, tributyltin hydride, microplastics and other harmful pollutants (Borja et al., 2016). The suspension and exposure of deeper sediments layers by dredging, dumping and extracting results in these substances being released to the water column and accumulating in the food chain. These activities may also cause organic matter, sulphides or ammonium that are bound in the sediment to be released into the water column, decreasing water quality and oxygen levels to concentrations that are critical to fish and other marine organisms (Schultze & Nehls, 2017). All ecosystem services linked to the functioning of benthic ecosystems are affected.

The operation of marine vessels is also associated with disturbances from propeller wash and the wake of the vessels. In shallow waters, these can stir up bottom sediment and contribute to bank and seafloor erosion. Anchorage and mooring can affect bottom substrate and habitats (Byrnes & Dunn, 2020), especially sensitive areas such as the Posidonia fields in the Mediterranean Sea. In addition, trawling gear used in fisheries causes seafloor disturbance.

Key knowledge gaps on the impact of seafloor disturbance on coastal resilience include the need for better site-specific understanding of how much the seafloor can be disturbed before impacting resilience; to what extent this changes if the seafloor is left undisturbed for some decades in order to recover from the past 100 years of disturbance; and an improved understanding of whether it is better for overall resilience to have slightly disturbed areas everywhere or some fully protected areas.

3.2.6. Noise

Underwater sound can arise from both natural (e.g. marine mammal calls, snapping shrimp, waves) and anthropogenic sources (e.g. vessels, maritime construction, sonar, marine energy devices). The addition of new, unnatural and often louder or more persistent anthropogenic noise can impact the ability of marine species to detect natural sounds on which they rely, with some sources having the potential to cause behavioural changes or physical harm. For example, this can lead to reduced foraging and increased stress in marine species, and in extreme cases, to stranding or death (Duarte et al., 2021). Underwater noise sources that are of particular relevance to coastal regions include leisure boats, shipping, dredging and aggregate extraction, construction, and energy extraction.

The impact of anthropogenic noise depends on the source and its acoustic properties (intensity, frequency, etc.), the duration over which it is being emitted, the physical conditions of the area in which the noise is propagating, and the noise sensitivity and typical use of sound by the species detecting it (Thomsen et al., 2021). Extrapolating to wider coastal systems, ecosystem-impacts of underwater noise have the potential to indirectly affect sectors such as fisheries and tourism.

It is estimated that between 2014 – 2019 the *“total accumulated underwater radiated noise energy more than doubled in EU waters, with container ships, passenger ships and tankers generating the highest noise energy emissions”* (European Environment Agency, 2021a). This trend holds both globally and in Europe, especially with the ongoing focus on developing the Blue Economy, and with continued growth in sectors such as offshore energy extraction and shipping.

In Europe, the MSFD is the main driver for increased knowledge and understanding of underwater noise, which is addressed in Descriptor 11 aiming for introduction of energy, including underwater noise, to not exceed levels that adversely affect the marine environment. It requires Member States to conduct measurements of ambient noise in their waters, as well as to collaborate regionally to monitor noise. It has also led to increased research into approaches for reducing or mitigating underwater noise emission, although further research is needed to understand the efficacy of these solutions. At present, noise is generally governed on a sectoral basis. Globally agreed standards covering all aspects of underwater noise are needed.

As discussed in (Thomsen et al., 2021), key knowledge gaps for understanding the impact of noise on coastal resilience include a more holistic understanding of the population- and ecosystem-level impacts of underwater noise, and of how underwater noise as one of many stressors affecting coastal areas combines with others to produce cumulative impacts; how to improve management of shipping to and from ports and of recreational vessels, and what practices would decrease noise pollution and avoid vulnerable areas e.g. breeding grounds; and understanding the efficacy of solutions for reducing or mitigating underwater noise emissions, especially in shallow water environments.

Credit: Gary Cunliffe (Pixabay)

The development of offshore energy platforms is leading to new impacts.

3.2.7. Marine coastal infrastructure

Marine coastal infrastructure includes structures developed for aquaculture, tourism, urbanisation, housing, ports, energy devices and coastal protection. Coastal development has historically occurred primarily in response to socio-economic needs, with less emphasis on ecological or cultural considerations (Floerl et al., 2021). The adverse impacts of coastal "hardening" are well documented and especially prevalent in Europe where built-up areas along, for example, the coasts of Belgium, Italy, France and Spain exceed 45% of land-cover (European Environment Agency, 2006). Coastal hardening is not limited to the land: the intertidal and nearshore zones (i.e. area of the sea relatively close to the shoreline, typically to depths of 20m) are increasingly being altered by built structures such as seawalls and breakwaters. The coast can also be modified for commercial and navigation activities (ports, marinas, jetties), or land reclamation, which can modify natural sea-coast dynamics. In deeper water, the development of offshore energy platforms is leading to new impacts. Akhtar et al. (2022) showed that large-scale clustered offshore wind farms modify the regional surface climate, e.g. temperature and wind. The consequences of this for marine ecosystems remain to be explored.

Offshore renewable energy is rapidly becoming an important European industry, bringing increased opportunities (e.g. 400,000 jobs). The European Commission aims to scale up the share of renewable energy to at least 42.5% by 2030[33] to meet the objectives of the European Green Deal, and European Climate Law and REPowerEU[34], and this includes both onshore and offshore sources. This poses new risks such as negative impacts on ecosystems from species avoiding areas with introduced hard substrates, but also potential opportunities such as an increase in biodiversity and biomass with the formation of new habitats around hard structures, particularly when fishing activities are restricted in these areas (Soukissian et al., 2023). These risks and opportunities are site-specific and must be carefully considered using decision-support tools when planning offshore renewable energy installations, as well as other marine coastal infrastructure developments as part of the Marine Spatial Planning (MSP) Directive. In addition, the proposed increase in renewable energy, specifically offshore renewable energy e.g. as part of the Ostend Declaration of Energy Ministers[35], will increase competition for the use of the Ocean by other users.

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[33] https://ec.europa.eu/commission/presscorner/detail/en/IP_23_2061

[34] https://ec.europa.eu/commission/presscorner/detail/en/ip_22_3131

[35] https://kefm.dk/Media/638179241345565422/Declaration%20ENERGY_FINAL_21042023.pdf

Key knowledge gaps to understand the impact that coastal infrastructure has on coastal resilience include understanding of risks and opportunities posed to coastal resilience by scaling-up offshore renewable energy; understanding the impacts on natural coastal dynamics (physical and ecosystem) and associated consequences; and understanding the impact that the proposed increase in offshore renewable energy will have on the available space for other industries and the impact that will have on coastal resilience.

3.3 Cumulative consequences

An increasing number of studies show that many types of pressure-response relationships exist, i.e. linear (where the response is proportional to the magnitude of the pressure), non-linear (where small changes in a pressure triggers a disproportionately large response) and threshold-type relationships (where abrupt changes occur once a tipping point is crossed), and the impact of non-linearities are as common as linear relationships (Hunsicker et al., 2016). This is a direct consequence of the interactions of multiple pressures, e.g. climate change in combination with fishing, eutrophication and/or pollution (Blenckner et al., 2015). An example is the decline of shellfisheries in Galicia in the north-west of Spain from reduced landings and sales value of key species such as the edible cockle and Atlantic goose barnacle. This may be a result of cumulative pressures including overfishing, poaching, degradation of habitats, pollution, disease outbreaks and Ocean warming. These pressures slowly impact the CSES and are likely at some point to trigger a non-linear, disproportionately large response. Despite the development of new fisheries (e.g. algae, anemones and polychaetes), the overall decline has important social-ecological impacts on Galician society due to the traditional link between shellfishing and coastal communities (Pita et al., 2019). Galician mussel aquaculture is the largest aquaculture production in the EU and is suffering from the cumulative impacts of climate change (Fuentes-Santos et al., 2021) and red ties (a type of harmful algal bloom). Red tides make the mussel industry more vulnerable to climate change impacts and strain the capacity of the sector to supply the seafood (Avdelas et al., 2021).

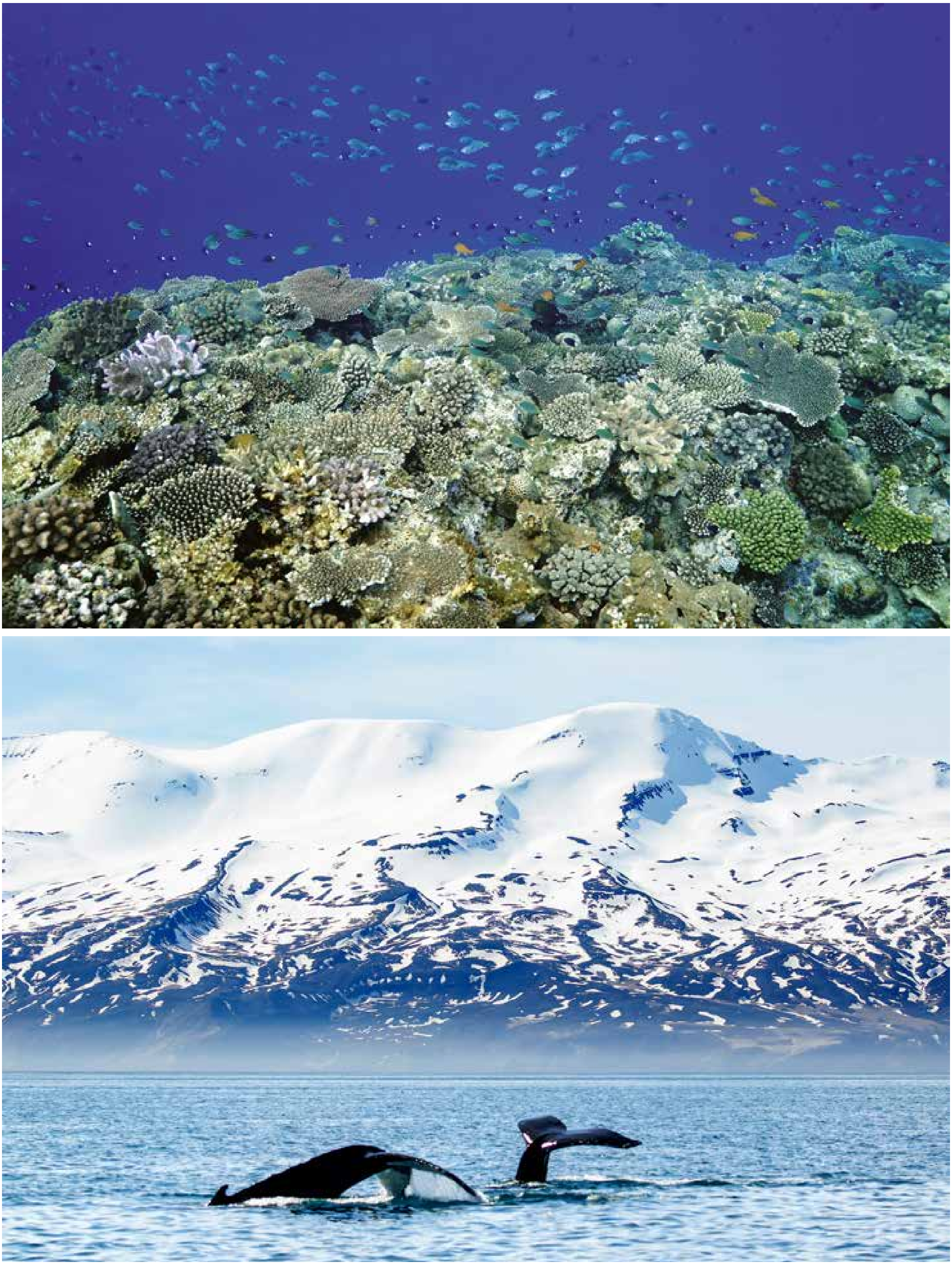
Synergistic responses, i.e. when the response exceeds the sum of individual pressure effects, are often due to amplified feedbacks and are the most challenging to manage. Such synergies often lead to drastic changes in the structure and functioning of ecosystems (Côté et al., 2016), also known as regime shifts (Scheffer et al., 2001). An example is the collapse of kelp forests due to pressures including overfishing and disease, and the subsequent expansion in sea urchin populations. The underlying mechanisms behind regime shifts are often hypothesised to be weakened system resilience due to cumulative pressures (Folke et al., 2004), together with a subsequent sudden perturbation from one pressure which may trigger the actual shift (Scheffer et al., 2001). Although recovery to an original state is often the primary management goal (Selkoe et al., 2015), ecosystems often show hysteresis meaning that the system can exist in two alternative states and the state exhibited depends on historical conditions. Practically this means that after undergoing a regime shift, the response of the system will lag substantially behind management interventions and returning the system to the environmental conditions at which the the state shift occurred is not sufficient to return to a system to it's original ecological state (Scheffer et al., 2001). Despite a strong theoretical foundation of non-linear system responses to cumulative impacts from multiple interacting pressures, literature reviews indicate that significant knowledge gaps exist (Côté et al., 2016), especially since most cumulative pressure-response relationships have not been analysed on an ecosystem level. In general, such relationships have proven to be considerably more complex than expected from theory as they are highly context dependent and variable across space, seasons, environmental conditions and types of species interaction (Crain et al., 2008). Socio-economic systems also have tipping points, for example the establishment of new MPAs can create wide-spread change by marginalising small-scale fishers from historical areas where they have been fishing.

Key knowledge gaps to understand the impact that cumulative pressures have on coastal resilience include: how to predict when an ecosystem approaches a tipping point or regime shift, and how to prevent that from happening in coastal ecosystems; social and natural responses at different spatial scales; and the social and natural carrying capacity of specific coastal ecosystems to impacts of increased use of the coastal system.

3.4 European coastal systems as part of the Global Ocean

CSESs are defined by connectivity, and coastal systems are not isolated from the Global Ocean. The resilience of European coastal ecosystems and the services they provide to society are both reliant upon and subject to pressures from outside Europe. For instance, puffins from Ireland feed on forage fish such as capelin and sand lance off the east coast of Canada (Jessopp et al., 2013). Impacts to those fish stocks could have profound knock-on effects on European puffin populations. Similarly, humpback whales calve and rear their young in the calm waters of the tropics, before undertaking the long migration back toward and past European waters to feed on vast amounts of krill during the Arctic summer (Kennedy et al., 2014). This marine megafauna is an important part of European coastal heritage, and contributes to supporting coastal tourism. Impacts to these species and their migration routes will affect their presence in European marine systems, and that can have knock-on effects on the coastal food web and tourism, and therefore entire CSESs.

Likewise, actions undertaken in Europe can also affect coastal resilience in other regions of the world. For instance, shallow tropical coral reefs are arguably the most vulnerable marine ecosystems to climate change mediated heat stress (Hoegh-Guldberg et al., 2019). While Europe and North America contribute approximately one third of global greenhouse gas emissions (Friedlingstein et al., 2020), most coral reefs are located outside these regions in the tropics. These ecosystems support hundreds of millions of people through



Credit top: Ada Sacchi. Credit bottom: Luana Millecamps

Coastal Social-Ecological Systems (CSESs) are connected to the Global Ocean, and actions taken in Europe can impact coastal resilience in other parts of the world, including tropical coral reefs, and migratory species such as humpback whales.

fisheries and tourism alone, and losing these ecosystems would severely reduce the ecological, social, and economic resilience of these coastal communities (Laurans et al., 2013). Thus, actions taken in Europe to curb greenhouse gas emissions will have direct effects on improving the resilience of coastal communities beyond areas of European jurisdiction (Morrison et al., 2019).

These examples highlight the connectivity between coastal marine ecosystems, the Global Ocean and land-based activities, yet there are many more connections, which can be more complex and need further research. Managing these cross-border, trans-oceanic issues takes international and interdisciplinary actions, such as efforts under the Paris Agreement[36] to limit climate change and the target to effectively conserve 30% of the land and sea under the Global Biodiversity Framework[37]. Thus, efforts to manage our highly connected Global Ocean for resilience should be focused on a transdisciplinary systems approach, requiring cross-sectoral policies, adaptive responses and when necessary, transformative interventions (Morrison et al., 2020).

3.5. Conclusions and overarching knowledge gaps

Despite strong mechanistic and theoretical understanding and scientific documentation for the impacts of single pressures, quantitative knowledge of site-specific, multiple and often non-linear pressure-response relations is limited. Although the potential threat from current pressures is acknowledged and to some extent addressed in EU Directives and regulations, these initiatives are insufficient to protect, rebuild and future-proof coasts towards resilience. The impacts of cumulative pressures, as well as the future overarching impacts of climate change, are not sufficiently addressed in current policy-making (see Chapter 6 for recommendations to improve management and policy to build resilient coasts). This hampers mitigation towards climate-adaptive and multiple pressure management. Given the absence of complete knowledge about pressures to CSESs, it is important to ensure that CSESs have intrinsic resilience (i.e. the ability to persist, adapt and transform) so that they are less vulnerable to unanticipated events.

Addressing the following key knowledge gaps will improve our understanding of coastal pressures and impacts in relation to CSES resilience:

- Impacts of single pressures on CSESs, as described in each section of this Chapter;
- Site-specific, multiple, cumulative pressure-response relationships in the coastal zone. This includes: the interactions of climate-induced pressures as well as other anthropogenic-induced pressures; synergistic and additive responses; impacts on the structure and function of ecosystems and on ecosystem services; behaviour of recovering ecosystems; potential time-lags; regime shifts; tipping points and non-linearities; and where tipping points occur and the consequences of crossing them;
- Understanding desirable and unintended consequences of social tipping points at local, national and European levels. Considerations of what needs to change, who is being asked to change and where the change or its impacts will be felt and by whom, are fundamental questions that require a level of reflexivity and systemic understanding in decision-making;
- Understanding the impacts of coastal pressures on socio-economics and human-Ocean interactions, which is critical for developing mitigation and adaptation measures and understanding their costs and risks;
- Socio-economic research on responses of coastal communities to coastal pressures, including how best to assist human populations to migrate to areas away from the coast as a response to crossing tipping points;
- Understanding resilience properties, including integrated ecological and social tipping points, which are required to tackle extreme events and will help to reduce uncertainty;
- Links between coastal pressures and impacts on CSES resilience properties;
- Model prediction capacities of cumulative pressures into the future world (magnitude, timing, location) and their potential coastal impacts; and
- How to scale-up sustainable practices to reduce coastal pressures.


Credit: Anjelina Potin

Socio-economic research on the responses of coastal communities to coastal pressures is needed.

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[36] https://unfccc.int/process-and-meetings/the-paris-agreement

[37] https://www.cbd.int/gbf/targets/3/

4

Tools, barriers and enablers to build coastal resilience

Credit: Eugene Farrell

Coastal pressures and their impacts prompt the need for human responses to build resilience (see Box 1 in Introduction for definition of coastal resilience). However, the multitude of interacting pressures in the coastal zone makes it uniquely difficult to govern. Coastal zones host diverse economic activities, cultures, and political arrangements and this influences governance efforts towards just transitions and enhancing resilience. Competition between the many users of coastal marine and terrestrial space and the environmental, economic and social impacts of both exogenic and endogenic pressures prompts the need for a holistic and systems-based approach to the management of coastal zones that considers the complexity of the system and the diverse users of coastal space (Bennett et al., 2022).

The challenge of building and enhancing resilience is a political and science-driven attempt to organise the actions of people (Farrell et al., 2023). The science aspect refers to understanding the impact of pressures and the extent to which they could disrupt human life, and physical and natural capital, through scientific observations and model predictions. The political-driven aspect refers to the deeply human phenomena including ideologies, societal values and paradigms, demographic factors such as age and gender, and the political climate. There are many barriers and enablers to human action, including factors specific to the coastal context. Applying a political lens to the enablers and barriers to enhancing coastal resilience highlights the necessity to embrace the context-specific, social-ecological, cultural and political processes such as the structural inequalities that underlie historically-produced vulnerabilities (Grasham et al., 2021). This Chapter discusses available “tools” to build coastal resilience including management and policy options, scientific data, technology and observations, as well as their associated barriers and enablers. Coastal protection and Nature-based Solutions (NbS) are described as examples of specific tools that can be used to build resilience to coastal pressures.

4.1 Pathways to build resilience

The concept of resilience is gradually replacing traditional management approaches and is becoming ubiquitous in research programmes and government strategy reports. Within European Union (EU) and national governments, resilience is viewed as a proactive expression of community and sectoral engagement in climate action and other policy areas including biodiversity, ecosystem loss and human health (Patel et al., 2017). This has been accompanied by debate as to what constitutes resilience (see section 1.2) and whether it is the same for governments, individuals, communities and industry (Nelson, 2011).

Pathways towards coastal resilience should first focus on minimising pressures and developing effective responses against pressures and threats to coastal zones that cannot be minimised,

Credit: Leonhard Niederwimmer (Pixabay)

Competition between the many users of coastal space and the environmental, economic and social impacts of multiple pressures prompts the need for a holistic and systems-based management approach.

Historically, pressures on the coastal zone and risk from extreme events have not prevented the occupation of the coast.

while simultaneously maintaining the socio-politico-economic integrity and welfare of human coastal communities. When considerable local and global management efforts to reverse human pressures and undesirable changes are made, they are highly expensive in terms of intergenerational equity when they are taken after regime shifts take place, with potential irreversible ecological and socioeconomic costs, thereby negatively affecting future generations. Appropriate responses may face obstacles but also benefit from potential catalysts. This is a significant task that depends on transnational agreements, management and policy frameworks (see Chapter 2), institutions and regulations. Its success will depend on resilient coastal communities with adaptive capacity to respond to pressures on Coastal Social-Ecological Systems (CSESs), determining the proper scale and level of action, and policy coherence, integration and implementation.

The focus of CSES management needs to transition from asking how the coastlines can be "saved" from pressures such as erosion or how they can become flood proof, to considering how they can be managed in a sustainable, holistic way so that they can adapt and transform in response to change for the benefit of both nature and people. Policies and regulations relevant to the coastal zone need to build in flexibility, take advantage of co-benefits (such as the creation of space for recreation and nature), and involve diverse stakeholders for co-design, awareness-raising, decision-making and policy implementation (OECD, 2019). There is no one-size-fits-all management approach given the diversity of uses of coastal zones (see Chapter 2 for an overview of frameworks relevant for coastal management). Barriers to effective coastal management include when policies or Directives are not reviewed frequently enough or do not have sufficient monitoring and enforcement of commitments. There are also ongoing challenges in Europe to achieve a compromise between EU Directives and coastal management that is the responsibility of Member States. The time needed for regulations which Member States are responsible for to change in response to adapted EU Directives reduces the efficacy of the adaptive management process. More recently, there has been an emphasis on decentralisation and integrated management of the seas and coasts in Europe (e.g. France[38]). This requires management and advisory bodies to liase between sectors and different administrative levels with interests in coastal management. The United Kingdom (UK)'s shoreline management plans[39] are based on adaptive management and are updated perioically based on lessons learnt. They are also a good example of integrated and inclusive coastal management as they have been developed by coastal groups with members from local councils and the Environment Agency.

In November 2019, the European Parliament declared a climate emergency, acknowledging the existing scientific and political information relating to climate change. Of the 27 EU Member States, nine have now declared a climate emergency (Howarth et al., 2021). Some Member States have since developed explicit policies on climate action and others have coupled their policy response to

[38] https://coastal-management.eu/governance/france.html

[39] https://www.gov.uk/government/publications/shoreline-management-plans-smps

both the climate and ecological crises, both of which are relevant to enhancing the resilience of CSESs. However, there are major issues meaning that Member States cannot meet current climate and environmental obligations, nor plan for and respond to future challenges and legislation. These issues are strategic (e.g. lacking specific details for implementation of goals), structural (e.g. gaps in knowledge, learning and feedback loops), and related to capacity and resources (e.g. inadequate resources and/or expertise).

Trade-offs exist and governments must recognise and appreciate how everything is connected – beaches, dunes, wetlands, farming, pollution, human health – in order to make good planning decisions. A systems approach and holistic perspective is needed to enable resilience. Historically, pressures on the coastal zone and risk from extreme events have not prevented the occupation of the coast. People accepted the risks in exchange for the wealth of benefits, especially those founded in culture and place identity, which they perceive to exceed personal damages (Costas et al., 2015). This local perception of risk can be different to the vision of policymakers, coastal managers, insurers and scientists thereby complicating the operationalisation of new climate and environmental policies created to address social and economic development needs. The pathway to a preferred future resilient state will require negotiation and compromises within and between different stakeholder groups. It is important to also recognise that tipping points exist for management strategies, when change means that certain measures are no longer sufficient. These are know as 'adaptation tipping points' and are explored further in the Ocean and Climate Chapter of Navigating the Future VI[40].

4.1.1 Resilient human communities

There are five key, interconnected factors that enable the adaptive capacity of human communities at a local level, namely assets, flexibility, social organisation, learning and agency (Cinner et al., 2018). This finding builds on adaptive capacity, vulnerability and resilience concepts (Adger, 2003), and overlaps with Ostrom's (1990) governance factors that enable collective action, and factors that contribute to community resilience (Patel *et al.,* 2017) (see section 2.8). Enhancing adaptive capacity by addressing these five factors allows adaptation to the multiple interacting pressures acting on the resilience of CSESs. These five factors may be relevant to enhance adaptive capacity beyond the community level, e.g. at national or European levels, although data collection is needed to verify their efficacy in these wider contexts. These five factors are described below, with examples:

1. **Assets** that people can draw upon in times of need include finance, expertise, tools, technology, information, knowledge, natural and other resources. These can be either public or private. Over time, policy and economic sectors have generated infrastructure and social, economic, social-ecological, and political structures, which may be disrupted by significant changes. New policies can require risky and expensive long-term investments that might be difficult to maintain while potentially disrupting critical revenue generating activities (Whitney et al., 2017). Community assets vary and communities vary in their ability to access external assets. For example, Zsamboky et al. (2011) highlight the variation in available assets (e.g. lack of funding) as a barrier for coastal communities in the UK to meet the challenges of climate change. For more information on financing see section 4.1.4 and for observations, monitoring, data and models contributing to knowledge see section 4.2.

2. **Flexibility** to change strategies can be enabled by economic and social diversity, and by having human communities that are knowledgeable, well-connected and open to innovation. Barriers to flexibility include dependence on a single industry, the legacy of previous approaches such as infrastructure and human settlement patterns, the institutional legacy of previous policy, social or geographic isolation, lack of knowledge and data, being heavily invested in existing solutions and industries, and lack of assets. Examples of institutional legacy creating barriers to flexibility are the national regulatory decisions made in Norway in the 1930's creating a "locked-in" (i.e. limited openness to change and the use of sub-optimal policies even though better alternatives are present) development path for local indigenous (Sami) communities (Johnsen & Søreng, 2018) and the EU's preference for large-scale fisheries, inhibiting the development of community-anchored and more environmentally friendly small-scale fisheries (Percy & O'Riordan, 2020). For more information on access to knowledge and data see section 4.2.

3. **Social organisation** refers to the ability to organise and act as a collective, to cooperate, and to share knowledge. This can be formal or informal and either public or private. Traditionally, policies are based on economic sectors, and this has created siloed policy communities that struggle to coordinate and integrate existing sector goals and policies, and incorporate new ones (Piet et al., 2019). More acceptable policies can be enabled by bottom-up policy formulation where stakeholders are central. The Maritime Spatial Planning (MSP) Directive rethinks coastal management, although it has not fully materialised yet due to the time it takes for EU Directives to be transcribed into national policies and for Member States to create their marine spatial plans. Trust and cooperation are essential characteristics for the resilience of the process of equitable social organisation within CSESs (Villasante et al., 2021). In Europe, citizens must be willing to adopt policies that have long-term and indirect benefits. They must trust both the government and other citizens. Trust can be generated by "social capital", which can be either bonding (i.e. strong social relationships that tie groups together with similar backgrounds or interests), or bridging (i.e. connections that link groups together who typically may be divided across society). Strong community ties (bonding social capital) can be created by empowering stakeholders, but this can in turn create friction if bridging capital is lacking (Agnitsch et al., 2006). For example, in the Dutch fishing industry, de Vos & Mol (2010) studied the introduction of trans-regional fisher study groups and found that these study groups established new personal contacts

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[40] https://www.marineboard.eu/navigating-future-vi

among fishers and other actors, leading to the recognition of common values and interests. This in turn generated new lines of trust across the boundaries of traditionally closed, highly homogenous, and insular fisher communities. It contributed to increased cooperation within the broader fishing community, and with scientists and national authorities. For more information on cross-sectoral policies see section 4.1.3, and for stakeholder engagement see the six-step approach to building coastal resilience in section 2.10.

4. **Learning** to recognise and adapt to change, while managing uncertainty is an important factor to enhance adaptive capacity. Coastal residents experience changes in their ecosystem services and can contribute data, but obtaining systematic natural and social scientific knowledge that is useful to individual communities is often a barrier to their learning. Another barrier is if this knowledge is not shared among all interested parties, if the messages are not understandable, or communities are not open to the message that the knowledge sends. Ciampa et al. (2021) illustrate the usefulness of accessing necessary local knowledge for engaging stakeholders in developing solutions to coastal flooding. For more information on observations, monitoring and data sharing see section 4.2.

5. **Agency** is the ability of individuals or groups of people to choose how to respond to environmental change. It is enabled by people's beliefs in their own ability to manage situations and control events, and it requires empowerment, motivation and understanding. Agency is created by investment in and ownership of local projects. Conversely, Dijk et al. (2016) showed that it is difficult to convince ageing populations of the Wadden Sea to invest in averting future problems. Communities lack agency when the causes of change lie beyond their control (Folke et al., 2007), as was the case in the UK when national authorities assumed control of the process to designate Marine Protected Areas (MPAs), known as marine conservation zones. This shift to a top-down process led to the disengagement of a wide range of stakeholders in the process and less support for the proposals for protected sites (Gaymer et al., 2014). Financial and other assets, such as knowledge, skills, innovation potential, as well as organisational factors such as including stakeholders and giving them the political space to make and apply decisions, also enable agency. People need to know their range of options to be able to plan and have the assets to make a meaningful choice among these options. Trust in the data and other information is essential for action, for which assets such as education, organisational capacity and social capital are critical. For more information on stakeholder engagement see the six-step approach to building coastal resilience in section 2.10 and for observations, monitoring, data and models contributing to knowledge see section 4.2.

Credit: Daniela Anahi Asar

Institutional legacy can create barriers to flexibility, such as preference for large-scale fisheries, which inhibits the development of community-anchored and more environmentally friendly small-scale fisheries.


Credit: Eugene Farrell

Coastal communities are essential for implementing solutions to coastal resilience.

4.1.2 Scale and level of action

Identifying the scale at which to operationalise policy responses to the pressures outlined in Chapter 3 is fundamental (Folke et al., 2007). Polycentric governance is a key principle for enhancing resilience of Social-Ecological Systems (SESs), and involves the interaction between well-connected, multiple governing bodies to make and enforce rules. However, the lack of principles on how to implement this type of governance is a challenge (Biggs et al., 2012). The implementation of global targets for climate, biodiversity and sustainable development should go beyond the responsibility of one minister or policy community. It requires the active involvement of all policy communities and a wide range of stakeholders for a whole-of-government/whole-of-society perspective. This will require high-level political commitment, strategic policy transfer, and effective and well-functioning institutional coordination mechanisms.

It could be tempting to assume that the highest authority (e.g. the nation-state or, in some cases, international bodies facilitating the interactions among nation-states) should create the policies because of the cumulative effects generated by sectors operating in the coastal zones. However, researchers have found smaller groups of stakeholders or "coastal communities" (Agnitsch et al., 2006) to be an essential level, because this is where people experience and enact their lives. There is a portfolio of potential policy solutions at local, regional and national level. However, local government, delivering adaptation and mitigation strategies informed by both national and local actors, plays an important role in responding to climate change and coastal management (Porter et al., 2015).

Climate change is a new area of responsibility for local authorities, with new resource demands and challenges. Programmes for capacity building, and mobilisation of financial and human resources and tools, are needed to provide support to local governments to enable effective planning for resilient coasts, including climate mitigation and adaptation. Protection, enhancement and restoration plans for coastal ecosystems and other NbS (see section 4.4) need to be prioritised locally and nationally. Operationalising effective national plans and mechanisms to meet global and EU biodiversity and climate targets, and coastal management are not mutually exclusive. These plans need to be fair and consider social, economic and environmental factors, especially in marginalised communities, and they should be coordinated to not negatively impact neighbouring communities.

Managing the coast at a scale too large or too small can create competition among communities, deepen regional imbalances, disperse resources, and can lead to the mismanagement of sectors. In between the two extreme levels (local vs global), "regions[41]" are a flexible and effective level of governance, recognizing not only sectoral differences, but also differences among the same sectors operating in different coastal zones and varying socio-economic roles of coastal zones (Graziano et al., 2022).

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[41] In the context of this document, 'regions' refers to European marine regions e.g. Baltic, Mediterranean, North-East Atlantic and Black Sea.

Resilience frameworks (see Chapter 2) should be used to assess what structures or processes can facilitate action at all levels: from individual, household, social group and community to national, regional and European. To understand the enablers and barriers to actions that might enhance or erode resilience along the coast, inspiration can be drawn from these frameworks while understanding that each case exists within a very specific regional context containing different stakeholders.

4.1.3 Policy coherence, integration and implementation

One of the key challenges to enhancing coastal resilience is ensuring that policy responses are coherent across all sectors and various levels of governance, meaning that they have a holistic approach with aligned objectives that do not undermine or conflict with each other. This is needed to enhance the social organisation needed for the adaptive capacity of human communities (see section 4.1.1). Governance institutions, including government, public and private agencies, and private actors, tend to be "locked into" ways of thinking and working that reflect their traditionally siloed origins organised by economic sector. Silos generate institutional barriers that can be difficult to transcend in the effort to develop integrated approaches.

Policy coherence can be a problem within climate change policy, and also in how other policies respond to climate change, where sectors interpret objectives differently. The European Green Deal and its Climate Law, creates spatial conflicts that could impact other EU policies, such as the EU Biodiversity Strategy, which calls for 30% protection of land and sea by 2030[42]. The area that will be needed for offshore renewable energy installations, and the area that will need to be protected, will inevitably cause conflicts with other users, such as fishers or the shipping industry. Another example is the desire to develop coastal tourism in line with the Sustainable Blue Economy Strategy, which might not be coherent with the aims of nature conservation (Wolf et al., 2019). Undoubtedly, the spatial configuration of many coastal areas creates conflicts over resources, space and sometimes identity. It is essential that policies are designed and implemented with special attention to both mitigating conflict (before the problem arises) and problem-solving solutions (when a conflict is already apparent).

Coherence is important both for policy and the way in which policies are translated into action. There is a distinction between policy coherence, namely, that policies communicate the same issues and options, and policy integration, i.e. that policies are effectively translated into institutional structures and efforts "on the ground" (Di Gregorio et al., 2017). The evolution of coastal management policies should include a step-by-step approach, whereby countries assess their existing capacities and design future policies that are consistent with the capacity level they can reasonably reach within a given time frame (OECD, 2003). Responding to current and future climate change demands urgent, transformative


Credit: Sheila Heymans

The desire to develop coastal tourism might not be coherent with the aims of nature conservation and can create spatial conflict.

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[42] https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en

change, yet in many policy systems inaction continues to prevail (Groen et al., 2023) e.g. due to deep-rooted institutional policy and planning practices that are resistant to change and the persistence of business-as-usual through a "lock-in perspective" (Cooper & McKenna, 2008). It is paramount that new national and regional policies have mechanisms to identify and overcome these barriers, and develop new innovative, sustainable and resilient economic spaces (Anton et al., 2020).

Participatory tools are needed to facilitate new management approaches that prioritise environmental protection whilst respecting economic, social and cultural sustainable development. The Coastal Collaborative Land-Sea Integration Platform[43] is a good example of a tool that enables integration of management and planning across the land-sea boundary. It provides a platform for knowledge exchange and sharing solutions, best practices, guidelines, roadmaps, system models of land-sea interactions and scenarios from different regions across the EU, and a forum for stakeholders to exchange experiences. Other examples of participatory tools are the recently developed JPI Oceans Knowledge Hub on Sea-Level Rise[44], which is a networking platform to generate, synthesise, exchange and integrate knowledge on local, regional and global historic and future sea-level rise; and the European Blue Forum[45] stakeholder group aiming to discuss shared challenges and priorities, and to develop solutions. Serious gaming[46] involving role play and simulations, as is used in the Marine Spatial Planning Challenge[47], is another tool that can help stakeholders understand complex topics, promote long-term systems thinking, experiment with consequences of different choices over time and understand the interests of diverse groups. The MSP Challenge uses advanced game technology to integrate marine data and simulation models into a game for stakeholder engagement and planning. Finally, the Coastal Resilience Index developed by the National Oceanographic and Atmospheric Administration (NOAA) in the United States has a Coastal Storms Program that is a good example of a self-assessment tool that has been developed for communities to assess their level of preparedness for extreme events[48].

Due to the Integrated Coastal Zone Management (ICZM) aspect of maritime spatial planning not entering into force with the MSP Directive (see section 2.4), it is not possible to determine the potential impacts of climate change on the coasts of Europe because MSP only applies from the lower water mark to the seaward limits of national jurisdiction (Farrell et al., 2023). The lack of an ICZM Directive in the EU means that there is no legislative obligation of Member States to design and operationalise plans to sustainably manage our coastline that consider land-sea interactions. This has resulted in the distribution of investments in coastal management being disproportionately low for marginalised coastal communities considering their vulnerable location and unique natural heritage. This low investment level is also due to lack of awareness of the value of natural capital. The climate and ecological emergencies, the inertia of institutions (i.e. unwillingness to act), difficulty to act and growing levels of inequality highlight the urgent need for transformative policies that embrace new forms of understanding and acting.

At present, the thresholds of the eleven Marine Strategy Framework Directive (MSFD) Descriptors for Good Environmental Status (GES) are being addressed independently of each other, with limited consideration of the policy overlaps or cumulative effects of these different stressors. Without coherent policy implementation, managing each pressure individually creates significant cumulative effects. For example, assuming that the loss of a small proportion of a species' population is acceptable within GES for each Descriptor does not consider cumulative loss. To address these cumulative effects, ecosystem-based management is needed. This is not a novel approach, but it is still not implemented in our Ocean or on the coasts (Heymans et al., 2018). Previous work has shown that recommendations from coastal adaptation or ecosystem-based management studies never get implemented locally because they carry too much political risk (Gibbs, 2016). Political influence usually follows initial studies on coastal urbanisation, climate adaptation or ecosystem-based management (i.e. to decide on risk, management options and strategies) because new policies will impact different stakeholders in different ways and could redistribute the community's resources. Besides lacking political support, adaptation measures are also deprioritised due to other obligations and short-term statutory duties, insufficient budgets and institutional capacity (OECD, 2003).

4.1.4 Financing

Finance is an important asset that enhances the adaptive capacity and resilience of human communities to be able to cope with pressures (see section 4.1.1). There is a need to align the global economy with sustainability goals, which will require transformative change in government policies, and radical shifts in deeply-rooted human values, education systems and behaviour (Nyström et al., 2019). Top-down influence from governments and finance ministries is needed to drive change in banks and financial markets (Jouffray et al., 2019).

The 2021 European Commission communication "Forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate[49]" specifically targets long-term financing to incentivise and assist Member States to rollout NbS via InvestEU[50]. This mechanism is in addition to Cohesion Policy programmes, investments, eco-schemes and advisory services which cumulatively have potential to change how the Common Agricultural Policy (COM/2018/392 final, 2018) (at the land-sea boundary) and, potentially, the Common Fisheries Policy (when NbS come to fruition) are implemented to focus more on benefits from NbS. However, more investment and mecanisms are needed.

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[43] https://coastal-xchange.eu/

[44] https://www.jpi-oceans.eu/en/sea-level-rise

[45] https://maritime-spatial-planning.ec.europa.eu/european-blue-forum

[46] https://octogroup.org/serious-games-for-coastal-and-marine-conservation-management-and-adaptation/

[47] https://www.mspchallenge.info/

[48] https://toolkit.climate.gov/tool/coastal-resilience-index

[49] https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vlgmmvuksywg

[50] https://investeu.europa.eu/index_en

Galician shellfishers have developed a wide range of adaptation strategies to anticipate and respond to climate change impacts, namely harvesting pricier and more abundant species, reducing household expenses and increasing social involvement in shellfishery associations.

The multiple social and economic values of natural capital to our economies, and societies and the interdependencies of nature with other societal objectives need to be reflected in private and public decisions, indicators and accounting systems (IPBES, 2022). We have less than half of the investment needed for the NbS required to limit climate change to 1.5°C above pre-industrial levels and to halt biodiversity loss by 2025, and only a third of the investment needed to achieve 2030 targets (UNEP, 2022). Investment in marine NbS is only 9% of the total NbS investment, and this needs to increase given the potential role of the Ocean in mitigating climate change and supporting adaptation, food security and biodiversity (UNEP, 2022). Currently global investment in MPAs amounts to only 980 million USD, but we will need between 8-11 billion USD to achieve the 30x30 targets, and private sector investment in NbS is currently only 17% of total NbS investment and needs to increase (UNEP, 2022). A stable regulatory and policy environment, high quality, investible projects, and ways to overcome the higher risk associated with Ocean sectors are needed to finance a sustainable Ocean economy (Sumaila et al., 2021).

The Ocean economy should generate benefits to all, especially vulnerable groups such as women, youth and marginalised communities (Bennett et al., 2022). For example, in Galicia, Spain women shellfishers are strongly affected by the impacts of climate change. Less fishing experience and lower engagement in fisher associations tend to increase the economic vulnerability of fishers. Vulnerability decreases with larger households, while fishers who pay a mortgage and live in households with fewer active members tend to be more vulnerable. Galician shellfishers have developed a wide range of adaptation strategies to anticipate and respond to climate change impacts, namely harvesting pricier and more abundant species, reducing household expenses and increasing social involvement in shellfishery associations (Villasante et al., 2022b).

Knowledge, data and human capacity are required to stop financing activities that work against nature and to develop private-public partnerships to simulate the flow of investments. We therefore need a holistic set of financial mechanisms in Europe to support various activities that contribute to coastal resilience, through supporting relevant activities, including the consideration of multiple values of ecosystem services (IPBES, 2022, see section 2.5). Progress is being made in this regard with the new EU taxonomy for sustainable activities[51] that aims to help direct investments to activities in line with the objectives of the European Green Deal and for public and private funders to be informed on the sustainability of activites they fund.

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[51] https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en

4.2 Observations, monitoring, data and models

Knowledge and understanding of coastal processes and change is critical to make informed planning decisions that reduce the short-, medium- and long-term risks of climate change and other coastal pressures to our natural capital, development and infrastructure. Increasing and improving access to knowledge is key to enhancing assets, flexibility, learning and agency of human communities, thereby increasing their adaptive capacity (see section 4.1.1). To adopt sustainable and resilient pathways, it is necessary to understand the complex system dynamics of coastal areas and the interactions between the multiple and interacting pressures. This requires coherence between research communities at the land-sea interface, as is currently being done by the International Centre for Advanced Studies on River-Sea Systems (DANUBIUS-RI[52]), a pan-European research infrastructure supporting interdisciplinary research. Improved observation, monitoring, data analysis and storage, and modelling capacity are also required, including the integration and prioritisation of local and indigenous knowledge, which can contribute significantly to developing innovative solutions to coastal resilience (Porri et al., 2023).

4.2.1 Coastal observation and monitoring services

Multi-platform (i.e. satellite, airbourne and *in situ*) and multi-scale observations in the coastal zone are needed to understand and predict changes in CSESs on appropriate spatial and temporal scales. While satellites allow the collection of data with high spatio-temporal resolution, *in situ* observations are equally important to capture changes that occur below the surface.

Integrated coastal Ocean observing systems have been operationalised by European Regional Operational Oceanographic Systems (ROOS[53]), which are structures within the European Global Ocean Observing System (EuroGOOS[54]), to address the full value chain from observations to data, models, and services and products for end users across Europe. An example of a ROOS is the Mediterranean Operational Network for the Global Ocean Observing System (MONGOOS[55]), which functions also as a global regional alliance to include North African countries. Examples of multidisciplinary and multi-platform coastal observatories delivering physical, biological, and chemical data and climate information include the Coastal Observing System for Northern and Arctic Seas (COSYNA[56]), Balearic Islands Coastal Observing and Forecasting System (SOCIB[57]), and the Monitoring Forecasting and Information System for the Greek Seas (POSEIDON[58]). In addition, over the last 10 years, the Joint European Research Infrastructure network for Coastal Observatories (JERICO[59]) has been developing an integrated, pan-European, multidisciplinary and multiplatform research infrastructure of coastal observatories focused on a holistic approach to observing and monitoring changes in coastal marine systems covering the land, sea and atmosphere interface. These infrastructures are critical and need to be operationalised for monitoring and developing alert systems (see Atlantic Maritime Strategy Pillar 4 on Coastal Resilience[60]).

For satellite observations, a technical challenge is determining how to seamlessly embed space-based services (e.g. Copernicus) and datasets within research programmes. Examples include the European Space Agency funded Coastal Erosion projects (Space for Shore[61] and Coastal Erosion[62]) that have brought together services providers and authoritative end-users to operationalise the use of satellite borne observation to monitor coastal erosion. A challenge also exists to incorporate socio-economic data with physical data to enable a full system's approach. The European Marine Observation and Data Network (EMODnet) is addressing this through their Human Activities data layers[63], which give information on different Blue Economy users of the coastal area through different use cases[64] such as detection of abnormal vessel behaviour or geological data that is used by the offshore renewable energy sector. EMODnet's multi-disciplinary marine data service also includes marine and land-sea geological products, including high resolution maps of coastal erosion, e.g., shoreline migration, showing which coastlines are eroding, accreting and staying stable[65]. This integration of socio-economic and physical data can enable researchers to achieve insights into physical and socio-economic system behaviour not previously possible.

Another example is the Earth Observation Advanced Science Tools for Sea level Extreme Events (EOatSEE[66]), which is a European Space Agency-funded project investigating short- and long-term coastal change and Ocean processes, including extreme sea-level events and coastal hazards, using the latest advances in Earth observation technology. Earth observations can enhance the spatial and temporal resolution of remotely sensed images, although there is a trade-off between temporal and spatial resolutions as it is difficult to have highly detailed images with the daily overpass of satellites covering large regions (Poggio & Gimona, 2013). Geospatial Big Data, artificial intelligence and deep-learning can resolve the low spatial and temporal resolution of environmental modelling by downscaling and providing (near) real-time observations covering very large surface areas with high temporal frequency (i.e. five days between observations at a single point).

Coastal operational networks feed data to pan-European portals such as EMODnet and Copernicus Marine Environment Monitoring Services (CMEMS[67]), which are user-driven services that create open and freely accessible data-driven decision tools for regional governments and research agencies policy requirements on monitoring. Copernicus coordinates a dedicated "Coastal Thematic Hub[68]" that gathers coastal Earth observation data and information for use in policy, academic and industry applications, and the European Copernicus Coastal Flood Awareness System[69] to support

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[52] https://www.danubius-ri.eu/index.html

[53] https://eurogoos.eu/regional-operational-oceanographic-systems/

[54] https://eurogoos.eu/

[55] https://mongoos.eurogoos.eu/

[56] https://www.hereon.de/institutes/carbon_cycles/cosyna/index.php.en

[57] https://www.socib.es/

[58] https://poseidon.hcmr.gr/

[59] https://www.jerico-ri.eu/about/

[60] https://atlantic-maritime-strategy.ec.europa.eu/en/article/pillar-4-coastal-resilience-healthy-ocean

[61] https://eo4society.esa.int/projects/coastal-erosion-1/

[62] https://eo4society.esa.int/projects/coastal-erosion-2/

[63] https://emodnet.ec.europa.eu/en/human-activities

[64] https://emodnet.ec.europa.eu/en/use-cases?field_portal_taxonomy_tid=27

[65] emodnet.ec.europa.eu

[66] https://eoatsee.eu/

[67] https://marine.copernicus.eu/

[68] https://www.coastal.hub.copernicus.eu/

[69] https://www.efas.eu/en


Credit: Sheila Heymans

Coastal observing and monitoring services provide data on pressures including waves, extreme sea-level and storm surges.

preparatory measures before flooding strikes.

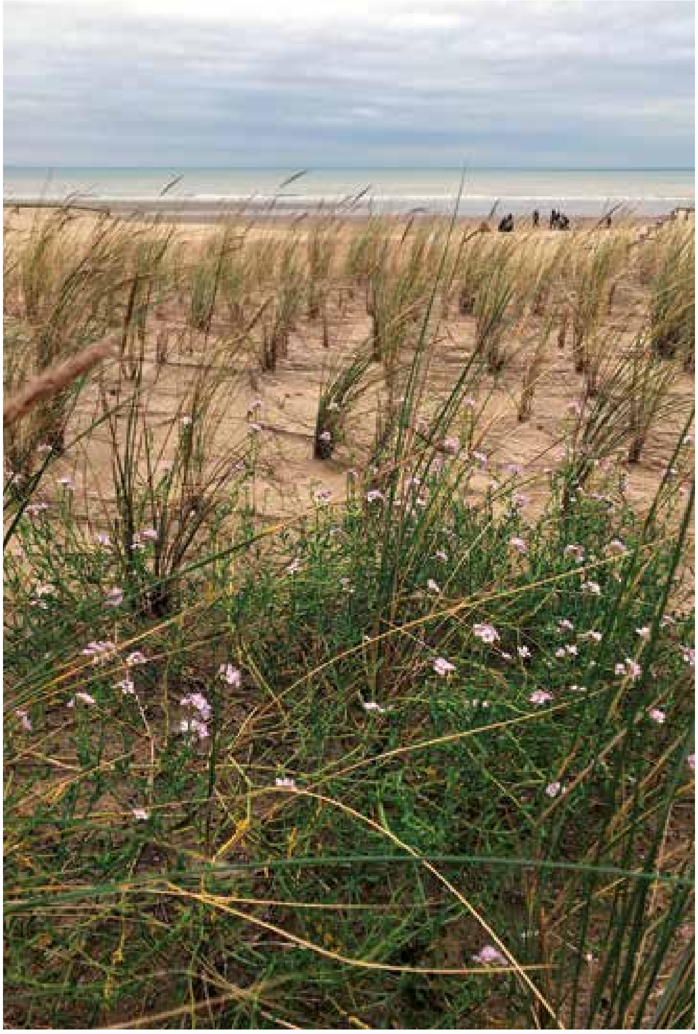
These services help to meet the unprecedented number and diverse array of monitoring requirements needed to assess the status and pressures within the coastal zone including:

- Environmental data (wave, biogeochemistry, sea-ice, atmosphere) with high to very high spatial and temporal resolution, from models, satellite and *in situ* observations;
- River inputs (freshwater, sediments, nutrients, waste) for historical, near real-time and forecasts;
- Accounting for specific processes relevant for the coastal zone (e.g. tides, waves, upwelling, downwelling, harmful algal blooms, eutrophication, extreme sea levels including storm surges);
- Mapping of the status and changes in land/sea natural characteristics and human use;
- Land/sea habitat status, habitat change, species distribution and migration (including invasive species); and
- Marine/land pollution (including litter), and nutrient enrichment.

In addition, monitoring is necessary to follow up on the success of implemented tools and solutions to adaptation and mitigation of coastal pressures and to inform their potential modification. Barriers to the use of these services include when they are not compatible with a particular jurisdiction’s institutional framework, are not relevant to the needs of end users (Lawrence et al., 2021) and when practitioners are not sufficiently trained to use and extract data. The Policy Brief “Sustaining *in situ* Ocean observations in the Age of the Digital Ocean” (European Marine Board, 2021) highlights the benefits as well as the funding and governance challenges of *in situ* Ocean observations, and the investment needed for their transformation and sustainability. There are still observation-related barriers for research institutes, private companies, environmental agencies, NGOs, governmental and public agencies, national and local authorities and communities to realign their philosophy and/or structures with services and initiatives that mitigate pressures on the coastal zone. These barriers include (long-term) funding for observations, data access and management, perceived low reliability of climate information, and lack of engagement and/or communication between data producers and end users, or issues of scale, particularly extrapolations from large-to-small(er) spatial or temporal scales.

4.2.2 Data

Services developed using holistic and integrated datasets will better enable the streamlining of management practices (see Figure 1.2 of Chapter 1 for overview of European Legislative Frameworks relevant for Coastal Management). However, the availability and integration of multiple environmental and social datasets is a challenge and is needed to make the difficult planning decisions in coastal areas (Rumson et al., 2017). New approaches to data collection, analysis and visualisation are therefore required. Rapid advances in technology are revolutionising data collection, management and analysis of environmental and socio-economic datasets for coastal zones (Pollard et al., 2019). However, this does not necessarily mean that we have the right data to answer all the critical scientific questions and to make well-informed, data-driven management decisions on the sustainable use of coastal and marine resources (Guidi et al., 2020). The prodigious increase in volume of new and existing data is challenging. New analytical approaches are needed to deal with these diverse, disparate datasets, which span multiple disciplines and link environment with societal activities (de Alencar et al., 2020).


Credit: Sheila Heymans

The condition of 50% of dune habitats in Europe is unknown.

An example is the use of satellite-borne datasets, which is limited due to the large storage and processing requirements, and remains largely untapped for the coastal zone. These barriers have been overcome by at least three strategic initiatives funded by the European Commission: Coastal Waters Research Synergy Framework[70]; the H2020 Blue-Cloud and newly funded Blue-Cloud 2026[71]; and the European Space Agency's Coastal Thematic Exploitation Platform[72]. These platforms simplify the process of extracting relevant information from raw Earth observation data and provide access to a virtual environment where data processing is done before results can be downloaded. Advanced algorithms and methodologies enable the extraction of key physical parameters such as bathymetry, topography and land cover to be automated, drastically speeding up workflows.

EMODNet's "collect once and use many times" philosophy benefits all coastal and marine data users. Free and open access data is critical to enable the harmonisation and coordination of Europe's coastal observations, and to deliver information that, in time, should be linked to a suite of agreed upon coastal resilience indicators.

Significant data gaps also exist, for example in qualitative social datasets and in monitoring the status of European habitats. The condition of 63% of coastal habitats and 50% of dune habitats in Europe is unknown (Röschel et al., 2020) and therefore habitat areas in need of restoration are probably much larger than has been estimated. The EMB Working Group on Marine Habitat Mapping[73] will make recommendations to advance knowledge of *inter alia* marine habitat status in Europe. This barrier needs to be prioritised and explicitly linked with management interventions to enable the increase in restored habitats proposed as part of the EU's Nature Restoration Law (COM/2022/304 final, 2022). Data on the geographic variability in adaptive capacity of coastal human communities would also be useful to collect. In addition, there is a need for long-term datasets to be integrated into services in order to gain a historical perspective on current monitoring data, and citizen science initiatives can also make an important contribution to data collection (Garcia Soto et al., 2017).

4.2.3 Modelling, forecasting, scenario analysis and early warning systems

Modelling coastal change at local- and regional-scales is critical to understand how different pressures manifest and interact, and models should be validated by continuous observations and monitoring of key indicators. Forecasting and scenario analysis are used to explore the future using models. Forecasting is based on what is expected to happen and provides one possible future, while scenario analysis is based on what could happen under different conditions and provides multiple possible futures. Forecasting is more suitable for shorter-term planning, while scenario analysis is more useful for longer-term planning and to explore possible futures to help build anticipatory governance capacity to resolve conflict, e.g. in the fisheries sector (Spijkers et al., 2021).

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[70] https://cordis.europa.eu/project/id/687289

[71] https://blue-cloud.org/about-h2020-blue-cloud

[72] https://www.coastal-tep.eu/

[73] https://www.marineboard.eu/marine-habitat-mapping

Accurate forecasting and scenario analysis of coastal change requires rigorous consideration of local, regional and global factors, and reliable models based on knowledge of regional rates of sea-level change (e.g. best- to worst-case scenarios), and the impact of other natural and human influences (Cooper et al., 2011). In both cases uncertainty analysis should be included to indicate the range of future projections. Advances in Big Data (such as machine learning and data mining) and 'ensemble' modelling (using outputs from different models) can produce short- (<10 years) and long-term (100+ years) scenario analysis of coastal ecosystem responses to climate change (Berdugo et al., 2020), while probabilistic methods (i.e. those that predict the likelihood of events) can elucidate ecosystem dynamics and alternative states or potential thresholds (Dakos & Kéfi, 2022).

One example of shoreline forecast modelling is the "Forecasting Coastal Evolution" model (Davidson, 2021), which allows shoreline change in sediment budgets or sea-level to be predicted from days (i.e. storm events) to decades and beyond. It integrates waves, tidal and sea-level rise data with past and present beach measurements (e.g. sediment volume) to forecast short- and long-term beach evolution, which links to coastal resilience as ecosystems services provided by beaches include defence against erosion and flooding.

To reduce the high level of uncertainty of the current climate predictions at smaller spatial and temporal scales, we need better predictions at the regional- and local-level, since ecosystems react differently to climate change in different geographic regions. Geospatial data, e.g. from satellite observations (Mentaschi et al., 2018), allow regional "downscaling" of global/Ocean-basin climate change prediction models, which can assist in developing protection and adaptation measures to build and enhance resilience along vulnerable parts of the coast. For example, the Coordinated Regional Downscalling Experiment – European Domain (EURO-CORDEX[74]) initiative is advancing research towards an improved understanding of regional climate processes and their drivers, specifically regarding climate extremes (Jacob et al., 2020).

Addressing the impact of multiple stressors on CSESs, and the possible impact that policy drivers might have, requires a more complex approach, as explained in the European Marine Board Future Science Brief on Marine Ecosystem Modelling (Heymans et al., 2018). This requires linking outputs from physical models to biogeochemical models, and then using those to drive ecosystem models and network models (Wedding et al., 2022), and linking those to socio-economic models to understand how the changes that we make to the physical environment will impact the socio-economics of CSESs. This sets the foundation for the Digital Twin Ocean (DTO).

Any modelling of coastal change, either for forecasting or scenario analysis purposes, faces the challenge of visualising


Credit: Daniela Anahi Asar

The Digital Twin Ocean will enable researchers to predict how climate change and human activity will affect marine ecosystems.

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[74] https://www.euro-cordex.net/

and communicating the modelling assumptions, uncertainties and outcomes to both coastal specialists and decision-makers (e.g. Payo et al., 2020). The visualisation of simulation outcomes is difficult because the more abstract scientific visualisation techniques favoured by specialists for data exploration and hypothesis-testing do not always engage decision-makers and planners. Environmental models used in decision making should be transparent and reproducible, as well as adequately represent system properties and behaviours. For example, while sub-surface geology has long been recognised as an important factor for mesoscale coastal evolution (i.e. at time and length scales of the order 10 – 100 years and 10 – 100 km, Cowell et al., 1992), the problem of ensuring that models have sufficient representation of the sub-surface has often been approached in an ad-hoc way that makes it difficult to trace back to the original geological data. Pan European initiatives such as the Geological Survey for Europe[75] are partially addressing this barrier.

The European Commission's Destination Earth[76] initiative aims to develop a highly accurate global digital model of the Earth to model and predict natural and human activity, and the development and scenario testing for more sustainable development. Destination Earth will create digital twins of Earth to model Earth systems quickly, accurately and interactively and will give local detail and access to information. It aims to create "a digital space providing access to vast amounts of data, models, artificial intelligence and other tools, which will allow the replication of the properties and behaviours of marine systems, including Ocean currents and waves, marine life and human activities, and their interactions, in and near the sea" (European Commission, 2022). The DTO will include Big Data, scientific models and a cutting-edge virtual collaborative environment to allow access and provide a platform to share data to enable researchers to predict how climate change and human activity will affect marine ecosystems or to test the effectiveness of blue and green infrastructures resilient to sea-level rise.

Observations, data, modelling and forecasting all feed into the development of robust early warning systems, which are needed to detect and forecast major disruptions, hazards or coastal change (e.g. in geomorphology or ecology). These systems can reduce the vulnerabilities, risks and impacts linked to climate change and other pressures and allow coastal communities and relevant stakeholders to prepare and respond in a timely manner. Existing early warning systems and data hubs in Europe for extreme weather, climate events and risks include Meteoalarm[77], Copernicus Climate Change Service[78], and the Risk Data Hub of the Disaster Risk Management Knowledge Centre[79]. In addition, there are various national, sub-national and local-level early warning systems in Europe[80]. A significant challenge is the development of multi-hazarad early warning systems that consider the multiple interacting pressures in the coastal zone.

4.2.4 Resilience indicators

There are multiple guidelines available for measuring SES resilience. One example is the Resilience, Adaptation and Transformation Assessment Framework to operationalise these concepts to address global policy priorities (O'Connell et al., 2015). However, our ability to estimate measures of resilience variables in real-world situations remains challenging largely due to the many different approaches that vary by discipline. Within ecology, engineering and ecological resilience have been perceived as alternative 'worldviews' that are studied independently of each other using different metrics. Pimm (1984) defined engineering resilience as "the rate with which a system returns to a reference state after a disturbance", while Holling (1973) defined ecological resilience as "the magnitude of disturbance that can be absorbed before a system flips to another state". Efforts have attempted to bridge this gap to develop a coherent concept and measures of ecological resilience (Dakos & Kéfi, 2022). Studies in the realm of marine ecosystems in the Baltic Sea (Tomczak et al., 2013) and elsewhere (Heymans & Tomczak, 2016) have also quantified ecosystem resilience using ecological network analysis, however measurements of social and community resilience are limited (Saja et al., 2019). In addition, vulnerability assessments for both people and nature should be measured to assess ecological and social resilience.

There is no single number or metric to measure CSES resilience and no standardised approach to measure coastal resilience in Europe. Standardised resilience indicators are required to identify where pressures and threats to resilience exist, and where deviations from resilience occur. Such indicators would provide a useful starting point to coordinate transnational, national and regional efforts, and to focus participatory research with local communities and authorities to build resilience. A pan-European framework to clarify and standardise the definitions and practice of coastal resilience is needed to operationalise such a set of standardised indicators in practice.

Credit: NIOZ

Standardised resilience indicators would provide a useful starting point to focus participatory research with local communities and authorities to build resilience.

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[75] https://www.geologicalservice.eu/

[76] https://destination-earth.eu/

[77] https://www.meteoalarm.org/en/live/

[78] https://climate.copernicus.eu/

[79] https://drmkc.jrc.ec.europa.eu/risk-data-hub#/

[80] https://climate-adapt.eea.europa.eu/en/metadata/adaptation-options/establishment-of-early-warning-systems

Building artificial reefs is a type of blue-green, nature-based infrastructure for coastal protection which also increases local biodiversity.

Credit: O.Dugornay & M. Bouchoucha (Ifremer)

4.3 Coastal protection

Coastal protection and risk reduction measures are required to minimise the impact of continued sea-level rise, storm surges, coastal flooding and erosion along Europe's coastlines. Coastal protection is an important component of resilience during weather disasters and coastal protection infrastructure helps to minimise damage and support recovery. Coastal protection can consist of a spectrum of grey and blue-green infrastructure (Schoonees et al., 2019), which can be further classified according to their degree of 'naturalness' (Chávez et al., 2021). Although public awareness of blue-green infrastructure has significantly increased, its implementation in coastal areas is still limited and grey infrastructure is most frequently designed and implemented (Arkema et al., 2017). The choice of coastal protection strategy is context- and place- specific, and sometimes there is no feasible alternative to grey infrastructure e.g. in harbours. It is important to always consider in planning and monitoring the potential consequences of coastal protection strategies on the environment, e.g. on water quality, bottom topography, sediment characteristics and living organisms (Greene, 2002). In order to make informed site-specific decisions on coastal management interventions, an inventory is needed of the existing interventions that should include information on: their efficacy to build and enhance resilience (e.g. by reducing risk); their impacts on coastal ecosystems; their socio-economic impact; and their long-term value in preparing for sea-level rise, extreme weather events and changing socio-economic conditions. Resilient solutions to coastal protection are likely to be a mix of grey and blue-green (Singhvi et al., 2022).

4.3.1 Grey infrastructure

Grey infrastructure typically includes 'hard' engineered solutions and artificial man-made structures such as concrete seawalls, breakwaters, groynes, rock armour, stilling wave basins and storm surge barriers, and these can mimic natural processes. In most cases, grey infrastructures are single-purpose structures, with an expected design lifetime of around 50 years. They offer protection from erosion and/or flood risk and maintain the viability of buildings and socio-economic activities in many coastal locations. Grey infrastructure has historically been a preferred strategy because it delivers the most predictable levels of protection against coastal extremes and climate risks in specific locations. However, it has been used widely without any a priori knowledge of the "local" or "regional" coastal processes operating in the area. This leads to unintended consequences in adjacent coasts, including geomorphic and ecological impacts (Pilkey & Cooper, 2014) such as sediment deficits and chronic coastal erosion, beach lowering, blocking of natural littoral drift (i.e. the natural movement of sediment along the shoreline), habitat and biodiversity loss and coastal squeeze (i.e. the loss of natural habitats or deterioration of their quality arising from anthropogenic structures or actions, preventing the landward transgression of those habitats that would otherwise naturally occur in response to sea-level rise in combination with other coastal processes). Therefore, grey infrastructure can be both a barrier and an enabler to enhancing coastal resilience. It may provide a false sense of security and, over time, fail to adequately protect coastal communities and infrastructure from winter storms and sea-level rise, specifically if the infrastructure is not maintained and upgraded to account for future climate change. Current planning decisions on grey infrastructure focus on the risks emanating from coastal protection developments (e.g. ecosystem degradation; reduction and alteration of habitat; impacts on natural processes; increased erosion to adjacent coastlines; reduction of aesthetics of the coast; contribution to coastal squeeze). Building infrastructure that can fail catastrophically will reduce long-term coastal resilience as the rate of environmental change accelerates, creating a greater likelihood of failure. Grey infrastructure may therefore create liabilities rather than assets for future generations, who will bear the costs of its removal or replacement, thereby lowering the resilience of future generations (Hirschfeld & Hill, 2017). Planning decisions should consider the risks to the actual infrastructure from climate hazards (Flannery et al., 2015). One possible solution to build resilience in certain situations may be the removal or rearrangement of infrastructure. There is a growing requirement for grey infrastructure to be multi-functional, sustainable, resilient and to work with nature to provide ecosystem services (Naylor et al., 2017).

Credit: Sheila Heymans (top), Rijkswaterstaat (bottom)

Breakwaters (top) and storm surge barriers (bottom) are examples of grey infrastructure for coastal protection.

Credit: David Thomas, Bangor University

Figure 4.1 Bioblocks are habitat enhancement unit that create artificial pits and rock pools to provide habitat for native species.

4.3.2 Blue-green, nature-based infrastructure

Blue-green infrastructure can consist of hybrid infrastructure (see section 4.3.3), soft infrastructure and environmentally-friendly grey infrastructure (i.e. ecologically-enhanced hard infrastructure) (Schoonees et al., 2019). Soft infrastructure includes a range of landward NbS (see Section 4.4.1) and seaward NbS (see section 4.4.2) that contribute to dynamic coastal protection (i.e. with the potential to adjust to external pressures). Within Europe, NbS include fully natural solutions such as the conservation and restoration of saltmarshes, wetlands, dunes and beach ecosystems, kelp forests, seagrass meadows, oyster reefs and mussel beds, as well as building artificial reefs (Temmerman et al., 2013); managed natural solutions such as nourishment of beaches that mimic natural processes (although this can also be categorised as grey infrastructure when it does not take advantage of natural-processes); vegetated dunes and marshes; and 'green' structural engineering (e.g. vegetated engineering, sand fences that help to stabilise dunes). Bioblock (Figure 4.1) is a habitat enhancement unit that creates artificial pits and rock pools to provide habitat for native species (Firth et al., 2014) and is an example of environmentally-friendly grey infrastructure as it enhances biodiversity and reduce negative impacts of grey infrastructure (MacArthur et al., 2020). NbS contribute to resilience to pressures beyond those that require coastal protection and are explained in detail in section 4.4.

4.3.3 Hybrid solutions

Hybrid solutions combine natural (blue-green) features with grey infrastructure, where both the natural and grey-engineering aspects are required for reliable functioning (Schoonees et al., 2019). This approach combines nature-based and built infrastructures to provide maximal coastal protection by harnessing the strengths and minimising the weaknesses of both (Sutton-Grier et al., 2015). Examples include marsh-levee (levee is also known as a dyke) systems, dune-dyke systems, double dykes with transitional polders, and artificial beaches, dunes or shellfish reefs placed in front of seawalls to provide the first line of defence against storm waves, thus prolonging the life of the wall and providing added benefits (Schoonees et al., 2019). Research shows that the operational application of these techniques has been successful, yet their adoption into mainstream engineering practice remains limited (Moraes et al., 2022). The hybrid engineering approach is very attractive when nature-based infrastructure is inappropriate, unfeasible or too uncertain to deliver the required resilience and protection. Some of these hybrid solutions can also be viewed as poor substitutes for natural habitats and can be seen as 'greenwashing' to make new developments appear more acceptable (Firth et al., 2020), but this is not always the case.

Double dykes with transitional polders are examples of hybrid solutions to coastal protection.

4.3.4 Context-specific planning for coastal protection and risk management

Not all coasts are equal and physical settings will significantly affect the choice of coastal defence strategy (Haasnoot et al., 2019). The need for coastal protection structures to mitigate erosion and enhance flood safety depends on the large-scale morphology of the coastal landscape. Different strategies should be implemented in e.g. expansive, low-lying coastal landscapes formed by river deltas, narrow strips of economically valuable low-lying land backed by much higher elevated areas, high coastlines such as fjords and the extensive cliff coastlines, and expansive gently sloping areas.

The expansive, low-lying coastal landscapes formed by river deltas, such as the North-East coast of Italy between Venice and Ravenna and the Scheldt-Rhine-Meuse delta on the coast of Belgium and the Netherlands, are areas most in need of coastal flood defences. Here, “hold the line” solutions, aiming to maintain the coastline at its current position, may have clear benefits in terms of short-term protection against erosion and flooding, yet these may prove unsustainable in the long-term given projected sea-level rise. Building wide landward flood defences may be a better solution, for which hybrid grey-green solutions are key. An example is the concept of building transitional polders between double dykes (Zhu et al., 2020; Figure 4.2), where natural processes are used to gradually elevate low-lying areas, enhancing their ability to maintain long-term flood safety. The concept is heavily debated and large-scale pilots are under discussion in the Netherlands. A first Dutch pilot project[81] uses a system where the outer dyke remains the primary flood-protection, while in the future, the system of both dykes and the land in between should function as primary flood-protection. These solutions can only be applied in spatious rural settings as they require large surface areas.

The elevated topography of high coastlines protects against flooding, however coastal erosion can be catastrophic.

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[81] https://www.provinciegroningen.nl/projecten/dubbele-dijk/

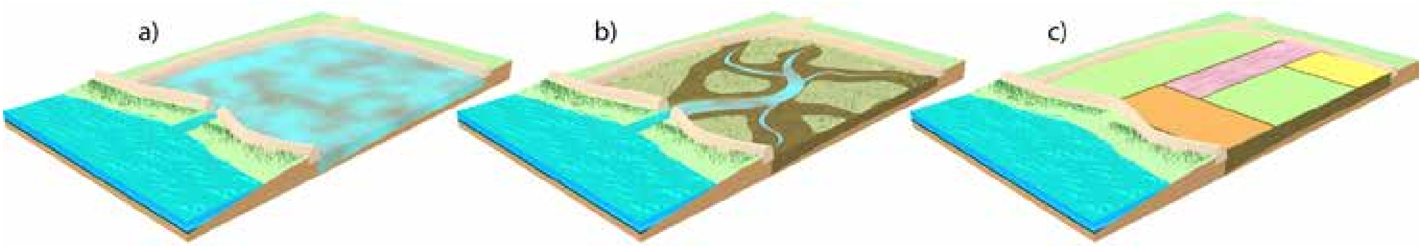

Figure 4.2 Evolution of double dykes. (a) Dykes inhibit sediment deposition on land, and to raise the land-level, the dyke is breached. (b) Sediment is imported by the tides and elevates the transitional polder. (c) The transitional polder may eventually be closed off and returned to its original function, e.g. farmland (Weisscher *et al.,* 2022; CC BY 4.0).

Conversely, for narrow strips of economically valuable low-lying land backed by much higher elevated areas, space for nature-based protection and retreating is typically sparse. Unless seaward NbS can be applied (e.g. by restoring wave-attenuating reefs), the only option is to apply engineering protection strategies. Examples of this type of landscape morphology include the French Riviera and parts of the coast of Spain, with cities like Santander and Bilbao in the north, and Malaga in the south.

High coastlines, such as fjords and the extensive cliff coastlines in Ireland and the UK, vary in geology and coastal dynamics (e.g. reduced sediment supply leading to thinning of beaches and accelerated cliff erosion). Although the elevated topography protects against flooding, erosion can be a catastrophic, irreversible hazard that has significant impacts. However, in the case where the majority of elevanted areas are safe and damage is limited to small, local-scale land and/or property loss, it may be considered not to invest in expensive coastal protection works, but rather to compensate communities for local loss.

Many grey and NbS traditionally aim to "hold the line". However, in expansive gently sloping areas, managed realignment or creating coastal setback zones is also an option. In applying managed realignment, engineering defences are removed and an area is allowed to regularly flood and accrete to follow sea-level rise, while urban developments have to retreat to higher ground. In applying coastal setback zones, buffer areas are designated where some or all types of development are forbidden or restricted, thereby making the area less sensitive to economic damages by occasional irregular flooding.

4.3.5 Examples of managed realignment and coastal setback zones

Medberry, a nature reserve in South-East England, is the largest managed realignment (e.g. managed retreat) of the open coast in Europe. Here the line of defence has been deliberately shifted back from the coast, creating 500 hectares of new functional wetland ecosystems (intertidal, freshwater and terrestrial habitats) and recreational areas. This flood risk management scheme is designed


Credit: Paula Kellett

Houses at risk of falling into the sea due to eroding chalk cliffs at Birling Gap on the south coast of the UK.


Credit: Peter Ganderton

Figure 4.3 The village of Torcross in England where the coastal planning strategy emphasises the geomorphic and ecological functioning and accepts loss of the road (Masselink & Lazarus, 2019; CC BY 4.0).

to be resilient to sea-level rise for at least 100 years and replaced a "hold the line" flood defence strategy consisting of an artificially maintained shingle bank (i.e. made of small round stones) that was not sustainable, did not protect the land from flooding and offered little in terms of ecosystem function and services. In the UK, government policies on coastal management are shifting away from viewing the coastline as static, linear or fixed, toward a coastal zone management approach that acknowledges and appreciates the inherent natural capital of dynamic coasts that serve to improve society's resilience to climate change impacts (Rennie et al., 2021).

Planning for coastal risk management can be a highly contentious issue especially where decisions are made to withdraw from maintaining an uneconomic defence or to undertake managed realignment (Greene, 2006). An example of withdrawing from maintaining an uneconomic defence is the village of Torcross in South Devon, UK, situated at the end of a narrow gravel barrier that separates a freshwater lagoon from the sea (Figure 4.3). An important road runs along the crest of the barrier. The management policy for the village is "hold the line", and recent reinforcement of the seawall has contributed to protecting against erosion and enhanced socio-economic resilience in the short- to medium-term (up to 2050), although compromising the natural behaviour of the beach in front of the seawall. This type of protection is costly, and in contrast the current management policy for the road is "no active intervention". In case of significant damage to the road it will not be repaired and will cease to function. This is likely to have a negative impact on socio-economic resilience, but it will allow the barrier–lagoon system to function more naturally, thus enhancing ecological and geomorphological resilience.

Another example of the contentious nature of coastal risk management is the village of Fairbourne in Cardigan Bay, Wales, UK. The land is protected by a natural shingle bank, which has been reinforced with a seawall to protect the village from the sea, and the village is protected from flooding from within the estuary by a tidal embankment. The village is at risk from climate change, increasing sea-level rise and increasing intensity of rainfall events[82] and although the local council recommended to decommission the village[83] (Figure 4.4) the local community council rejected these plans, arguing that the cost of decommissioning (£27 million) was based on a worst-case sea-level rise scenario and was substantially underestimated as it did not include compensation for residents who will lose their homes. It is still unknown if the Fairbourne community will become the first in the UK to be decommissioned as a result of climate change as it remains a contentious issue and the community continues to fight for increased support from government organisations. There are many locations in Europe similar to Fairbourne where building coastal defences may not be the best method of adaptation and managed retreat is inevitable. Reaching agreement for managed retreat will be extremely difficult. A first policy response would be for countries to clarify the social equity and justice aspects of these options, as well as the development of legislation and procedures around compensation for those forced to relocate.

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[82] https://democracy.gwynedd.llyw.cymru/Data/Cabinet%20(E)/20130122/Agenda/05_02_Shoreline%20Management%20Plan%20-%20Section%206%20Summary%20and%20Comparison%20of%20Policy.pdf

[83] http://fairbourne.info/wp-content/uploads/2019/10/Fairbourne-Masterplan-Structure_Final-Issue-2.pdf

Fairbourne Preliminary
Coastal Adaptation Masterplan

JULY 2018

Figure 4.4 The Fairbourne Coastal Adaptation Masterplan recommended to decommission the village.

In France, setback zones have been established after the major coastal storm Xynthia in 2010. Many Mediterranean countries also use coastal setback zones that restrict future construction, while rarely requiring existing assets to be relocated away from the flood zone e.g. the Italian region of Emilia-Romagna (Perini et al., 2016) and Croatia (Lincke et al., 2020). Lincke et al. (2020) found that the economic impacts of sea-level rise on coastal flooding can be reduced by 39% by combining protection and construction restriction in setback zones, and by 93% when combining protection and managed retreat in setback zones. This is significant when the costs of maintaining sandy beaches are high due to coastal erosion. However, research is needed on how to shift the mindset of people to be more open to migrating to areas away from the coast.

4.4 Nature-based Solutions (NbS)

NbS (see Box 1 in Introduction for definition) is an “umbrella concept” that includes a wide range of approaches, such as the ecosystem approach, sustainable management, ecosystem-based disaster risk reduction, building with nature, green infrastructure and blue-green infrastructure. The use of NbS to adapt to climate change is also known as “ecosystem-based adaptation”. NbS are an opportunity to build climate resilience, meet adaptation and biodiversity targets, and contribute to disaster risk reduction. NbS address multiple global societal challenges simultaneously (Cohen-Shacham et al., 2016). NbS can constitute the protection and/or enhancement of existing natural areas or restoration of natural areas to their previous extent and function. They can have multiple environmental (biodiversity recovery, carbon sequestration), social (reduced pollution, human health-related benefits, heat reduction) and economic (tourism, cost-effective solutions, new economies, green jobs) co-benefits that need to be identified, promoted and, where feasible and appropriate, monetised. For example, coastal habitat conservation and restoration projects that measure carbon fluxes are important to enable the inclusion of coastal blue carbon ecosystems into national greenhouse gas inventories (Cott et al., 2021), however more research is needed.

To ensure climate resilience we need to test new and scale-up known NbS (Riisager-Simonsen et al., 2022). The scaling-up of NbS is particularly relevant in Europe as the Biodiversity Strategy for 2030 stipulates that out of the 30% of terrestrial and marine habitats that must be protected, one-third must be under “strict protection”. The proposed Nature Restoration Law aims to repair ecosystems that are in poor condition (i.e. 80% of ecosystems). NbS are also specifically mentioned in the EU’s Sustainable Blue Economy Strategy. There is however work to do to increase awareness and acceptance of NbS among the general public compared with legacy grey infrastructure for coastal protection.

When using NbS for coastal protection, nature must be included in the design strategy from the start to ensure that these measures are beneficial to ecosystems. For example, in France, local and sub-national governments (municipalities, cities, regions and

Credit: Natalie Hicks (top), NIOZ (bottom)

Nature-based Solutions can constitute the protection and/or enhancement of existing natural areas or restoration of natural areas to their previous extent and function, such as salt marshes.

provinces) must integrate and prioritise NbS in their policies and regional climate and land-use plans with quantified and operational targets. For example, the LIFE project, Ad'Apto[84], demonstrates how ecosystems and natural coastal habitats can be included in flexible coastal management plans to improve climate change adaptation. NbS typically require more space than grey infrastructure. For example, an ecosystem used to attenuate waves before they reach a seawall should be wide enough to be effective during extreme storms when protection is particularly needed (Zhu et al., 2020), and the protection of natural coastal areas needs enough space to ensure natural coastal sediment dynamics occur to naturally shape shorelines[85]. They also require more time to develop and there is more uncertainty regarding their benefits.

Coastal protection and ecosystem persistence (i.e. the ability of an ecosystem to return to an equilibrium state after a perturbation) are two strongly interdependent issues which should be considered when designing resilient coastal defence strategies. While grey infrastructure flood defences are typically designed to be effective for at least 50 years, NbS require ecosystems to persist for at least the lifespan of the envisioned flood defence target (i.e. 50 to 100 years, Bouma et al., 2014). For dynamic shorelines (i.e. those that incorporate NbS), ecosystems can adjust to external pressures such as sea-level rise and increased storminess, can recover rapidly after storms (Bridges et al., 2015), and can potentially persist, whereas static shorelines, predominantly reinforced with grey infrastructure cannot (Möller, 2019). Coastal ecosystems may get lost or enhanced, depending on the solutions selected to defend the coast. Coastal defence strategies may also change ecosystems by physically shifting the coastline and a combination of conservation and active restoration ecosystem is needed to achieve ecosystem persistence. It is also essential to assess how climate change (i.e. global warming, storminess, sea-level rise, acidification and deoxygenation) will affect the future of the coastal ecosystem. For example, changing wind patterns impact coastal ecosystems in different ways. Some ecosystems are sensitive to small increases in average wind speeds, while others are only affected by more frequent storms (de Smit et al., 2021). Thus, changing wind conditions as a result of climate change can be used to predict the persistence of ecosystems, which are important for nature-based coastal protection. Investing in the restoration and protection of coastal ecosystems that through good local management will persist for sufficiently long periods compared to the investment required will enable support of critical ecosystem services and the recovery of flows of mass and energy to natural states (Chávez et al., 2021).

It might not be possible to restore these areas to their previous condition. The effectiveness of a particular NbS depends on the state of the ecosystem and its history (Riisager-Simonsen et al., 2022). Consideration of the impact of future coastal protection strategies on ecosystem function must always be included in the multidisciplinary frameworks discussed in Chapter 2. Integration with the more recent climate resilient pathways analyses (see section 2.7), may help to design climate resilient future coasts. There is a need for multidisciplinary projects to measure, model and monitor the physical, ecological, and socio-economic positive and negative impacts of both landward and seaward NbS to understand the scientific, economic, social and governance enablers and barriers to their implementation.

Credit: Johny Goerend (Unsplash)

Restoration of coastal habitats can reduce the risk of erosion and flooding and subsequent impacts of landslides.

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[84] https://www.lifeadapto.eu/

[85] http://www.eurosion.org/

Coastal habitats in pristine condition due to either restoration, long-term good management practices or lack of human interference, provide a wide range of ecosystem services, including biodiversity conservation, nutrient retention, carbon sequestration, water quality regulation, eco-tourism and recreation. As a result, restoration and conservation measures typically provide a positive return on investment, with an estimated saving of approximately €50 billion annually due to the reduction of associated disaster damage (European Environment Agency, 2021b). For example, natural restoration of coastal habitats can reduce the risks of erosion and flooding by enhancing coastal morphology to be larger and stronger, which acts as a natural defence, or buffer, against erosion and flooding. This reduces the impact of sea-level rise, storms, coastal erosion and landslides, strengthening the stability of coastal morphology through vegetation. Root structures retain soil in terrestrial coastal environments, and vegetated structures, often including roots and shoots, retain sediments in shallow coastal areas. Both provide more stable physical coastal habitats that are more resilient to the impacts of erosion, and increasing vegetation cover that can act as an inland barrier during storms, attenuating up to 60% of wave energy (Cunniff & Schwartz, 2015), reducing the chances of flooding (Zhu et al., 2020) and reducing wind speed (European Environment Agency, 2021b).

We generally have the conceptual and technical understanding on how to effectively restore ecosystems, however successful implementation relies on: i) effective communication between scientists and practitioners so that state-of-the-art knowledge is used in restoration projects, ii) collaborative research between scientists and commercial contractors so that state-of-the art technology is applicable at the landscape-scale, iii) a shift in the way of thinking about coastal management so that restoration projects can be better connected to long-term environmental and socio-economic trends and activities in adjacent systems, and iv) sufficient financial resources to cover the high cost of restoration. Deely et al. (2020) found that there are institutional, governance, socio-cultural, technical, biophysical, knowledge and funding barriers that inhibit the development of NbS (Table 4.1).

4.4.1 Landward Nature-based Solutions

There are numerous ways that nature may help protect coastlines using landward NbS. For example, beaches with sand-dunes may prevent the need to build seawalls (Temmerman et al., 2013) and saltmarshes may reduce the depth of a seawall breach, saving lives (Zhu et al., 2020). The restoration of beaches, dunes, wetlands and salt marshes therefore reduce the impact of coastal hazards and are cost-effective if the cost of grey infrastructure is much higher than the value of the land or assets being protected, the long-term value of protection and the cost of restoration.

An example of the deployment of landward NbS is on the Dutch coastline, which is prone to flooding and had historically been eroding. In the past, the coast was protected using storm surge barriers and dykes. However, in 1990 the management strategy of the Dutch government shifted to “dynamic preservation”, which additionally uses other measures such as beach and dune nourishment (de Ruig & Hillen, 1997). In the 1980s, this was done

Credit: Sheila Heymans

Beaches with sand-dunes may prevent the need to build seawalls.

by bringing sand onto the beach, but around 1990 the strategy shifted towards nourishing the below-water foreshores and using the force of the sea to bring the sand onto the beaches[86]. In 2011, the Dutch government built a large sandy peninsula near The Hague, called the sand motor[87], using 21.5 million cubic metres of sand. This project uses the "Building with Nature principles[88]", where Ocean currents, waves and wind gradually spread this sand along the coast and into the dunes, thereby reinforcing the coastline in the long term, with less human effort and natural disturbance, while creating an attractive area for leisure and nature.

Table 4.1 Barriers to the development of NbS for coastal protection. Aadapted from Deely *et al.*, 2020 (CC BY 4.0).

INSTITUTIONAL AND GOVERNANCE BARRIERS
Lack of clear leadership
Roles and governance responsibilities
Interagency and interinstitutional cooperation
Long-term vision
Legislation and regulation
Lack of climate change policies
Competing priorities
SOCIO-CULTURAL
Culture and behaviour
Societal perception of Nature-based Solutions
Community empowerment
Impacts on future land use
KNOWLEDGE
Lack of knowledge
Institutional inexperience
Lack of technical guidance
Lack of success stories
Negative past experiences
Lack of clear cause-effect relationships
TECHNICAL AND BIOPHYSICAL
Onsite limitations
Design challenges
Construction challenges
Maintenance and performance challenges
FUNDING AND MARKET
Lack of funding
Estimating benefits and costs
Linking providers and users

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[86] https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/maatregelen-om-overstromingen-te-voorkomen/kustonderhoud/wat-is-zandsuppletie

[87] https://dezandmotor.nl/en/about-the-sand-motor/

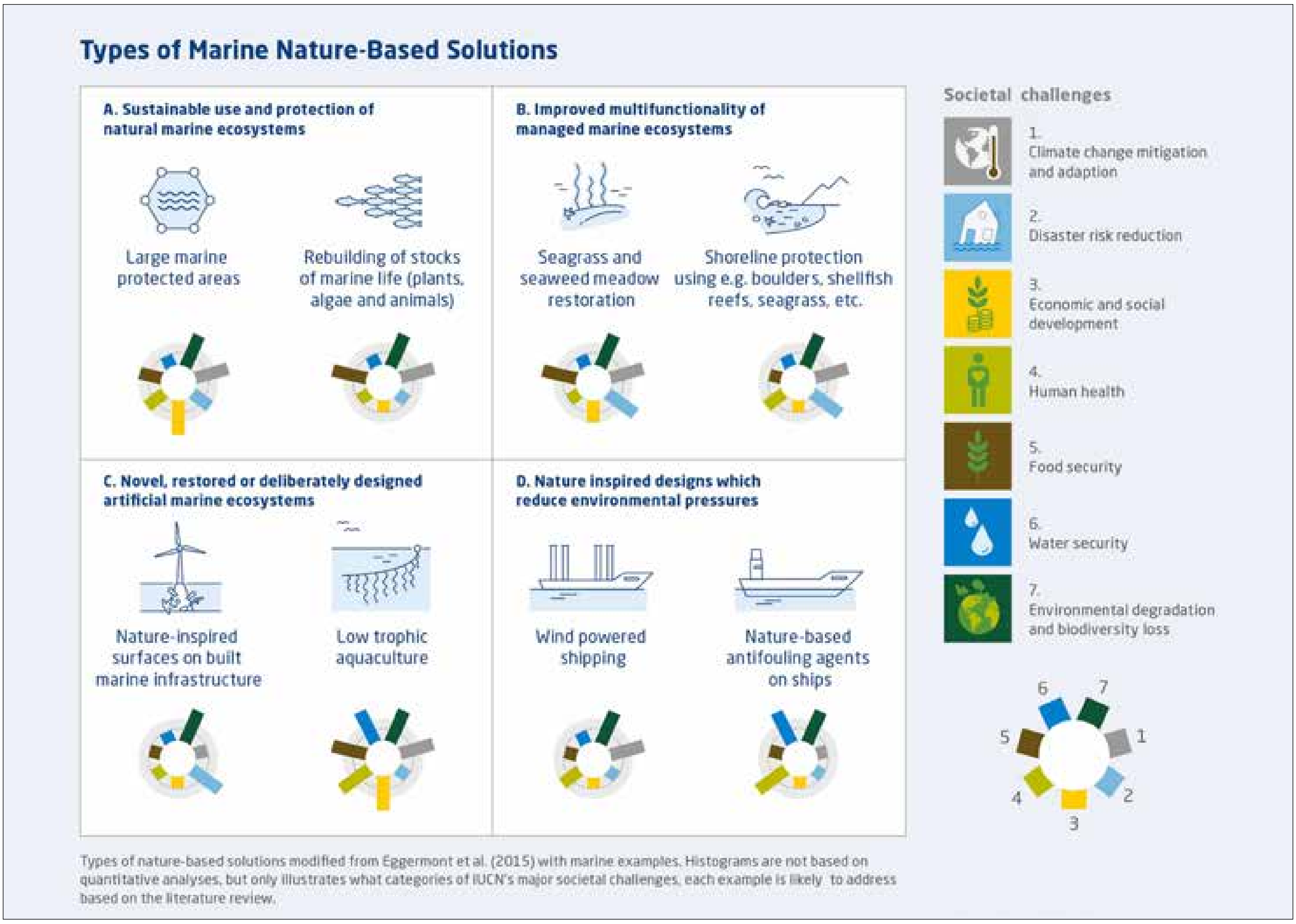
[88] https://boskalis.com/about-us/company-profile/building-with-nature

The hybrid solution of integrating ecosystem restoration and grey infrastructure enables the success of landward NbS. For example, when restoring intertidal ecosystems such as tidal flats, salt marshes and coastal dunes, it is important to consider the threats that these ecosystems will face and the extent to which these can be counteracted. Intertidal ecosystems are threatened by drowning under sea-level rise due to limited sediment availability, coastal squeeze and enhanced erosion due to larger waves. Counteracting these threats will require enough space for these ecosystems to shift landward, which depends on the management of the coast. Recent research on marsh restoration indicates that seedling expansion depends more on local conditions such as sediment supply, wave height and tidal flat bathymetry than on sea-level rise, providing hope for the impact of local management measures in light of climate change pressures, which are more difficult to manage (Hu et al., 2021).

4.4.2 Seaward Nature-based Solutions

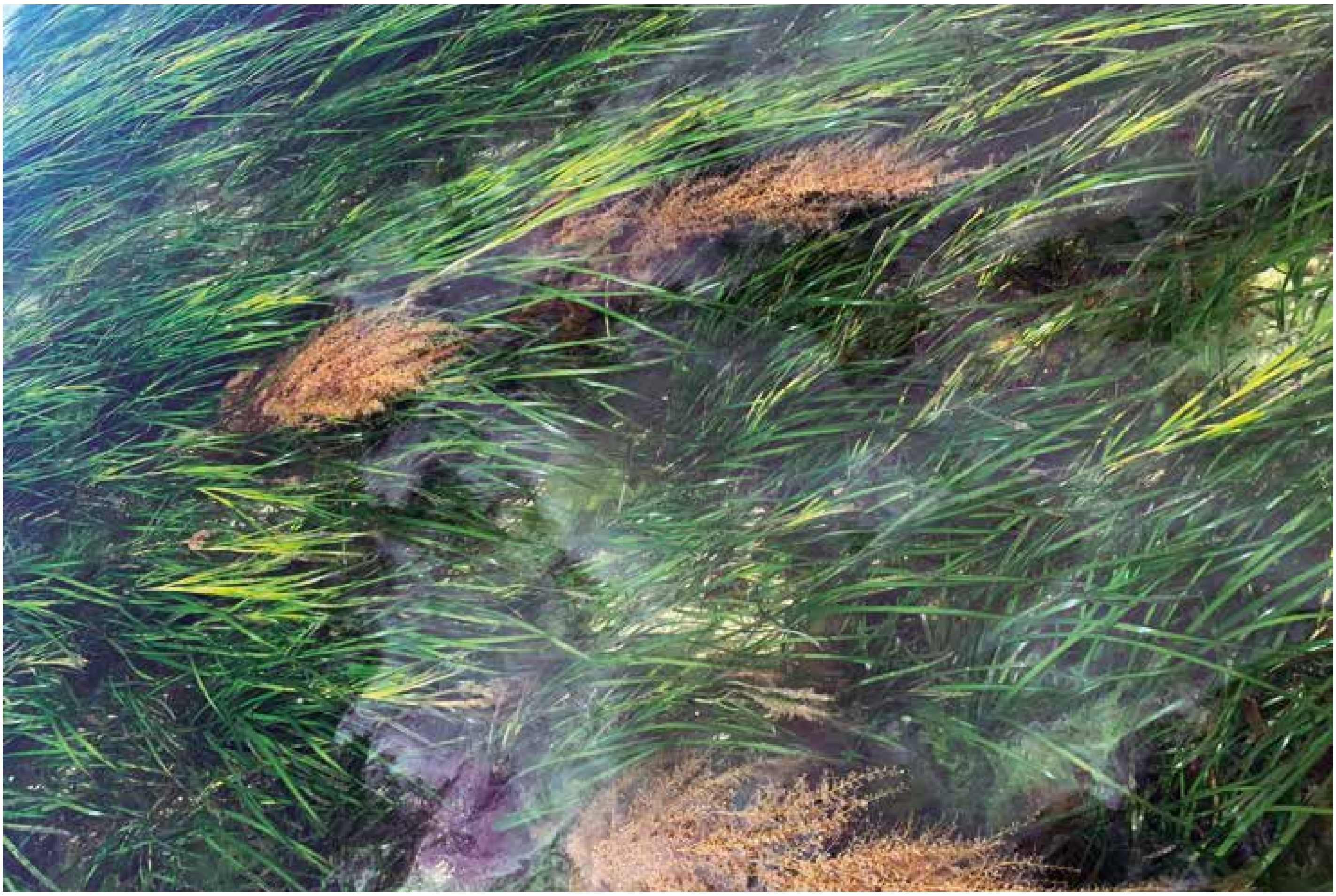
Riisager-Simonsen et al. (2022) have classified seaward NbS as: a) sustainable use and protection of natural marine ecosystems including through sustainable fisheries management and MPAs, b) improved multifunctionality of managed marine ecosystems, e.g. shoreline protection from marine ecosystems, c) novel, restored or deliberately designed artificial ecosystems, including low trophic aquaculture, and d) nature-inspired designs which reduce environmental pressures e.g. wind powered shipping (Figure 4.5). Seaward NbS may also include integrated multi-trophic aquaculture and the multi-use of Ocean space. These solutions can target both pressures and impacts.

In contrast to the landward NbS, the use of seaward NbS for coastal protection is relatively unexplored in terms of practice and planning, although the ability of coastal ecosystems such as kelp forests (Morris et al., 2020), seagrass meadows (Ondiviela et al., 2014), offshore reefs (Hynes et al., 2022) and mussel beds (Borsje et al., 2011) to reduce current velocities and dampen waves has been well documented. Seagrass meadows may also stabilise foreshores, preventing erosion and the need for expensive sand-nourishment (James et al., 2019). Offshore reefs may significantly reduce wave run-up onto shores and/or seawalls, but their effectiveness strongly depends on their position in the water column. As a rule of thumb, the higher a reef-structure is raised in the water, the more effective they are for wave attenuation (Bouma et al., 2014). Thus, reefs that are nowadays effective in wave attenuation, may become less effective if they cannot keep up with sea-level rise (James et al., 2023). Similarly, reefs that need to be submerged continuously will be less effective at attenuating waves in areas with large tidal



Types of nature-based solutions modified from Eggermont et al. (2015) with marine examples. Histograms are not based on quantitative analyses, but only illustrates what categories of IUCN's major societal challenges, each example is likely to address based on the literature review.

Figure 4.5 Types of marine Nature-based Solutions with examples. The length of the bars in the histograms illustrate links to the International Union for the Conservation of Nature's (IUCN) major societal challenges (Riisager-Simonsen *et al.*, 2022; CC BY NC 4.0).



Seagrass meadows may stabilise foreshores, preventing erosion and the need for expensive sand-nourishment.

amplitudes than in areas with small tidal amplitudes (Bouma et al., 2014). The benefits of seaward NbS are highly site-specific, e.g. the optimal conditions for enhanced coastal protection by seagrass ecosystems are shallow water with low wave energy, with the best protection provided by large, long lived and slow growing seagrass species that can withstand high hydrodynamic conditions (Ondiviela et al., 2014).

There are critical knowledge gaps on the feasibility and potential benefits of large-scale seaward NbS for coastal protection. Site-specific research on which coastal habitats and species provide protection under which conditions is a priority. For example, Morris et al. (2020) found that the ability of kelp beds to dampen wave energy depends on geomorphology, habitat location, forcing conditions, and the kelp species' morphology and extent. In spite of these knowledge gaps on site-specific applicability of specific solutions, the potential benefits of eco-engineering large-scale seaward NbS have the potential to address a wide-range of societal challenges in Europe and are attractive to commercial, recreational, environmental, cultural and societal stakeholders.

Another potentially promising NbS that needs more research is the use of low- and integrated multi-trophic aquaculture, which is required to enable a shift to sustainable food production from the sea (SAPEA, 2017). Low trophic aquaculture involves farming species such as bivalves, shellfish and seaweeds. It has low environmental impact, as they are grown without feeding or fertiliser, and it can also enhance biodiversity and remediate eutrophication (Krause et al., 2022). Multi-trophic aquaculture, also known as regenerative Ocean farming, involves farming multiple species together, using the waste from one species to feed others. This approach also requires zero inputs and therefore has low environmental impact, while contributing to shoreline protection by rebuilding marine ecosystems, providing blue carbon and nitrogen capture, mitigating excess nutrients, and supporting commercial farming through products that can be used as fertiliser and animal feed. Vertical Ocean farming can be combined with multi-trophic aquaculture to maximise the use of marine space. To expand low- and multi-trophic aquaculture it is necessary to reduce regulatory barriers that exist within the seafood industry and increase the market demand for such products (Krause et al., 2022).

Multiple EU-funded projects (e.g. Multi-use in European Seas[89], Marine Investment for the Blue Economy[90]) have studied the connectivity of uses and users of the multi-use of Ocean space, highlighted the importance of resource sharing to be sustainable, efficient and fair, and identified the many benefits either directly to the users themselves (e.g. economic benefits) and to society at large (e.g. ecological benefits).

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[89] https://maritime-spatial-planning.ec.europa.eu/projects/multi-use-european-seas

[90] https://maritime-spatial-planning.ec.europa.eu/projects/marine-investment-blue-economy

Credit: Scottish Institute of Marine Science (SAMS)

Seaweed farming is an example of low-trophic aquaculture with low environmental impact and the potential to enhance biodiversity.

Credit: Jonathan Muñoz Pérez

Clam farming in Thessaloniki, Greece.

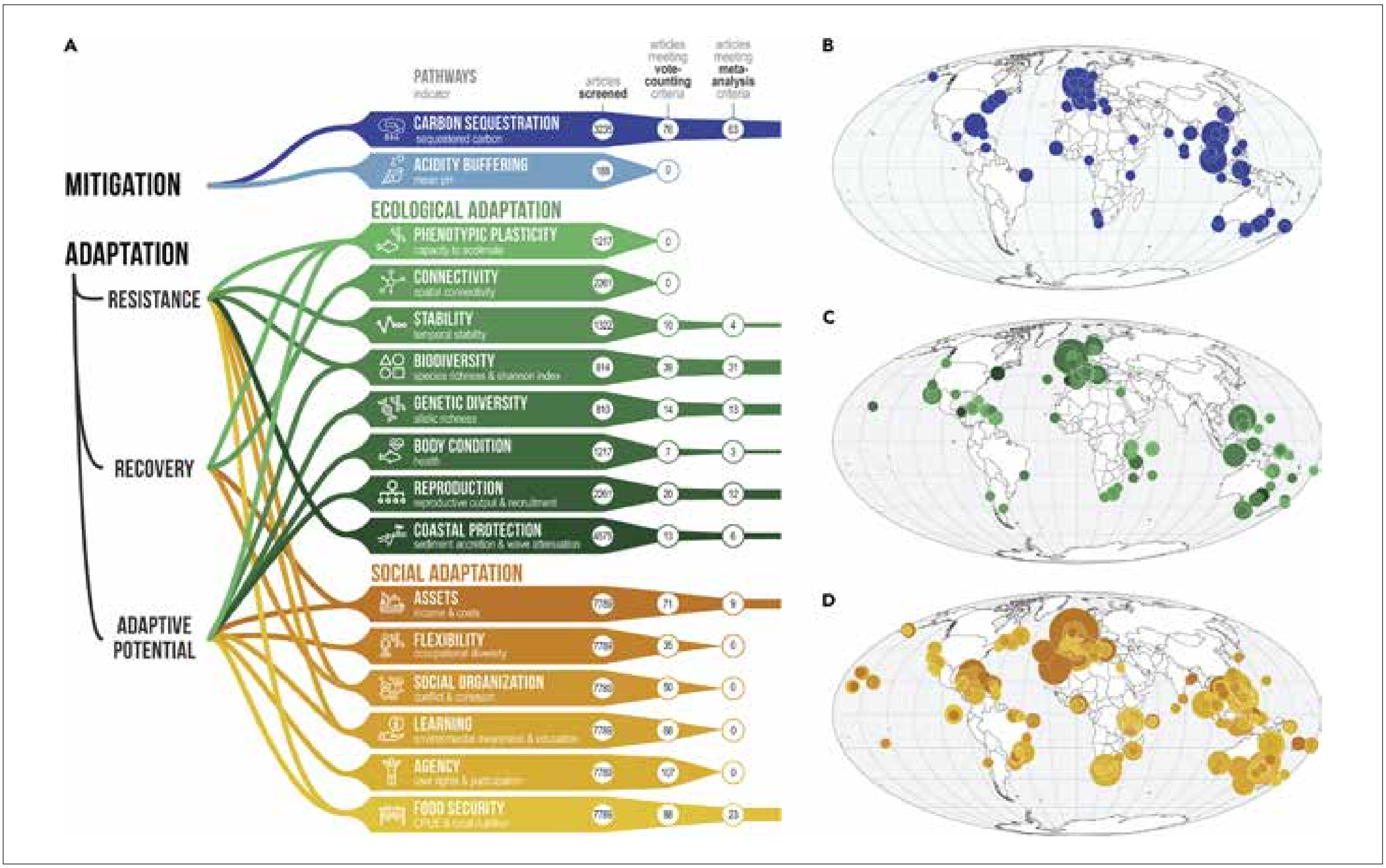

Figure 4.6 Overview of the contribution of Marine Protected Areas to climate change mitigation and adaptation. (A) indicates climate pathways and indicators, and (B-D) indicate the location of associated study sites (Jacquemont *et al.*, 2022; CC BY-NC-ND 4.0).

As seaward NbSs, active restoration and protection through MPAs offer huge potential to realise ambitious conservation, biodiversity and climate mitigation targets while enhancing coastal resilience (Duarte et al., 2020). MPAs that protect coastal ecosystems such as seagrass meadows, oyster reefs and mussel beds can provide shoreline protection through reduced erosion and wave attenuation, while sequestering carbon, increasing biodiversity, improving fisheries catches and income, and helping with social adaptation (Figure 4.6). However, the majority of these benefits depend on full protection (i.e. where no extractive activities are allowed) or high protection levels (i.e. where only infrequent use of some types of low impact activities are allowed) (Jacquemont et al., 2022). Transitioning from theoretical commitments to actual designation and implementation of MPAs is challenging. A key barrier to the implementation of conservation measures in MPAs in Europe is that all Member States must agree on proposed measures. A case-study in France highlighted additional barriers including differing stakeholder perceptions and impaired interactions between stakeholders and decision-makers, and identified potential enablers, such as enhancing participation and holding decision-makers accountable for their commitments, whilst mobilising financial capital and simplifying governance (Schultz et al., 2022).

Enhancing fisheries resilience as a seaward NbS requires adaptive management to respond to short-term stresses, long-term trends in climate change, changing fisheries yields and increasing fuel costs. Solutions include reducing the carbon footprint of fishing practices, changes in vessel and gear technologies, changes in fishing techniques, and shifts in target species to account for changes in species distribution due to rising water temperatures. The need for flexible, adaptive, well-informed and well-enforced management to effectively manage EU fisheries within a changing climate is highlighted in a review of case-studies encompassing the North-East and tropical Atlantic, and the Mediterranean, Baltic and Black Seas (Bastardie et al., 2022). These attributes help to ensure resistance, robustness and recovery of the system towards resilience.

4.5 Conclusions

Overarching science, innovation, management and policy recommendations are presented in Chapter 6. Achieving these recommendations will require overcoming a series of inter-related barriers in order to manage coasts using a systems approach. Enablers of action to build resilient coasts require integrated and innovative thinking and the organisation, investment, data and action to make that thinking meaningful. Research funding, data and knowledge systems need to be reoriented to support and develop the required integrated approaches to build coastal resilience. However, the legacy of the past persists and overcoming this heritage and further developing a holistic, integrated approach will require increased political will and a sense of urgency.

Credit: NIOZ

Measuring the position of flood marks on the dyke along the Dutch Wadden Sea.

5

Case-studies

Credit: Eugene Farrell

This Chapter describes three case-studies in coastal areas that are facing pressures on their Coastal Social-Ecological Systems (CSESs), namely the Maharees Peninsula in Ireland; the Venice Lagoon in Italy; and the Belgian Coast. These case-studies cover various different challenges and solutions for addressing coastal resilience and provide practical context to the theory within this document i.e. concepts and frameworks to assess coastal resilience (Chapter 2), pressures and impacts on the coast (Chapter 3), and tools, barriers and enablers to build coastal resilience (Chapter 4).

5.1 The Maharees Peninsula, Ireland

Background

The Maharees (Na Machairí in Gaelic) Peninsula is a low-lying island attached to the mainland by a narrow strip of land in County Kerry, Ireland. It is an area of outstanding natural beauty and hosts unique and protected species and habitats within a coastal landscape predominantly composed of sandy beaches and dunes. Coastal dunes are sensitive ecosystems protected under the European Union (EU)'s Habitats Directive and are home to diverse plant communities, which are often endemic species. The peninsula has the highest number of protected habitats (16) and third highest number of protected species (28) in Ireland. In the past four decades the area has transitioned away from farming and fishing towards tourism and recreation, with the main services now provided being recreation activities such as surfing, sea kayaking, windsurfing, paddle boarding, sea safari, waterparks and diving, and access to facilities that support these.

Pressures and impacts

The Maharees Peninsula is impacted by multiple pressures, including sea-level rise, heat waves, overcrowding from tourism and land-use management. Sea-level rise results in more frequent flooding and chronic coastal erosion and a one-meter rise in sea-level is projected by 2150 using the Intergovernmental Panel on Climate Change (IPCC) moderate greenhouse gas trajectory. In June 2023, a heatwave off the coast of Ireland resulted in sea-surface temperatures near Maharees almost 4°C higher than the average June temperature. Overcrowding due to tourism during the peak summer months creates traffic congestion, littering, pollution, trespassing, and increases in wild camping. Tresspassing and wild camping contribute to the destabilisation of the fragile dune ecosystems that are already highly vulnerable to Atlantic storms. Pressures linked to human impacts from land use management include grazing, sand extraction and the introduction of invasive

Credit: Maharees Conservation Association

Coastal resilience issues and Nature-based Solutions (NbS) at the Maharees Peninsula, Ireland.

Credit: Maharees Conservation Association

Figure 5.1 Example of community-led Nature-based Solution (installation of dune fences) to mitigate wind-blown sand leading to closure of the road in the Maharees Peninsula, Ireland.

species. Sea buckthorn, which was introduced in the 1970s to stabilise the shifting dunes and mitigate wind-blown sand hazards and has aggressively increased to cover 30% of the area over the last 50 years, and is negatively impacting the dune habitats and the sensitive and rare flora they foster.

Concepts and frameworks to assess coastal resilience

In the Maharees Peninsula, the "Building Coastal and Marine Resilience in Ireland" project has contextualised climate and development initiatives in the area using the IPCC opportunity space and climate resilient pathways approach (see section 2.7) to develop a roadmap using community-driven perceptions of a resilient future (Farrell et al., 2023). This approach can lead to states of higher resilience and lower risk (and vice-versa) and was used to structure the collaborative engagement within and across stakeholder groups to identify key vulnerabilities to climate change and other pressures and assess opportunities for reducing risk. It prompted discussions on past and future actions around a particular threat or opportunity and made the connections between agents, systems and institutions in order to build resilience (Moench, 2014). Two main outcomes from this approach were that that communities were able to identify their specific needs and articulate their own vision for a sustainable future, while government agencies were not set up to quickly react to the needs of coastal communities in Ireland.

Tools, barriers and enablers to build resilience

Resilience on the Maharees Peninsula is being built through continuous and collaborative engagement between the community volunteer group, Maharees Conservation Association (MCA[91]), formed in 2016, and relevant stakeholders in local and national government departments and public bodies, as well as the research agencies charged with managing the protected sites. The MCA was formed in response to both climate threats and pressures on the Maharees Peninsula CSES. The group evolved from the lived experiences of the pressures and threats the community faced as there were no apparent mechanisms for their voices to be heard within existing systems of local government and national agencies. The efforts of the MCA, which has received significant national and international recognition, have led to significant actions to mitigate some of these impacts. These sustained and targeted coastal management actions have been successful in the short-term and provide a window into what a future managed coastal landscape could encompass in Ireland (Farrell et al., 2023). The MCA has recognised that, despite their success and national recognition, their efforts neither lead to permanent solutions, nor to formal empowerment to manage pressures and determine their own resilience pathways. Continued community mobilisation and actions will maintain current efforts (despite the significant cost to local residents in terms of mental stress and workload). However, without a means to co-design and implement a sustainable, integrated and enforceable coastal plan, building resilience of the Maharees Peninsula will remain

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[91] https://www.mahareesconservation.com/

Figure 5.2 Community-led marram grass planting on the Maharees Peninsula, Ireland.

difficult. The "Building Coastal and Marine Resilience in Ireland" project identified key institutional (governance, legal responsibility, stakeholder forum, tourism) and technical (climate adaptation, funding, environmental designations, varying terminology around climate resilience and sustainability, erosion and flooding, seasonal tourism) barriers to the Maharees coastal community enhancing resilience to climate change. Other barriers to sustainable management of the area include lack of access to expertise and decision-makers who can support local volunteer actions, confusion of how to manage Special Areas of Conservation, lack of appreciation of the value and fragility of the coast by visitors, and the lack of access to funding and expertise to carry out any volunteer actions.

The project results emphasise the need for the coordination of actions and regional priorities of local authorities for coastal adaptation, the critical need to empower and resource local authorities and communities to manage their coasts, and a coherent national plan to prioritise erosion and flood risks. There is a need to coordinate community-led actions between a large number of government departments, agencies and other public and private sector interests whose actions and/or responsibilities can impede or facilitate the wishes of communities to both define and enact their vision of resilience. On the Maharees Peninsula, the community illustrated to the key stakeholders that coastal management and biodiversity conservation are not mutually exclusive. Community-led Nature-based Solutions (NbS), e.g. installation of dune fences to reduce sand deposition on the road (Figure 5.1) and community-led marram grass planting (Figure 5.2; Farrell & Farrell, 2023), can enhance resilience locally and provide the foundations for ancillary activities linked to education, heritage and tourism. The Maharees Peninsula community experiences are changing the future management of the Irish coastline. For example, newly established government bodies in Ireland will target all these legacy issues of coastal governance and management (The National Coastal Change Management Strategy Steering Group Climate Action Regional Offices, Climate Change Advisory Council Adaptation Committee) and are learning from the MCA and scientists working with them.

5.2 The Venice Lagoon, Italy

Background

The Venice Lagoon is a shallow coastal water body in the Northern Adriatic Sea with a surface area of 550km^2, hosting a unique and biodiverse environment and a UNESCO World Heritage Site. The Venice Lagoon System is the result of a complex interplay of historical, natural, and human forcing and of evolving adaptation and mitigation measures applied to maintain the system in its present state. For centuries, the Venice Lagoon was managed by carefully balancing the needs of economic growth, military security, sanitary/public health and food production. The maintenance of the Lagoon's water quality (which included both hydraulic and biogeochemical targets) was key to those objectives. To preserve the morphological structure of the Lagoon, restrictions to its use were imposed and severely enforced (Caniato, 2005). Effective water circulation was maintained by preventing the opposite trends of silting and erosion, and access to Venice from the mainland was hindered through lagoon management, which included sustainable exploitation of natural resources. The different Venice CSESs were tightly connected until the fall of the Venice Republic in 1797. Subsequently, and as a result of the industrial revolution, connections between local CSESs became weaker, cross-scale interactions increased, and multiple layers of governance were set. Thus, the ability to respond to changes and pressures slowed down. The onset of industrialisation and modernisation severely impacted the CSES cycles. Industrialisation decreased the local dependence on natural resources and the Lagoon lost its strategic priority. Natural resources lost their value and the CSES set new priorities that led to increasing pressures (see Chapter 3) on the ecosystems and loss of conservation priorities. Jobs and social structure changed. Motorboats shortened lagoon travel times, improved fishing efforts, enhanced individuality vs. community and prompted an open access attitude toward the exploitation of the Lagoon commons. Tourism became the dominant driver of change in the historical city of Venice, outcompeting residential needs and setting new targets and priorities. Tourism has increased constantly since the 1950's, going from 2.7 million tourists per year in 1960 to 12.9 million per year in 2019, while the number of residents decreased from 145,000 inhabitants in 1960 to 51,000 in 2020. These changes occurred faster than the ability of the governance systems to respond.

Pressures and impacts

The Lagoon balances opposing pressures of silting/erosion, eutrophication/dystrophy (i.e. nutrient concentrations which are too high or low to support life), and different economic interests (e.g. tourism; population growth; agriculture, aquaculture, and other industries; conservation; grey and blue-green coastal protection infrastructure). It is surrounded by a watershed heavily impacted by anthropogenic activities.

Credit: European Space Agency

The Venice Lagoon viewed from the Sentinel-2 processed in natural colour on 28th February 2019.

The main pressures and drivers on the Venice Lagoon system include:

1. Mass tourism: increase in global connections has increased mass tourism and large cruise ships that outcompete urban residential needs and priorities, and the traditional uses of the Lagoon;
2. High-waters: the concurring actions of climate change-induced sea-level rise and subsidence (driven by groundwater extraction mainly in the 1950's) generate high waters and flooding of the historical town (Umgiesser, 2020);
3. Fisheries crisis: the decline of traditional fisheries, the increasing efficiency of tools for fishing and the introduction of non-indigenous species, such as the Manila clam (Canu et al., 2010), induced several critical outcomes for the fishing community with impacts on the economy and the Lagoon ecology; and
4. Pollution: land-based industrial and agricultural pollution causing sediment pollution hot-spots and dystrophic events, in particular in the 1980's, before the implementation of new environmental legislation.

These drivers and pressures originate from inside the Venice Lagoon CSES, but are also connected to national, European, and global drivers such as climate change, tourism, the market demand for fisheries products, and the demand for industrial goods and agricultural products of the wider market (Figure 5.3).

Credit: Daniela Anahí Asar

Mass tourism and high waters are two of the main pressures affecting the Venice Lagoon.

Concepts and frameworks to assess coastal resilience

The Driver-Pressure-State-Impact-Response (DPSIR) framework (Figure 5.3; see section 2.3) has been used in several studies related to CSES analysis to manage the Venice Lagoon (e.g. Canu & Solidoro, 2017) and in the River Basin Management Plan (Autorità di Bacino del distretto della Alpi Orientali, 2015). These temporal and spatial scales of the DPSIR framework are critical issues for enhancing resilience that need to be considered. For example, the impacts of the introduction of the Manila clam were evident quite quickly (i.e. within a few years), whereas other impacts, such as high water, flooding and pollution took decades to be clearly recognised and tackled. In many cases, the Venice Lagoon system experienced some critical impacts due to the mismatch betweek the time required for a pressure to induce an impact and the time needed to respond. This is not only a symptom of ineffective planning and response, but also the result of the time needed to conduct intensive scientific, social and political democratic debates in times of quick paradigm and value changes, and in a very complex and stratified CSES. The time lag occurring between the recognition of the impacts and the implementation of the "response" is critical for the CSES. In some cases, this persisted for several years in the Venice Lagoon, until the CSES found a new configuration. The scientific, social and political debate arena also had to incorporate values, laws, rules and targets pertaining to the wider community (i.e. national and EU). The resilience of the Venice Lagoon System has also been promoted using an Integrated Coastal Zone Management (ICZM) approach (see section 2.4) for zoning the Lagoon and resolving conflict issues.

Tools, barriers and enablers to build coastal resilience

ICZM was supported by various tools including the best available scientific knowledge, used modelling tools to produce scenarios, and included social participation and debates. A range of blue-green infrastructures including morphological restoration of channels and salt marshes, and seagrass transplantation were employed. Grey infrastructures in the form of mobile barriers and elevation of lower parts of the historical city were used to prevent high water events and restore the Lagoon's morphology. A co-management approach supported by scientific knowledge was implemented to manage Lagoon fisheries, which improved governance and participation. Nutrient loads have been regulated since 1999 based on the total maximum allowed load (the Water Framework

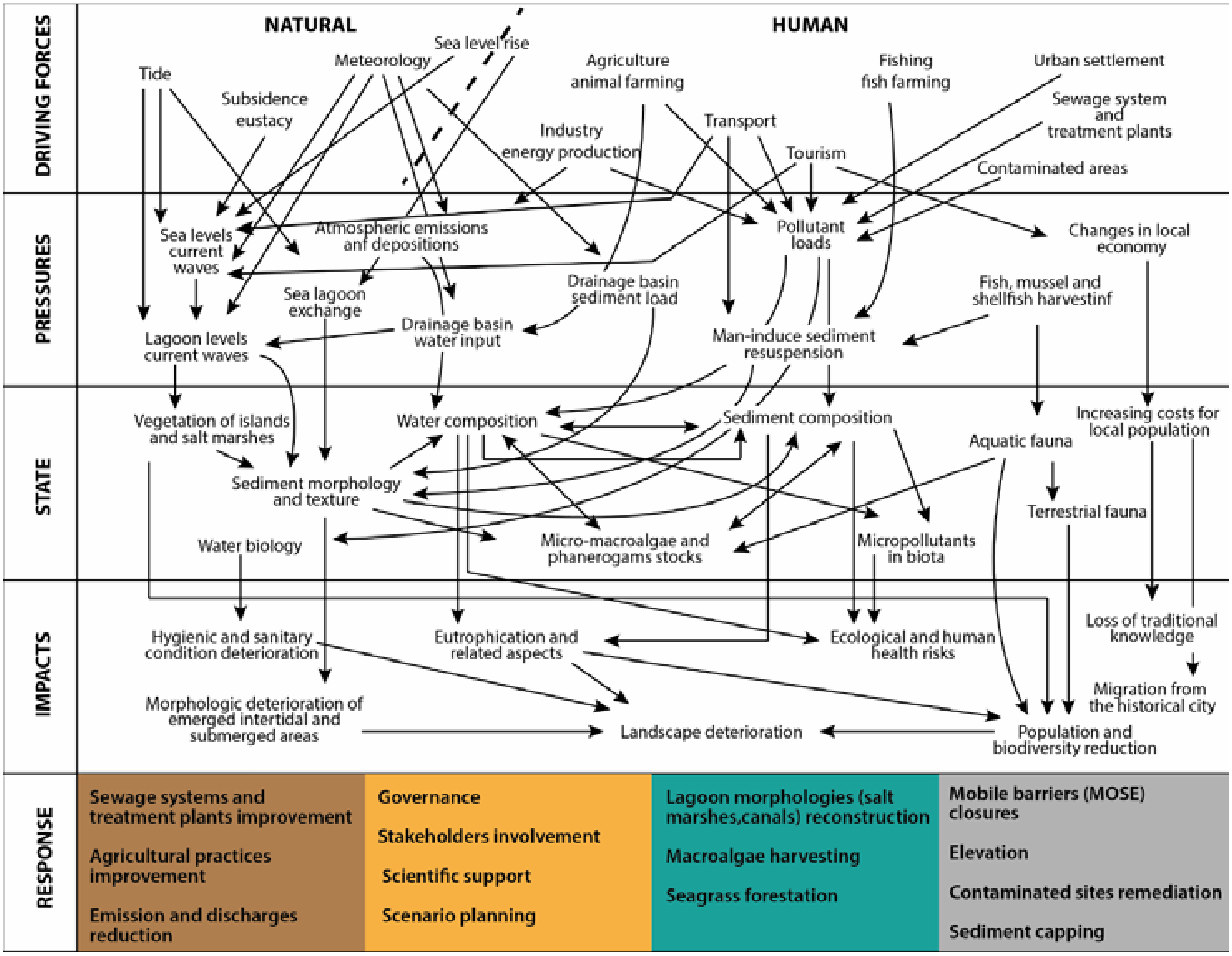

Figure 5.3 DPSIR scheme for the Venice Lagoon System highlighting the links between the most relevant drivers and related pressures, states and impacts. Responses are classified as 1) brown: action on drivers; 2) yellow: governance and knowledge; 3) green: green structures; 4) grey: grey infrastructures. Adapted from Canu *et al.,* 2011 (CC BY-NC 4.0).


Credit: Unsplash

The decline of traditional fisheries and the increasing efficiency of tools for fishing has had critical outcomes on the fishing community, local economy and Lagoon ecology.

Directive approach) and are supported by monitoring, assessment and scenario modelling.

Some of the aforementioned crises (fisheries, pollution, high waters) can be considered tackled: rules, laws and the institutional systems have been set, and the issues are governed and progressively recovering. This process has been supported by a special legislation for safeguarding Venice, the Special Law n°. 171 of 1973[92] (further followed by other Special Laws). This was the first legislation that considered all of the components of the Venice CSES in a broad perspective and was issued after the dramatic flood of 1966. These rules define the strategic objectives, the procedures to achieve them and the competences of the various actors implementing the interventions in a coordinated way. The Special Law has a broad perspective stating that the "Italian Republic guarantees the protection of the landscape, environment, historical, archaeological and artistic values of the city of Venice and the Lagoon, protects its hydraulic balance, preserves its environment from atmospheric and water pollution and ensures its socio-economic viability in the framework of general development and territorial planning of the Region".

The implementation of the law was not smooth. The need to coordinate among various actors with different and sometimes overlapping competencies was a challenge, and the existence of different and contrasting economic and socio-economic interests often polarised the debate and slowed decision-making. The pressure from tourism is still a hot issue. The debate is ongoing among the different stakeholders about which measures can be set to limit this pressure and to find a win-win solution that could benefit tourists, the tourism market and residents.

Trying to learn from past crises suggests that most of the tools needed to promote coastal resilience in the Venice Lagoon are available: i.e. laws and regulations, plans, funding, scientific knowledge (CSES data, assessments), debate arenas, attention of the media and citizen participation. However, the major issues are mediating among different perspectives and capacity to foresee the impacts from their onset. This points to the need for structuring a permanent and open exchange of information, supported by scenario planning, even for activities that can be seen as marginal in respect to the main CSES interests, and of adopting different perspectives. Past crises also highlight the need to address the issue of uncertainty, avoid oversimplification and promote real debate based on reciprocal learning.

Reducing uncertainty in assessments is strongly recommended. This requires (even for a coastal zone that is already heavily monitored) increased monitoring to address the effects of multiple and synergic impacts on the ecosystem. This will require integrating different observing systems in a coherent and unified platform, using autonomous and remote tools to collect data, using artificial intelligence to analyse Big Data, and exploiting new technological advances to improve both monitoring and the analysis of data.

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[92] http://www.edizionieuropee.it/law/html/34/zn5_01_004.html

5.3 The Belgian coast

Background

The Southern North Sea is a shallow sea that formed by sea-level rise after the last ice age. The Belgian coast is 67 km long and is part of the southern sandy North Sea coastline system. It consists of large sandy beaches, dunes and polders (i.e. low land reclaimed from water) and is always changing due to erosion and accretion. Currently available data indicates that 50% is in an erosive state, 20% is in accretion (i.e. the accumulation of coastal sediment) and the rest is stable (Deronde et al., 2004). The coast alternates between short natural stretches with high dunes and coastal towns where low dunes are present. The entire Belgian coast is situated in the Province of Flanders, and thus coastal policy is mainly a Flemish competence. The Flemish government is responsible for some impacts beyond the low water line, including coastal safety (i.e. coastal protection infrastructure and the maintenance of navigation channels to the Flemish seaports). Specifically, for floods originating from the sea, the Flemish Coastal Division of the Agency for Maritime Services and Coast[93] is responsible for protecting the Flemish coast against flooding. The federal government has competence for the area seaward from the low water line and the Flemish government also has competences with impact beyond the low water line.

Pressures and impacts

The pressures on the Belgian coast are both natural and anthropogenic. Long-term sea-level rise is estimated at two mm/year for the period 1925-2019 (Willems, 2014). Storm surges occur at least once per year, which often cause significant beach erosion and increased flooding hazard. The coast was also substantially modified in the mid-19th century when coastal protection and polders were built (Charlier et al., 1995). It is densely populated: around 32% of the Belgian population live in ten coastal towns and cities. More than 50% of the coastal area is intensively used by maritime transport, commercial harbours and ports, marinas, tourism and recreation, and the low-lying polders further inland are mainly used for agricultural purposes.

Concepts and frameworks to assess coastal resilience

With the need to protect the coast from erosion and flooding, the Risk, Vulnerability and Adaptive capacity (RVA) framework has been applied to improve adaptive capacity (see section 2.6). An initial vulnerability assessment of coastal protection in 2007 and 2008 showed that about one third of the coast needed additional protection against the impact of heavy storms (i.e. those with a probability of occurrence of 0.1% per year). Sea-level rise and other climate change-related effects (such as changes in storm and precipitation intensity and frequency) could exacerbate this vulnerability. The 2011 Flemish Masterplan for Coastal Safety[94] describes the measures that need to be taken by 2050 to adequately protect the coastline and the adjacent low-lying polders against a storm surge with a return period (i.e. likelihood of occurring) of 1,000 years, and considers sea-level rise of 30cm by 2050 and 80cm by 2100. The Masterplan has been implemented in stages since its approval by the Flemish government on 10 June 2011 and is now in an advanced phase.

During its implementation phase, the safety of the entire Flemish coast has been re-assessed through periodical analysis (every six years) and after severe storm events. The assessments update flood maps and calculate residual risks after the implementation of measures. An update of the assessment in 2017[95] revealed that at the locations where measures have already been implemented, the level of protection has clearly increased.

Tools, barriers and enablers to build coastal resilience

With climate change and sea-level rise, protecting the coastal region against storm surges and flooding is a top priority. More than 100 groynes, several dykes, piers, sea walls, jetties and breakwaters have been constructed to protect the beaches, buildings and harbours from storms. There is an increasing trend in recent years to use NBS as much as possible to protect, sustainably manage and restore natural ecosystems (e.g. beach and dune nourishment), complemented by engineering approaches where necessary to reach the proposed safety level outlined in the Masterplan.

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[93] https://www.agentschapmdk.be/nl/afdelingen/kust

[94] https://www.agentschapmdk.be/nl/masterplan-kustveiligheid

[95] https://www.vlaanderen.be/en/departement-mobility-and-public-works/projects/coastal-protection

Credit: © Province of West Flanders

On the Belgian coast groynes, dykes, piers, sea walls, jetties and breakwaters have been constructed to protect the beaches, buildings and harbours from storms.

Credit: © Province of West Flanders

There is an increasing trend in recent years to use Nature-based Solutions as much as possible to protect, sustainably manage and restore natural ecosystems

6

Future challenges and recommendations

Credit: Lucia Diaz

This Chapter presents key challenges and recommendations for scientists, policymakers, and communities in order to build the resilience of Coastal Social-Ecological Systems (CSESs) to multiple, interacting pressures.

6.1 Scientific and innovation challenges and recommendations

An overarching scientific challenge is that the impacts of cumulative pressures on coastal zones, and specifically on coastal resilience, as well as the future overarching impact of climate change and biodiversity loss, are largely unknown. When predicting future impacts of pressures on the coastal zone, it is also challenging to extrapolate trends from large-to-small(er) spatial and temporal scales and vice-versa. A further challenge is to determine thresholds and tipping points for individual and cumulative pressures, in order to identify where threats to resilience and deviations from resilient pathways are occurring. There are also critical knowledge gaps on the environmental and socio-economic co-benefits, site-specific feasibility and impacts of various combinations of nature-based and hybrid solutions to build coastal resilience.

To improve our knowledge on how to build coastal resilience, we recommend to:

1. Establish integrated, transdisciplinary research on CSESs through engagement with local stakeholders to address knowledge gaps on single pressure and site-specific multiple and cumulative pressure-response relationships, including characterisation and consequences of crossing social-ecological tipping points. This will require coherence between research communities at the land-sea interface and a better understanding of how to effectively implement transdisciplinary research. Increased collaboration is also required between stakeholders so that state-of-the-art knowledge and technology is used in local-scale projects.

2. Develop and operationalise standardised coastal resilience indicators for Europe to identify where threats to resilience and deviations from resilient pathways are occurring. Improved knowledge of resilience properties, including robust, integrated ecological and social tipping points, will help to develop and interpret resilience indicators. This will ensure intrinsic resilience of CSESs to be better prepared for extreme events and to reduce uncertainty. The development of a pan-European framework is needed to operationalise resilience indicators, develop methodologies to measure and monitor resilience over time, and to improve clarity and standardisation.

3. Develop sufficient observational, monitoring and data capacity to inform decision making to build the resilience of CSESs in the face of future climate change and biodiversity loss. Coastal data from different observation systems need to be integrated into a unified interdisciplinary platform. Data services should be expanded to allow integration of environmental and social datasets that will streamline management practices across disciplines and should be linked to coastal resilience indicators. Investment in Big Data and artificial intelligence technologies will help to deal with large, diverse and disparate datasets spanning multiple disciplines. Monitoring efforts should be increased to address the ecological and socio-economic impacts of multiple and synergistic coastal pressures, and to link trends in habitat condition with management interventions.

4. Improve predictive capacity to forecast and develop future scenarios on the magnitude, timing, location and impact of multiple and cumulative pressures on CSESs. This includes using machine learning, data mining and ensemble models to develop short- (<10 years), mid- (10-100 years) and long-term (>100 years) forecasts of CSES responses to climate change and other pressures, and methods to elucidate ecosystem dynamics, alternative states and potential tipping points. Coastal processes must be fully represented in ecosystem models, and network models should be used to link multiple stressors to policy options. Global to local climate change projections must be improved to translate global climate change impacts into local challenges.

5. Invest in research on nature-based and hybrid solutions to build coastal resilience, and identify their environmental and socio-economic co-benefits, site-specific feasibility and impacts of various combinations of seaward, landward and hybrid solutions. Scientific and socio-economic barriers and enablers to their implementation should be identified.

6.2 Management and policy challenges and recommendations

Key challenges for management and policy for building and enhancing coastal resilience coastal resilience include dealing with the complexity of multiple pressures on CSESs and their cumulative impacts. These potential threats are acknowledged and to some extent addressed in EU Directives and regulations. However, this is insufficient to address the impacts of cumulative pressures, and the overarching impact of climate change and biodiversity loss to protect and future-proof coastal zones to build resilience. An overarching challenge is that from a policy and management perspective, the coast is currently not thought of as a single, dynamic system, but rather as separate land and sea systems. Additional challenges include a lack of knowledge on environmental and social tipping points and understanding the policy implications of these tipping points, challenges associated with decision-making under uncertainty and incomplete knowledge, and how to change mindsets of stakeholders to be open to change.

To improve management and policy to build coastal resilience, we recommend to:

1. Adopt a systems approach to coastal management based on adaptive, cross-sectoral and coherent policies. The Integrated Maritime Policy (IMP) should be updated to include all aspects of the land-sea interface and links between marine- and land-based policies should be improved. Adaptive coastal management, including participation of local communities, should consider activities in adjacent areas (including on land) and aim to balance mitigation of and adaptation to multiple pressures. More participatory tools are required to facilitate adaptive spatial planning, and forecasting and scenario analysis should be integrated into land-sea regional plans. Deep rooted institutional practices should be overcome and policy objectives aligned between different legislation. Transboundary cooperation and timely risk management through effective early-warning systems are required.

2. Enhance adaptive capacity at multiple scales (community, local, national, regional, and European) by: increasing assets that are available in times of need (e.g. finance, expertise, tools, technology, information); developing flexibility to change strategies; improving the ability to organise and act collectively; promoting learning to recognise and respond to change and; developing agency to decide how to respond to change. Specific actions that enhance adaptive capacity include providing training on resilience concepts, frameworks, data analysis and analytical tools to ensure that all stakeholders share the same vision, and developing fora to bring all relevant stakeholders together. Such fora should aim to: stimulate debate based on reciprocal learning; build consensus in relation to preferred futures and possible pathways; address different interests and priorities; provide a structure to discuss gaps in knowledge, policy, governance and management; and to place these within the context of processes and decisions required to build resilience. When adaptive strategies to governance are not sufficient to build resilience to cumulative pressures, transformative change might be required.

3. Include nature and people from the beginning of the design process of coastal resilience solutions, including for coastal protection and when using an ecosystem-based management approach. Nature-based Solutions that consider social, economic and environmental factors, especially in marginalised communities, should be considered in local, national and EU planning structures and legislation. An inventory should be made of existing coastal management interventions, including their impact on the resilience of CSESs, and their long-term value in preparation for the impacts of multiple cumulative coastal pressures and changing socio-economic conditions.

4. Reflect the multiple social and economic values of natural capital in public policies and decision-making processes. The contribution to human wellbeing of all types of ecosystem services should be recognised and assessed with non-monetary valuation methods. The social, economic and environmental co-benefits of Nature-based Solutions should be promoted and valued, and the regulatory and policy environment should ensure high quality, investible projects and private-public partnerships.

5. Follow the six-step approach for developing site-specific solutions for coastal resilience i.e. conceive the whole process as long-lasting and permanently adaptive, define the issue to be addressed and select frameworks to use, define the boundaries and dynamics of the CSES, engage stakeholders, identify tools to build coastal resilience, and sort and refine possible solutions (see section 2.10).

6.3 Community challenges and recommendations

Communities (e.g. volunteer groups) are key actors in building coastal resilience. Challenges for communities to engage in enhancing coastal resilience include: being open to the message that scientific knowledge sends; consideration of who will be the winners and losers in terms of community response and inequalities; dissolution of culture and local knowledge of coastal communities; and defining visions of desirable states of coastal zones with communities that are rapidly changing. To increase participation of local communities in enhancing coastal resilience we recommend to:

1. Obtain systematic natural and social scientific knowledge that is useful to individual communities and share this among all interested parties with clear messages;
2. Develop and adhere to coherent national coastal plans to coordinate community actions with the regional priorities of local authorities;
3. Co-design citizen science initiatives that support communities to collect and understand coastal data and resilience issues; and
4. Enhance the adaptive capacity of local communities by: providing access to finance, expertise, participatory tools, technology and knowledge to facilitate co-design of solutions; developing education on the complexity and importance of coastal resilience; developing and strengthening national and international networks between different cities and communities so they can learn from each other; and promoting ownership of local projects to increase communities' agency to decide to change.

Credit: Eugene Farrell

Communities (e.g. volunteer groups) are key actors in building coastal resilience.

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Glossary

Accretion – The accumulation of coastal sediment; the opposite of erosion.

Adaptability — The capacity of actors in a social-ecological system to influence resilience (i.e. to manage it).

Adaptation pathway – An approach that provides insight into the sequencing of actions over time, potential lock-ins, and path dependencies.

Adaptive policy-making — A stepwise approach for developing a basic plan, and contingency planning to adapt the basic plan to new information over time.

Agency — The ability of individuals or groups of people to choose how to respond to environmental change.

Antifouling compounds — Substances used to prevent the buildup of unwanted organisms, like algae or barnacles, on surfaces submerged in water, such as boat hulls.

Armchair stakeholders — Stakeholders who live far from the coast but who care deeply about a coastal place.

Artificial intelligence — The theory and development of computer systems that are able to perform tasks or exhibit behaviour normally requiring human intelligence.

Benthic — Organisms or habitats at the bottom of the Ocean.

Big data — High volume, high velocity, and/or high variety information assets that require new forms of processing to enable enhanced decision-making, insight discovery and process optimisation.

Bioblock — A habitat enhancement unit that creates artificial pits and rock pools to provide habitat for native biodiversity.

Biomass — The total amount or weight of living things, like plants and animals, in a certain area.

Bioturbation – Mixing and disturbance of soil or sediment by living organisms, like animals and plants.

Blackwater – Wastewater containing sewage.

Blue economy — The ensemble of economic activities taking place on, below and/or adjacent to Ocean ecosystems.

Bog — A freshwater wetland with wet and poorly drained peat-rice soil.

Bonding social capital — Strong social relationships that tie groups together with similar backgrounds or interests.

Breakwater — A barrier built out into the sea to protect a coast or harbour from the force of waves.

Bridging social capital — Connections that link groups together who typically may be divided across society.

Coastal hardening — The process of protecting coastlines from erosion or sea-level rise by building structures like walls or barriers.

Coastal plain – A flat or low-lying piece of land next to the Ocean.

Coastal setback zones — A strategy in which buffer areas are designated where some or all types of development are forbidden or restricted, thereby making the area less sensitive to economic damages by occasional irregular flooding.

Coastal squeeze – The loss of natural habitats or deterioration of their quality arising from anthropogenic structures or actions, preventing the landward transgression of those habitats that would otherwise naturally occur in response to sea-level rise in combination with other coastal processes.

Complex adaptive systems — Systems composed of a large number of interacting components each with complex behaviour, and capable of adaptation and self-organisation in response to changes in their environment.

Deep-learning — A subfield of supervised machine learning that refers to powerful algorithms able to learn a model with complex raw data as its input.

Deep uncertainty — The condition in which analysts do not know or the parties to a decision cannot agree upon (1) the appropriate models to describe interactions among a system’s variables, (2) the probability distributions to represent uncertainty about key parameters in the models, and/or (3) how to value the desirability of alternative outcomes.

De-growth — Shrinking rather than growing economies, using less resources and putting wellbeing ahead of profit.

Dyke — A long wall or embankment built to prevent flooding from the sea. This is also known as a levee.

Dynamic shoreline/preservation/coastal protection — A shoreline that incorporates Nature-based Solutions and has the potential to adjust to external pressures.

Dystrophy — Nutrient concentrations which are too low to support life.

Ecosystem-based adaptation — The use of Nature-based Solutions to adapt to climate change.

Ecosystem-based management — An approach to management where all interactions within an ecosystem, including human interactions, are considered holistically.

Ecosystem persistence — The ability of an ecosystem to return to an equilibrium state after a perturbation.

Endogenic pressure — The pressures affecting the coastal stem from sources inside the managed coastal zone.

Ensemble modelling — Using outputs from different models.

Eutrophication — The process of nutrient enrichment in aquatic ecosystems causing the productivity of the system to cease to be limited by the availability of nutrients. This stimulates the growth of algae, ultimately resulting in depletion of oxygen.

Exogenic pressure — The pressures affecting the coast stem from sources outside the managed coastal zone.

Fen – Low-lying wetland with grassy vegetation.

Forecasting — Predictions based on what is expected to happen and provide one possible future.

Foreshore — The part of a shore between high- and low-water marks, or between the water and cultivated or developed land.

Greenwashing — The process of conveying a false impression or misleading information about the environmental friendliness of a solution or product.

Greywater — Wastewater from sinks, showers and washing machines.

Groundwater aquifer — Layers of rock, sand or gravel that can absorb water and through which water can flow.

Groyne — A low wall or sturdy barrier built out into the sea from a beach to check erosion and drifting.

Harmful algal bloom — An algal bloom that causes negative impacts to other organisms.

Hold-the-line solutions — Solutions that aim to maintain the coastline at its current position.

Human capital – Skills, knowledge, experience and abilities that individuals possess, which contribute to personal and economic growth.

Hysteresis — The possibility of a system to exist in two alternative states, with the state exhibited dependent on historical conditions.

Institution — A systems for organising standardised patterns of social behavior.

Institutional inertia — Unwillingness of institutions to act.

Institutional structures — Established systems, organisations and arrangements within a society that shape how decisions are made, resources are distributed, and rules are enforced.

Intertidal — Areas of the coast that are covered at high-tide and uncovered at low-tide.

Invasive species — Species that have been introduced outside their previous or present natural range by human activities. These are also known as non-indigenous species.

Lock-ins — When there is limited openness to change and sub-optimal policies are used even though better alternatives are present.

Managed realignment — A strategy in which engineering defences are removed and an area is allowed to regularly flood and accrete to follow sea-level rise, while urban developments have to retreat to higher ground.

Mesoscale coastal evolution — Coastal evolution at time and length scales of the order 10 - 100 years and 10 - 100 km.

Natural capital — The stock of natural resources.

Natural littoral drift — The natural movement of sediment along the shoreline.

Nearshore — The area of the sea relatively close to the shoreline, typically to depths of 20m.

Oligotrophication — Nutrient deficiency in aquatic ecosystems.

Panarchy — A set of adaptive cycles of social-ecological systems nested into a hierarchy.

Path dependencies — Basing outcomes on previous decisions, habits and actions.

Peat — The surface organic layer of a soil that consists of partially decomposed organic matter.

Polder — Land that has been reclaimed from a body of water, often through the use of dykes and drainage systems.

Policy coherence — A holistic approach with aligned objectives that do not undermine or conflict with each other.

Policy integration — The effective translation of policies into institutional structures and efforts ‘on the ground’.

Post-glacial rebound — The uplifting of land after the weight of ice sheets has been removed.

Post-growth — Changing the composition and structure of economic activity to achieve the multiple goals of a more rounded vision of economic and social progress.

Probabilistic quantitative methods — Methods that estimate the likelihood that a given risk will occur.

Problemshed — A spatial unit focused on the issues at stake.

Recovery — The time it takes for a system’s performance to recover to a desired functionality following one or more adverse events.

Regime shift — Drastic changes in the structure and functioning of ecosystems caused by amplified feedbacks.

Regions — European marine regions e.g. Baltic, Mediterranean, North-East Atlantic and Black Sea.

Resistance — A system's ability to actively change while retaining its identity or to passively maintain system performance following one or more adverse events.

Robustness — The probability of a system to maintain its identity and not cross an undesirable (possibly irreversible) threshold following one or more adverse events.

Rock armour — Large boulders used to reduce wave energy reaching the shoreline.

Sand fences — Structures or barriers that are placed on beaches or coastal areas to capture blowing sand and help stabilise dunes.

Scenario analysis — Predictions based on what could happen under different conditions and provides multiple possible futures.

Seawall — A wall or embankment built to prevent the sea encroaching on or eroding an area of land.

Shingle bank — An embankment made of small stones.

Siloed — Separated from other people or things.

Social learning — Learning new behaviours by observing and imitating others.

Stakeholder — A person, group, or organisation that has an interest or concern in a particular project, decision, or issue. Stakeholders can be affected by or influence the outcomes of these situations.

Static shoreline — A shoreline predominantly reinforced with grey infrastructure and which cannot adjust to external pressures.

Storm surge barrier — A type of floodgate designed to prevent a storm surge from flooding the area behind the barrier.

Stratigraphy architectures —The arrangement and composition of geological layers of sedimentary rock and deposits.

Strong sustainability — Requires that both man-made and natural capital remain intact separately, considering that they are not substitutes but rather complement each other and that most environmental damage is irreversible.

Subsidence — Gradual shrinking of the land in coastal areas over time leading to problems like flooding.

Synergistic responses — When the response exceeds the sum of individual pressure effects.

Systems theory/thinking/approach — Based on the principle that the parts of a system can best be understood in the context of the relationships with each other and with other systems, rather than in isolation.

Thermal expansion — Water expansion as it gets warmer, causing sea-level rise.

Tidal embankment – Man-made structure built along coastlines, estuaries, or tidal areas to protect land from the effects of tidal flooding, storm surges and rising sea-levels.

Tipping point — The critical point at which a transition to a new state is triggered.

Transformability — The capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable.

Triage — Structured decision-making approach to help define coastal resilience issues and their scope.

Vulnerability — Exposure to, sensitivity to and ability to adapt to disturbances.

Watershed — A land area that channels rainfall and snowmelt to creeks, streams and rivers, and eventually to outflow points such as reservoirs, bays and the Ocean.

Weak sustainability — The idea that human capital can substitute natural capital.

Wicked problem — A problem that is difficult or impossible to solve because of its complex and interconnected nature.

List of Abbreviations

CFP	Common Fisheries Policy
CMEMS	Copernicus Marine Environment Monitoring Services
COSYNA	Coastal Observing System for Northern and Arctic Seas
CO_2	Carbon Dioxide
CR	Community Resilience
CRP	Climate-Resilient Pathways
CSES	Coastal Social-Ecological System
DANUBIUS-RI	International Centre for Advanced Studies on River-Sea Systems
DTO	Digital Twin Ocean
DPSIR	Driver-Pressure- State-Impact-Response
DESCR	Drivers, Exchanges, State of the environment, Consequences and Responses
ECWL	Extreme Coastal Water Levels
EEA	European Environment Agency
EMODnet	European Marine Observation and Data Network
EnMPs	Endogenic Manageable Pressures
EOatSEE	Earth Observation Advanced Science Tools for Sea level Extreme Events
ESA	Ecosystem Service Assessment
EU	European Union
EURO-CORDEX	Coordinated Regional Downscalling Experiment – European Domain
ExUPs	Exogenic Unmanageable Pressure
FAO	Food and Agriculture Organization of the United Nations
GES	Good Environmental Status
ICZM	Integrated Coastal Zone Management
IMP	Integrated Maritime Policy
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for the Conservation of Nature
JERICO	Joint European Research Infrastructure network for Coastal Observatories
MARPOL	International Convention for the Prevention of Pollution from Ships
MCA	Maharees Conservation Association
MHW	Marine Heat Wave
MONGOOS	Mediterranean Operational Network for the Global Ocean Observing System
MPAs	Marine Protected Areas
MSFD	Marine Strategy Framework Directive
MSP	Marine Spatial Planning
NbS	Nature-based Solutions
NGO	Non-Governmental Organisations
NIA	Non-Indigenous Species
NOAA	National Oceanic and Atmospheric Administration

OA	Ocean Acidification
PCB	Polychlorinated Biphenyls
POSEIDON	Monitoring Forecasting and Information System for the Greek Seas
RVA	Risk, vulnerability and Adaptive capacity
ROOS	European Regional Operational Oceanographic Systems
SD	Sustainable Development
SES	Social-Ecological System
SLR	Sea-Level Rise
SOCIB	Balearic Islands Coastal Observing and Forecasting System
SOFIA	State of World Fisheries and Aquaculture
SST	Sea-Surface Temperature
TEEB	The Economics of Ecosystem Services and Biodiversity initiative
TBT	Tributyltin
UK	United Kingdom
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNESCO	United Nations Educational, Scientific and Cultural Organization
USD	United States Dollar

Annex 1: Members of the European Marine Board Working Group on Coastal Resilience

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