NBRACER
Nature Based Solutions
for Atlantic Regional Climate Resilience

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A conceptual framework for the design and scaling of NbS: development and application

Deliverable 5.1

Final version

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About NBRACER

The impacts of climate change on people, planet and prosperity are intensifying. Many regions and communities are struggling to avoid losses and need to step up the effort to increase their climate resilience. Ongoing natural capital degradation leads to growing costs, increased vulnerability, and decreased stability of key systems. Whilst there has been noticeable progress and inspiring examples of adaptation solutions in Europe, the pressure to make rapid and visible progress has often led to a focus on stand-alone, easy-to-measure projects that tackle issues through either direct or existing policy levers, or sector-by-sector mainstreaming. But the dire trends of climate change challenge Europe, and its regions, needs exploration of new routes towards more ambitious and large-scale systemic adaptation. The European Mission on Adaptation to Climate Change (MACC) recognizes the need to adopt a systemic approach to enhance climate adaptation in EU regions, cities, and local authorities by 2030 by working across sectors and disciplines, experimenting, and involving local communities.

NBRACER contributes to the MACC by addressing this challenge with an innovative and practical approach to accelerating the transformation towards climate adaptation. Transformation journeys will be based on the smart, replicable, scalable, and transferable packaging of Nature-based Solutions (NbS) rooted in the resources supplied by biogeographic landscapes while closing the NbS implementation gap. Regions are key players of this innovative action approach aiming at developing, testing, and implementing NbS at systemic level and building adaptation pathways supported by detailed and quantitative analysis of place-specific multi-risks, governance, socio-economic contexts, and (regional) specific needs.

NBRACER works with 'Demonstrating' and 'Replicating' regions across three different Landscapes (Marine & Coastal, Urban, Rural) in the European Atlantic biogeographical area to vision and co-design place based sustainable and innovative NbS that are tailor-made within the regional landscapes and aligned with their climate resilience plans and strategies. The solutions are upscaled into coherent regional packages that support the development of time and place specific adaptation pathways combining both technological and social innovations. The project is supporting, stimulating, and mainstreaming the deployment of Nature-based Solutions beyond the NBRACER regions and across biogeographical areas.

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Summary

This document presents a conceptual framework designed to enhance climate resilience through the implementation of Nature-based Solutions (NbS). The model provides a biophysical framework for addressing climate risks and socio-ecological vulnerabilities across multiple spatial scales, from localized ecosystems to broader regional contexts.

The model is based on the use of landscape functional units, which represent areas defined by their biophysical characteristics. These units help identify climate hazards and enable the design of NbS tailored to specific environmental and socio-ecological conditions. By focusing on these functional units, the model allows for a detailed understanding of localized climate risks, such as floods, droughts, and erosion, and how NbS can mitigate their impacts.

At a broader scale, the model organizes these functional units into landscape archetypes, which share common ecological and socio-economic characteristics. This facilitates the identification of synergies between NbS and enables the scaling of solutions to address multiple climate risks simultaneously. The goal is to promote interconnected NbS networks that enhance biodiversity, improve ecosystem services, and support community resilience.

A key element of the model is the integration of Climate Risk Impact Chains (CRICs), which are used to visualize the relationships between climate hazards, exposure, and vulnerabilities. The CRCs provide a structured approach to address climate risks, helping to identify critical intervention points where NbS can be most effective. Although the model does not directly incorporate a multi-scale governance framework, it uses CRCs as a tool to insert governance or other socioeconomic considerations into the analysis. This provides a foundation for future development of governance and socioeconomic strategies that support the broader implementation of NbS.

In conclusion, the use of CICs allows linking biophysical processes to socio-ecological factors, thus, the model supports the development of scalable, context-specific solutions that enhance long-term socio-ecological resilience. The developed conceptual model offers a comprehensive framework for integrating NbS into regional climate adaptation strategies.

Keywords

Meta-ecosystems; ecosystem services; functional units; landscape archetypes; climate hazards; Climate Risk Impact Chains.

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Abbreviations and acronyms

Acronym	Description
BGI	Blue and Green Infrastructure
CRIC	Climate Risk Impact Chains
ES	Ecosystem Services
KCS	Key Community System
NbS	Nature-based Solutions
SBA	Service-benefiting areas
SCA	Service-connecting areas
SPA	Service-providing areas
WP	Work Package

Definitions

Table 1. Definitions.

Term	Definition
Functional unit	Spatial units that meet the spatial scale required by the biological component to generate the biophysical interaction involved in generating an ES (Laca 2021).
Biological community, biotope, habitat, ecotope	Living components of the biosphere. We use this term irrespective of the scale of aggregation to which we refer (i.e., organism, population, community, or ecosystem).
Adaptation	The process by which systems adjust to hazards, moderate harm, or exploit beneficial opportunities. In the SoS context, this refers to the capability of interconnected systems to evolve in response to environmental changes and hazards.
Community Resilience	The capacity of communities to endure, adapt, and grow in the face of environmental hazards. Within a landscape, it focuses on empowering communities through adaptive governance, infrastructure, and social networks to enhance resilience.
Complex Adaptive Systems (CAS)	Dynamic networks comprised of numerous agents (e.g., individuals, species, cells, institutions) interacting in parallel. The control within CAS is dispersed and decentralized, with coherent behavior emerging from the agents' mutual competition and cooperation, rather than from any external control. Key features include **emergence**, where system behavior arises unpredictably from individual interactions; **self-organization**, enabling spontaneous structure formation without external guidance; and **adaptation**, allowing the system to evolve through learning from experiences.
Critical Functionality	Refers to the essential capabilities and performance characteristics that allow the landscape to adapt to changes. This definition emphasizes the ability of the landscape to maintain its core operations and achieve its objectives in the face of varying conditions, focusing on the adaptability of its critical functionalities.
Disaster Risk Management (DRM)	A systematic process to identify, assess, and reduce the risks of disaster. It involves the development and application of policies, strategies, and practices to minimize vulnerabilities and disaster risks throughout a society, within the context of SoS, to enhance the resilience of interconnected systems against natural and human-made hazards.
Conceptual framework	An analytical model or structure that represents and simplifies complex ideas or systems by organizing key concepts and explaining how they function in the real world. In this context, it would outline the

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	essential elements, relationships, and processes that should be considered when integrating NbS into SoS to enhance resilience.
Geographic Information Systems (GIS)	Tools for gathering, managing, and analysing data rooted in the science of geography. GIS integrates many types of data. It analyses spatial location and organizes layers of information into visualizations using maps and 3D scenes. Within DRM, GIS is pivotal for mapping hazards, vulnerabilities, and risks, thereby supporting decision-making processes for disaster risk reduction and resilience building in SoS.
Governance and Institutional Resilience	The adaptability and effectiveness of governance structures and institutions in managing and responding to environmental challenges. In SoS, this includes the mechanisms for stakeholder engagement, decision-making, and policy implementation to ensure system-wide resilience.
Interdependent Resiliencies of a System of SoS	It refers to the comprehensive and collaborative capacity of a SoS and its constituent systems to withstand, adapt to, and recover from a multitude of hazards through a symbiotic integration of resilience features and capacities. This concept is grounded in the four foundational resilience features—Robustness, Redundancy, Resourcefulness, and Response (the 4Rs)—and extends through the resilience capacities of absorption, adaptation, transformation, and response/recovery at the level of constituent systems.
Key Community Systems (KCS)	A system that meets important basic societal needs but that is increasingly impacted by climate change. A key community system is an area of innovation and transformation for the Mission, part of a larger interdependent system (European Mission, 2021). KCS include critical infrastructures and social systems—healthcare, education, social networks, and governance—vital for the resilience of urban, rural, and marine & coastal communities. The impact on communities is significant, with adaptation measures, governance structures, and community engagement shaping the resilience of these systems. Stakeholders play a pivotal role, from planning to implementation, ensuring systems are adaptable and communities are empowered to face environmental challenges. This approach aligns with the MIP4ADAPT mission, emphasizing stakeholder collaboration in building resilient, adaptable, and sustainable communities across diverse environments, addressing specific vulnerabilities, and leveraging opportunities for innovative climate adaptation strategies.
Model	A specific representation or abstraction of a system, used to understand, predict, or simulate the behavior or dynamics of the system under various scenarios. The NBRACER NB-SoS **Conceptual Model** would thus detail the components, interactions, and mechanisms through which NbS can be effectively operationalized within SoS exhibiting CAS characteristics to improve resilience.
Landscape (SoS) Resilience	Landscape resilience refers to the ability of integrated natural and built environments—such as forests, rivers, cities, farms, and coasts—to **anticipate, absorb, adapt to, and recover from** multi-hazard impacts while maintaining essential functions. Rooted in the principles of **Complex Adaptive Systems (CAS)** and **Nature-based Solutions (NbS)**, resilient landscapes leverage **redundancy, resourcefulness, and adaptive capacity** to minimize disruptions and sustain ecological and community well-being. This resilience framework enables hierarchical analysis to assess NbS roles at different levels across hazard scenarios (e.g., floods, droughts, heatwaves). It also establishes a **baseline ("zero point")** for evaluating resilience dynamics and NbS effectiveness over time.
Infrastructure Resilience	The ability of infrastructure systems to withstand, adapt to, and recover from the impacts of hazards. In SoS, this concept extends to ensuring infrastructure systems are designed and managed to support the resilience of interconnected systems.
NbS Implementation	The process of planning, deploying, and managing nature-based solutions to address environmental challenges. In SoS, it involves integrating NbS with other system components to maximize resilience benefits.
Nature-based Solutions (NbS)	In NBRACER, Nature-based Solutions (NbS)—such as green spaces, wetlands, urban forests, and coastal mangroves—are recognized as resilience boosters within landscape systems. By mitigating environmental risks (e.g., flooding, heat islands, coastal erosion) and enhancing biodiversity, NbS play a critical role in sustaining ecosystem services essential for community well-being. Their adaptive capacity allows landscapes to respond dynamically to environmental changes, while stakeholder engagement ensures that NbS implementation aligns with both community needs and long-term resilience objectives.
Network	In NBRACER, landscapes are seen as Systems of Systems (SoS), where interconnected ecological, social, physical, and governance networks interact to sustain resilience. Each network—whether natural (e.g., forests, wetlands), built (e.g., infrastructure, cities), or societal (e.g., communities, governance)—operates independently yet remains interdependent. Changes in one network can create cascading effects across the system, highlighting the need for integrated planning, cross-network coordination, and adaptive governance to enhance landscape resilience.
Socio-Ecological Systems	Integrated systems that include both ecological and social components, emphasizing the interdependence of humans and nature. Their resilience in SoS highlights the need for strategies that consider both ecological dynamics and human interventions.
Spatial Analyses	The technique used to handle spatial information to extract valuable insights from it. It involves the examination of the positions, attributes, and relationships of features in spatial data, through methods such as overlay analysis, buffer analysis, and spatial interpolation. In the context of SoS and DRM, spatial

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	analyses enable the understanding of complex spatial patterns of risks and vulnerabilities, facilitating targeted intervention strategies for enhanced resilience.
Strategic moments	Tipping points or critical thresholds at which specific actions or decisions can have a significant impact on the system's trajectory
System of Systems (SoS)	An integration of independent, complex systems that collaborate to achieve a common goal. In resilience terms and as it is defined for NBRACER, SoS refers to the coordinated management and adaptation of landscape, NbS, and community systems to enhance overall resilience to multiple hazards.
Transformation	A fundamental change in the structure and function of systems to achieve a significant level of change in resilience and sustainability. Within SoS, it involves reconfiguring the entirety of interconnected systems to ensure long-term resilience against multi-hazard threats.

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1 Introduction

1.1 Setting the Scene: the NBRACER approach

The NBRACER project offers a holistic approach to enhancing climate resilience, particularly for regions facing multiple, overlapping hazards. By examining the physical, social, and governance landscapes as an interconnected system, the NBRACER approach aims to foster adaptive, scalable, and sustainable solutions that strengthen the capacity of regions to anticipate, respond to, and recover from various climate-related hazards. This systems-based logic is embedded into both the conceptual and operational frameworks of the project and directly informs the technical process workstreams in WP5 (and WP6).

The NBRACER approach leverages Nature-based Solutions (NbS) as foundational elements that integrate with regional landscapes and enhance resilience. By considering the interplay of NbS with climate hazards, Key Community Systems (KCS), and the socio-economic environment, the framework seeks to produce cascading benefits (e.g., reducing stress on emergency services, stabilizing water resources, and supporting public health) across different community dimensions. This approach enables operational resilience, requiring stakeholders to rethink their roles in maintaining and restoring resilience amidst dynamic threats. The structure and logic of this approach are operationalised through the technical tasks of WP5, where ecosystem services (ES), functional units, and risk propagation are mapped and translated into actionable planning layers.

In this context, the conceptual framework developed in this document serves as a critical tool within the NBRACER approach (Figure 1), providing a structured method to implement NbS tailored to specific regional needs. The conceptual framework establishes the biophysical basis for considering the relationships between climate hazards, the risk they generate on a territory (threatening KCS) and how these could be mitigated using the regulating capacities of ecosystems. The conceptual framework provides the basis for developing an operational framework for mapping climate risks, functional units, ES and modelling their interactions for designing NbS. This aligns with steps one and two suggested from the P2R framework (i.e., step 1: Establish a regional baseline; step 2: Methodology for climate risk assessment and NbS planning), although it is also extensible to steps three to eight (see figure below). The iterative logic and interconnection between domains reflected in the eight steps of the NBRACER journey are supported technically by WP5 (and WP6), allowing flexible entry points and cross-domain feedbacks. In addition, the conceptual framework establishes the biophysical template on which iteratively connect the developments related to the climate risk and governance scenarios linked to the subsequent steps.

Specifically, within WP5, Deliverable 5.1 (D5.1) lays the foundation for: 1) Identifying the biophysical components of the territory and their interactions with the social environment, which must be considered to build landscape resilience by integrating NbS into climate risk management, 2) operationalizing a methodology to map these components and upscaling NbS implementation. In this sense, D5.1 integrates, within the climate risk assessment and scenario framework presented in Deliverable 5.2 (D5.2, Task 5.2), the ecosystem components that have the potential to regulate climate risks. Moreover, it provides the conceptual structure necessary not only to identify the subcomponents but also to define the key elements required to later develop

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methods for quantifying and categorizing (Task 5.3) these relationships. This enables the design of strategies for identifying, planning, monitoring (Task 5.4), and scaling (Task 5.5) NbS across different regions. In doing so, it builds the technical foundation that links each stage of the conceptual framework to specific decision-support tools, monitoring systems, and multi-scenario planning—ensuring that the framework remains both analytically grounded and actionable.

This document is structured as follows:

- Section 1 outlines the need for this conceptual framework in the design and scaling of NbS—not only within the scope of the NBRACER project but also as a response to the broader global challenges.
- Section 2 establishes the theoretical foundations upon which the conceptual framework is built, defining its key statements and hypotheses.
- Section 3 presents the developed conceptual framework, focusing on its rationale, components, levels, and the implications derived from its structure.
- Section 4 provides a practical guide for implementing the conceptual framework.
- Section 5 showcases a series of case studies based on the conceptual framework, illustrating its theoretical applications.
- Section 6 offers a roadmap for regions outlining the next steps for applying the conceptual framework in practice, specifically within regional planning processes.

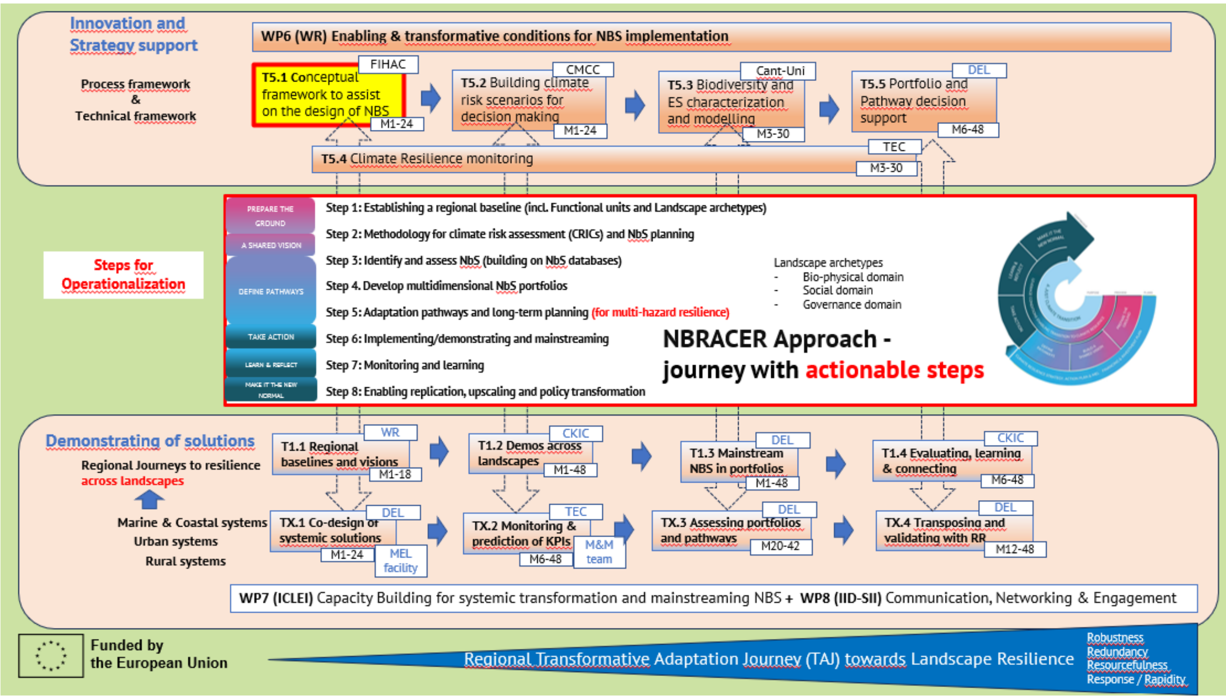

Figure 1. NBRACER approach.

1.2 Target groups

This document is aimed at both governmental and non-governmental organizations and professionals involved in regional planning, climate resilience, and environmental management. It seeks to assist decision-makers, urban and rural planners, and technical experts working across

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local, regional, and national levels in designing and implementing NbS as part of climate adaptation strategies.

The main objective of this document is to provide a solid conceptual framework that shapes the biophysical component involved in the implementation of NbS, integrating this biophysical realm into the overall risk assessment framework and identifying relationships with the social and governance system. The conceptual framework helps to identify and apply NbS tailored to specific risks and landscapes, while proposing the biophysical basis to account for the socio-economic and governance contexts in which these solutions operate.

This document is particularly valuable for practitioners who:

- Require a standardized approach to link climate risks with ES and NbS.
- Are engaged in planning and spatial optimization of climate adaptation strategies across multiple levels, from individual functional units (e.g., hillslopes, river channels) to broader landscape and regional scales.
- Aim to align NbS with local community systems, promoting socio-ecological resilience and long-term sustainability.
- Need tools to assess, monitor, and evaluate the impact of NbS, considering multiple climate hazards and the capacity of ecosystems to continue delivering essential services under changing conditions.

By offering a comprehensive understanding of how NbS can mitigate climate risks, this document supports the creation of interconnected NbS networks that enhance biodiversity, improve ecosystem functionality, and strengthen community resilience to climate change.

1.3 Need and scope of the conceptual framework for the implementation of Nature-based Solutions

The growing recognition of climate change as a critical global challenge (Folke et al. 2021; Steffen et al. 2011; Lewis and Maslin 2015) has highlighted the urgency of developing innovative approaches to mitigate its impacts and adapt to its consequences (Barnosky et al., 2017; Harvey et al., 2017; Higgs et al., 2018; Valiente-Banuet et al., 2015). Traditional methods of risk management and conservation, often focused on isolated engineering solutions or species-level interventions, have proven insufficient to address the complexity and scale of the current environmental crisis. This has paved the way for NbS as a holistic approach that not only enhances ecosystem resilience but also delivers critical ES to human societies. This new approach moves the focus on conserving only undisturbed ecosystems to a perspective that recognizes humans as components of ecosystems, valuing the function, adaptability and resilience provided by nature more (Palmer et al. 2004). This view has been defined by Mace (2014) as a "people and nature" framing of conservation. It emphasizes the importance of cultural structures and institutions for developing sustainable and resilient interactions between human societies and the natural environment, not only to generate ES but also to build dynamic, resilient and resistant socio-ecosystems (Garmestani and Benson 2013).

At the core of this conceptual framework (Figure 2) lies the recognition that society relies on KCS — essential structures and processes that underpin socioeconomic resilience and well-being.

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Protecting these systems from climate-related threats is vital to ensure the proper functioning of resilient societies. Escalating risks, driven by the increased frequency and intensity of extreme climatic events and greater societal exposure, demand innovative strategies to reduce system vulnerabilities. NbS offer a pathway to enhance the intrinsic properties of socio-ecological systems (SES), empowering them to adapt, buffer, and mitigate the impacts of these threats (Woroniecki et al. 2023). Moreover, NbS can act as a protective barrier between climate hazards and their potential negative impacts on KCS by leveraging the capacity of ecosystems to provide regulating ES (Debele et al. 2023).

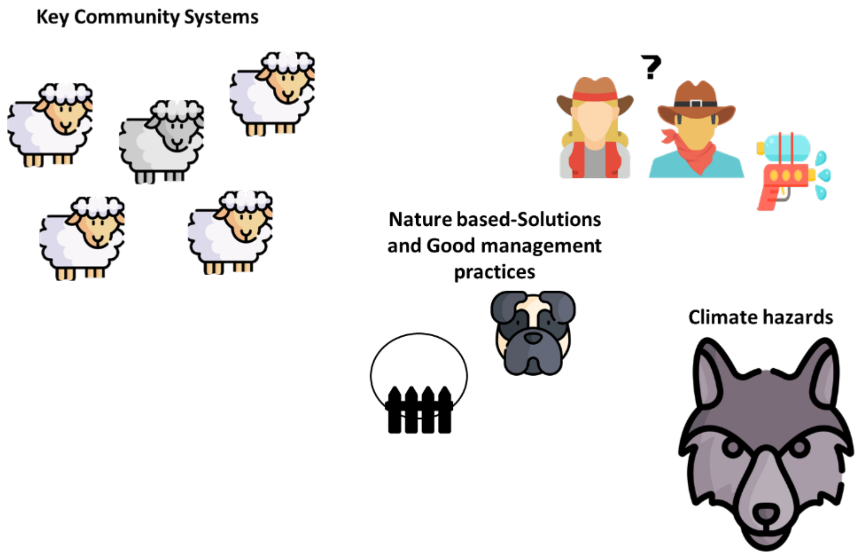

Figure 2. How do we protect our wonderful KCS herd from the wolf by using nature and soft management practices? Hunting is not the only way!

To design and implement effective solutions, it is essential to answer critical questions: where to act, at what scale, which types of ecosystems are most suitable depending on biophysical conditions, and which solutions are also viable from a socio-economic perspective. Furthermore, optimizing the spatial arrangement of NbS across the landscape is crucial to maximize their effectiveness and multifunctionality. Addressing these challenges requires a biophysical model capable of guiding decision-making by identifying the most appropriate interventions for specific contexts. Such a model provides the foundation to assess the feasibility, scalability, and potential benefits of NbS, ensuring that they are tailored to the unique characteristics and needs of the territory, reaching a holistic perspective, but also saving time and resources. This becomes essential to integrate NbS into the broader context of climate risk management and sustainable development.

2 Foundations of the conceptual framework

The primary objective of the conceptual model is to provide a biophysical framework that establishes the relationships between climate risks and ecosystems, facilitating the identification of appropriate NbS that can be applied within specific territories to protect KCS in order to enhance climate adaptation and resilience. To achieve this, the conceptual framework relies on five theoretical pillars:

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- *The Risk Assessment Framework*. Effective implementation of NbS requires a clear understanding of the risks posed by climate change, including the drivers, exposure, and vulnerabilities within a socio-ecological system. The conceptual framework must incorporate tools to map and evaluate these risks, providing a basis for targeted interventions and management actions.
- *The Paradigm of Nature/Ecosystem-based Solutions*. Moving beyond traditional conservation strategies, the model embraces the dynamic and adaptive potential of NbS to address climate risks while promoting long-term socio-ecological resilience. This includes leveraging interconnected networks of NbS, such as riparian buffers, wetlands, and urban green spaces, to ensure multifunctionality, connectivity across landscapes and biodiversity conservation.
- *Meta-Ecosystem Theory*. Recognizing the interconnected nature of ecosystems is crucial for designing NbS that operate across ecosystem scales and boundaries. By applying meta-ecosystem principles (Gounand et al., 2018), the model considers the flow of energy, matter, and biotic interactions between ecosystems, ensuring that interventions generate cascading benefits across landscapes.
- *The Ecosystem Services Framework*. NbS are grounded in their ability to sustain and enhance the provision of ES, such as water purification, flood regulation, and biodiversity conservation. The conceptual framework must link ecosystem dynamics with societal needs, ensuring that NbS are designed to maximize their socio-economic and ecological benefits.
- *Landscape Resilience.* Socio-ecological resilience is the ultimate objective of the conceptual framework, aimed at increasing the capacity of interconnected human and natural systems to adapt to and recover from climate-related impacts. Within this framework, NbS play a pivotal role by enhancing the intrinsic properties of ecosystems to regulate climate risks providing also other ES critical for societal well-being. By reinforcing the ability of ecosystems to absorb disturbances and maintain functionality, NbS contribute to creating robust SES capable of withstanding current and future challenges.

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Below we describe in more detail the components of these five theoretical pillars to understand how they are intertwined and related and how they are subsequently used to build the conceptual framework (Figure 3).

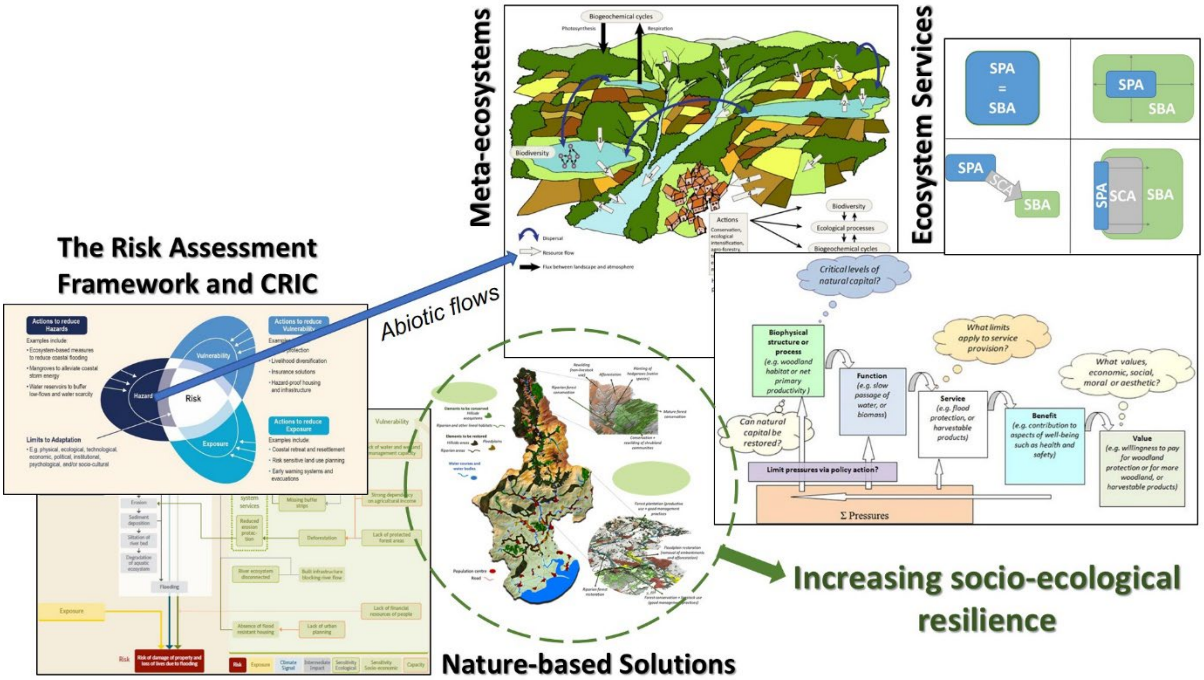

Figure 3. Conceptual relationships between the five theoretical pillars of the model.

2.3 The Risk Assessment Framework

Risk management, defined as plans, actions, strategies or policies to reduce the likelihood and/or magnitude of adverse potential consequences, based on assessed or perceived risks, is a central factor in our society. Risk assessment is a fundamental component in various fields, including environmental management, health and safety, and organizational operations. It involves identifying potential risks, analyzing their impacts, and determining appropriate measures to mitigate them. Systems for climate risk assessment have evolved to address the growing complexity and interconnected nature of climate hazards, exposure, vulnerability, and responses. These frameworks provide a structured approach to evaluating the potential impacts of climate change on SES and are crucial for identifying effective adaptation and mitigation strategies. The most widely adopted frameworks, such as those developed by the IPCC, emphasize a multi-dimensional understanding of risk that incorporates both immediate and cascading effects (IPCC, 2023).

Recent advancements in climate risk assessment have introduced concepts such as compound risks, where multiple hazards occur simultaneously or sequentially, and cascading risks, where one event triggers a series of secondary effects. For example, a drought may lead to water shortages, which in turn disrupt agricultural production, exacerbate food insecurity, and impact local economies. These integrative frameworks highlight the need to assess risks not as isolated events, but as dynamic processes shaped by interactions across natural and human systems.

Central to these frameworks is the interplay between four main components (Figure 4):

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- **Hazards**: These are natural or human-induced physical events or trends, such as extreme rainfall, heatwaves, or sea level rise, that have the potential to cause harm. These physical forces will trigger, intensify or reduce abiotic flows (i.e., spatial flow of energy -e.g., thermal and light solar radiation- or non-living matter -e.g., resource flows of inorganic nutrients, detritus and organisms dying; and water- that can be driven by passive physical processes or organismal movement) that will interact in subsequent order with the SES, altering the rate of input of materials and/or energy into the system. They include both rapid-onset events (e.g., storms) and slow-onset trends (e.g., desertification).
- **Exposure**: This refers to the presence of people, infrastructure, ecosystems, and economic activities in areas that could be affected by hazards. The degree of exposure often determines the magnitude of potential impacts.
- **Vulnerability**: This captures the sensitivity and capacity of exposed systems to cope with and adapt to hazards. The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. Vulnerability is shaped by factors such as social inequality, governance structures, ecological health, and infrastructure resilience.
- **Impacts**: The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ES), and infrastructure. Impacts may be referred to as consequences or outcomes and can be adverse or beneficial.
- **Responses**: Recently incorporated into risk assessment frameworks, responses consider how governance, policies, and adaptive actions influence risk outcomes. Effective responses can reduce vulnerabilities and mitigate the negative impacts of climate hazards, while ineffective responses can amplify risks.

These components are evaluated through multi-hazard interactions, which assess how hazards, exposure, and vulnerability combine to generate specific risks. By including responses as part of the risk framework, modern systems also account for the dynamic feedback loops that influence socio-ecological resilience over time.

The integration of compound and cascading risks, along with the recognition of responses, has advanced the ability of risk assessment frameworks to support climate-resilient development pathways. These systems enable decision-makers to identify hotspots of vulnerability, prioritize interventions, and develop adaptive strategies that balance trade-offs and maximize co-benefits for human and ecological systems.

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Figure 4. The risk frameworks developed by the Intergovernmental Panel on Climate Change (IPCC) within the Sixth Assessment Report (AR6; IPCC; 2023).

Ultimately, climate risk assessment frameworks are essential tools for navigating the challenges of climate change. By understanding the drivers, dynamics, and outcomes of risks, these systems provide a foundation for building resilience, reducing vulnerabilities, and fostering sustainable development in the face of an uncertain future.

Climate Risk Impact Chains

Climate Risk Impact Chains (CRIC) form the foundation for understanding the interactions between climate risks, ecosystem processes, and affected communities. These chains will be driven by the bio-physical relationships revealed through the model, highlighting how climate hazards trigger a series of effects on both natural and social systems. The bio-physical relationships within the model provide the necessary basis to define the components of the impact chains, allowing for the identification of the critical pathways through which climate risks affect ecosystems and communities. This approach not only helps assess the impacts but also identifies the NbS that can mitigate these effects, contributing to the overall resilience of the territory.

In this sense, CRIC are essentially conceptual frameworks designed to visualize and understand how climate-related hazards (e.g., floods, droughts, heatwaves) propagate through SES, resulting in direct and indirect impacts (Estoque et al., 2022). The core idea is to map out the cause-effect relationships between hazards, exposure, and vulnerability to a specific risk (an example in Figure 5).

These chains are used to systematically assess risks by highlighting how different factors interact to create a risk. For example, torrential rain (hazard) on steep, deforested hillsides (exposure) can lead to increased erosion and landslides (impact). CRIC are beneficial because they provide a visual and analytical tool to:

- Identify key vulnerabilities in a system.
- Support decision-making by suggesting entry points for adaptation, such as restoring ecosystems or building flood defences.

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- Incorporate stakeholder input, making the participatory process context-specific, which is essential for adaptation planning.

These models are particularly useful for assessing climate risks across sectors like water management, agriculture, or urban planning, and they often include both qualitative and quantitative data to enhance the analysis. One key advantage is that they enable the assessment of multiple risks and cascading impacts in a structured manner, helping to inform both short-term and long-term adaptation strategies. However, they can sometimes struggle with capturing dynamic feedback and validating hybrid models, which involves a mix of quantitative data and expert judgment.

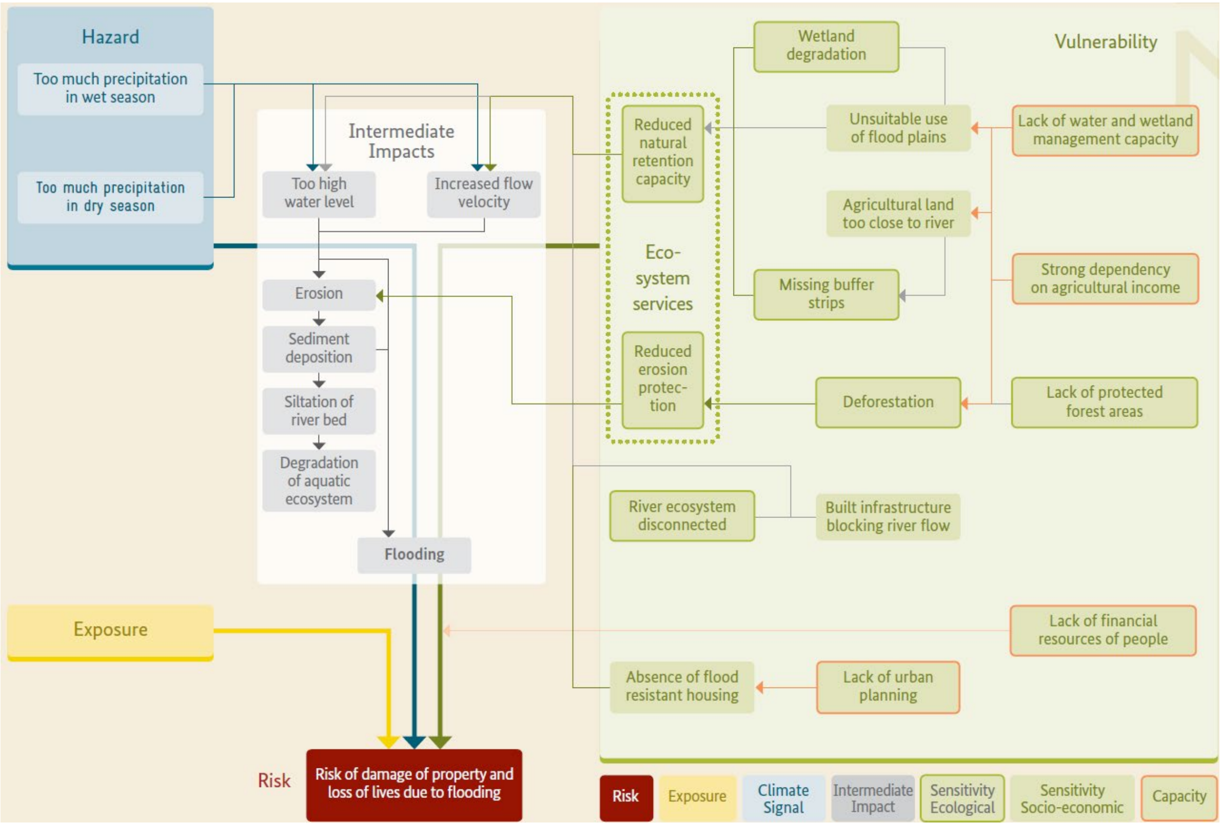

Figure 5. Example of a Climate Risk Impact Chain (CRIC). Extracted from GIZ, EURAC & UNU-EHS (2018): Climate Risk Assessment for Ecosystem-based.

2.4 The Paradigm of Nature/Ecosystem-based Solutions

Integrated landscape management practices have been shifting to a more holistic approach that seeks to integrate hard engineering interventions and new soft solutions to address water-energy-food challenges and threats to continental and marine ecosystems in a more sustainable and resilient way (Liu et al. 2020; Chausson et al. 2020). Indeed, ecosystems are impacted by multiple human activities in a landscape that modify both biotic and abiotic flows, such as land use changes, water withdrawals, topographical alterations, hydraulic infrastructures or the introduction of invasive species (Dudgeon 2019). Paradoxically, many of these impacts are caused by hard interventions for regulating abiotic flows (e.g., embankments and dams for flood protection or slope terracing for water and soil retention). Although they are usually successful in achieving the intended objective, few provide any additional benefit (Jones, Hole, and Zavaleta

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2012). In fact, a limited view of interactions across the landscape frequently produces sustainability problems and increase hazards in other areas of the landscape (e.g., Brookes 1987; Grill et al. 2019; Pérez-Silos, Álvarez-Martínez, and Barquín 2021). In this context, NbS are currently gaining considerable socio-political traction as evidence mounts on the multiple benefits they simultaneously provide to human societies as they effectively buffer the effects of climate hazards but also substantially contribute to biodiversity conservation (Chausson et al. 2020). NbS not only improve the ecosystem where they are embedded, but their effects might also extend across ecosystem boundaries. This makes them capable of addressing a wide range of both present and future environmental challenges.

Embracing NbS offers different conservation, restoration/rehabilitation and managing strategies applied to natural and semi-natural ecosystems (Cohen-shacham et al. 2019). NbS can not only enhance regulating ES provision by simultaneously harnessing multiple ecosystem functions but also provide resilient and sustainable solutions that follow seasonal and temporal changes in ecosystems (Meli et al. 2014). These regulating ES modify abiotic flows resulting from a climate hazard and reduce its potential impacts on society (Table 2). However, to fully harness the potential of NbS, it is essential to move from isolated projects towards the creation of interconnected networks of NbS that span entire landscapes. These networks not only enhance ecological connectivity, supporting species migration and genetic diversity, but also ensure that ecosystem services are delivered across multiple regions and sectors. For example, the restoration of riparian zones and wetlands throughout a watershed can mitigate flooding downstream, improve water quality, and create recreational opportunities for local communities. Similarly, urban green spaces can help regulate temperatures, reduce air pollution, and improve mental health, while also providing habitat for wildlife in densely human populated areas.

In Europe, the term NbS has been used within the EU policy discourse as "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 well-being, ES, resilience and biodiversity benefits" (European Commission 2017). In parallel, NbS are being considered an umbrella concept by the scientific literature, covering a range of ecosystem-based independent approaches and actions (habitat restoration, conservation, management, but also Blue and Green Infrastructure; BGI) that address specific or multiple societal challenges (Cohen-Shacham et al. 2016). Particularly, the term BGI evolved from the concept of ecological networks (Jongman and Pungetti 2004). The most significant step in establishing the term was probably taken by the European Commission with the EU's Green Infrastructure Strategy (European Commission 2013). Here, the definition from Benedict & McMahon (2006) was refined, extending its scope illustrating its added socio-economic value to integrated landscape management: "a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ES". But the strategy also defined BGI "as a successfully tested tool and methods for providing ecological, economic and social benefits through natural solutions". In this sense, while the use of the BGI term is being diluted under the concept of NbS (Cohen-shacham et al. 2019) when used to refer to individual elements, a growing number of studies have used the term "Blue and/or Green Infrastructure Network" (e.g. Pozoukidou 2020; Ferreira, Monteiro, and Silva 2021) or "a Network of Green Infrastructures" (Hermoso et al. 2020; Lanzas et al. 2019) to refer to the spatial arrangement of natural landscape elements which could be seen as

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interlinked components of a landscape planning strategy. Therefore, BGI networks constitute a spatial entity at a higher hierarchical level compared to independent NbS. Independently of considering isolated NbS or BGI networks, these solutions meet the following guiding principles: multifunctionality, biodiversity, connectivity, multi-scale and social integrative. Moreover, they share strong links and interrelationships with each other, especially because their implications in the provision of ES.

Table 2. Some examples showing the relationship between Nature-based solutions (NbS) and blue and green infrastructure (BGI) components and their relationships with some of the abiotic flows they regulate.

Nature-based Solutions (NbS)	Blue and Green Infrastructure component (BGI)	Type of landscape	Main abiotic flows potentially regulated
Restoration of riparian ecosystems to sediment retention (Lind, Maher, and Laudon 2019)	Riparian forest	Urban – Rural (Green)	Water, sediments, nutrients and solar radiation from hillslopes to the river (erosion and landsides
Wetland conservation for flood-water storage areas (Acreman et al. 2011)	Wetlands	Urban – Rural – Coastal (Blue)	Water, sediments and nutrients in different parts of the landscape
Converting intensive forestry to “close to nature” practices (e.g., increasing stand diversity) to increase resilience to climate change threats (Gyenge et al. 2011)	Plantations	Rural (Green)	Water, sediments and nutrients
Renaturation of watercourses to increase biodiversity and reduce flood risks downstream (Bechtol and Laurian 2005)	Rivers	Urban – Rural (Blue)	Water and sediments
Green roofs for absorbing rainwater and providing insulation (Carter and Butler 2008)	Green roofs	Urban (Green)	Water and solar radiation
Allowing for passive natural revegetation of former agrarian fields to reduce erosion and restore hydrological properties and soil quality (Cao et al. 2011)	Shrublands, forests	Rural (Green)	Water and sediments in the catchment
No-take marine-protected areas (e.g., coral reefs) to increase ecosystem resilience (Cinner et al. 2013)	Sea, coral reefs	Coastal (Blue)	Waves and nutrients

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2.5 Meta-Ecosystem Theory

Traditionally, ecosystems have been studied as relatively autonomous units (Odum, 1971; Likens, 1985), with research focusing on internal ecological processes, energy flows, and nutrient cycling within bounded systems. However, this perspective overlooks the complex interactions that shape ecosystems across spatial and temporal scales. Ecosystems are not isolated entities; they are embedded within a broader landscape matrix where the exchange of energy, organisms, and nutrients plays a fundamental role in shaping their structure and function. Large-scale disturbances such as climate change, habitat fragmentation, and land-use shift further underscore the need for an integrative framework that accounts for these cross-ecosystem fluxes and dependencies (Loreau et al. 2003). In this context, meta-ecosystem theory (Gounand et al., 2018) provides a more holistic approach, where ecosystems are constantly interconnected through flows of matter, energy, and organisms. These exchanges regulate key ecological processes and, in turn, shape biodiversity patterns, biogeochemical cycles, and ES (Figure 6). So, a meta-ecosystem perspective is crucial for understanding how natural systems not only respond to environmental disturbances but also play a role in regulating and redistributing climate risks.

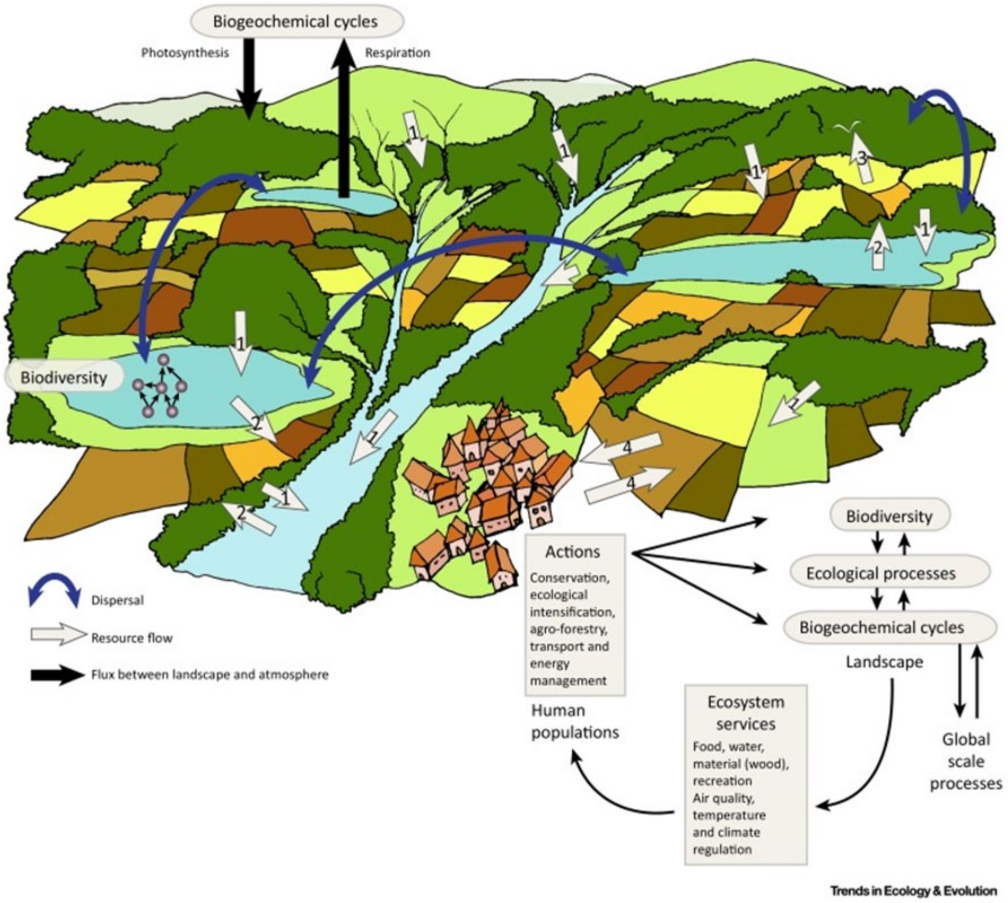

Figure 6. This conceptual diagram proposed by Gounand et al. (2018) shows the importance of the flows of matter and energy that connect different ecosystems (i.e. meta-ecosystems). For example, river ecosystems mostly receive resource flows from terrestrial ecosystems at different parts of the catchment. These flows affect biodiversity and ecosystem processes, which themselves affect global cycles in different ways. Human populations benefit from ES provided by the landscape, and human actions conducted at the

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landscape scale modulate biodiversity and ecosystem functioning, and ultimately biogeochemical cycles, which in turn affect ES provision.

The meta-ecosystem perspective thus integrates several key elements that are essential to understanding how landscapes operate as dynamic SES (Loreau et al. 2003; Gounand et al. 2018):

Flows of Abiotic and Biotic Components: On the one hand, ecosystems are connected by the movement of water, nutrients, sediments, and organic matter, which can shape productivity and ecological interactions across space. On the other hand, organisms migrate, disperse, and interact across ecosystem boundaries, affecting population dynamics, community structure, and genetic exchange.

Multi-Scale Spatial Dynamics: Ecosystems are organized across different spatial scales, from local habitat patches to large-scale ecological networks. According to this theory, the interaction between local processes (e.g., primary production, decomposition) and cross-ecosystem exchanges determines broader landscape-level patterns of biodiversity and function. The capacity of an ecosystem to influence others is mediated by landscape heterogeneity and the degree of ecological connectivity. In this sense, ecosystems are interlinked across multiple spatial scales, meaning that local processes can generate cascading effects in neighboring ecosystems or even in distant ones. The movement of organisms, the transport of nutrients, and the exchange of energy between ecosystems create a dynamic web of interactions that shape ecological functions and the delivery of ES.

Dispersal of Organisms and the Role of Connectivity: The movement of species between ecosystems affects trophic interactions, competition, and ecosystem stability. Dispersal not only allows species to track environmental changes but also redistributes ecological functions, influencing resilience to disturbances. Connectivity between ecosystems can mitigate localized environmental stressors by facilitating species migration and genetic flow, buffering against biodiversity loss.

Interaction of Niche Processes and Cross-Ecosystem Flows: The classic ecological niche theory explains species distributions based on environmental conditions and resource availability (Hutchinson 1959), but the meta-ecosystem perspective expands this by integrating incident flows of energy and materials. Ecosystem configurations are shaped not only by internal conditions (e.g., local nutrient cycling, species interactions) but also by the influence of external fluxes arriving from adjacent ecosystems. This dynamic interplay can drive unexpected ecological outcomes, such as the enhancement of ecosystem productivity due to nutrient subsidies from upstream environments.

Temporal Dynamics and Ecosystem Regulation of Risk Flows: Meta-ecosystem interactions are not static but fluctuate over time, driven by seasonal cycles, disturbance regimes, and long-term climate variability. The capacity of ecosystems to regulate environmental risks (e.g., floods, droughts, heatwaves) depends on their ability to buffer and redistribute these disturbances across connected systems. By absorbing and redistributing climate-related stressors, ecosystems act as natural regulators of risk, mitigating localized impacts and enhancing overall landscape resilience.

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2.6 The Ecosystem Services Framework

As mentioned previously, ES are the various benefits that humans derive from healthy ecosystems (e.g., from carbon sequestration to clean water provision or recreation value; Fisher et al., 2009). The ES paradigm encompasses the direct and indirect benefits that people obtain from natural capital (Potschin and Haines-Young 2011).

Three types of ecosystem services emerge from these interactions between the ecosystem and its abiotic environment (See also Appendix 1.1.4):

- **Provisioning ES**: resource provision (e.g., provision of water, materials, wood, fishes…)
- **Regulating ES**: regulation of abiotic flows (e.g., carbon sequestration, erosion regulation, flood regulation…)
- **Cultural ES**: non-consumptive benefits, which are more dependent on the social context and the setting (e.g., recreational use, aesthetic values, cultural heritage…)

According to Potschin and Haines-Young (2011), the idea of a “service cascade” can be used to summarize much of the logic that underlies the contemporary ES paradigm and key elements of its conceptual basis. This cascade model shows how biophysical structures and ecological processes support ecosystem functions whose outputs are transferred as services that are defined and valued socio-economically (Figure 7). Specifically, biological components are involved in a large number of physicochemical cycles and biological interactions that occur within and across ecosystem boundaries, providing different ecological processes and functions simultaneously, such as productivity or recycling nutrients (Manning et al. 2018). In more detail, each ecological function has its origin in the biophysical interaction between the biological components at their different levels of organization (e.g. populations, communities or food webs) and the physical processes that control the multiple abiotic flows circulating through the landscape (e.g., flows of water, energy or matter; (Kremen and Ostfeld 2005). At the landscape level, humans get benefit from ecosystem functions in the form of a wide range of ES when the biophysical interaction occurs at the spatial scale required by the specific process (Křováková et al. 2015; Syrbe and Walz 2012a; Laca 2021; Schirpke et al. 2020). For example, vegetation provides regulating ES such as flood mitigation or erosion protection by retaining part of the water and sediment flows in areas that drain into the river network, respectively. Similarly, provisioning ES follow the same rationalization. For example, in the pasture production ES, nutrient, water and radiation flows are used by plant organisms in defined (or undefined) socio-ecological spatial units (Schirpke et al. 2020) to generate aerial biomass that can be used for nutritional purposes.

The ES cascade model therefore attempts to capture the prevailing view that there is something of a ‘production chain’ linking ecological and biophysical structures and processes on the one hand and elements of human well-being on the other, and that there is potentially a series of intermediate stages between them. According to (Potschin and Haines-Young 2011), this framework should also help framing a number of important questions about the relationships between people and nature, including: (1) whether there are critical levels, or stocks, of natural capital needed to sustain the flow of ES; (2) whether that capital can be restored once damaged; (3) what the limits to the supply of ES are in different situations; and (4) how we value the contributions that ES make to human well-being.

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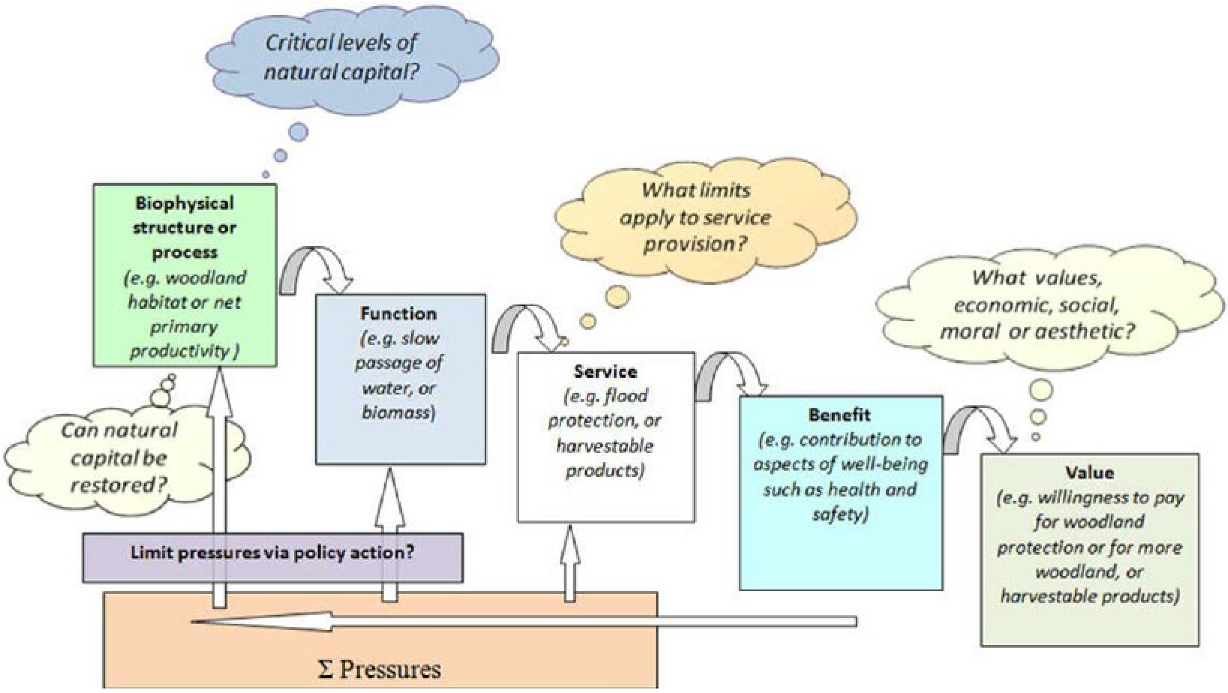

Figure 7. ES cascade model.

Spatial and temporal dynamics of ecosystem services

ES are usually provided within process-related landscape units such as catchments, specific habitats, or natural units (i.e. functional units *sensu* Křováková et al. 2015; Laca 2021). An outstanding advantage of the ES approach is that it shows the conditions under which nature creates benefits. However, the areas that provide ES might differ from those areas in which society benefits from these services. In this sense, we can differentiate three types of areas in the landscape in relation to different ES flows (Figure 8; Syrbe and Walz 2012a):

- **Service-providing areas** (SPA): spatial units that are the sources of ES in a given landscape. Areas where the biophysical interaction lead by ecosystems occur to generate the ES.
- **Service-connecting areas** (SCA): spatial units connecting providing areas with benefiting areas in a given landscape.
- **Service-benefiting areas** (SBA): spatial units where the benefits from ES are required/consumed in a given landscape. Locations where ES are delivered to society.

On the other hand, the ES provided by a given biological component may also fluctuate over time (Rau, von Wehrden, and Abson 2018). Sometimes this variation is due to changes in abiotic and biotic fluxes within the functional unit that impact on the service-generating biophysical interaction (e.g., during the winter period, lower incident radiation leads to reductions in plant productivity and thus in pasture provisioning ES). On other occasions, the change in ES provision is determined by changes in demand (e.g., increased demand for water provision during the summer months in tourist areas where the population is concentrated during holiday periods). Finally, in certain ES there is a time lag between the generation of the ES and its final delivery. This occurs more frequently in ES with a directional spatial relationship between the service-providing areas (SPA) and service-benefiting areas (SBA). For example, in the drought risk

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mitigation ES, aquifer recharge occurs during the rainy season, but its benefit is mostly generated during the dry periods.

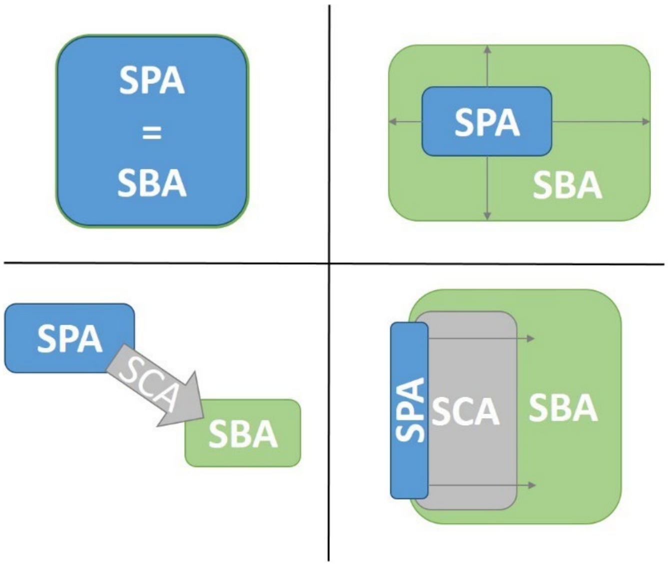

Figure 8. Conceptual diagram showing possible spatial relationships between service providing area (SPA) and service benefiting area (SBA; according to (Fisher, Turner, and Morling 2009). On the upper left 'in situ' situation: SPA and SBA are identical, i.e. the service is provided and benefits realized in the same area. On the upper right 'omni directional' situation: SBA extends SPA without any directional bias. On the lower left 'directional' – slope dependent situation: SBA lies downslope (downstream) from SPA, i.e. the service is realized by gravitational processes (cold air, water, avalanche, landslide). On the lower right 'directional' – without strong slope dependence situation: SBA lies 'behind' the SPA relating to higher-ranking directional effects. Adapted figure obtained from (Syrbe and Walz 2012a).

Relationships between ES

Recent research explores the spatial patterns of provision of multiple ES across landscapes, focusing on the spatial overlap among ES provisioning as evidence of win-win opportunities for conservation of multiple ES and biodiversity (e.g. (Chan et al. 2006; Egoh et al. 2008; Naidoo et al. 2008; Nelson et al. 2009). The results of these studies show there are important relationships among ES, even if the authors have not explicitly been looking for such. That is, some ES often appear together on the landscape while others seem to cancel each other. These relationships among ES are mainly caused by two mechanisms (Bennett, Peterson, and Gordon 2009). On one hand, multiple ES respond to the same driver (e.g., land uses, precipitation, etc.). Consequently, changes in a specific driver may lead to simultaneous changes (but not necessarily in the same direction) in the provision of some ES related to this driver. For example, increasing fertilizer use to improve crop production can have a significant negative effect on local provision of clean water in addition to the intended effect of increasing crop yields. On the other hand, interactions among ES themselves may cause direct or indirect changes in one ES to alter the provision of another. For example, afforestation enhances carbon sequestration, but the process of tree growth increases evapotranspiration, decreasing water availability (Pérez-Silos, Álvarez-Martínez, and Barquín 2021). In this sense, relationships of ES pairs can be categorized into the following four (and their respective six variants) situations:

- **Synergies**: situations in which both ES either increase or decrease (i.e., in Figure 9: b-synergy, c-mutual loss). For example, a synergistic relationship exists among erosion

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protection and flood risk mitigation. The roots of forest vegetation increase soil consistency, reducing sediment production, while increasing infiltration and reducing runoff that favours flood events (Pérez-Silos, Álvarez-Martínez, and Barquín 2021).

- **Trade-offs**: situations in which one ES increases and another one decreases (i.e., in Figure 9: a-trade-off). For example, water quality and agricultural production are a well-known trade-off due to differing responses to the addition of nutrients to the agricultural landscape (Carpenter et al. 1998).
- **Exclusions**: situation in which provisioning of one ES excludes the other (i.e., in Figure 9: d-exclusion). Soil sealing excludes all ecosystem services based on plant production (Wratten et al. 2013).
- **No-effect**: situations in which there is no interaction or no influence between two ES (i.e., in Figure 9: e-no interdependency). For example, the presence of a riparian forest buffer has positive effects on the thermal regulation of rivers, with negligible negative effects on the production of adjacent agricultural fields (Pérez-Silos 2021; Pérez-Silos, Álvarez-Martínez, and Barquín 2019).

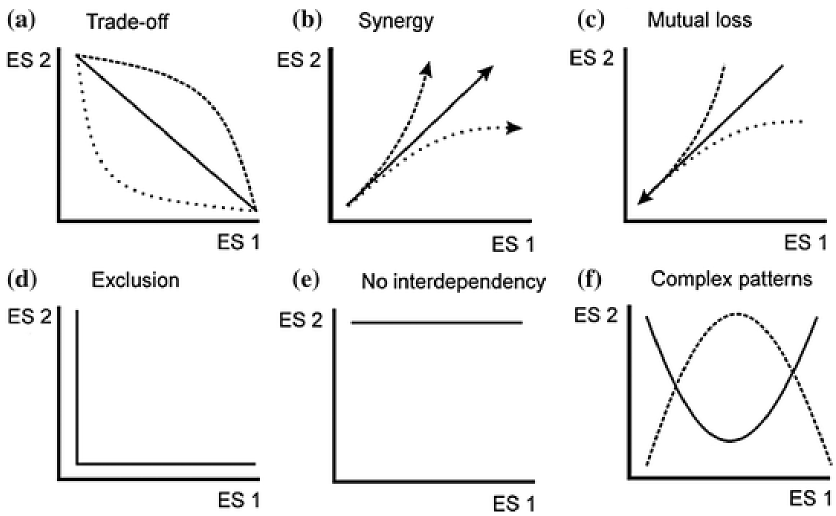

Figure 9. Competition for Land-Based Ecosystem Services: Trade-Offs and Synergies (Müller, D. et al. 2016).

These relationships between ES often follow non-linear trajectories that vary according to spatial and temporal scale (Lee and Lautenbach 2016; Lindborg et al. 2017). For example, the ability of floodplains to store surface water provides a flood risk mitigation service during the wet season (specifically, during flood events). In turn, floodplain inundation causes timely damage to the pasture provision ES provided by grasslands in these areas (i.e., trade-off relationship). However, at larger temporal scales, the relationship between both ES is synergistic. Firstly, the use of the provisioning ES and the activation of the flood regulation ES do not usually coincide in time. In addition, floods periodically fertilize these floodplain fields, increasing their productivity in the medium and long term.

In conclusion, the relationships that emerge between different ES led to the emergence in the landscape of areas with similar ensembles of ES that repeatedly appear together across space or time. Such ensembles, known as ES bundles (Raudsepp-Hearne, Peterson, and Bennett 2010), are

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a direct consequence of synergies, tradeoffs or exclusions, and constitute unique providers of multiple ES, reflecting relevant SES (Figure 10).

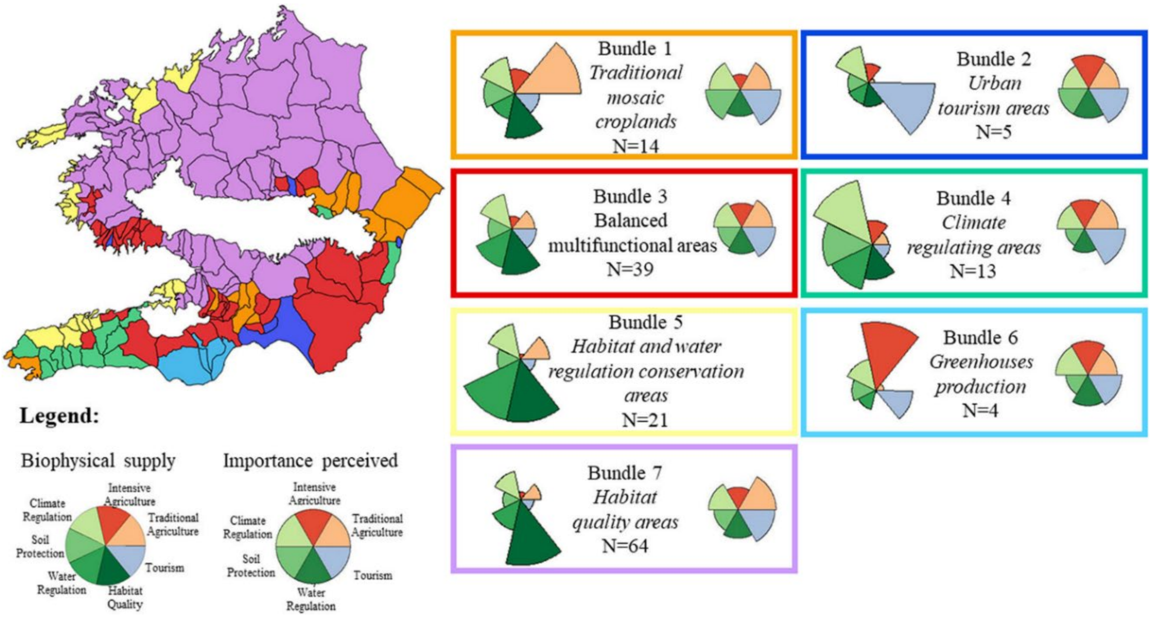

Figure 10. Examples of the ES bundles identified for a specific territory (extracted from Quintas-Soriano, et al. 2019)

2.5 Landscape Resilience

The NBRACER framework conceptualizes landscape resilience as a dynamic, interconnected process that integrates socio-ecological, infrastructural, and governance aspects, acknowledging that KCS are embedded within landscapes across both social and physical domains. Rather than simply bouncing back after disruptions, resilient landscapes absorb disturbances, adapt to evolving conditions, and reorganize while maintaining essential functions and structures (Holling, 1973; Walker et al., 2004). Given the growing pressures of climate change, urbanization, and land-use transformations, strengthening landscape resilience is essential to ensure the long-term functionality of KCS, the sustainability of natural ecosystems, and the well-being of communities.

At the core of this approach is NBRACER's Approach, which integrates principles from resilience thinking, spatial planning, transformative governance, and a System of Systems (SoS) perspective. This methodology recognizes that landscapes function as adaptive systems, where KCS—including critical infrastructure, mobility networks, water management, public health services, and ecological networks—are integral components of both the social and physical fabric. By embedding KCS within landscape resilience planning, the framework fosters adaptive, scalable, and sustainable solutions that strengthen the capacity of regions to anticipate, respond to, and recover from climate-driven hazards.

To make resilience a practical and operational concept, it is useful to distinguish between:

- **Resilience Features** – These include robustness, redundancy, resourcefulness, and response, which provide structural and functional stability to landscapes and their KCS, ensuring that critical services, ecosystems, and infrastructure remain functional under stress.

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- **Resilience Capacities** – These include absorptive, adaptive, transformative, and response/recovery capacities, enabling landscapes and their KCS to withstand shocks, adjust to gradual changes, and transition toward more sustainable configurations.

Beyond individual resilience features and capacities, landscapes function within interdependent systems, where resilience is shaped by the way different KCS interact. This aligns with the interdependent resiliencies of a SoS with complex adaptive properties (CAS) concept, suggested by Tzavella (2020), which extends resilience thinking beyond single systems to their cascading effects and interdependencies. This perspective emphasizes that the resilience of one system is influenced by, and contributes to, the resilience of others, reinforcing a collaborative and systemic approach to climate adaptation. Incorporating CAS thinking into climate adaptation strategies emphasizes systemic, place-based approaches. It advocates for understanding and mapping interdependencies, recognizing potential cascading effects, and fostering cross-system resilience. The approach aligns with the collaborative methodologies in climate adaptation, ensuring that interventions consider the broader system context and support holistic, long-term resilience-building. Specifically, the resilience of a SoS with CAS properties is grounded in the 4Rs—Robustness, Redundancy, Resourcefulness, and Response (Table 3)—and extends across different capacities at the level of constituent systems in an interdependent manner:

- **Absorptive capacity**: The ability of interconnected systems (e.g., transport networks, flood control systems, emergency services) to withstand and mitigate initial impacts.
- **Adaptive capacity**: The flexibility of these systems to adjust their functions and operations in response to gradual changes.
- **Transformative capacity**: The ability of systems to undergo fundamental shifts in structure and function to ensure long-term sustainability.
- **Response/recovery capacity**: The speed and efficiency of systems to restore essential services and adapt post-hazard.

Table 3. This table illustrates how different resilience features translate into real-world mechanisms that enable landscapes to sustain their functionality under climate pressures.

Resilience Features	Definition	Resilience capacity	Landscape Resilience Across Biophysical, Social, and Governance Domains including KCS -Examples
Robustness	The ability of landscapes to withstand direct climate stressors (e.g., floods, heatwaves, droughts) while maintaining critical functions and structures.	Absorption capacity	**Biophysical:** Ecosystems regulate and buffer climate extremes (e.g., wetlands absorbing floodwaters). **Social:** Community preparedness and strong social networks enhance coping mechanisms. **Governance:** Policies enforce protective measures (e.g., zoning laws for flood-prone areas).
Redundancy	The presence of multiple pathways for maintaining landscape functionality, ensuring resilience through overlapping ecosystem services, social structures, and governance mechanisms.	Adaptation capacity	**Biophysical:** Diverse land covers (e.g., forests, wetlands, agricultural zones) enhance resilience under different hazard scenarios. **Social:** Decentralized community resources ensure adaptability. **Governance:** Institutional flexibility enables multi-scalar adaptation strategies.
Resourcefulness	The ability of landscapes to transform and reorganize in response to changing conditions, particularly through NbS, ecosystem restoration, and community-driven adaptation.	Transformation capacity	**Biophysical:** NbS (e.g., green infrastructure, ecological corridors) enhance adaptation. **Social:** Innovation and knowledge-sharing drive community adaptation. **Governance:** Enabling policies integrate NbS into regional planning and climate resilience strategies.

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Response & Recovery	The efficiency and speed of landscape systems in recovering from climate shocks, ensuring continued ecosystem service provision and community well-being.	Rapidity of Response	**Biophysical:** Ecosystem-based adaptation (e.g., coastal dune restoration post-storm surge) accelerates recovery. **Social:** Community resilience networks support rebuilding efforts. **Governance:** Emergency response frameworks and recovery funding enable rapid restoration.

These interdependent capacities shape how climate risk impact chains (CRICs) propagate through landscapes, influencing the capacity of KCS to maintain stability under climate stressors (Figure 11).

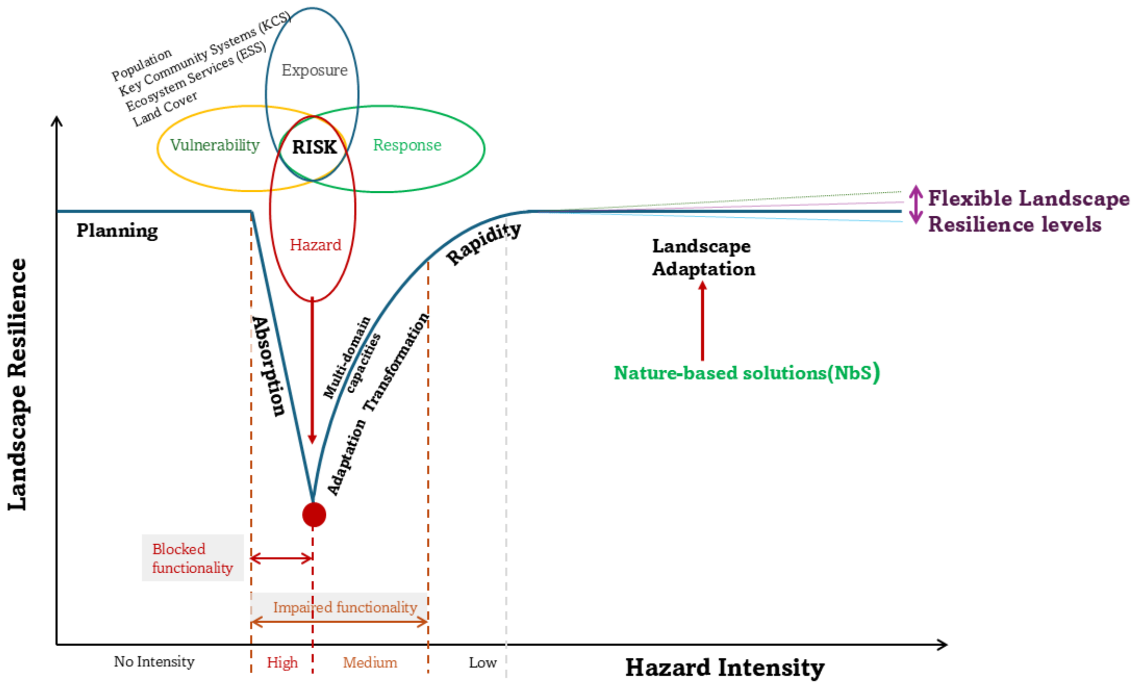

Figure 11. Landscape Resilience Curve – Interdependent Resiliencies of a System of Systems– adapted from (Tzavella K., 2020) This figure illustrates how landscapes function as adaptive SoS, where different KCS—such as critical infrastructure, ecological networks, mobility systems, water management, and public health services—are interdependent in shaping resilience outcomes. The curve represents flexible resilience levels, where biophysical, social, and governance domains sub-function within defined thresholds but retain overall system functionality. When hazard intensity increases beyond a critical threshold, the system may transition into a state shift, requiring transformative resilience strategies.

The ability of a landscape to maintain its functionality under increasing hazard intensity depends not only on its individual resilience capacities but also on how different systems/domains interact and reinforce one another. As hazards intensify, landscapes may reach critical thresholds that trigger systemic changes, requiring coordinated adaptation efforts across biophysical, social, and governance domains. Therefore, beyond simply defining resilience features and capacities, it is essential to explore the underlying characteristics that enable landscapes to absorb shocks, adapt to gradual changes, and recover from disturbances.

Further building on the resilience features and capacities outlined above, the following sections examine how these dynamics shape landscape (*a SoS with CAS properties*) resilience in practice. They highlight the interplay between key resilience mechanisms—including adaptive capacity, feedback loops, and cross-scale interactions—and their role in sustaining essential ecosystem functions and KCS under evolving climate, socio-economic, and governance conditions.

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Adaptive Capacity and Learning in Landscape Resilience: Resilient landscapes possess the ability to adapt, learn, and evolve in response to changing environmental conditions. This adaptive capacity is supported by diverse land covers, ecosystem types, and hydrological networks, which provide the flexibility needed to withstand both gradual shifts, such as changing precipitation patterns, and sudden shocks, such as extreme weather events (Carpenter et al., 2001; Folke et al., 2005). Just as biodiversity strengthens ecosystem stability, variability in land use and ecological systems enhances a landscape's ability to absorb and respond to disturbances. Equally important is the role of social learning and innovation in shaping landscape resilience. Communities that actively engage in knowledge-sharing, experimentation, and adaptive governance are better equipped to anticipate, prepare for, and recover from climate challenges like droughts and floods. Collaborative decision-making and cross-sectoral partnerships strengthen the governance structures that support adaptive management, ensuring that landscapes continue to function effectively under changing conditions. By embedding adaptive capacity and learning into resilience planning, the NBRACER framework recognizes that landscapes are not static entities but living, evolving systems. Through continuous monitoring, feedback mechanisms, and flexible policy approaches, regions can develop context-specific strategies that enhance both ecological and socio-economic resilience, enabling landscapes to sustain their essential functions while adapting to future uncertainties.

- **Feedback Loops and Adaptive Landscape Resilience:** Landscape resilience is shaped by feedback loops that influence stability across multiple domains—biophysical, social, and governance. Positive feedbacks, such as land degradation accelerating erosion, can amplify vulnerabilities, while negative feedbacks, like wetlands buffering floodwaters or vegetation stabilizing slopes, enhance stability (Gunderson & Holling, 2002). These loops are critical within risk assessments, helping identify how disturbances propagate across systems and where interventions can disrupt destabilizing cycles. NbS play a key role in managing these interactions by reinforcing self-regulating ecological functions, strengthening community adaptation mechanisms, and informing governance strategies that promote long-term resilience.
- **Thresholds and Regime Shifts in Landscape Resilience:** Landscape resilience operates across biophysical, social, and governance domains, where critical thresholds—such as extreme hazard intensities, ecosystem degradation, or governance failures—can trigger regime shifts that fundamentally alter system functionality. When these tipping points are crossed, landscapes transition into new, often less resilient states, requiring significant intervention to recover (Scheffer et al., 2001). For instance, excessive deforestation or urban expansion can disrupt hydrological cycles, leading to increased flood risks and degraded ecosystem services. Similarly, governance systems weakened by social or economic pressures may struggle to implement adaptive responses, exacerbating landscape vulnerability. Identifying and managing these thresholds through risk-based planning, ecological restoration, and adaptive governance is crucial to maintaining long-term landscape resilience and preventing irreversible transformations.
- **Cross-Scale Interactions in Adaptive Landscape Resilience:** Landscape resilience emerges from the dynamic interactions across its biophysical, social, and governance domains, where changes at one scale influence and are influenced by processes at others. This aligns with the concept of panarchy (Gunderson & Holling, 2002), which describes how

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systems operate within nested hierarchies. For instance, biophysical changes, such as local deforestation, disrupt regional hydrological networks, increasing flood risks. Simultaneously, social and governance responses—ranging from local land-use planning to global climate policies—shape adaptation measures and long-term resilience pathways. Because landscapes are structured by feedback loops across these domains, resilience strategies must integrate interventions at local, regional, and global levels to prevent maladaptive outcomes and enhance long-term sustainability. This requires risk-informed, cross-scale coordination, ensuring that NbS, governance frameworks, and socio-economic planning are aligned to maintain both stability and adaptability under shifting climate conditions.

- **The Social Dimension of Landscape Resilience:** Landscape resilience extends beyond ecological processes to include the social dimension, recognizing that human systems shape and are shaped by landscapes. Social resilience reflects the ability of communities to organize, learn, and adapt to environmental disturbances through governance, equity, and collective action (Adger, 2000). Governance structures influence adaptive capacity by enabling or constraining decision-making, while inclusive participation ensures that resilience strategies address the needs of vulnerable populations (Walker et al., 2006). Strong social networks and knowledge exchange enhance the ability of landscapes to absorb change, reorganize, and sustain essential functions, reinforcing long-term resilience.
- **Diversity and Redundancy in Adaptive Landscapes:** Resilient landscapes maintain diversity and redundancy to sustain functions despite disturbances. Ecological diversity, spanning forests, wetlands, and agriculture, buffers against shocks by ensuring multiple pathways for ES (Elmqvist et al., 2003). Redundancy safeguards resilience by allowing overlapping functions to compensate for disruptions. In SES, varied governance, land-use, and knowledge systems enhance adaptability, enabling landscapes to absorb, reorganize, and recover. Recognizing landscapes as dynamic systems, maintaining functional redundancy and ecological heterogeneity strengthens their ability to self-organize and adapt to change, ensuring long-term resilience.
- **Transformative Resilience in Landscapes - Biophysical, Social, and Governance Domains:** Landscape resilience is not only about maintaining stability but also about transforming in response to long-term environmental and societal shifts (Walker et al., 2004). In the face of intensifying climate change, land degradation, and socio-economic pressures, transformative resilience enables landscapes to reorganize their structures, functions, and governance mechanisms to sustain essential processes and adapt to new conditions.

  - **Biophysical Transformation:** Degraded landscapes can shift from resource-extractive states to multi-functional ecosystems that enhance biodiversity, regulate hydrology, and store carbon. NbS facilitate this transition by restoring ecosystem functions and strengthening ecological connectivity, ensuring that landscapes can adapt to future stressors.
  - **Social Transformation:** Communities dependent on vulnerable landscapes must adapt their livelihoods, knowledge systems, and adaptive capacities to climate-driven changes. Social resilience is reinforced through education, innovation, and participatory decision-making, allowing communities to shift towards more

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- **Governance Transformation:** Institutional structures and policies must evolve to support adaptive governance, integrated planning, and multi-level collaboration. This includes shifting from reactive crisis management to proactive, risk-informed policymaking that aligns ecological, social, and infrastructural resilience. Ensuring inclusive governance fosters equitable resilience-building, particularly for vulnerable populations.

Landscape Resilience as a Dynamic and Adaptive Process: Landscape resilience is not a static outcome but an ongoing process that balances ecological, social, and governance dimensions while sustaining KCS under evolving climate and socio-economic pressures. It requires adaptive governance, community participation, and spatial optimization to ensure that interventions align with regional biophysical and socio-economic contexts. By integrating NbS and system redundancy, the NBRACER framework fosters collaboration, resource efficiency, and long-term resilience within interconnected socio-ecological and infrastructural networks. The SoS perspective within NBRACER enables landscapes to function as adaptive, self-sustaining systems, ensuring the resilience of critical infrastructure, community services, ecological networks, and governance capacities in the face of climate risks. By integrating KCS into resilience planning, this multi-scale, cross-sectoral approach safeguards landscape functionality, socio-economic stability, and ecological integrity. Additionally, it fosters cross-institutional collaboration, ensuring that climate adaptation efforts drive systemic, long-term sustainability through policy transformation and sustained funding.

3 Rationalization of the conceptual framework

This section describes the conceptual framework, which has been developed based on the foundations presented in the previous section. First, the Social-Ecological System Perspective underlying the framework is introduced. This perspective proposes an integrated view of the territory and the socio-ecosystems it encompasses, drawing on the meta-ecosystem theory (Gounand et al., 2018) and the ES assessment framework proposed by Syrbe and Walz (2012). The following subsection presents the structure and components of the conceptual framework, combining this Social-Ecological System Perspective with a risk assessment framework and the emerging paradigm of NbS. Finally, the section explores how NbS implementation can be optimized in the territory to reduce climate risks and enhance socio-ecosystemic resilience. To this end, hypotheses are proposed regarding the relationship between NbS implementation and its impact on the response variables considered: risk and resilience.

3.1 A Social-Ecological System Perspective of the landscape

Our proposed Social-Ecological System Perspective of the territory recognizes the profound interconnection between ecosystems and social systems (Figure 12). It emphasizes how ecosystem flows and ES not only sustain societal functionality but are also intricately shaped by human activity. By framing these interactions more clearly, the bidirectional dependencies between social and ecological systems become evident, setting a foundation for sustainable and resilient strategies. Territories are conceptualized as complex entities where biotic and abiotic

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flows converge with social, cultural, and economic dynamics, creating a continuously evolving balance that underpins sustainability and resilience.

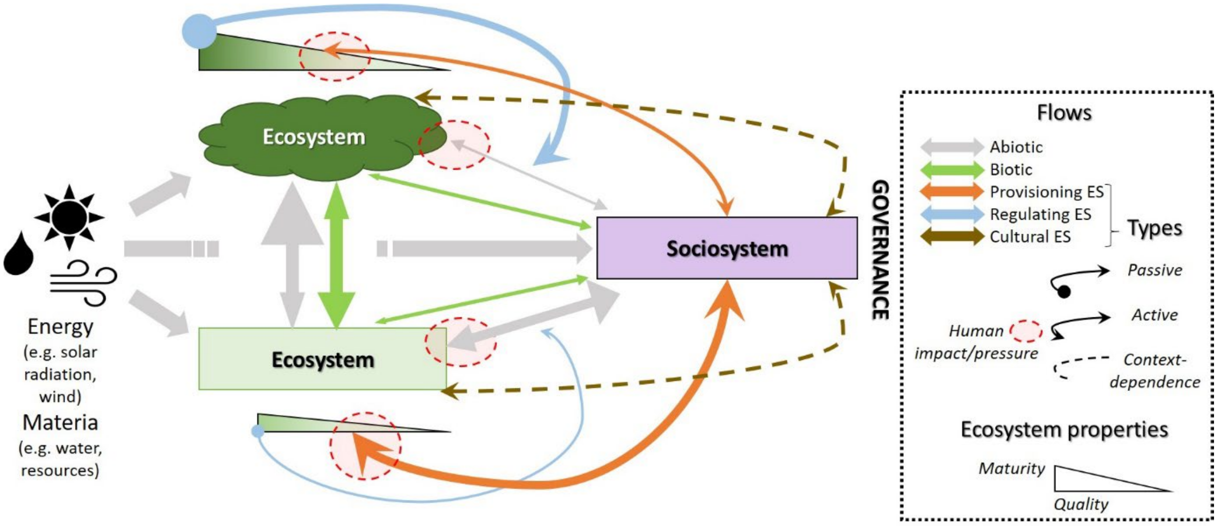

Figure 12. Social-Ecological System Perspective of the landscape. The social system is connected to ecosystems through multiple abiotic and biotic flows (represented in gray and green, respectively). The socio-ecosystem receives various benefits in the form of ES (indicated by orange, blue, and brown arrows), depending on how the biological components of ecosystems interact with these abiotic and biotic flows. Thus, the intrinsic properties of ecosystems (such as maturity and ecological status) determine the extent to which different ES are provided. The social system actively modifies ecosystems to obtain provisioning ES and some cultural ES, whereas regulating ES are typically provided passively, without requiring direct alterations to the ecosystem. These interactions between the social system and ecosystems are structured, hierarchical, and influenced by governance systems, which ultimately shape the landscape's structure and composition based on how it is utilized.

Ecosystems are interconnected through biotic flows (e.g., organisms, genetic material, pollination networks) and abiotic flows (e.g., water cycles, energy transfers, nutrient exchanges), which differ based on the type, position, and conservation status of ecosystems within the sea-landscape (Gounand et al. 2018b). Abiotic flows, such as hydrological cycles and nutrient exchanges, link ecosystems across landscapes, while biotic flows, such as pollination networks or wildlife migrations, connect biodiversity across regions (Gounand et al. 2018). These flows highlight the necessity of viewing ecosystems as interdependent components of a larger metasystem. Ecosystems in poor quality states may disrupt these flows, reducing overall system resilience and limiting the availability of critical ES (MEA 2005).

A central element of this Social-Ecological System Perspective is the recognition that social systems are both agents and beneficiaries of ES. These abiotic and biotic flows not only imply the exchange of resources and energy between ecosystems but also determine the types and magnitude of ES provided, emphasizing the role of ecosystem interdependence in maintaining ecological and social resilience. In this sense, ecosystem properties play a critical role in determining the nature and extent of ES they can provide. Healthy ecosystems with high-quality states and mature ecological processes are better able to deliver regulating ES (e.g., regulation of floods and droughts, water quality, temperature stabilization, etc.), whereas provisioning ES (e.g., food, timber, raw materials) are often exploited directly from more simple ecosystems (i.e., forest plantations, agro-systems, etc.), or from mature ecosystem that frequently leading to

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anthropogenic pressures (e.g., fishing in marine ecosystems; Balvanera et al. 2006; Rey Benayas et al. 2009). Indeed, the exploitation of ES—especially provisioning ES—often generates negative feedback loops that compromise ecosystem quality. Land-use changes, resource overexploitation, and pollution degrade ecosystems, thereby reducing their capacity to deliver ES. These pressures, in turn, impact social systems, leading to vulnerabilities in economic productivity, public health, and cultural stability (Folke et al., 2004). Through active management and sustainable practices, social systems have the capacity to mitigate pressures and enhance ecosystem resilience. For instance, restoration projects, reforestation efforts, and sustainable agricultural practices can reverse degradation trends and foster co-benefits for ecosystems and society (Benayas et al., 2009). Conversely, unsustainable exploitation exacerbates ecological degradation, compounding risks for future generations (Rockstrom et al., 2009).

The Social-Ecological System Perspective underscores the bidirectional relationship between ecosystems and societies. While ecosystems provide essential ES that underpin social systems, human activities shape and, often, compromise ecosystems. This dynamic highlight the need for adaptive governance frameworks that integrate ecological science with socio-economic planning. Governance strategies must prioritize the coevolution of social and ecological systems, ensuring that changes in one domain do not compromise the functionality of the other. For example, adaptive governance frameworks such as integrated catchment management or ecosystems and nature-based planning have proven effective in harmonizing social and ecological needs, enabling both systems to evolve synergistically. Ultimately, fostering socio-ecological resilience is pivotal to this vision. Sustainable resource management, coupled with inclusive governance and community engagement, forms the foundation for building resilient and harmonious socio-ecological systems.

3.2 The conceptual framework: pieces and components

The primary objective of the conceptual framework is to provide a biophysical framework that establishes the relationships between climate risks and their regulation by ecosystems. This framework facilitates the identification of appropriate NbS that can be applied within specific territories to enhance climate adaptation and socio-ecological resilience. To achieve this, the framework focuses on strengthening the links between the ecological integrity of the sea-landscape and its self-sustaining capacity to provide ES. These ES are crucial for safeguarding KCS that underpin social protection and sustainability, such as food, water, and energy systems. The framework (Figure 13) is rooted in the meta-ecosystem theory proposed by Gounand et al. (2018) and the ecosystem services assessment framework outlined by Syrbe and Walz (2012). These foundations underpin the Social-Ecological System perspective described in the previous subsection, integrating climate risk assessment with a social perspective to enhance its utility.

We considered the spatial interactions between abiotic flows (e.g., water, wind, thermal radiation, sediments) triggered by environmental hazards (e.g., heavy precipitation, heatwaves, fluvial flooding, landslides, coastal erosion) and the presence of specific ecosystems in the sea-landscape. Ecosystem management optimizes these interactions to produce societal benefits, such as through the implementation of NbS. Meta-ecosystem theory conceptualizes how material, water, and thermal-energy flows are driven by physical forces (e.g., water potential, gravity, insolation) that connect ecosystem patches across the sea-landscape. These patches range from

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upland hillslopes to river networks and estuaries, as well as from marine systems to coastal areas. Abiotic flows are modified by ecosystem functions as they cross different ecosystem patches of the sea-landscape matrix, altering the input/output balance of materials and energy.

Human actions, such as land-use changes, pollution, and overexploitation, affect ecosystem integrity and the distribution of communities across sea-landscapes. Targeted management actions—such as conservation or restoration—can regulate abiotic flows in terrestrial and aquatic domains, generating societal benefits. According to the ES assessment framework, such management efforts should focus on SPA, which are directly connected to SBA where social demands for the generated ES exist.

Ecosystems (their processes, functions and, consequently, ES) are shaped and adapted to specific environmental conditions dominated hierarchically by climate and geomorphological processes. Our framework captures these interactions by interrelating three components: climatic envelope (and hazards)**,** functional units, and biodiversity (see in Appendix 1, 2 and 3 for having a list of these components):

- **Climate hazards**: The potential occurrence of climate-related physical events or trends that may cause damage and loss.
- **Functional units**: Spatial units that meet the spatial scale required by the biological component to generate the biophysical interaction involved in generating an ES (Laca, 2021).
- **Biodiversity (and ecosystems)**: The living components of the biosphere, regardless of scale (i.e., organism, population, community or ecosystem), although we use the term ecosystems to refer specifically a system formed by organisms in interaction with their environment.

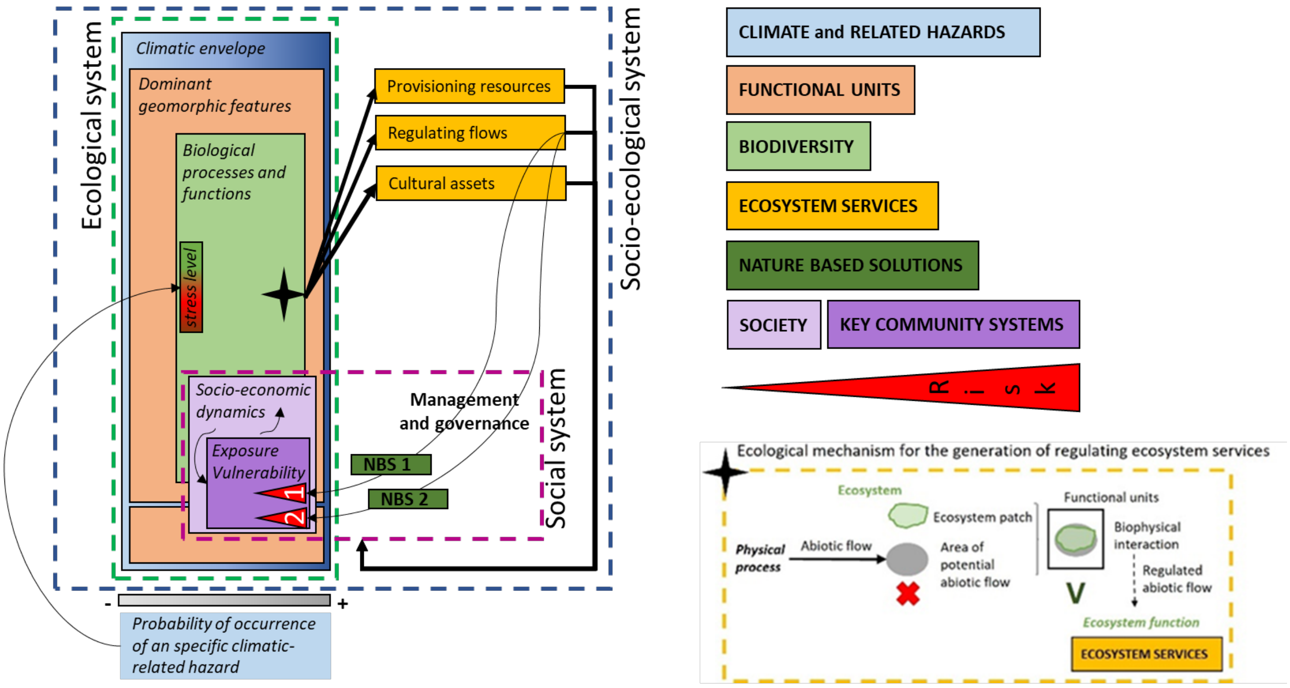

Figure 13. Conceptual framework for NbS implementation.

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Our framework aligns with Pérez-Silos et al. (2023), which conceptualizes the sea-landscape as an array of geomorphic patches, formed by regional acting factors such as the catchment geomorphology and climate, hydrologically connected to each other. Geomorphic patches result from shifts in geomorphic processes that govern abiotic flows and constitute physical habitat type, structure and dynamics (Montgomery 1999). Each type of geomorphic patch has a specific ecological potential that roughly shapes biodiversity and ecosystem functioning. This portrayal of the landscape extends the vision proposed by (Thorp et al. 2006) by incorporating a meta-ecosystem perspective and the specific elements to explore ES patterns and dynamics in river ecosystems. Geomorphic patches are here equivalent to functional units. They capture and aggregate the biotic and abiotic interactions that take place in functional process zones at the scale needed to generate ES. Since the biophysical interactions for ES provision change among functional units (i.e., geomorphic patches), both the ES they generate and their role in the ES flow also differ between functional units. This spatial segregation of the sea-landscape enables tracking of potential ES flows between SPA functional units—characterized by specific abiotic and biotic conditions—and SBA units. Depending on the functional unit (e.g., hillslope, coast, river channel), there will be a specific set of dominant processes, climatic hazards, and potential ecosystems.

A core idea of the framework is that when socio-ecological systems are integrated by appropriate ecosystems, the social systems are better protected against climate hazards, being more resilient. This is particularly true when the overlap involves KCS, as well-maintained ecosystems can generate regulating ES that mitigate or improve abiotic flows triggered by climate hazards. Effective land management entails conserving, restoring, or rehabilitating these ecosystems that generate regulating ES through various NbS (see Appendix 4, 5 and 6).

- **Ecosystem services (ES)**: direct and indirect benefits that people derive from the ecological functioning of ecosystems (De Groot et al., 2002).
- **Nature-based solutions (NbS)**: actions to address societal challenges through the protection, sustainable management and restoration of ecosystems.
- **Key community systems (KCS)**: A system that meets important basic societal needs but that is increasingly impacted by climate change. A key community system is an area of innovation and transformation for the Mission, part of a larger interdependent system (European Mission, 2021).

However, ecosystems have limits to their resilience. Beyond certain thresholds, recurrent climatic hazards may induce stress levels that alter species composition and degrade ecosystem functionality (Hoegh and Bruno 2010; Linder et al. 2010). In such contexts, the absence of ecosystems capable of mitigating climate hazards through regulating ES significantly increases the risk to social systems.

The conceptual framework proposes hypotheses about the impacts of NbS, both isolated and combined, on physical processes triggered by climate hazards. NbS can reduce specific climate-related risks and enhance social resilience via three pathways:

1. **Reducing risks at the source (SPA)**: NbS mitigate the intensity or frequency of the impacts produced by hazards at their origin by targeting the processes and forces that generate abiotic flows associated with climate hazards. This pathway focuses on enhancing ES that

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directly reduce the magnitude or frequency of the impacts produced by the hazard in the areas exposed to its occurrence (i.e. SBA). Some examples include:

   a. Forest ecosystems: Forests on slopes enhance infiltration and reduce surface runoff during heavy rainfall events, lowering the risk of flooding and soil erosion (Bonan, 2008). By stabilizing soil, forests also reduce landslides triggered by excessive precipitation or seismic activity.
   b. Carbon sequestration: Vegetation sequesters atmospheric CO_2 in its biomass and soil, directly reducing greenhouse gas concentrations (Smith et al., 2014). This helps mitigate global climate change, which is a driving force behind extreme weather events and ocean acidification.
   c. Wetlands: By functioning as natural reservoirs, wetlands absorb excess water during precipitation events, acting as buffers against floods while replenishing groundwater reserves (Acreman et al., 2011).

   In these examples, NbS reduce the abiotic forces driving hazards (e.g., runoff, wave energy, CO_2 emissions) and directly address the source of climate risks. Such interventions highlight the importance of targeting SPA ecosystems to reduce the scale and intensity of hazards before they propagate their impacts downstream or across sea-landscapes.

2. **Reducing risk at the connecting areas (SCA)**: This pathway focuses on reducing risk by implementing NbS in the areas that connect the service provision areas (SPA) with the areas exposed to hazards (SBA). These interventions aim to regulate and modulate the transmission of hazard-related processes, acting as buffers or transition zones that minimize the cascading effects of climate risks. By enhancing ecosystem connectivity and optimizing landscape-scale resilience, this pathway ensures that NbS function as integrated networks rather than isolated interventions. Some examples include:
   a. Floodplain restoration: Restoring and maintaining floodplains between upstream forested catchments (SPA) and downstream urban settlements (SBA) allows excess water to be absorbed and slowly released, reducing peak flood intensity. This approach not only protects communities but also enhances biodiversity and groundwater recharge (Opperman et al., 2010).
   b. Agroforestry corridors: Establishing tree and shrub corridors between agricultural lands and urban areas creates multifunctional landscapes that reduce wind and water erosion, filter pollutants, and stabilize microclimates. These corridors act as buffers that slow down hazard propagation, such as storm surges or extreme temperature fluctuations, thereby lowering the exposure of downstream regions (Jose, 2009).
   c. Dune and barrier island reinforcement: Coastal dune systems and barrier islands, strategically positioned between open sea environments (SPA) and coastal settlements (SBA), dissipate wave energy and reduce storm surge impacts. By maintaining and restoring these natural features, NbS help safeguard infrastructure while supporting dynamic coastal processes and habitat stability (Feagin et al., 2015).

   These examples illustrate how NbS in SCA function as intermediaries that regulate and moderate the spatial transmission of climate hazards. By ensuring that landscapes

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work as cohesive units, this approach strengthens overall resilience, preventing risk accumulation between service-providing and risk-exposed areas.

3. **Reducing risks in exposed areas (SBA)**: This pathway addresses the vulnerability of exposed areas by enhancing their capacity to absorb and mitigate the impacts of climate hazards. SBA rely on regulating ES to reduce the intensity of abiotic flows once hazards occur. Some examples include:
   a. Mangroves and coastal ecosystems: Mangroves play a critical role in buffering wave energy, reducing coastal erosion, and protecting infrastructure and communities from storm surges (Spalding et al., 2014). Their dense root systems trap sediments and prevent shoreline retreat, decreasing the vulnerability of coastal zones to climate hazards.
   b. Green infrastructure in urban areas: Urban green spaces, such as parks and green roofs, reduce the urban heat island effect by cooling local temperatures and providing shade. During heavy rainfall, these systems capture and filter stormwater, mitigating flooding risks in densely populated areas (Carter & Butler, 2008).
   c. Riparian buffers: Vegetation along riverbanks absorbs and slows floodwaters, reducing their erosive power and protecting downstream communities (Dosskey et al., 2010).

   These examples demonstrate how NbS contribute to reducing exposure and vulnerability in SBA by managing the flow of impacts derived from hazards. By integrating such solutions into planning, exposed communities can benefit from enhanced protection and greater adaptive capacity.

The conceptual framework highlights the need for a multi-functional approach, where NbS simultaneously address multiple risks and provide co-benefits. For example, wetland restoration can mitigate flooding, improve water quality, and enhance biodiversity. However, maximizing these synergies requires careful spatial planning and trade-off management (e.g., balancing water retention with agricultural productivity). Decision-making must consider socio-ecological and governance factors that influence NbS implementation. Effective strategies involve participatory approaches that engage local communities and stakeholders, ensuring solutions are contextually appropriate and socially equitable (Reed et al., 2009). By optimizing synergies between NbS and minimizing trade-offs, territories can achieve integrated risk management that enhances resilience across ecological, social, and economic dimensions.

3.3 Levels of the conceptual framework

The conceptual framework is structured in three interconnected levels (Figure 14). Each level focuses on a specific domain -biophysical, social and governance-, containing the components and interactions necessary to develop an integrated and holistic perspective on how NbS are selected, designed and planned within a territory to create optimal and resilient landscapes. While these levels are associated with specific domains, they are not rigid stages nor tied to fixed spatial scales. Instead, they reflect system dimensions that are dynamically interlinked. Each domain can operate across multiple spatial scales depending on the processes and decisions under consideration. Although the three levels can be analysed separately, a complete socio-ecological

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vision of the landscape emerges through their ongoing interaction and reciprocal influence across spatial and institutional scales. The social and governance levels are built upon a biophysical structure that determines how they are organized. The biophysical level can initially be considered independently to explore, in detail, the relationships between biological components and physical processes that influence the available types of NbS and their potential design constraints. However, it must later be recognized as an integral part of a social system that determines implementation needs, optimizes design, and ultimately shapes the biophysical environment through human interventions.

These levels highlight the scalability and versatility of NbS, ranging from localized interventions to broader systemic integration. In fact, while the model's levels are not strictly spatial, they do correspond more or less to certain scales and spatial entities depending on the nature of the processes considered at each stage (see also section 4.1.1). However, this correspondence should not be seen as fixed as scale is finally determined by the specific nature of the biophysical, social, or governance process under investigation—not by the domain alone. In this sense, Level 1 requires a local spatial scale that aligns with the scale of the biophysical interactions being analysed and how processes connect through different physical entities in the landscape (i.e., functional units). Level 2 is highly flexible in terms of spatial scale, as it applies to contexts of varying sizes (a catchment, a city, a municipality, etc.). However, it still requires a level of spatial precision sufficient to account for the social and biophysical interactions occurring within functional units. Lastly, Level 3 incorporates governance relationships, which, while operating and having effects at the local level, are established across different administrative and social organization levels. Therefore, they typically need to be considered at larger spatial scales. Here, landscape archetypes serve as spatial entities capable of synthesizing this information across diverse scales. These archetypes reflect the integration of all three domains and serve as boundary-crossing entities—where governance decisions are informed by both biophysical functionality and social priorities, regardless of scale.

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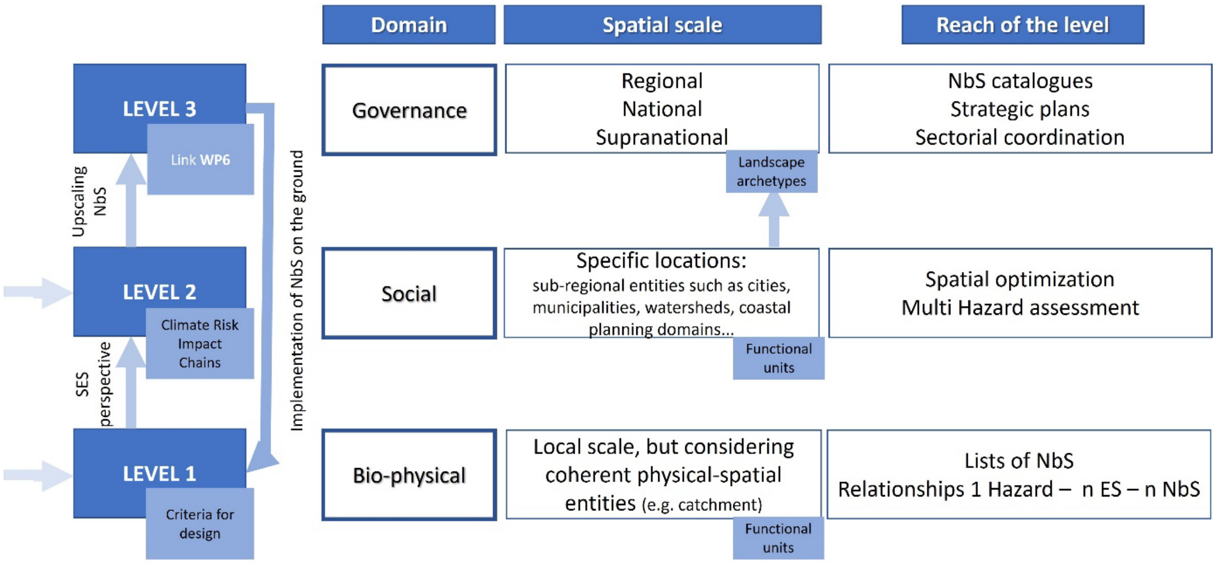

Figure 14. The figure illustrates the three interconnected levels of the conceptual model, each linked to a specific domain and spatial scale to guide NbS implementation. Level 1 (Bio-physical) establishes the relationships between hazards, ES, and NbS, providing the foundation for design. Level 2 (Social) builds on this by integrating climate risk impact chains, ensuring spatial optimization and adaptation at sub-regional scales. Level 3 (Governance) incorporates these relationships to develop governance mechanisms for upscaling NbS at regional, national, and supranational levels. While Levels 1 and 2 operationalize the model, Level 3 translates these insights into strategic planning, ultimately requiring Level 1 for on-the-ground implementation.

Level 1: Climate Hazards and NbS in Functional Units (bio-physical domain).

At the most granular level, this scale focuses on delineating the physical processes that determine specific climate hazards (e.g., floods, droughts, heatwaves) within defined functional units such as hillslopes, beaches, or river channels. By analysing the interactions between climate hazards and the ecosystems that mitigate these risks at the very local scale, decision-makers can identify a range of NbS that are contextually appropriate for implementation.

This level is crucial for operationalizing and implementing NbS in the field and includes developing comprehensive lists that links specific hazards to corresponding NBS available within the landscape. For instance, in a flood-prone area, the model might identify wetland restoration, floodplain reconnection, and urban green infrastructure as viable NbS options. The technical prescriptions produced at this level ensure that these solutions are designed with consideration for the local environmental variables that influence their effectiveness, thereby facilitating targeted and site-specific planning for climate adaptation. However, while this level is essential for operationalizing and implementing NbS on the ground, its narrow bio-physical focus requires integration into broader social contexts to address interconnected climate risks comprehensively.

Although this level considers interactions in fine detail at a local scale, it does not mean that there is no broader perspective on the processes occurring across the landscape. Through the connections between functional units, it is possible to understand how abiotic flows interact with biological components in different areas, determining abiotic flows regulation and, consequently, reducing risks in zones beyond where these regulatory processes take place. For example, flood regulation does not necessarily occur only where the flood happens—reforestation in headwaters can help reduce peak flows at the source. This perspective allows for identifying potential

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connections between SPA and SBA, thus conceptualizing intervention strategies (SPA-SCA-SBA pathways) to mitigate specific climate risks. This cross-unit perspective illustrates how biophysical processes extend beyond the scale of individual interventions, reinforcing the need for systemic design thinking across domains.

At this level, socio-ecological resilience is based on how specific ecosystems and their ES interact with human communities in a potential way. Key considerations include:

- Potential interactions between communities and ecosystems: Communities and ecosystems within functional units (e.g., hillslopes, riverbanks) are closely linked. ES, such as flood regulation or water provision, are essential for local livelihoods and well-being.
- Absorptive capacity of ecosystems: At this level, resilience depends on the absorptive capacity of the ecological system. For instance, restoring local wetlands can improve flood absorption capacity.
- Ecological resilience: Well-preserved or restored ecosystems, which maintain high biodiversity and functionality, contribute to greater adaptive capacity to local climate risks. Ecological redundancy, meaning the presence of species that fulfil similar roles, is crucial for ecosystem resilience. Importantly, these ecological interactions do not exist in isolation but are embedded in social and governance processes that influence—and are influenced by—how ecosystems are used, valued, and maintained.

Level 2: Multiple Climate Hazards and NbS Networks (social domain)

The second level expands the view to the social domain, incorporating the social components that influence the processes occurring in the biophysical environment (and the ES it generates). It also spatially situates and localizes these components to determine the impacts they experience and how they could be regulated.

At this level, the model aims to spatially optimize NbS networks, leveraging synergies among interventions to provide multi-functional benefits. For instance, restoring riparian buffers not only mitigates flooding but also improves water quality, enhances biodiversity, and supports local economies. Moreover, this level allows for the identification of potential trade-offs between NbS and KCS. For instance, implementing a NbS aimed at flood control might involve restoring natural habitats that could reduce land available for agricultural production, thus creating a trade-off between flood regulation and food provisioning. Recognizing these trade-offs and understanding the spatial-temporal dynamics of NbS implementation is essential for optimizing the overall resilience of both ecosystems and communities. By considering the interconnections between KCS within a socio-ecological framework, decision-makers can prioritize interventions that maximize resilience while managing trade-offs effectively. Decision-makers can utilize this understanding to develop comprehensive management scenarios that illustrate the potential consequences of different NbS implementations on both environmental regulation and community well-being.

To achieve this, this level must operate at a spatial scale that captures these social and biophysical interactions, while being broad enough to replicate the spatial configuration that connects all potential NbS intervention pathways (SPA, SCA, and SBA). This means the spatial scale cannot be limited only to areas where the risk is occurring—it must also consider the functional units where the hazard originates. While this level engages more explicitly with social

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processes, it remains interconnected with both biophysical constraints and governance mechanisms. Thus, its spatial expression is flexible and relational, not fixed.

At this level, socio-ecological resilience is evaluated more broadly, where multiple communities and ecosystem interactions play a critical role:

- Synergies between NbS and social systems: At this level, socio-ecological resilience involves identifying NbS that provide multiple simultaneous benefits. For example, restoring riparian systems not only prevents flooding but also improves water quality and creates recreational opportunities, which in turn strengthens the local economy.
- Interdependence between KCS: Communities that depend on the same ecosystems have higher interdependence. It's essential to spatially optimize NbS to ensure that ecosystem services flow through the catchment to areas with higher social demand. Intercommunity collaboration can enhance regional resilience.
- Reducing shared risks and vulnerabilities: At the catchment or regional level, the model should consider how different communities face climate risks and how interconnected NbS can minimize shared vulnerabilities (such as water scarcity or droughts). A catchment with interconnected solutions (e.g., wetland networks) increases its resilience to multiple hazards.
- Trade-offs and prioritization**:** Balancing ES provision with other land uses (e.g., agriculture) requires careful spatial and temporal planning to optimize resilience without compromising livelihoods. The capacity to manage these trade-offs depends not only on spatial data and biophysical modelling, but also on governance and institutional mechanisms—emphasising the need for cross-domain coordination.

Level 3: Coordination of Strategies at Various Spatial Scales (governance domain)

The highest level of application of the model considers the administrative, political, financial, and social conditions that can affect the implementation of NbS across different scales. This level emphasizes the need for a multi-layered governance approach that facilitates the scaling up of NbS, accounting for the varying administrative contexts—from local municipalities to national and supranational jurisdictions. Unlike a top-down hierarchy, this governance level interacts continuously with biophysical and social domains, both shaping and responding to local conditions and institutional feedback.

For this reason, this level must be capable of incorporating broad spatial scales that include different administrative levels while also considering the biophysical and social relationships identified in previous levels that transcend administrative boundaries. For example, a municipality located in the lower part of a catchment may lack the authority to implement upstream reforestation projects because those areas belong to another municipality. However, Level 3 must integrate these relationships identified in Level 2 and develop mechanisms to overcome such governance challenges.

In this context, decision-makers are tasked with identifying areas within the territory that possess conducive conditions for NbS implementation, such as public land availability or regional initiatives aimed at conservation. Conversely, this level also highlights zones where restrictive conditions exist, preventing effective NbS deployment. By addressing these barriers and exploring potential compensation mechanisms, such as financial incentives or collaborative governance

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structures, regions can transform areas of constraint into zones of opportunity for NbS implementation. All of these factors contribute to the creation of spatial entities that integrate information from all three domains (biophysical, social, and governance), forming landscape archetypes. These archetypes can then be used to generate NbS catalogs that align climate risk regulation strategies with the characteristics of different landscapes.

Additionally, this level stresses the importance of policy alignment and institutional coordination, ensuring that NbS are not viewed as isolated interventions but as integral components of broader climate adaptation strategies. By harmonizing local, regional, and national objectives, the application of the conceptual framework contributes to a systemic approach that enhances resilience across entire landscapes and regions, ultimately supporting sustainable development goals and the well-being of communities.

At the broadest scale, where policies and strategies are coordinated, socio-ecological resilience requires an integrated vision of ecological and social dynamics:

- Adaptive multi-level governance and policies: Resilience at this scale is linked to the transformative capacity of policies and institutional frameworks that support NbS implementation across multiple levels. Communities and ecosystems must be able to adapt flexibly to changing climate conditions. This includes creating policies that promote community participation in NbS management and flexible funding for projects.
- Aligning social and ecological goals: For strategies at regional or national levels to be resilient, they must align with both social and ecological objectives at the local and catchment levels. This requires coordinating efforts between different governance scales and ensuring that local communities have a voice in decision-making.
- Transformation through interconnected NbS networks: At the large scale, socio-ecological resilience is achieved by establishing interconnected NbS networks that address multiple climate threats (such as coastal erosion or urban flooding). These networks enable scaling solutions, creating more adaptive regions that are less vulnerable to extreme events.

3.4 The response variable: reducing climate risks for increasing Landscape Resilience

Socio-ecological resilience is a dynamic attribute that reflects the ability of interconnected social and ecological systems to withstand, adapt to, and recover from climate hazards while continuing to provide essential ES. This type of resilience is not a static state but varies depending on several interrelated variables, such as ecological integrity, biodiversity, functional redundancy, and the capacity of human systems to manage risks (Figure 15). As illustrated in the conceptual framework, socio-ecological resilience emerges from the interaction of these factors, and its variability can be observed across different spatial and temporal scales.

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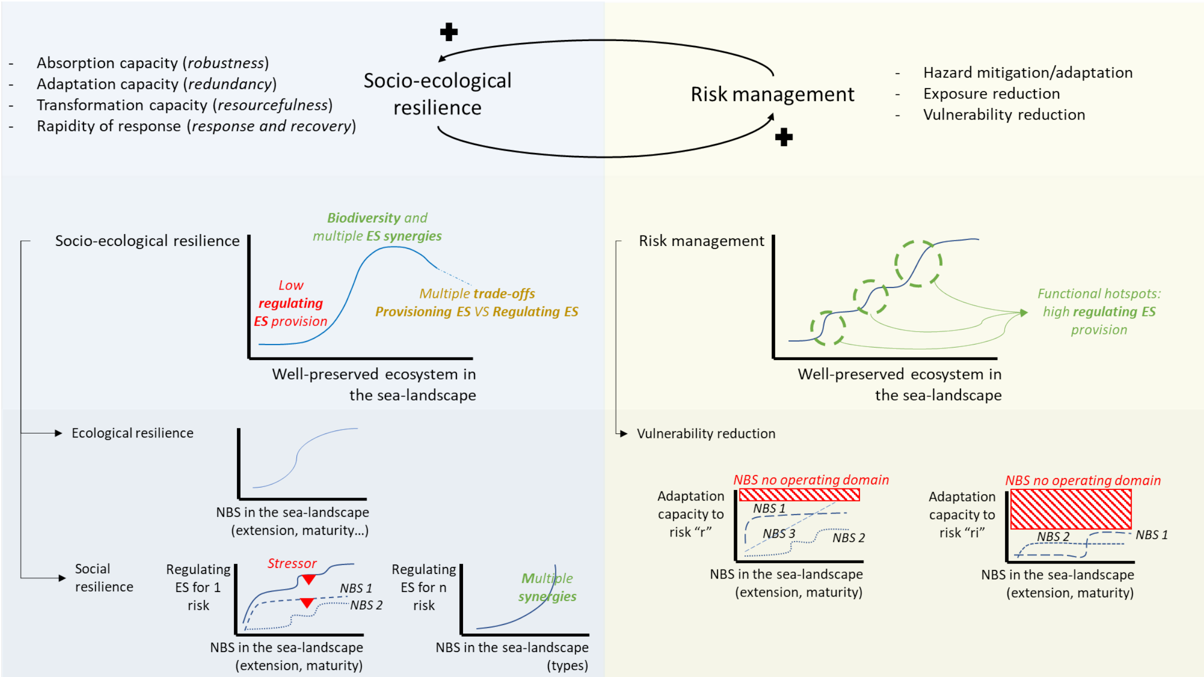

Figure 15. The figure illustrates the hypotheses derived from our conceptual framework regarding how NbS implementation within a risk management framework strengthens socio-ecological resilience. The upper section of the diagram establishes the relationship between socio-ecological resilience and risk management. The middle section presents hypotheses on how ecosystems (the ecological component) influence both resilience and risk management. The lower section breaks down the key elements of these two factors and hypothesizes how NbS implementation enhances them.

One of the key components in building resilience is functional redundancy. This concept refers to the presence of multiple components within an ecosystem or community that perform similar functions, ensuring that the loss of one component does not compromise the overall capacity of the system to continue delivering essential services. In ecosystems, this redundancy is most evident in biodiversity, where multiple species fulfil similar ecological roles, such as pollination, water purification, or nutrient cycling. This functional overlap ensures that even if certain species are affected by climate hazards, the system can continue to function effectively, maintaining the services crucial for the well-being of communities. However, the framework also acknowledges that ecosystems themselves have limits to their resilience. As climate hazards become more frequent and intense, ecosystems may experience stress that exceeds their adaptive capacity, leading to degradation and a loss of functionality. This is particularly relevant in regions where ecosystems have already been weakened by human activities, making them more vulnerable to additional climate stress. For example, areas with degraded wetlands or deforested landscapes may not be able to provide the same level of flood mitigation or carbon sequestration as healthier, more resilient ecosystems.

On the social side, redundancy plays a similar role. Communities that possess diverse knowledge systems, institutions, and collaborative networks can adapt more effectively to changing conditions. The functional redundancy of KCS ensures that critical social functions—such as disaster response, resource management, and health support—persist under stress. This adaptability is crucial when climate hazards disrupt everyday life, as it enables communities to maintain essential services and safeguard livelihoods. The interconnectedness of these systems

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creates a buffer that helps societies withstand shocks, further reinforcing the socio-ecological resilience.

Risk management is another critical factor in fostering socio-ecological resilience. By reducing exposure to climate hazards and addressing vulnerabilities, risk management strategies can enhance both the ecological and social components of resilience. The conceptual framework identifies three key pathways for risk reduction: reducing the impacts of the hazard at its source (SPA), reducing vulnerability in exposed areas (SBA) and reducing intermediate impacts between the areas that connect the hazard to the exposed areas (SCA). These pathways offer complementary ways to reduce risks, but the relationship between NbS implementation and hazard reduction is not always linear. For some hazards, such as erosion, interventions in specific hotspots (e.g., steep slopes, riverbanks) can provide immediate benefits, whereas for others, such as flood regulation, broader ecosystem restoration (e.g., protecting headwaters) may require larger-scale interventions to achieve significant outcomes (Pérez-Silos, 2022).

The framework also highlights the trade-offs that can arise when implementing NbS, particularly in balancing the provision of different ES. For instance, restoring wetlands might prioritize regulating ES, such as flood control or carbon sequestration, but this could temporarily limit provisioning ES, like agricultural productivity. Conversely, efforts to enhance provisioning ES, such as increasing crop yields, might reduce an ecosystem's capacity to provide regulating services like flood mitigation. This dynamic is illustrated by a trade-off curve in the framework, where different strategies need to be carefully evaluated to find a balance between the various services provided by ecosystems. Resilience emerges when this balance is optimized, while acknowledging that certain thresholds—referred to as "limits for the operability of NbS"—may constrain the effectiveness of these interventions.

Another important aspect in the resilience framework is the identification of "functional hotspots" in the sea-landscape. These are areas where the interaction between well-preserved ecosystems and socio-ecological functions generates disproportionately high resilience benefits (Pérez-Silos, 2022). By prioritizing NbS interventions in these hotspots, decision-makers can maximize the positive impact on resilience. However, the framework also acknowledges that there are limits to the effectiveness of NbS, especially when ecosystems are highly degraded or when hazards surpass the capacity of interventions to provide adequate protection. Understanding these limits, and actively managing the hotspots through adaptive management, ensures that interventions remain effective under changing climatic and socio-economic conditions.

In conclusion, the variable nature of socio-ecological resilience emphasizes the need for adaptive, context-specific strategies in the design and implementation of NbS. By balancing functional redundancy, managing trade-offs, and targeting functional hotspots, decision-makers can help build resilient territories that are capable of sustaining critical ES in the face of a wide range of climate scenarios. This adaptive and integrated approach supports the development of sea-landscapes that are better prepared to withstand and recover from the diverse impacts of climate change.

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4 Application of the Conceptual framework – A Practical Guide

Designing and prioritizing NbS in landscapes requires a holistic framework that captures the interplay between ecological processes, social systems, and governance structures. Landscape resilience, as conceptualized in the Conceptual Framework, refers to the ability of landscapes to absorb disturbances, adapt to changing conditions, and reorganize while maintaining essential functions and structures. This resilience is not only about preserving ecosystems but also about ensuring that landscapes continue to provide critical ES that sustain KCS, including water supply, energy, transportation, and public health.

To achieve this, an effective NbS implementation-oriented framework must:

- Bridge ecological and human systems, ensuring that NbS support both natural processes and socio-economic needs.
- Recognize spatial and temporal dynamics, considering how water, energy, and material flows shape resilience across different landscapes.
- Embed governance mechanisms, aligning land-use planning, policy frameworks, and institutional coordination to support resilient landscapes.
- Support climate risk assessments, providing regions with tools to identify hidden risks, interdependencies, and cascading impacts that might not be immediately visible.

The conceptual framework follows the Pathways to Resilience (P2R) framework (see also figure 1 in the Introduction) but expands upon it by integrating a multi-hazard approach across governance levels. It ensures NbS implementation is scalable and responsive to evolving climate risks by leveraging spatial interdependencies, socio-ecological interactions, and governance processes. To this end, the proposed conceptual framework in NBRACER provides the necessary mechanisms to relate the elements involved in achieving the aforementioned points.

4.1 Knowing your Landscape/Region: Establishing a Baseline

Before regions can effectively design NbS strategies, they must first understand and characterize their landscape by systematically identifying and mapping key biophysical, social, and governance dimensions. This foundational step ensures that NbS interventions are tailored to regional characteristics and align with local resilience needs.

This process aligns with Level 1, utilizing datasets such as CORINE Land Cover, Urban Atlas, and EUNIS ecosystem types to define landscape archetypes. These archetypes offer a structured approach to scaling NbS, ensuring that resilience strategies are designed to regional needs while remaining adaptable to broader climate challenges. The approach ensures that key hazards, socio-economic vulnerabilities, and governance interdependencies are spatially mapped to guide effective NbS placement.

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To facilitate this process, regions must input relevant geo-based information into a structured framework that captures:

- **Biophysical Domain** – Identifies dominant ecosystem processes, climate hazards (e.g., flooding, heat stress, salinization), and land use patterns using datasets such as CORINE Land Cover, Urban Atlas, and Coastal Zones. Additionally, this step should assess ecological fragmentation, which determines the ecological capacity for NbS interventions such as wetland restoration, riparian buffer zones, and green corridors. Identifying areas where ecosystem connectivity is disrupted helps prioritize NbS strategies that restore natural hydrological and ecological functions.
- **Social Domain –** Defines key demographic and socio-economic characteristics, including population trends, economic dependencies (GDP, employment sectors), and cultural values that influence vulnerability and adaptation capacity. This assessment should also identify high-vulnerability population areas, particularly neighbourhoods with elderly populations, socially marginalized communities, and individuals with limited adaptive capacity. Also this domain includes the exposed system, mapping and characterizing the KCS, which are the receptors of NbS implementation (see appendix 6).
- **Governance Domain –** Maps relevant policy frameworks, administrative levels (NUTS 1, 2, 3), and institutional actors responsible for implementing resilience strategies.

4.1.1 From Functional Units to Regional Strategies: a multi-level approach

By structuring landscapes into hierarchical units, this framework enables a systematic approach to resilience planning. It allows regions to identify vulnerabilities, recognize interdependencies, and implement NbS that are both locally relevant and scalable across different landscapes. While the structure appears hierarchical in spatial organisation, the relationships among these units are not linear or domain-bound. This hierarchical structure consists of three levels interconnected by different spatial entities (Figure 16): functional units, landscape archetypes, and regions. Each level builds upon the other, creating an integrated framework for planning and action.

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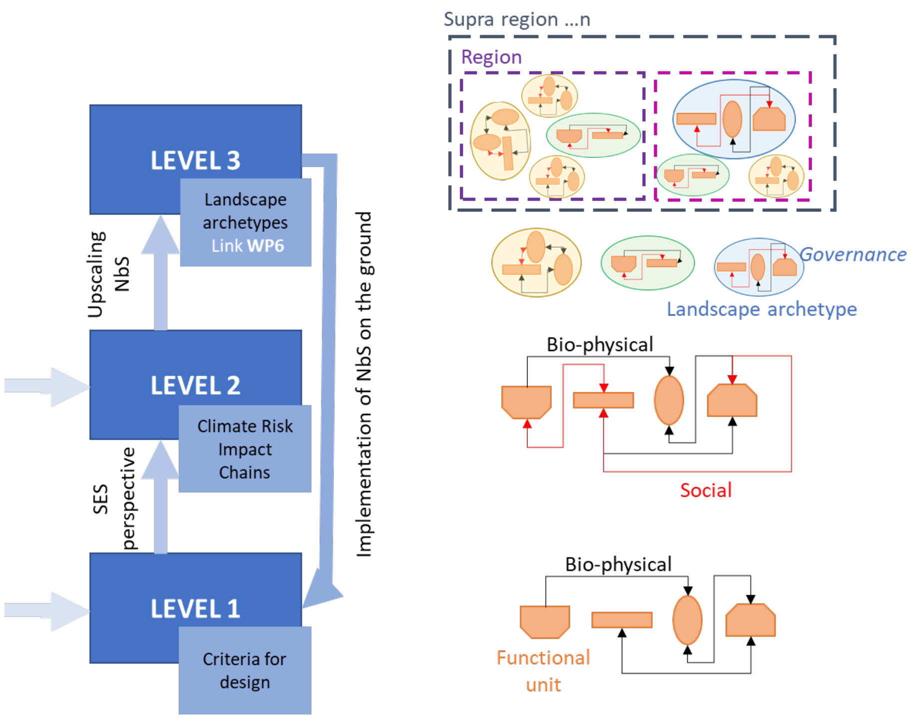

Figure 16. Relationship between the levels of the conceptual model and the spatial entities that structure and operationalise each of its levels.

- **Functional Units** represent the smallest spatial scale within this framework. These are localized, hydrologically connected areas where specific ecological and socio-economic processes interact—for instance, wetlands absorbing stormwater or agricultural zones providing food security. Understanding the dynamics within these units is essential, as they are the foundational elements where resilience strategies can be directly applied and tested.
- Building on these localized areas, **Landscape Archetypes** emerge as broader categories that group together multiple functional units sharing similar characteristics and resilience dynamics. These archetypes are defined by common biophysical, social, and governance features, which reflect shared challenges and opportunities for NbS implementation. Specifically, functional units serve as the building blocks of landscape archetypes, representing distinct ecological spaces like wetlands, forests, or agricultural fields that contribute to ES. By aggregating functional units with similar resilience profiles, landscape archetypes enable the development of targeted and scalable NbS strategies, ensuring that local interventions can be adapted and replicated across similar landscapes.
- At the largest scale, **Regions** encompass multiple landscape archetypes and represent the level where governance coordination and cross-sectoral policies play a pivotal role. This level focuses on the integration of NbS into long-term climate adaptation and risk management strategies, ensuring that local actions are supported by broader institutional frameworks and policy instruments. Effective regional coordination is crucial for managing interdependencies between different landscape archetypes and aligning governance actions to promote resilience across the entire territory.

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4.2 Structured Methodology for Climate Risk Assessment and NbS Planning

The conceptual framework for resilience planning is structured into three interrelated levels, each corresponding to a key domain—biophysical, social, and governance. Together, these levels provide a holistic view of the territory and enable a comprehensive approach to identifying vulnerabilities, tracking risk propagation, and implementing NbS effectively (Figure 16). These levels are not hierarchical stages, but interdependent lenses through which resilience can be understood and strengthened. While each level emphasises a distinct domain, they are interlinked and influence one another through continuous feedback, shared processes, and overlapping spatial expressions.

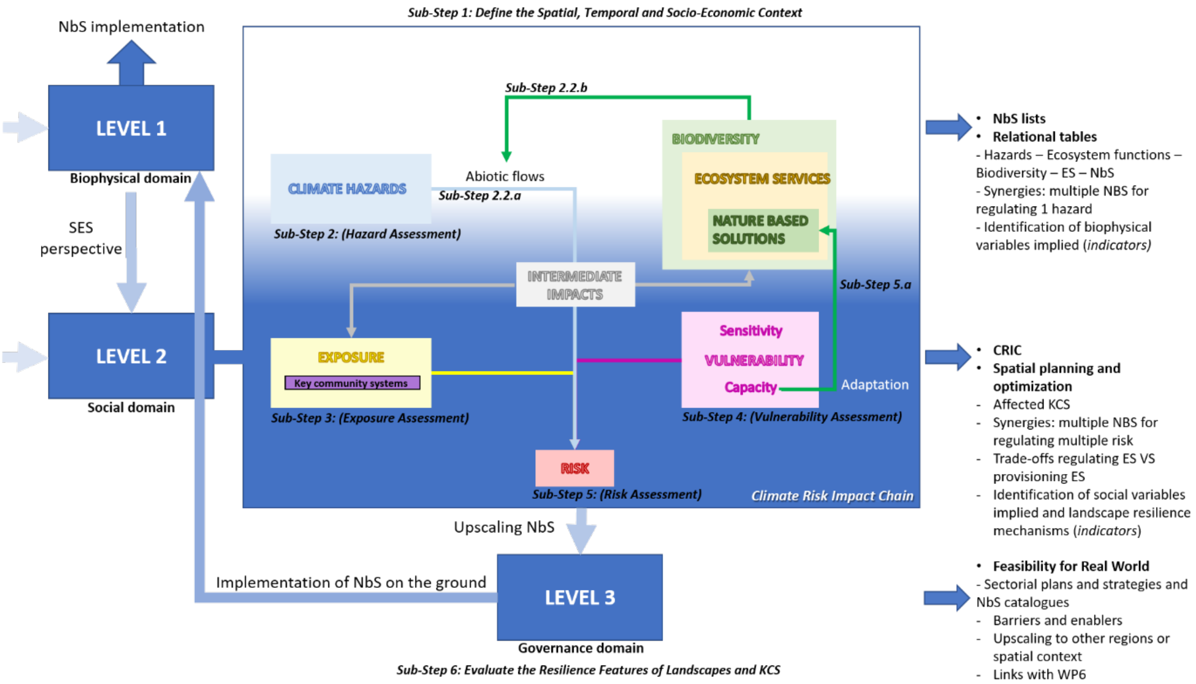

Figure 16. Operationalization of the conceptual framework. We exposed the relationships between the different levels, as well as the main intermediate and final products that could be produced at each one. Each level generates specific outputs that inform the others, and operationalisation often occurs through recursive, cross-domain interactions.

Level 1: Biophysical Interactions That Produce and Regulate Abiotic Flows of Climate Hazards

This level defines the biophysical relationships between climate hazards, the functional units where they occur, and the ecosystems (along with their ES) that regulate these hazards. It identifies the natural processes and ES essential for mitigating climate risks.

To operationalize the conceptual framework, this level can serve as the entry point for precisely characterizing the relationships between a specific hazard, the physical processes that trigger it and are triggered by it, the landscape areas where it is most likely to occur, and the biodiversity components that generate the services regulating it. This process helps to define NbS packages that can be implemented for hazard regulation, highlighting their synergies. These steps

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contribute to constructing the adaptive capacity based on NbS when Level 2 of the model is applied. While it is not mandatory to enter the framework through this level, doing so is recommended for a comprehensive analysis of NbS interventions for a given hazard. Moreover, since this level provides the highest level of territorial detail, it serves as the foundation for NbS implementation at the local scale, offering valuable information and indicators for designing and evaluating their effectiveness.

Level 2: Connecting the Ecological System with the Social System

At this level, the framework integrates the social dimension by analyzing how ecological processes intersect with socio-economic systems. It identifies how communities and infrastructure are exposed to climate risks and assesses their vulnerabilities. This level also introduces CRICs to map risk propagation and identify leverage points for NbS interventions (see appendix 7 for more information on the construction of the CRIC.).

It is recommended that this level builds upon the biophysical relationships identified in Level 1, although these can also be constructed directly within this level. Here, a multi-risk analysis is established (multiple hazards, multiple solutions), providing a holistic relational structure of the socio-ecological system. This enables the identification of key elements for planning and spatial optimization in the working context, including synergies, trade-offs between NbS implementation and economic systems, enablers conditions, and barriers. Therefore, Level 2 identifies the critical components that will be addressed in Level 3.

Level 3: Governance Mechanisms for NbS Implementation

The final level focuses on embedding NbS within governance structures, addressing barriers and enabling conditions for successful implementation. It emphasizes overcoming institutional challenges, ensuring policy coherence, and promoting cross-sectoral coordination to sustain resilience efforts over time.

The primary goal of this level is to overcome governance-related barriers that hinder NbS implementation and to develop strategies for scaling up NbS to equivalent landscape archetypes at the regional level. This level serves as the conceptual framework's connection to the developments of WP6 and, once again, relies on the detailed insights from Level 1 to execute NbS implementation on the ground. However, governance is not merely a final step. It both shapes and is shaped by biophysical and social processes—creating a dynamic interface between top-down mechanisms and local-level conditions. Governance decisions may initiate, enable, or constrain actions at any level of the framework.

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4.2.1 Assessing climate risks and planning NbS

Building on the theoretical framework, this section presents a step-by-step methodology for putting the framework into practice. The methodology is designed to systematically assess climate risks, identify vulnerabilities, and guide the strategic implementation of NbS. To ensure consistency with Figure 4, incorporate updates on risk definitions, and align with Deliverable 5.2, the methodology is structured into six sequential steps. These steps are aligned with standard risk assessment frameworks and integrate biophysical, socio-economic, and governance factors, ensuring a holistic and comprehensive approach to resilience planning and NbS implementation.

To achieve this, the methodology is primarily based on Level 2 of the model, using CRIC to synthesize the relationships between key elements that shape socio-ecological resilience through NbS. On one hand, Level 2 can draw on insights from Level 1 to enhance the level of detail in linking hazards with the biodiversity components that regulate them—thus identifying potential NbS and establishing design criteria for their implementation. On the other hand, Level 3 allows for the exploration of governance mechanisms that facilitate the implementation of NbS within the analyzed socio-ecological context, ensuring scalability and assessing how these solutions contribute to resilience-building.

- **Sub-Step 1: Define the Spatial, Temporal and Socio-Economic Context**
    - **a. Geographic Scope:**
        - Define the assessment boundary (e.g., catchment, region, landscape archetype).
        - Choose the unit of analysis appropriate for the scale and objectives of the assessment (e.g., administrative units, functional units, or landscape archetypes).
    - **b. Climatic, Ecological, and Socio-Economic Conditions:**
        - Assess key climatic hazards (e.g., sea-level rise, floods, heatwaves).
        - Map natural ecosystems (e.g., dunes, wetlands) and identify ecological fragmentation affecting resilience.
        - Analyze land use patterns, key economic sectors (e.g., tourism, industry), and population density.
    - **c. Pre-Hazard Criticality Assessment:**
        - Identify densities of critical infrastructure (e.g., hospitals, schools, elderly care, and transport networks).
        - Map vulnerable population hotspots (e.g., low-income, elderly, marginalized communities).
        - Highlight areas of ecological fragmentation to prioritize NbS that restore connectivity and ecosystem functions.
    - **d. Socio-Economic Trends:** Consider trends such as demographic shifts, migration patterns, and economic growth or decline that may influence future vulnerability and exposure.
    - **e. Temporal Scale:** Incorporate historical data, seasonal variations, and future climate projections to guide long-term NbS planning.
- **Sub-Step 2: Determine Hazards and Intermediate Impacts (Hazard Assessment)**
    - Identify primary climate hazards (e.g., excessive rainfall, droughts, heatwaves; Appendix 1) that impact ecosystems, infrastructure, livelihoods, and socio-economic systems.

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- Map how these hazards propagate through the landscape, affecting biophysical processes (e.g., erosion, water scarcity) and socio-economic systems (e.g., disruption to agriculture, supply chains, or transportation networks). The biophysical interactions can be more accurately reflected from Level 1 of the conceptual framework. To this end:
    - **a.** Determine the physical processes involved in generating the abiotic flows caused by these hazards. These physical processes and triggering flows are associated with certain functional units of the territory, which may be interconnected by these flows (Appendix 2). By identifying these physical processes, it is possible to pinpoint the variables affecting the intensity or frequency of these processes.
    - **b.** Assess biological functions that could regulate the abiotic flow in each functional unit. This helps locate ecosystem elements (Appendix 3) that could produce these functions and, in turn, the ES that regulate the flow. Identifying all biodiversity components involved in this function is crucial, even if they do not provide the maximum level of regulation. It is recommended to work at an ecosystem scale for simplification.
- Assess intermediate impacts, such as damage to agricultural productivity, loss of income sources, or disruptions to essential services (e.g., water, electricity, health systems) that can affect local economies and community well-being.
- Consider how these impacts influence vulnerable socio-economic groups, such as low-income populations, marginalized communities, or those dependent on climate-sensitive livelihoods.

➢ **Sub-Step 3: Determine Exposed Elements of the Socio-Ecological System (Exposure Assessment)**

- Identify the KCS (Appendix 5) and assets exposed to climate hazards, including:
- Natural ecosystems (e.g., wetlands, forests, coastal zones) that contribute to regulating ES like flood protection and water purification.
- Critical infrastructure (e.g., roads, bridges, energy and water supply networks, hospitals, educational facilities, urban centers) essential for economic productivity and social well-being.
- Socio-economically vulnerable groups (e.g., marginalized communities, elderly, low-income populations, indigenous groups, and those reliant on subsistence farming or informal economies).
- Analyse how exposure to hazards can disrupt economic activities (e.g., crop failures, damage to industries) and social systems (e.g., displacement, health risks).
- Define exposure indicators that reflect both ecological and socio-economic sensitivity to climate risks.

➢ **Sub-Step 4: Determine the Vulnerability of the Socio-Ecological System (Vulnerability Assessment)**

- Assess biophysical vulnerabilities, such as degraded ecosystems, loss of natural buffers (e.g., wetlands, forests), and reduced biodiversity that weaken natural resilience.
- Evaluate social vulnerabilities, focusing on factors such as poverty levels, education access, health disparities, and dependency on climate-sensitive livelihoods (e.g., agriculture, fisheries, tourism).
- Analyse infrastructure vulnerabilities, particularly critical infrastructure that is poorly maintained, lacks redundancy, or is located in high-risk areas.

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- Identify governance and institutional vulnerabilities, such as fragmented policies, weak coordination mechanisms, or limited access to financial resources for adaptation.
- Consider economic vulnerabilities, such as heavy dependence on single industries (e.g., agriculture, tourism) or limited access to diversified income streams.
- Evaluate the adaptive capacity of ecosystems, infrastructure, and socio-economic systems, focusing on how NbS can enhance their resilience by providing ES, supporting livelihoods, and reducing risk exposure

➢ **Sub-Step 5: Identify Potential Climate Risks (Risk Assessment: Hazard × Exposure × Vulnerability)**

- Identify intermediate impacts: the cascading effects that occur as hazards interact with the landscape, ecosystems, infrastructure, and socio-economic systems. These impacts serve as critical connectors between the initial hazard and the final consequences experienced by communities, ecosystems, and economies.
- Quantify risk levels for different regions and functional units by integrating hazard, exposure, and vulnerability data. This includes assessing risks to both natural ecosystems and socio-economic systems (e.g., loss of livelihoods, damage to economic sectors).
- Identify priority areas for NbS interventions, where they can mitigate the most significant risks and enhance socio-economic resilience. For this purpose, it is advisable to utilize Level 1 of the conceptual framework, which highlights the biophysical relationships (ecological functions) that should be strengthened. Ultimately, the goal is to refine the catalogue of potential NbS for implementation (Appendix 4), ensuring that they are selected based on the most relevant ecosystem characteristics previously identified (Sub-Step 2n). This process focuses on regulating the abiotic flows generated by the impact occurring within a specific functional unit, leveraging the capacity of ecosystems to mitigate risks effectively.
- Evaluate trade-offs between ES and socio-economic demands, ensuring that NbS enhance ecological functions while also supporting economic activities and reducing social vulnerabilities.
- Consider land-use conflicts and economic dependencies that may influence the feasibility of NbS interventions.

➢ **Sub-Step 6: Evaluate the Resilience Features of Landscapes and KCS** - To ensure that NbS effectively address climate risks, it is essential to assess the resilience features of both landscapes and KCS. These features reflect the capacity of ecological, infrastructural, and socio-economic systems to withstand, adapt to, and recover from climate-related disturbances. Moreover, understanding how these features relate to exposure, vulnerability, and adaptive capacity is crucial for designing NbS interventions that strengthen overall resilience. By assessing these resilience features, planners can ensure by applying Level 3 that NbS interventions are strategically designed, socio-ecologically integrated, and capable of supporting landscapes and communities in facing current and future climate risks.

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4.2.2 Next steps for best-fit NbS implementation and sustainability

This section provides a structured approach for developing NbS into multidimensional NbS portfolios, ensuring that selected interventions align with ecosystem functions, spatial risk assessments, and governance structures. By considering both ecological processes and socio-economic dependencies, this methodology supports the identification of optimal NbS strategies that enhance resilience at multiple scales—from local adaptation efforts to regional planning. The following subsections outline key steps in assessing, selecting, and implementing NbS, emphasizing their feasibility, long-term sustainability, and capacity to address multi-hazard risks.

A) Assessing Potential NbS for Climate Resilience

In tackling climate resilience, it's crucial to take a structured, science-based approach to identifying NbS that are not only ecologically effective but also practical and scalable. Within this framework, Level 1 of the biophysical model plays a key role in pinpointing which NbS are best suited to a given region. By analysing how climate threats interact with abiotic flows—such as water movement, sediment transport, or temperature fluctuations—alongside the ecosystems that naturally regulate these processes, we can make informed decisions about the most effective NbS interventions.

Rather than treating NbS as isolated solutions, this model allows us to understand the landscape holistically, ensuring that selected interventions not only mitigate risks but also enhance long-term resilience at regional and national scales. To achieve this, the model focuses on three critical aspects:

- **Understanding abiotic processes and climate threats** – Climate hazards like torrential rains, droughts, and floods generate abiotic flows (e.g., surface runoff, sediment transport) that shape the resilience of the landscape. By mapping these processes against functional units (e.g., river channels, hillslopes, estuaries), we can determine where interventions are most needed.
- **Linking landscape features to ecosystem functions** – Ecosystems don't operate in isolation; their effectiveness in managing abiotic flows depends on factors like topography, soil composition, and water availability. Understanding these relationships helps us select NbS that will function optimally within the natural landscape.
- **Identifying and prioritizing NbS interventions** – Once we've mapped out climate threats and ecosystem responses, the next step is to pinpoint practical interventions. For instance, wetland restoration can prevent flooding by storing excess water, while reforestation on hillslopes can stabilize soil and reduce erosion. Prioritization is key—NbS must first address immediate hazard mitigation before expanding to broader socio-economic benefits.

Structuring the NbS selection this way, the aim is to go beyond theoretical solutions and focus on real-world implementation, ensuring that interventions are not only feasible but also integrated into governance frameworks for long-term sustainability.

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B) Evaluating NbS Feasibility for Real-World Application

Before rolling out NbS interventions, we need to assess their feasibility to ensure they deliver tangible benefits. A strong feasibility assessment involves:

- Selecting ecosystem-based solutions that align with local climate risks while maintaining ecological integrity.
- Using biodiversity and ES modeling to quantify how effective a given NbS will be over time.
- Ensuring landscape connectivity by conducting ecological fragmentation analysis—this prevents interventions from being isolated and increases their resilience.
- Scoring and mapping NbS impacts on KCS and local populations, prioritizing those with the greatest hazard mitigation potential.

Taking these factors into account, we move from concept to action, ensuring that NbS are strategically placed and capable of delivering meaningful impact.

C) Planning NbS-Based Adaptations for Long-Term Impact

Once we have identified the right NbS and ensured their feasibility, the next step is to design interventions that are effective, scalable, and adaptable over time. This means:

- Aligning NbS with CRIC findings target the most vulnerable areas.
- Embedding governance mechanisms to ensure that NbS aren't just projects but long-term solutions integrated into regional planning.
- Setting up monitoring frameworks to track the effectiveness of NbS and adapt them as climate conditions evolve.

As part of this adaptive governance approach, we must continually ask:

- Are NbS maintaining their ecological functions under increasing climate stress? (Robustness & Absorptive Capacity)
- Do they provide redundancy, ensuring resilience across different sectors? (Adaptive Capacity)
- Are they enabling long-term transformation at the landscape and policy level? (Transformative Capacity)
- How quickly can NbS could be restored or restore critical services after extreme events or? (Response & Recovery Capacity)

Integrating these evaluation criteria into governance and funding mechanisms ensures that NbS don't just remain pilot projects—they evolve into scalable, system-wide solutions that drive regional climate resilience.

4.2.3 Adaptation pathways toward multi-hazard resilience

Developed by Deltares and Delft University of Technology, the Dynamic Adaptive Policy Pathways (DAPP) approach has been widely applied as a policy making support tool to deal with the changing conditions such as climate, environmental risks and socio-economic circumstances under deep uncertainty (Walker et al. 2013; Haasnoot et al., 2024). Adaptation pathway planning explicitly addresses decision making over time as conditions change. It provides decision makers with an adaptation roadmap presenting alternative policy pathways (sequences of actions), which

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makes policy-makers aware of the 'solution space' - the space within which opportunities and constraints determine why, how, when, and who adapts to climate risks (Haasnoot et al., 2020a), and helps to break adaptation into manageable steps over long timescales (i.e. > 50 years), starting with flexible near-term actions to avoid investing too much or too early, or locking in investments. The DAPP approach is built upon the notion that decisions are made over time in dynamic interaction with the system of concern and cannot be considered independently (Haasnoot et al., 2013).

The Adaptation Pathways approach provides a strategic framework for decision-making in the face of climate change uncertainty. It outlines a sequence of actions over time while remaining dynamic, allowing new information to be incorporated as it emerges. This flexibility ensures that decisions can be adjusted as conditions evolve, helping systems stay effective under a range of future scenarios. The foundation of ensuring the resilience of the system via adaptation pathways lies in the risk assessment as a core component. By evaluating potential climate risks or impacts, including the climate hazards, exposure levels and vulnerabilities, planners and decision-makers can identify or define critical thresholds where existing systems may fail or require significant changes to maintain the system significant and functional. Understanding these thresholds, which may be seen and used by decision-makers as early signals or tipping points, enables the formulation of pathways that proactively address risk/impacts before they escalate.

On the other hand, recognizing systemic interdependencies-how socioecological system interact-is key to designing NbS that enhances resilience across multiple sectors or key-community systems. By accounting for systemic interdependencies, adaptation pathways become more robust and resilient, reducing the risk of unintended consequences and ensuring that NbS in one are do not adversely affect others. This development of adaptation pathways will be further elaborated in Task 5.5 on Portfolio and Pathway decision support. This will involve a guidance document for the regions.

4.2.4 Implementing and mainstreaming

Despite all documented benefits of NbS advantages, large-scale implementation of NbS is still lacking (Sarabi et al., 2019, Karlsson-Vinkhuyzen et al., 2017, Runhaar et al., 2018; Johannessen & Mostert 2019). To speed up and upscale implementation, mainstreaming NbS in the context of development is necessary and involves integrating these solutions into policies, planning, and practices across various sectors (Figure 17). In development, mainstreaming NbS means ensuring that these solutions are considered and implemented as standard practice in urban planning, infrastructure development, and resource management (Cohen-Shacham et al 2016).

Expanding NbS innovations beyond pilots and experimental sites and implementing at systems level, requires as such transformative changes (in contrast to "add on" changes) of the governance system to enable large scale implementation (Duvall et al., 2018; Hölscher and Frantzeskaki 2020; Toxopeus et al. 2020, 2021; Schröter et al. 2021). For example, implementing another dike may only require more funding and building the dike a bit better, but implementing NbS as adaptation solutions may require new policies, new institutions, new knowledge, new kinds of financial arrangements etc which means the need for radical shifts in the governance system (transformations) for NbS to become a solution to have the same opportunities to be implemented as any other solution. These changes can be challenging as it requires changes to several different

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governance enablers that often interact. For example, for implementation to work, you require planners, financiers, developers, construction companies and engineering firms, and municipal maintenance and management departments to agree and work together in implementation. With new and novel solutions that needs to be mainstreamed, coming to these agreements means transaction costs, and as such resistance for the actors to implement the new solutions. The challenge is to keep multiple actors motivated in the chain of implementation, and make sure that the innovations (i.e., NbS) is not just ignored or removed in the need for being more efficient (Johannessen & Mostert 2019).

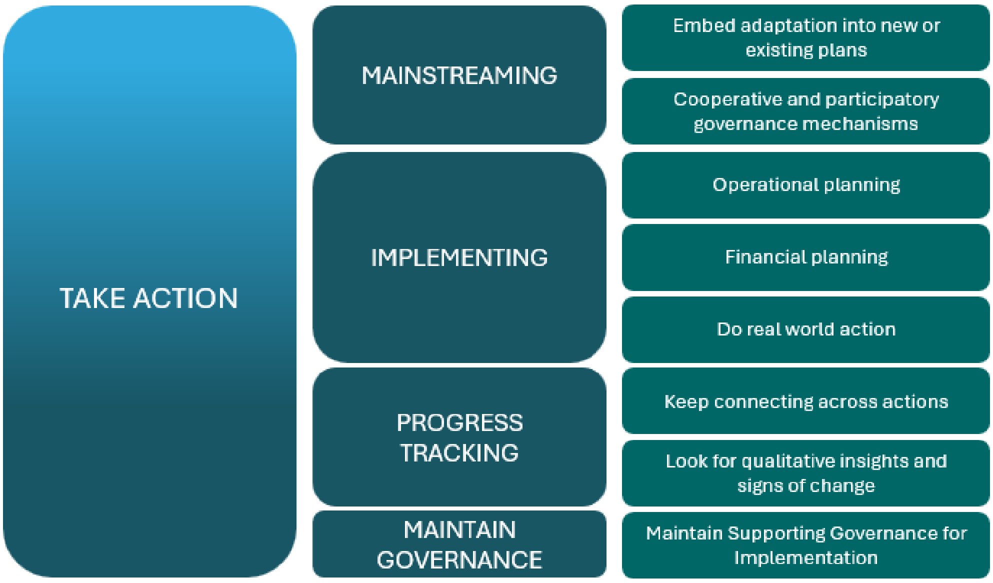

Figure 17. The "TAKE ACTION" step of the Regional Resilience Journey of the Pathways to Resilience (P2R) EU project - https://www.pathways2resilience.eu/regional-resilience-journey.

4.2.5 Monitoring and learning and enabling replication/upscaling of solutions

Monitoring the Effectiveness of NbS (Task 2/3/4.2) is designed as a multi-phase process that allows for both ex-ante and ex-post evaluation of NbS interventions, supported by a Regional Monitoring Team (RMT). This enables the performance of different solutions, analysed through the measurement of specific KPIs, to be compared with pre-monitoring scenarios. Various resources can be utilized for proper measurement of the selected indicators, such as sensors, multi-criteria analysis, modelling tools, community-based monitoring, and participatory approaches like group-based deliberative valuation.

NbS interventions support climate resilience by enhancing absorptive, adaptive, transformative, and response/recovery capacities. These capacities will be integrated into the monitoring framework, with indicators designed to track how NbS contribute to the core resilience features of robustness, redundancy, resourcefulness, and response efficiency across ecological, social, and governance systems. An NbS that is proposed to contribute to climate resilience should aim to reduce climate change impacts. It this case, they should focus on addressing a primary hazard, designed to mitigate a specific risk, while also contributing to the mitigation of additional risks.

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Therefore, a prior assessment, mapping and modelling the related impacts and risks – considering its three components: hazard, exposure, and vulnerability—should support the proposal of NbS.

The impacts to be generated by the NbS, as well as the expected co-benefits, should support the provision of certain ES. Modelling these ES (Task 5.3) generates a valuable input to guide decisions regarding the demand for NbS, the definition of types of NbS to be implemented, the co-design of solutions and development of an integrated portfolio of solutions, the identification of means to integrate and mainstream NbS into planning instruments, and the level of contribution to minimizing climate impacts. These models also help identify the potential for NbS to enhance resilience capacities over time (and space) by simulating their performance under different climate stress scenarios.

The monitoring process aims to lead to a robust impact assessment, which in turn helps understand the effectiveness of the implemented solution in generating the expected impact. Throughout this process, valuable learnings can be gathered from the challenges and enablers encountered (Task 2/3/4.2). This includes insight into how specific interventions support or hinder different resilience capacities, helping refine future design and implementation strategies.

After implementation, monitoring, evaluation of impacts, and reflections on learnings, alternatives for replicating and/or upscaling an NbS can be considered based on the level of success and analysis of enabling factors and barriers. Quantitative data and qualitative findings from previous stages help identify these enablers and barriers (e.g., regulatory, economic, social, and technical) that contribute to effective NbS implementation and deployment. Lessons from the monitoring process will also inform the strategic replication of successful solutions across scales, particularly by identifying which resilience capacities were strengthened and how.

Depending on the scale of the solution implemented, the direct impacts generated and level of success, it can contribute to climate resilience either by itself or through the practical implementation of a robust upscaling and replicating plan. In the case of NBRACER regions, the solutions to be monitored are mainly spot-based and very locally implemented, so the contributions to regional resilience could be known just after developing integrated portfolios (across landscapes) in combination with a proper replicating and upscaling plan. Transferability of knowledge may also be part of this process, with replicating successful lessons (Task 2/3/4.2) and learning extending beyond regional boundaries (WP7, Replicating Regions). The monitoring framework will also support cross-regional learning and feedback loops, helping align local NbS interventions with larger-scale adaptive resilience strategies and regional transformation pathways.

In a broader approach, considering the whole process of regional transformation based on the resilience and adaptation pathways, the monitoring actions play a different role. On one hand, monitoring progress by checking the varying socio-ecological conditions and thresholds may guide the user to evolve along the pathway. Lastly, in the cyclical planning of the resilience journey, performing a monitoring and learning (MEL) exercise (Task 1.4) is also key, with iterations of learning and rethinking being an important part of the process. This allows for reflexion about the approach in a fruitful cycle of improvement. Through systematic MEL exercises, NbS interventions will contribute to long-term resilience-building by supporting transformative change, cross-scale learning, and system-wide adaptation.

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5 Case examples

5.1 Fluvial flooding, erosion, and fires in a rural mountainous area

The conceptual framework was applied to a representative area in the Cantabria region to assess potential NbS interventions aimed at reducing the risks of fluvial flooding, erosion, and wildfires. The application followed a structured approach, beginning with Level 1, to gain a precise understanding of the physical processes underlying each hazard, the abiotic flows they generate, and the ecosystem functions most relevant to their regulation (by generating ES). By analysing these elements, it becomes possible to identify the biodiversity components that play a key role in regulating threats and the specific management measures needed for NbS implementation.

Step 1: Conceptualizing Bio-physical Interactions (Level 1)

The first step involved developing conceptual diagrams that illustrate how each hazard interacts within interconnected functional units (Figure 18). These diagrams provide a synthetic view of:

- The abiotic flows occurring in the landscape related to each specific hazard.
- The ecosystems that produce the ES regulating these flows (Figures 18).

The information extracted from these diagrams was then detailed in Table 4, linking:

- Potential NbS typologies available in the region.
- Indicators to quantify biophysical interactions with abiotic flows.

Step 2: Conceptualizing the model of social-ecological interactions (Level 2)

Building on the findings from Level 1, Level 2 was applied to develop the CRICs for each hazard. These CRICs (Figures 20, 21 and 22) illustrate the connections between the three climate-related risks in the specified region and provide key insights into how NbS interventions contribute to landscape resilience:

- In terms of intermediate impacts on exposed systems, the focus remained primarily on the biophysical processes triggering secondary climate hazards, such as erosion, wildfires, and flooding, rather than on the socio-economic consequences they generate. Nevertheless, the analysis identified how climate hazards lead to some grouped cascading impacts that affect KCS.
- Presence of interconnected risks: demonstrating how hazards such as flooding, erosion, and wildfires are not isolated but rather part of a complex system of interactions. For instance, flood risks are exacerbated by erosion and fire-induced landscape degradation, highlighting the need for multi-hazard management strategies. This interconnectedness underscores the importance of cross-sectoral coordination, as NbS interventions designed to address a single hazard often have implications for others. By recognizing these linkages, planning can shift toward more integrated and adaptive approaches that reflect the dynamic nature of risk propagation across the landscape.
- Identification of NbS interventions with synergistic effects, meaning that certain solutions regulate multiple hazards simultaneously, making them particularly valuable in

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resilience-building efforts. For example, hillside and riparian forests consistently appeared as key elements in the impact chains of erosion, wildfires, and flooding, reinforcing their role in stabilizing landscapes, retaining water, and moderating extreme events. This ability to absorb multiple impacts directly contributes to the robustness of the system, as these ecosystems function as buffers that reduce the intensity of climate hazards at various points in the landscape.

- Spatial relationships between NbS interventions and their cumulative effects on landscape resilience. The presence of functional redundancy—where multiple ecosystems provide overlapping regulatory functions—ensures that even if one NbS pathway is compromised, others remain active to maintain system stability. This adaptive capacity strengthens landscape resilience by ensuring that risk regulation does not depend on a single mechanism but rather on a network of interacting solutions. The CRICs demonstrated that each hazard is regulated by at least two ecosystem types, which reinforces the need to preserve and restore a diversity of natural elements across the landscape to maintain resilience in the face of shifting threats.
- Ttrade-offs and spatially decoupled relationships between the areas that provide ES and the areas that depend on them for risk mitigation. The fact that regulatory functions are not always located where the benefits are needed presents a governance challenge, requiring mechanisms that facilitate coordination across jurisdictions and stakeholders. Ensuring that investments in NbS align with these spatial dynamics is essential to maximizing their effectiveness and sustaining long-term resilience.

By integrating these insights, the conceptual model emphasizes that resilience is not simply about reducing individual hazards but about fostering a system that is both robust—through its ability to absorb impacts—and adaptive—through the functional redundancy that allows landscapes to maintain regulatory capacity despite disturbances. This final point underscores the need for cross-sectoral coordination and governance mechanisms to ensure investment in NbS is effectively allocated to areas where it can maximize resilience benefits.

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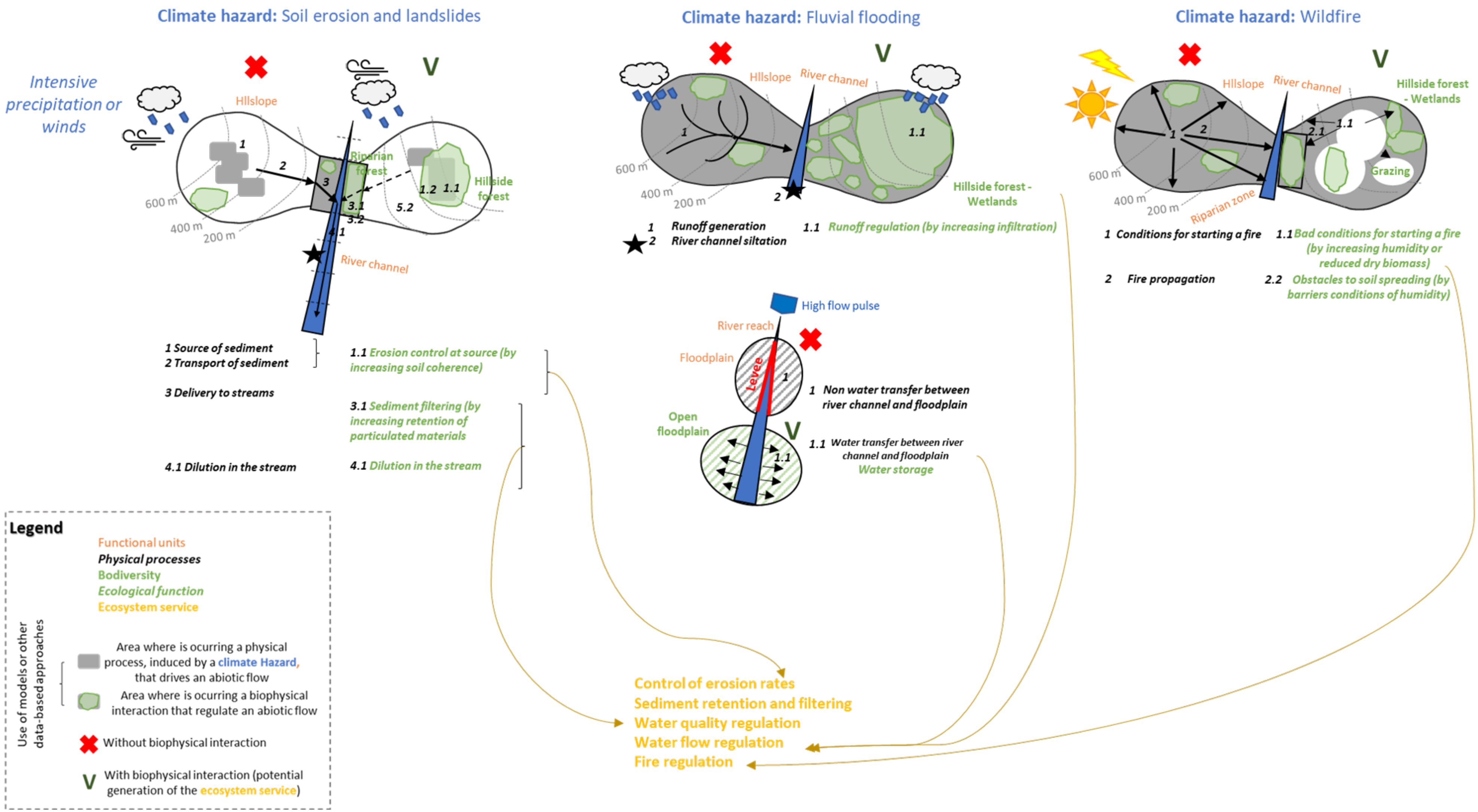

Figure 18. Application of level 1 of the conceptual framework for exploring bio-physical interactions in three hazards (erosion, fluvial flooding and fires) in a mountainous area.

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Table 4. Application of the Level 1 of the conceptual framework: relational table to identify potential NbS available to regulate fluvial flooding and erosion.

Climate hazard	Physical process	Functional unit (SPA)	Biophysical interaction underpinning **ecological function**	Biodiversity components where the best biophysical interaction occurs	Other biodiversity component where the biophysical interaction is altered	Main biodiversity features	Potential Nature based Solutions	Ecosystem Services provided by the biological component (**ecosystem service directly implied in the regulation of the physical process induced by the climate hazard)**. *SBA* Lower ES provision than the most adequate ecosystem for mitigating the climate hazard Conditioned ES provision than the most adequate ecosystem for mitigating the climate hazard Higher ES provision than the most adequate ecosystem for mitigating the climate hazard
Soil erosion and landslides	Source and transport of erosion	Hillslopes	**Erosion control at source**: Vegetation stabilize soil surfaces and impeding soil movement (Genet et al., 2010; Marden, 2012; Wang et al., 2014). Dense and well developed vegetation produce lower soil-losses in comparison to other vegetation covers (El Kateb et al., 2013)	**Hillside forest**: -Broad-leaved forest -Coniferous forest -Mixed forest -Sclerophyllous vegetation		Presence of tree cover: dense root system and interception of rainfall by the cover provided by the aerial vegetative part (as well as deposited organic matter)	-General protection measures -Ecosystem-specific conservation -Passive restoration (rewilding) -General management measures -Good forestry practices -Good livestock practices -Water management (of natural ecosystems) -Natural Water Retention Measures	**-Control of erosion rates** *(in situ)* **-Hydrological regulation** *(in situ; floodplain and riparian zone)* **-Water quality regulation** *(river channel)* -Soil degradation *(in situ)* -Flood *(river channel, floodplain and riparian zone)* -Drought *(river channel, floodplain and riparian zone)* -Hydrological variability *(river channel, floodplain and riparian zone)* -Changing temperature *(in situ; river channel)* -Biodiversity conservation *(in situ)* -Climate regulation – Carbon sequestration *(in situ; river channel, floodplain, riparian zone, estuary, coastal)* -Water provision *(river channel, floodplain and riparian zone)* -Food provision *(in situ)* -Raw materials provision *(in situ)* -Aesthetic value *(in situ)* -Recreation / Tourism *(in situ)*
					-Natural grasslands -Moors and heathland -Transitional woodland-shrub	Presence of vegetation cover: smaller vegetation may provide less interception capacity, as well as less strong roots that give less consistency to the soil.	-General restoration measures -Active restoration -Passive restoration (rewilding) -Good livestock practices -Changes in the habitat that favour the re-introduction of keystone species -Water management (of natural ecosystems) -Natural Water Retention Measures	**-Control of erosion rates** *(in situ)* **-Natural hazard regulation** *(in situ; floodplain and riparian zone)* **-Water quality regulation** *(river channel)* -Soil degradation *(in situ)* -Flood *(river channel, floodplain and riparian zone)* -Drought *(river channel, floodplain and riparian zone)* -Hydrological variability *(river channel, floodplain and riparian zone)* -Changing temperature *(in situ; river channel)* -Biodiversity conservation *(in situ)*

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							-Soil and Water Bioengineering	-Climate regulation – Carbon sequestration *(in situ; river channel, floodplain, riparian zone, estuary, coastal)* -Water provision *(river channel, floodplain and riparian zone)* -Food provision *(in situ)* -Raw materials provision *(in situ)* -Aesthetic value *(in situ)* -Recreation / Tourism *(in situ)*
					-Cultivated areas… -Pastures -Complex cultivation patterns -Agro-forestry areas -Sparsely vegetated areas -Burnt areas	Degraded areas or areas where land use significantly affects land cover and the ecological functions of vegetation on the land.	-General restoration measures -Active restoration -Passive restoration (rewilding) -General management measures -Good forestry practices -Good agricultural practices -Good livestock practices -Changes in the habitat that favour the re-introduction of keystone species -Water management (of natural ecosystems) -Natural Water Retention Measures -Soil and Water Bioengineering -Establishment of new ecosystems and their management	-Climate regulation – Carbon sequestration *(in situ; river channel, floodplain, riparian zone, estuary, coastal)* -Food provision *(in situ)* -Raw materials provision *(in situ)* -Aesthetic value *(in situ)* -Recreation / Tourism *(in situ)*
	Delivery of erosion to streams	Riparian zone	**Sediment filtering**: Riparian zone cover by dense tree vegetation is effective in trapping sediment by means of roots and other features than give spatial heterogeneity (Lind et al., 2019) (Lowrance et al., 1997; White et al., 2007)	**Riparian forest**: -Broad-leaved forest -Coniferous forest -Mixed forest -Transitional woodland-shrub		Presence of tree cover, as well as a well-developed herbaceous and shrub stratum: root system that retains incoming sediment particles. A well-developed herbaceous and shrub layer favours sediment retention when the flow is diffuse.	-General protection measures -Ecosystem-specific conservation -Passive restoration (rewilding) -General management measures -Good forestry practices -Good livestock practices -Water management (of natural ecosystems) -Natural Water Retention Measures	**-Control of erosion rates** *(in situ)* **-Natural hazard regulation** *(in situ)* **-Water quality regulation** *(river channel)* -Soil degradation *(in situ)* -Flood *(river channel and floodplain)* -Changing temperature *(in situ; river channel)* -Biodiversity conservation *(in situ)* -Climate regulation – Carbon sequestration *(in situ: river channel, floodplain, estuary, coastal)* -Food provision *(in situ)* -Raw materials provision *(in situ)* -Aesthetic value *(in situ)* -Recreation / Tourism *(in situ)*

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					-Natural grasslands -Moors and heathland	Tree and herbaceous strata is well developed: the sediment retention and filtering function could be further enhanced by the presence of tree vegetation.	-General restoration measures -Active restoration -Passive restoration (rewilding) -General management measures -Good livestock practices -Changes in the habitat that favour the re-introduction of keystone species -Water management (of natural ecosystems) -Natural Water Retention Measures -Soil and Water Bioengineering -Establishment of new ecosystems and their management	-**Control of erosion rates** *(in situ)* -**Natural hazard regulation** *(in situ)* -**Water quality regulation** *(river channel)* -Soil degradation *(in situ)* -Flood *(river channel and floodplain)* -Changing temperature *(in situ; river channel)* -Biodiversity conservation *(in situ)* -Climate regulation – Carbon sequestration *(in situ: river channel, floodplain, estuary, coastal)* -Food provision *(in situ)* -Raw materials provision *(in situ)* -Aesthetic value *(in situ)* -Recreation / Tourism *(in situ)*
					-Cultivated areas… -Pastures -Complex cultivation patterns -Agro-forestry areas -Sparsely vegetated areas -Burnt areas	Degraded areas or areas where land use significantly affects land cover and the ecological functions of vegetation on the land.	-General restoration measures -Active restoration -Passive restoration (rewilding) -General management measures -Good forestry practices -Good agricultural practices -Good livestock practices -Changes in the habitat that favour the re-introduction of keystone species -Water management (of natural ecosystems) -Natural Water Retention Measures -Soil and Water Bioengineering -Establishment of new ecosystems and their management	-**Control of erosion rates** *(in situ)* -**Natural hazard regulation** *(in situ)* -**Water quality regulation** *(river channel)* -Soil degradation *(in situ)* -Flood *(river channel and floodplain)* -Changing temperature *(in situ; river channel)* -Biodiversity conservation *(in situ)* -Climate regulation – Carbon sequestration *(in situ: river channel, floodplain, estuary, coastal)* -Food provision *(in situ)* -Raw materials provision *(in situ)* -Aesthetic value *(in situ)* -Recreation / Tourism *(in situ)*

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Fluvial flooding	Runoff generation	Hillslopes	**Runoff regulation:** Vegetation improves the infiltration capacity of surface soils (Bruijnzeel 2004; Ilstedt et al. 2007) and water retention (El Kateb et al. 2013). Catchments with more than 30% mature forest have higher hydrological stability (Belmar et al. 2018), lower peak flows and higher base flows	**Hillside forest**: -Broad-leaved forest -Coniferous forest -Mixed forest -Sclerophyllous vegetation **Wetlands**		Forest maturity. Mature forests and wetlands have an optimal structure to function as hydrological sponges, as their deep soils have a greater capacity to store water. The complex root network, combined with decomposer biota activity, enhances infiltration by creating more porous channels in the soil. Additionally, their dense tree canopy intercepts and retains a larger amount of precipitation, regulating water flow and reducing surface runoff.	-General protection measures -Ecosystem-specific conservation -Passive restoration (rewilding) -General management measures -Good forestry practices -Good livestock practices -Water management (of natural ecosystems) -Natural Water Retention Measures -Livestock exclusion (wetland perimeter fencing)	-Control of erosion rates *(in situ)* -**Hydrological regulation** *(in situ; floodplain and riparian zone)* -Water quality regulation *(river channel)* -Soil degradation *(in situ)* -**Flood** *(river channel, floodplain and riparian zone)* -Drought *(river channel, floodplain and riparian zone)* -Hydrological variability *(river channel, floodplain and riparian zone)* -Changing temperature *(in situ; river channel)* -Biodiversity conservation *(in situ)* -Climate regulation – Carbon sequestration *(in situ; river channel, floodplain, riparian zone, estuary, coastal)* -Water provision *(river channel, floodplain and riparian zone)* -Food provision *(in situ)* -Raw materials provision *(in situ)* -Aesthetic value *(in situ)* -Recreation / Tourism *(in situ)*
				-Natural grasslands -Moors and heathland -Transitional woodland-shrub		Their shallower soils store less water, and their root systems, while still contributing to infiltration, do not create as many deep channels as those of mature forests. Additionally, shrublands have a lower canopy cover, reducing their ability to intercept rainfall and increasing direct runoff.	-General restoration measures -Active restoration -Passive restoration (rewilding) -Good livestock practices -Changes in the habitat that favour the re-introduction of keystone species -Water management (of natural ecosystems) -Natural Water Retention Measures -Soil and Water Bioengineering	-Control of erosion rates *(in situ)* -**Hydrological regulation** *(in situ; floodplain and riparian zone)* -Water quality regulation *(river channel)* -Soil degradation *(in situ)* -**Flood** *(river channel, floodplain and riparian zone)* -Drought *(river channel, floodplain and riparian zone)* -Hydrological variability *(river channel, floodplain and riparian zone)* -Changing temperature *(in situ; river channel)* -Biodiversity conservation *(in situ)* -Climate regulation – Carbon sequestration *(in situ; river channel, floodplain, riparian zone, estuary, coastal)* -Water provision *(river channel, floodplain and riparian zone)* -Food provision *(in situ)* -Raw materials provision *(in situ)* -Aesthetic value *(in situ)* -Recreation / Tourism *(in situ)*

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	Water storage	Floodplains	**Flood-water storage:** The lateral connection between the river and its floodplain reduces floods, moderate peak flows by allowing overflow, and reduce flood wave velocity which mitigates flood risk (Jacobson, Lindner, and Bitner 2015; Vis et al. 2001)	**Floodplains**: -Forested -Wetlands		Storage volume of floodplain and rugosity of it. A higher water storage capacity is beneficial for temporarily retaining water and reducing peak flows. This effect is enhanced by the friction provided by vegetation elements, especially trees, which slow down water movement and promote infiltration		

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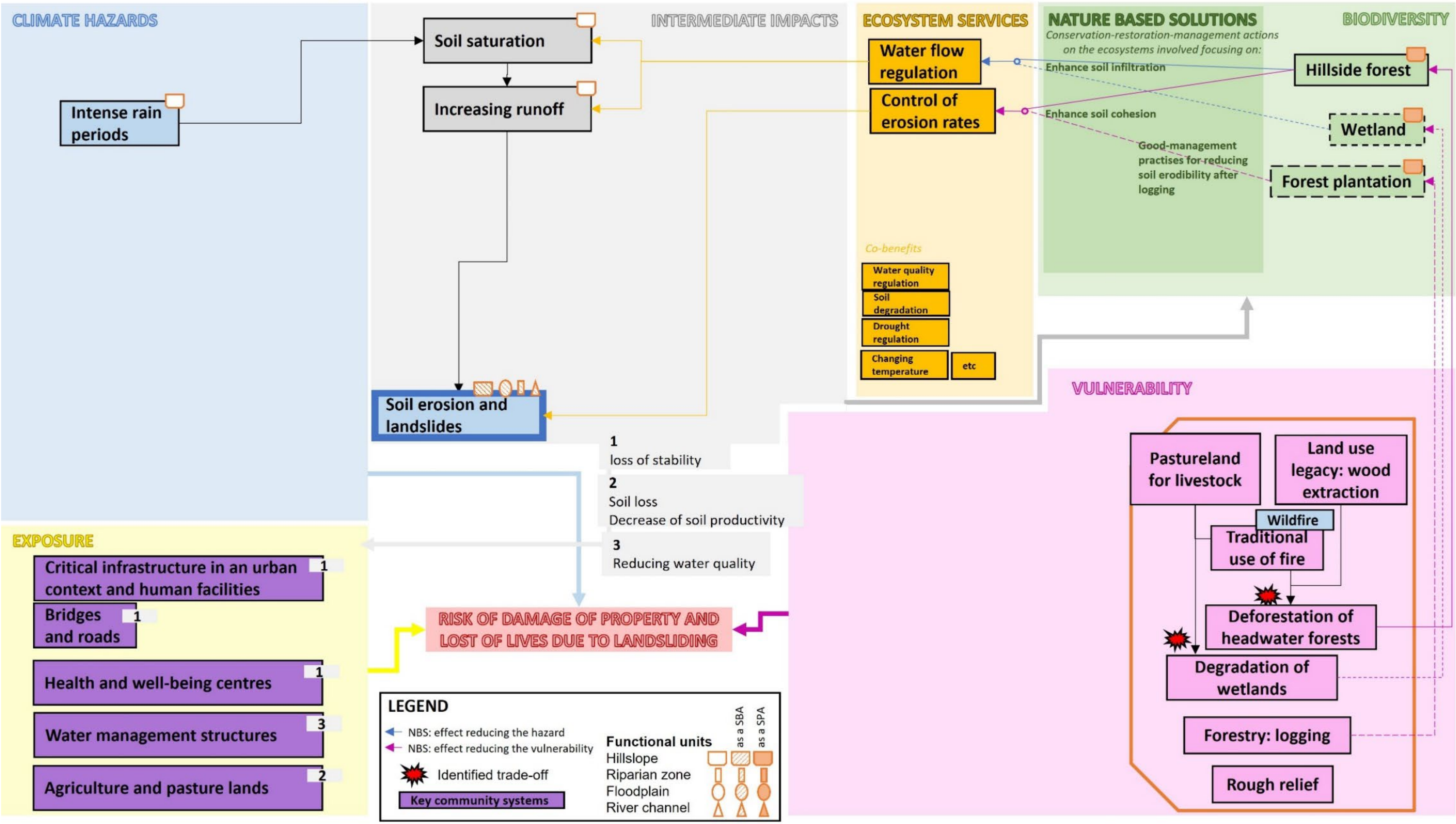

Figure 19. CRIC for landsliding risk.

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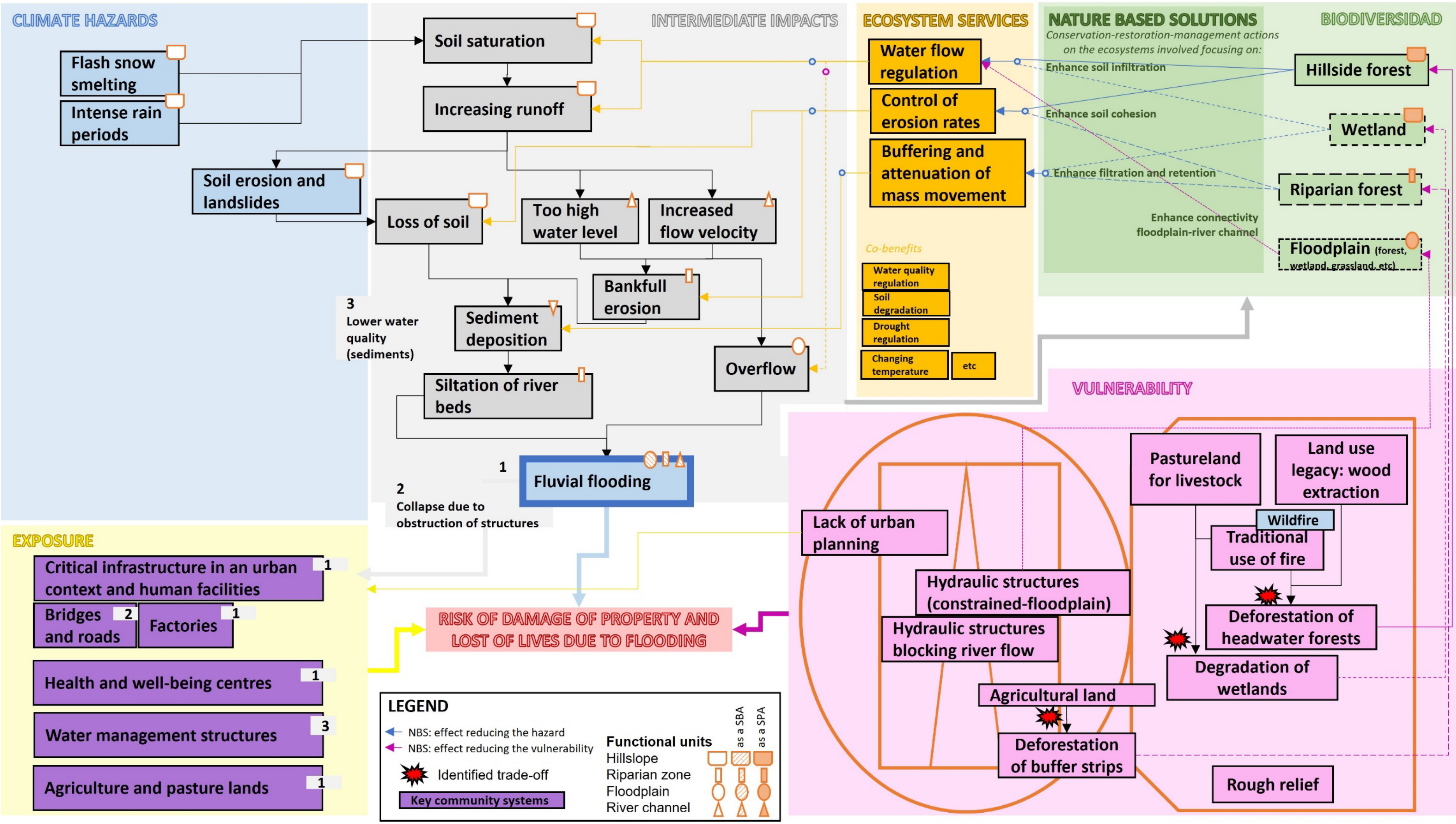

Figure 20. CRIC for flooding risk.

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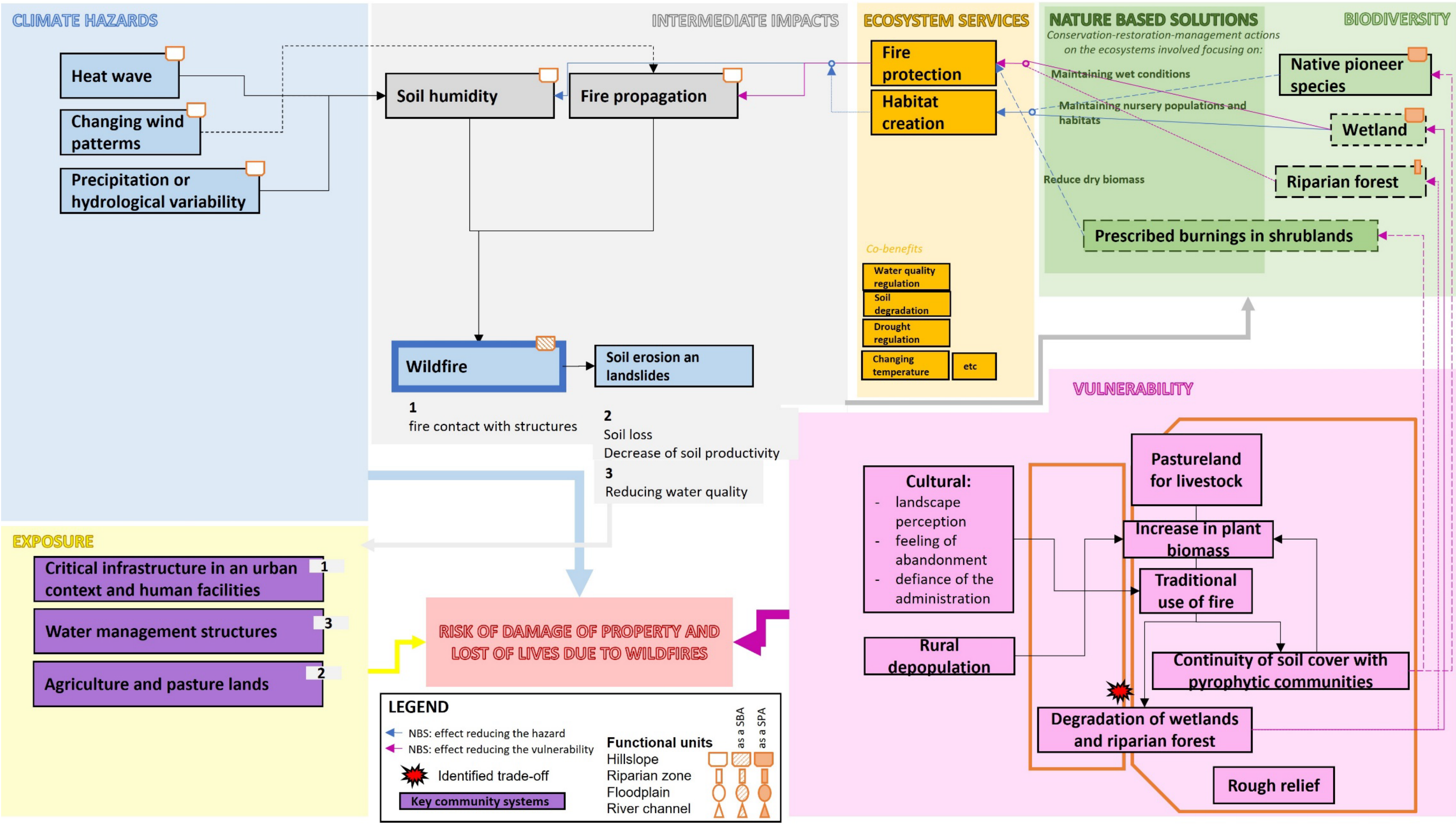

Figure 21. CRIC for wildfire risk.

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5.2 Coastal flooding and erosion in a coastal area

The conceptual framework was applied to a coastal area in Cantabria to assess the role of NbS in mitigating coastal flooding and erosion. In this case, only Level 2 was applied, constructing CRICs to analyse the cascading effects of these hazards and identify the most effective NbS interventions (Figure 23). This approach allowed for a comprehensive understanding of how climate drivers, biophysical processes, and ecosystem functions interact to regulate coastal risks:

- Intermediate impacts on exposed systems, focusing on the physical processes that amplify coastal flooding and erosion: rising sea levels and storm surges increase hydroperiods, triggering shifts in coastal ecosystems and, in some cases, their collapse. The resulting canopy loss and ecosystem die-off reduce the capacity of natural coastal defences, leading to higher hydrodynamic energy and sediment erosion. At the same time, modifications in sediment dynamics—driven by both natural processes and human activities—further degrade shoreline stability. This reinforced the importance of NbS that enhance sediment retention and accretion, helping maintain coastal integrity and reduce vulnerability.
- Interconnected risks: coastal flooding and erosion are mutually reinforcing. Increased erosion weakens estuarine vegetated ecosystems (such as seagrasses and saltmarshes), reducing their wave-buffering capacity and making coastal infrastructure more susceptible to storm impacts. Simultaneously, changes in hydrodynamics alter sediment transport, exacerbating shoreline retreat and the risk of coastal squeeze. By mapping these interdependencies, the analysis highlighted the need for integrated management strategies that simultaneously tackle multiple hazards, rather than treating them in isolation.
- Identification of key NbS interventions with synergistic effects, meaning that certain solutions regulate multiple risks simultaneously. Restoring and managing dune vegetation emerged as a priority intervention, as it helps buffer wave energy, trap sediments, and provide inland migration space for coastal ecosystems. Similarly, estuarine vegetated ecosystems play a vital role in stabilizing sediments, reducing wave energy, and mitigating both flooding and erosion. These interventions contribute to the robustness of the coastal system by absorbing the impacts of multiple hazards, ensuring a greater degree of protection even under intensifying climate conditions.
- Cumulative effects of NbS across the landscape, demonstrating the importance of functional redundancy in risk regulation. By incorporating different ecosystems—such as dunes, marshes, and submerged vegetation—into risk mitigation strategies, the system gains adaptive capacity. This redundancy ensures that if one component of the coastal defence network is compromised, alternative pathways remain active, sustaining protection functions. The presence of multiple NbS working together increases the probability that at least one regulatory mechanism will persist under changing conditions, reinforcing coastal resilience.
- Trade-offs and spatial mismatches between SPA (e.g., offshore seagrass beds that reduce wave energy) and SBA (e.g., coastal urban centers and agricultural lands vulnerable to flooding). These spatially decoupled relationships underline the necessity of coordinated governance and investment in NbS. Effective risk reduction requires bridging the gap between conservation efforts and the management of exposed assets, ensuring that ES-

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providing ecosystems are maintained and restored in alignment with regional risk dynamics.

By applying Level 2 of the conceptual framework, this case study demonstrated how CRICs enable a system-wide understanding of coastal risks, guiding the selection of NbS interventions that enhance landscape resilience through robustness (absorbing multiple impacts) and functional redundancy (ensuring adaptation capacity). These insights reinforce the need for integrated coastal management strategies that leverage NbS to mitigate interconnected hazards while promoting long-term ecological and socio-economic resilience

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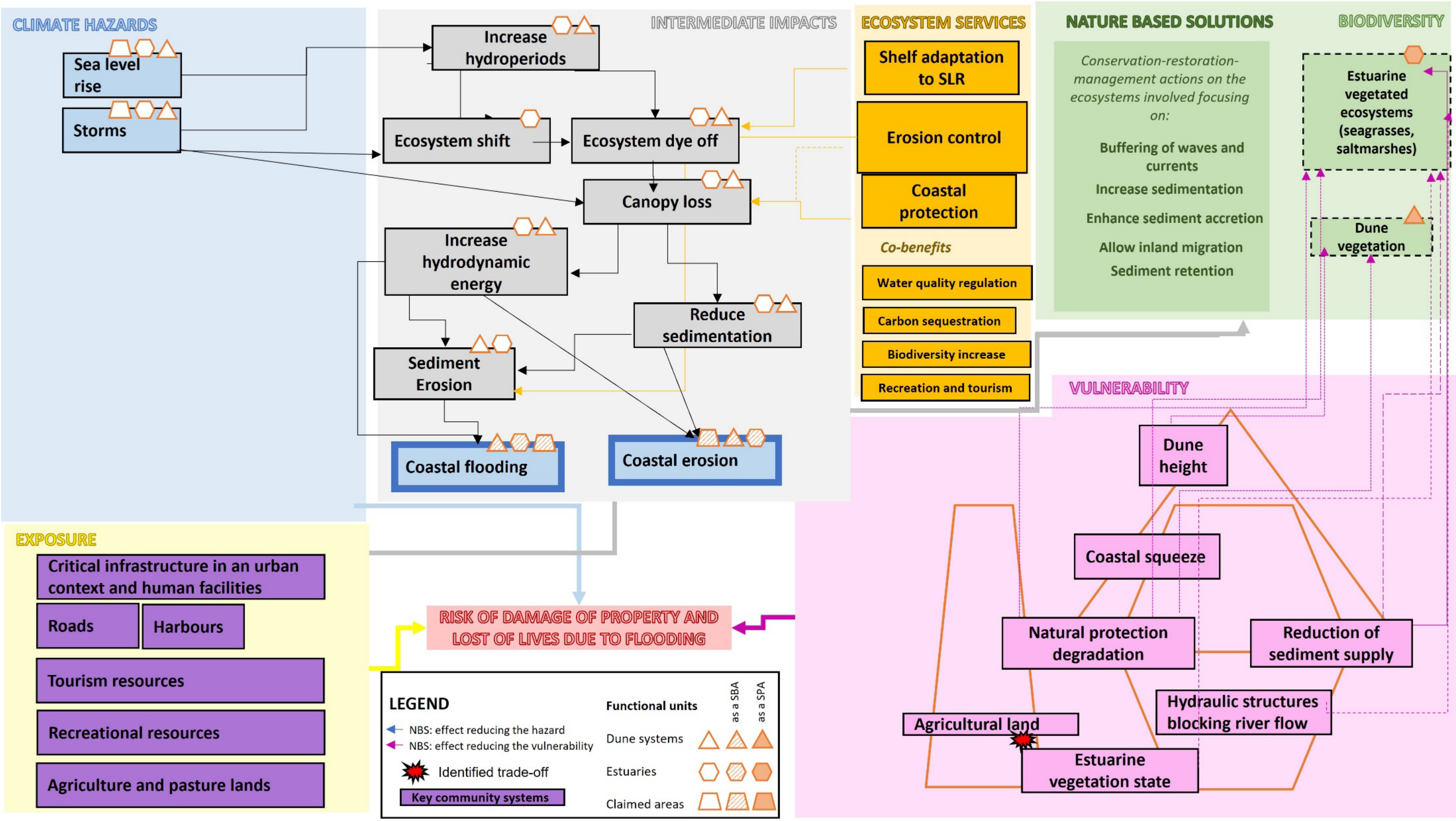

Figure 22. CRIC for coastal flooding and erosion risk.

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5.3 Heatwaves in an urban area

The conceptual framework was applied to a representative urban area in the north of Spain to assess potential NbS interventions aimed at reducing the risks of heatwaves. The application followed a structured approach, beginning with Level 1, to gain a precise understanding of the physical processes underlying the climate hazard (heatwaves), the abiotic flows it generates, and the ecosystem functions most relevant to their regulation (by generating ES). By analysing these elements, it becomes possible to identify the biodiversity components that play a key role in regulating threats and the specific management measures needed for NbS implementation.

Step 1: Conceptualizing Bio-physical Interactions (Level 1)

Based on relevant references (Kumar et al., 2024; Masson et al., 2020; Vázquez & Kanda 2018), Level 1 of the conceptual framework was applied to identify potential NbS available to regulate heatwaves (Table 5) by linking:

- Physical processes underlying the heatwaves.
- The abiotic flows occurring in the landscape related to heatwaves.
- The ecosystems that produce the ES regulating these flows.
- Potential NbS typologies available in an urban area.
- Indicators to quantify biophysical interactions with abiotic flows.

Step 2: Conceptualizing the model of social-ecological interactions (Level 2)

Building on the findings from Level 1, Level 2 was applied to develop the CRIC for the hazard (heatwaves) in urban areas. This CRIC (Figure 23) illustrates the connections between the climate-related risk in urban areas and provide key insights into how NbS interventions contribute to landscape resilience:

- Heatwave's hazard takes place when air temperature exceeds certain thresholds over days or weeks. In this sense, it could be expressed through an increase in frequency, duration or intensity of higher temperatures.
- In terms of intermediate impacts on exposed systems, the focus remained on the biophysical processes on human health and well-being and socio-economic consequences they generate. Other important KCS, such as urban natural ecosystem and NBS and water resources and management, would be negatively affected by the impacts. Specific relationships between exposed elements and intermediate impacts are indicated in the CRIC.
- Vulnerability is been defined in terms of sensitivity and adaptability, by including differentiated elements that could be representative in other urban environments located in a variety of functional units (hillslopes, riparian zones, floodplains and river channel).
- Many of the potential NbS proposed have synergistic effects, being able to regulate multiple hazards simultaneously, making them particularly valuable in resilience-building efforts. For example, the presence of tree cover, as well as a well-developed herbaceous and shrub stratum, would provide the service of controlling heatwaves not only by enhancing evapotranspiration but also fostering soil water infiltration.
- Although temperature regulation is the ecosystem service that regulates the climate hazard, the implementation of the proposed solutions will have positive effects through

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the provision of other indirect services and co-benefits, such as water provision, drought regulation, water quality regulation, biodiversity enhancement and natural hazard regulation.

- Spatial relationships between NbS interventions and their cumulative effects on landscape resilience. The presence of functional redundancy—where multiple ecosystems provide overlapping regulatory functions—ensures that even if one NbS pathway is compromised, others remain active to maintain system stability. This adaptive capacity strengthens landscape resilience by ensuring that risk regulation does not depend on a single mechanism but rather on a network of interacting solutions. The CRICs demonstrated that each hazard is regulated by at least two ecosystem types, which reinforces the need to preserve and restore a diversity of natural elements across the landscape to maintain resilience in the face of shifting threats.
- In urban areas, optimal biophysical interactions do not occur due to the very nature of the urban environment. However, the increased presence of well-connected urban NBS can substantially improve these types of interactions. Thereby, biodiversity components. where the best biophysical interaction occurs would be made up of larger urban woodlands bodies (woodlands and riparian woodlands), larger urban water bodies (lakes, rivers) and larger urban wetlands.
- Although no specific trade-offs have been marked in the CRIC, it is assumed that most of the grey traditional urban elements should be redesigned, adapted, replaced or eliminated to incorporate the biodiversity components that can provide the ES.

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Table 5. Application of the Level 1 of the conceptual framework: relational table to identify potential NbS available to regulate heatwaves in an urban area.

Climate hazard	Physical process	Functional unit (SPA)	Biophysical interaction underpinning **ecological function**	Biodiversity components where the best biophysical interaction occurs	Other biodiversity component where the biophysical interaction is altered	Main biodiversity features	Potential Nature-based Solutions	Ecosystem services provided by the biological component (**ecosystem service directly implied in the regulation of the physical process induced by the climate hazard**). *SBA* Lower ES provision than the most adequate ecosystem for mitigating the climate hazard Conditioned ES provision than the most adequate ecosystem for mitigating the climate hazard Higher ES provision than the most adequate ecosystem for mitigating the climate hazard
Heat wave (air temperature exceeds certain thresholds over days or weeks; Kumar et al. 2023)	Increased sensible heat flux (by reductions in evapotranspiration, enhancement of heat transport by turbulence, and increases in anthropogenic heat emissions (AHEs) and Larger thermal Inertia (it is the degree of delay in the temperature of an object matching that of its surroundings (Vázquez & Kanda 2018)	Hillslopes/ Floodplains	**Vegetation cover**: The urban heat island (UHI) trend is negatively correlated with vegetation cover. This relationship is more apparent with relatively high levels of vegetation cover, which result in more incoming radiation being converted to latent heat via transpiration than is present as sensible heat (Vázquez & Kanda 2018). Additionally, during evapotranspiration plants release moisture, which further cools the surrounding air by converting	(In urban areas, optimal biophysical interactions do not occur due to the very nature of the urban environment. However, the increased presence of well-connected urban NBS can substantially improve these types of interactions) Larger urban woodlands bodies (woodlands and riparian woodlands)	**Vegetation-based structures (green):** -Mixed (green-blue) -Amenity areas -Other public space -Garden -Parks -Linear features -Constructed GI (GBGI types in 10 key categories; Kumar et al. 2023)	Presence of tree cover, as well as a well-developed herbaceous and shrub stratum (described in the Biophysical interaction underpinning **ecological function** column**)**	**Vegetation-based structures (green):** -Mixed (green-blue): -Other public space: Cemetery, Allotment, City farm, Adopted public space -Garden: balcony, private garden, irrigating backyard -Amenity areas: Sports field, Playground, golf course, Shared open space -Parks: pocket Park, park, Botanical garden -Linear features: Street tree, Road verge, Riparian Woodland, Hedge -Constructed GI: Green roof, Green wall, Roof garden, Pergola (GBGI types in 10 key categories; Kumar et al. 2023)	-Natural hazard regulation *(in situ; floodplain and riparian zone)* -Water quality regulation *(river channel)* -Soil degradation *(in situ)* -Flood *(river channel, floodplain and riparian zone)* -Drought *(river channel, floodplain and riparian zone)* -Hydrological variability *(river channel, floodplain and riparian zone)* -Changing temperature *(in situ; river channel)* -Biodiversity provision *(in situ)* -Climate regulation – Carbon sequestration *(in situ; river channel, floodplain, riparian zone, estuary, coastal)* -Water provision *(river channel, floodplain and riparian zone)* -Food provision *(in situ)* -Raw materials provision *(in situ)* -Aesthetic value *(in situ)* -Recreation / Tourism *(in situ)*

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			sensible heat into latent heat (Kumar et al. 2023). Moreover, tree cover may regulate urban heat through shading and thermal insulation, lowering surface temperatures and mitigating the UHI effect via creating a cooler micro-climate.					
			Water areas: Absorbs heat and cools the surrounding area through evaporation (Kumar et al. 2023).	(In urban areas, optimal biophysical interactions do not occur due to the very nature of the urban environment. However, the increased presence of well-connected urban NBS can substantially improve these types of interactions) Larger urban water bodies (lakes, rivers)	**Water-based structures (blue):** -Hybrid GI (for water) -Non-sealed urban areas -Waterbodies	Presence of water areas (described in the Biophysical interaction underpinning **ecological function** column**)**	**Water-based structures (blue):** -Hybrid GI (for water): Permeable paving, Attenuation pond, Rain garden -Non-sealed urban areas: woodland (other), grass (other), shrubland (other) -Waterbodies: wetland, lake, reservoir, sea (incl. coast)	-Natural hazard regulation *(in situ; floodplain and riparian zone)* -Water quality regulation *(river channel)* -Soil degradation *(in situ)* -Flood *(river channel, floodplain and riparian zone)* -Drought *(river channel, floodplain and riparian zone)* -Hydrological variability *(river channel, floodplain and riparian zone)* -Changing temperature *(in situ; river channel)* -Biodiversity provision *(in situ)* -Climate regulation – Carbon sequestration *(in situ; river channel, floodplain, riparian zone, estuary, coastal)* -Water provision *(river channel, floodplain and riparian zone)* -Food provision *(in situ)* -Raw materials provision *(in situ)* -Aesthetic value *(in situ)* -Recreation / Tourism *(in situ)*
			Other non-sealed urban areas:	(In urban areas, optimal	**Vegetation-**	Presence of tree cover, as well as a	-Hybrid GI (for water): Permeable paving,	-Natural hazard regulation *(in situ; floodplain and riparian zone)*

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			Permeable surfaces facilitate water infiltration, reduce stormwater runoff, and recharge groundwater. Acting as sponges, this surfaces store water and release it during high air temperatures, thereby moderating temperatures in the vicinity by increasing water availability for evaporation through groundwater recharge (Kumar et al. 2023).	biophysical interactions do not occur due to the very nature of the urban environment. However, the increased presence of well-connected urban NBS can substantially improve these types of interactions) Larger urban wetlands	**based structures (green):** -Mixed (green-blue) -Amenity areas -Other public space -Garden -Parks -Linear features -Constructed GI (GBGI types in 10 key categories; Kumar et al. 2023)	well-developed herbaceous and shrub stratum (described in the Biophysical interaction underpinning **ecological function** column**)**	Attenuation Pond, Rain garden -Non-sealed urban areas: woodland (other), grass (other), shrubland (other) -Waterbodies: wetland, lake, reservoir, sea (incl. coast) Constructed wetlands	-Water quality regulation *(river channel)* -Soil degradation *(in situ)* -Flood *(river channel, floodplain and riparian zone)* -Drought *(river channel, floodplain and riparian zone)* -Hydrological variability *(river channel, floodplain and riparian zone)* -Changing temperature *(in situ; river channel)* -Biodiversity provision *(in situ)* -Climate regulation – Carbon sequestration *(in situ; river channel, floodplain, riparian zone, estuary, coastal)* -Water provision *(river channel, floodplain and riparian zone)* -Food provision *(in situ)* -Raw materials provision *(in situ)* -Aesthetic value *(in situ)* -Recreation / Tourism *(in situ)*

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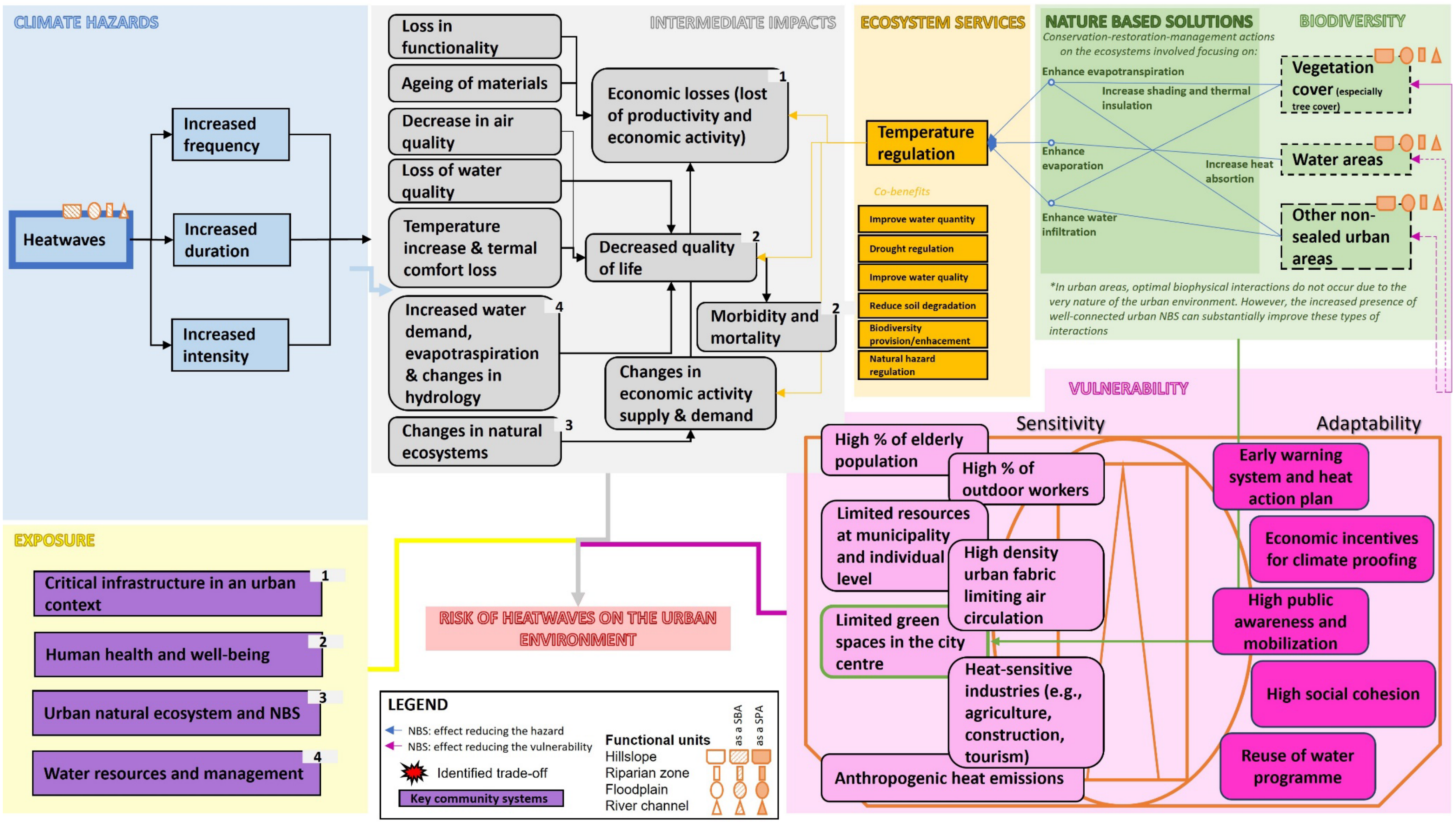

Figure 23. CRIC for heatwave risk in an urban area.

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6 A way forward for the NBRACER regions

The previous sections of this document analyse in detail and from a scientific and technical point of view the components, septs and main processes that should be considered when designing NbS for multiple climate hazards in landscapes. However, the regions within the NBRACER project (and quite likely, everywhere else) might need some guidance on how this conceptual framework could be practically implemented. To assist on this, the NBRACER team has devised a route map that could be followed in different regions to capitalise on existing datasets and models at the regional level (i.e., data rich regions) or by using national or pan-European digital resources (i.e. data-poor regions).

The proposed route map consists of three major blocks (Figure 25) that incorporate the following:

- ➢ Steps for a practical application of the conceptual framework in a given geographical setting.
- ➢ An operative digital framework to model and map (1) climate hazards and KCS risks, (2) biodiversity and (3) ES provisioning.
- ➢ A final module that acknowledges the need to serve the generated information in different formats depending on the main objectives.

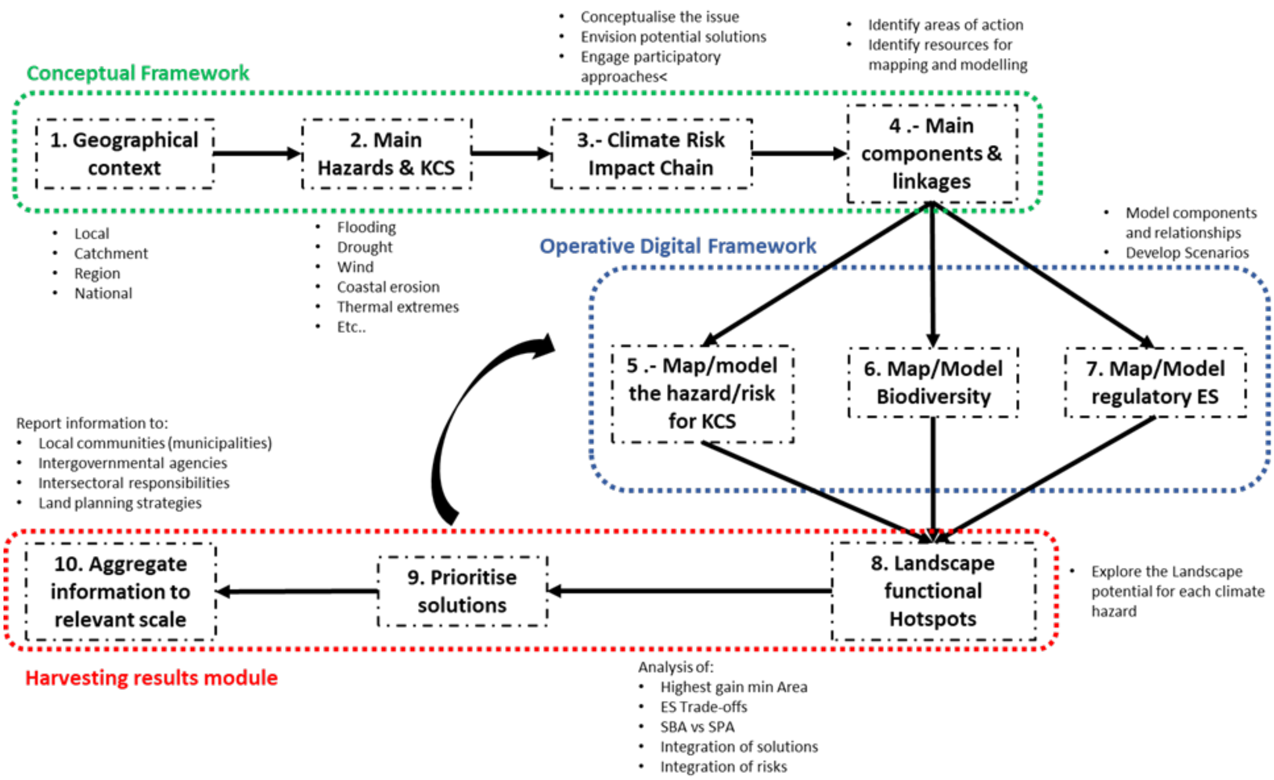

Figure 24. Diagram representing the different steps of a practical route map to assist on the design of NbS for multiple climate risk in the NBRACER regions.

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6.1 Practical application of the conceptual framework

This part of the route map considers 4 main steps that assist on setting the scene for the generation of relevant information. The steps are the following:

- **Step 1:** Set up the geographical context in which the analyses has to be developed within each of the regions. As it has been pointed out above, bear in mind that the areas impacted by a given climate risk could be managed by locations far away from them. We encourage the use of hydrological envelops (i.e. catchments) that include the area of risk.
- **Step 2:** Identify the main hazards in the geographical context and the KCS that need to be "protected". The NBRACER regions have provided already information for the baseline analyses (under NBRACER WP1) that could be taken to prioritise which climate risks should be considered with more detail. We encourage the selection of at least 2-3 climate risks, so that multi-hazard exercises could be developed to explore interactions among them.
- **Step 3:** Develop the CRIC for the different climate hazards selected. This exercise is largely illustrated under section 5 of the current document. It is important to mention that this conceptual work is essential to reveal cause-effect relationships and it could be used or redefined through participatory learning approaches in the regions.
- **Step 4:** Identify the main components and linkages from the CRIC that need to be mapped/modelled. This step is essential to focus the work of modellers. This step should involve the identification of needs in relation to existing local, national or pan-European models or datasets.

6.2 Operative digital framework

This block of the proposed route map considers three main tasks that could be developed in parallel. Most of these steps consider the need to use digital resources (data or models) to generate relevant information that could inform further decisions. The three components of this block are:

1. Look for existing "official" climate hazard/KCS maps or develop them depending on the region current needs. It should be noted that NBRACER D.5.2. has already given extensive support for this issue.
2. Map or model biodiversity at the lowest taxonomic level possible that could be related to specific ecosystem/habitat/species regulatory functions. This part will be developed further under D.5.3 within NBRACER.
3. Map or model regulating ES that relate to the biophysical flow of the climate hazard you aim to regulate/buffer. It should be noted that other provisioning ES (e.g. food or wood production) could also be modelled for trade-off analysis (regulating versus provisioning trade-offs). This part will be further developed under D 5.3 within NBRACER.

6.3 Harvesting results

The final part of the route map considers three main steps that can be developed in a recurrent-loop, revisiting the digital framework when needed. This part of the route map is essential to highlight the location of potential solutions in the landscape and it will need the assistance of

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geographic information systems to be able to connect service provisioning areas to service benefiting areas (see above in the conceptual framework). The three steps considered are:

1. Identification of landscape functional hotspots where current (conservation) or future (restoration or novel) ecosystem/habitat/species could play their regulatory role. The selection of this locations could be done on a basis of a threshold on the regulatory "quantity" that the location provide.
2. Selection of priority areas of solutions to reduce exposure or risk of KCS to specific climate hazards. This sept could involve the need of trade-off analyses between ES or the need to develop SBA-SPA agreements. This step calls for the need of a participatory process in which relevant stakeholders are informed and involved in the design process.
3. Integrate and aggregate information at the appropriate level of hexagons, functional units, sub-catchments, municipalities or any other (administrative) polygon. This step incorporates the final representation of results, in which different scenarios or decisions could be contrasted so that the design of pathways to resilience could be informed.

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Appendix 1: Climate hazards

Definition: Climatological-induced physical events or trends that have the potential to cause harm. (Laca, 2021).

Table 6. Identified climate hazards. They are the ones defined by the Technical Expert Group on Sustainable Finance of the EU and based on the identification of climate-related hazards which are limited to the potential occurrence of a weather and climate related natural physical event or trend (following what is defined by the IPCC). In italics, secondary climate hazards, i.e., those that are not strictly climatological and are derived from these hazards, have been indicated. In many cases, these secondary climate hazards are considered to be derivative or intermediate impacts rather than hazards per se. They can be found here (section 2.5 Classification of climate-related hazards): *https://finance.ec.europa.eu/system/files/2020-03/200309-sustainable-finance-teg-final-report-taxonomy-annexes_en.pdf*

Climate hazard (*secondary climate hazards)*	Type	Impact over biodiversity	Comments	Main physical processes and derived abiotic flows
Changing temperature	Temperature-related	Chronic	Air, freshwater, marine water	Energy: thermal radiation flows
Heat stress				Energy: thermal radiation flows
Temperature variability				Energy: thermal radiation flows
Permafrost thawing				Water flow and water conditions
Heat wave		Acute		Energy: thermal radiation flows
Cold wave/frost				Energy: thermal radiation flows
Wildfire				Energy: thermal radiation flows
Changing wind patterns	Wind-related	Chronic		Energy: eolic flows
Cyclone, hurricane, typhoon		Acute		Energy: eolic flows
Storm			Including blizzards, dust and sandstorms	Energy: eolic flows; wáter flow
Tornado				Energy: eolic flow
Changing precipitation patterns and types	Water-related	Chronic	Rain, hail and snow/ice	Water flow
Precipitation or hydrological variability				Water flow

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Ocean acidification				
Saline intrusion				
Sea level rise				Water flow
Water stress				Water flow
Drought		Acute		Water flow
Heavy precipitation			Rain, hail, snow/ice	Water flow
Pluvial flooding			Coastal and river flooding/pluvial and fluvial flooding	Water flow
Fluvial flooding				Water flow
Glacial lake outburst				Water flow
Coastal erosion	Solid mass-related	Chronic		Sediment flow
Soil degradation		Chronic		Sediment flow; soil properties
Soil erosion		Acute	Due to intensive precipitation or wind	Sediment flow
Solifluction		Chronic		Sediment flow
Avalanche		Acute		Sediment flow
Landslide			Due to intensive precipitation or wind	Sediment flow
Subsidence				Sediment flow
Biological hazards				Biotic flows

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Appendix 2: Functional Units

Definition: Spatial units that meet the spatial scale required by the biological component to generate the biophysical interaction involved in generating an ES (Laca, 2021).

According to our model, the landscape-seascape is considered as an array of geomorphic patches, formed by regional acting factors such as the catchment geomorphology and climate, hydrologically connected to each other. Geomorphic patches result from shifts in geomorphic processes that govern abiotic flows and constitute physical habitat type, structure and dynamics (Montgomery 1999). Each type of geomorphic patch has a specific ecological potential that roughly shapes biodiversity and ecosystem functioning. This portrayal of the landscape extends the vision proposed by (Thorp, Thoms, and Delong 2006) by incorporating a meta-ecosystem perspective and the specific elements to explore ES patterns and dynamics in river ecosystems. Geomorphic patches are here equivalent to functional units. They capture and aggregate the biotic and abiotic interactions that take place in functional process zones at the scale needed to generate ES. Since the biophysical interactions for ES provision change among functional units (i.e., geomorphic patches), both the ES they generate and their role in the ES flow also differ between functional units. This spatial segregation of the landscape allows us to track the potential ES flow between the SPA functional unit, characterized by some specific abiotic and biotic conditions that determine the generation of ES, and the SBA functional unit.

Table 7. Identified functional units. For each functional unit, the geomorphic processes that dominate the unit and therefore characterise it are listed. The functional units are defined according to two geomorphic classification systems (see last column). The element of the classification considered to be most like the functional unit and whose definition has been taken from it is shown in bold.

Functional units	Dominant geomorphic processes	Definition	Geomorphic Classification System
Interfluve	Pedogenetic processes associated with vertical subsurface soil water movement	The area between rivers; esp. the relatively undissected upland or ridge between two adjacent valleys containing streams flowing in the same general direction. (Bates and Jackson, 1995)	(Haskins, et al. 1998) [Common landform] **Interfluve**
Hillslope (Montgomery, 1999)	Slope processes	A positive relief generated by an unspecified tectonic/structural process. A positive relief generated by bedrock bedding (modified after Huggett, 2017).	(Nanson, et al., 2022) Solid Earth BGU: **Tectonic high** BGU-T: Compressional ridge; tectonic dome BGU: **Bedding ridge** BGU-T: Cuesta; homoclinal ridge; hogback
		A natural elevation of the land surface, rising rather prominently above the surrounding land, usually of limited extent and having a well-defined outline (rounded rather than peaked or rugged), and generally considered to be less than 300 m	(Haskins, et al. 1998) [Landscape Term] **Hill** [Landscape Term] **Mountain**

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		from base to summit; the distinction between a hill and a mountain is arbitrary and dependent on local usage. (Bates and Jackson, 1995). Any part of the Earth's crust higher than a hill, sufficiently elevated above the surrounding land surface of which it forms a part to be considered worthy of a distinctive name, characterized by a restricted summit area (as distinguished from a plateau), and generally having comparatively steep sides and considerable bare rock surface; it can occur as a single, isolated eminence, or in a group forming a long chain or range, and it may form by earth movements, erosion, or volcanic action. Generally, a mountain is considered to project at least 300 m above the surrounding land.	
Hollow/Torrent (Montgomery, 1999)	Processes of water flow concentration (runoff) only after precipitation events. The rest of the time, slope processes dominate	Though diverse in form, GULLIES tend to be relatively small (though larger than RILLS), steep, narrow, deeply incised SUBAERIAL CHANNELS that are carved into unconsolidated regolith (modified from Goudie, 2006).	(Nanson, et al., 2022) Coastal or fluvial BGU: Subaerial channel BGU-T: **Gully**
		A very small valley, such as a small ravine in a cliff face, or a long, narrow hollow or channel worn in earth or unconsolidated material (as on a hillslope) by running water and through which water runs only after a rain or the melting of ice or snow; it is smaller than a gulch. (b) Any erosion channel so deep that it cannot be crossed by a wheeled vehicle or eliminated by plowing, esp. one excavated in soil on a bare slope. (c) A small, steep-sided wooded hollow. (Bates and Jackson, 1995).	(Haskins, et al. 1998) [Common Landform] **Gully**
River channel and banks (Montgomery, 1999)	Stream processes, driven by water flow	Formed of alluvium, usually have mobile boundaries and are self-adjusting in response to changing conditions. Commonly parabolic or trapezoid in cross section with adjacent, roughly horizontal FLOODPLAINS are inundated when the channel exceeds bankfull capacity (modified from Goudie, 2006).	*(Nanson, et al., 2022)* Coastal or fluvial BGU: **Subaerial channel** BGU-T: River; Creek
		The bed where a natural body of surface water flows or may flow; a natural passageway or depression of perceptible extent containing continuously or periodically flowing water, or forming a connecting link between two bodies of water; a watercourse. (Bates and Jackson, 1995). The sloping margin of, or the ground bordering, a stream, and serving to confine the water to the natural channel during the	*(Haskins, et al. 1998)* [Fluvial Landform and Microfeature] Stream Processes (Subprocess Modifiers: Undifferentiated, Eroding, Transporting or Depositional) • **Channel** • **Bank**

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		normal course of flow. It is best marked where a distinct channel has been eroded in the valley floor, or where there is a cessation of land vegetation. A bank is designated as right or left as it would appear to an observer facing downstream. (Bates and Jackson, 1995).	
Riparian zone	Riparian processes, driven by a high lateral-vertical connectivity between the river and the terrestrial area	Transitional semiterrestrial areas regularly influenced by freshwater, normally extending from the edges of water bodies to the edges of upland communities. These are 'three-dimensional zones of direct interaction between terrestrial and aquatic ecosystems' (Gregory et al. 1991). In this sense, flood recurrence interval may be an objective approach to delineate the outward boundary of the riparian zone. In this regard, the 50-yr flood has been indicated as an appropriate hydrological descriptor for riparian zones as it usually coincides with the first terrace or other upward sloping surface (Ilhardt et al., 2000).	
Floodplain (Montgomery, 1999)	Recurrent river flooding processes	The relatively flat area of land between the banks of the parent stream and the confining valley walls, over which water from the parent stream flows at times of high discharge. The sediment that comprises a FLOODPLAIN is mainly alluvium derived from the parent stream (modified from Goudie, 2006) and can be comprised of CONFINED / CUT-AND-FILL, BRAIDED, LATERAL MIGRATION or ANABRANCHING FLOODPLAIN deposits (Nanson and Croke, 1992).	(Nanson, et al., 2022) Coastal or fluvial BGU: **Floodplain** BGU-T: High-energy confined floodplain; Medium-energy unconfined floodplain; Low-energy cohesive floodplain
		A small alluvial plain bordering a river, on which alluvium is deposited during floods. (Bates and Jackson, 1995).	(Haskins, et al. 1998) [Fluvial Element Landform] Stream Processes (Subprocess Modifiers: Undifferentiated, Eroding, Transporting or Depositional) • Floodplain ○ **Alluvial flat** ○ Meander scar ○ Meander scroll ○ Oxbow ○ Levee
Estuary	Marine-river mixing processes determined by the tidal cycle	A near-horizontal depositional surface formed above mean high water spring tide level. Typically located on the landward margins of saltmarshes and along **estuary** and lagoon shorelines.	(Nanson, et al., 2022) Coastal BGU: tidal flat BGU-T: supratidal flat
		The seaward end or the widened funnel shaped tidal mouth of a river valley where	(Haskins, et al. 1998) [Coastal Marine Landform]

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		freshwater comes into contact with seawater and where tidal effects are evident; e.g., a tidal river, or a partially enclosed coastal body of water where the tide meets the current of a stream (Bates and Jackson, 1995).	Shoreline Processes • **Estuary**
Delta	Sedimentation processes subject to tidal, waves and currents dynamics	A discrete shoreline sedimentary protuberance formed where a river enters a body of water and supplies sediment more rapidly than it can be redistributed by basinal processes (modified from: Elliott, 1986).	(Nanson, et al., 2022) Coastal and fluvial BGU: **delta** BGU-T: front; pro-; upper; lower; bayhead; shelf edge; tidal delta
		The low, nearly flat, alluvial tract of land at or near the mouth of a river, commonly forming a triangular or fan-shaped plain of considerable area, crossed by many distributaries of the main river, perhaps extending beyond the general trend of the coast, and resulting from the accumulation of sediment supplied by the river in such quantities that it is not removed by tides, waves, and currents. Most deltas are partly subaerial and partly below water. (Bates and Jackson, 1995) The level or nearly level surface composing the landward part of a large delta; strictly, an alluvial plain characterized by repeated channel bifurcation and divergence, multiple distributary channels, and interdistributary flood basins. (Bates and Jackson, 1995)	(Haskins, et al. 1998) [Landscape term] **Delta** [FLuvial Landform] Stream Processes (Subprocess Modifiers: terminal deposition) • **Delta** ○ **Delta plain**
Coastal cliff	Wave erosion	A steep slope, or ESCARPMENT formed in rock, ranging in height from tens to hundreds of metres.	(Nanson, et al., 2022) Coastal BGU: rocky coast BGU-T: **cliff**
		A cliff or slope produced by wave erosion, situated at the seaward edge of the coast or the landward side of the wave-cut platform, and marking the inner limit of beach erosion. It may vary from an inconspicuous slope to a high, steep escarpment. (Bates and Jackson, 1995)	(Haskins, et al. 1998) [Coastal Marine Landform] Shoreline Processes • **Cliff**
Intertidal reef	Tidal variation	A general term for an occurrence of rock, biogenic, or other stable material that lies at or near the sea surface and is elevated at least partially above the surrounding seabed (in the intertidal case: the area above water level at low tide and underwater at high tide). In-situ, positive relief, persistent build-ups of primarily skeleton-supported framework (+ internal binding), that influence the local sedimentary environment (Klement, 1967), and supports (or supported) living communities during active accretion. Definition modified from a range of sources: (Cumings, 1932; Goudie, 2006;	(Nanson, et al., 2022) Biogenic - Marine BGU: **reef** BGU-T:

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		Harris and Baker, 2020; Klement, 1967; Lo Iacono et al., 2018). Cf. REEF (Marine Setting)	
		A bioherm of sufficient size to develop associated facies. It is erected by, and composed mostly of the remains of, sedentary or colonial and sediment-binding organisms, generally marine: chiefly corals and algae, less commonly crinoids, bryozoans, sponges, mollusks, and other forms that live their mature lives near but below the surface of the water (although they may have some exposure at low tide; in fact, in the intertidal case: the area above water level at low tide and underwater at high tide). Their exoskeletal hard parts remain in place after death, and the deposit is firm enough to resist wave erosion. An organic reef may also contain still-living organisms. (Bates and Jackson, 1995)	(Haskins, et al. 1998) [Coastal Marine Landform] Shoreline Processes • **Organic reef**
Subtidal coast		A low gradient surface formed below mean low tide level. Typically located at the seaward of saltmarsh and mangrove communities.	(Nanson, et al., 2022) Coastal BGU: tidal flat BGU-T: **subtidal flat**
		(a) A strip of land of indefinite width (may be many kilometers) that extends from the low tide line inland to the first major change in landform features (remains submerged except during particularly low tides). (Bates and Jackson, 1995) An extensive, nearly horizontal, marshy or barren tract of land that remains submerged except during particularly low tides and consisting of unconsolidated sediment (mostly mud and sand). It may form the top surface of a deltaic deposit. (Bates and Jackson, 1995)	(Haskins, et al. 1998) [Landscape term] **Coast** [Coastal Marine Landform] Shoreline Processes • **Subtidal flat**
Coastal land-reclaimation area or polder		Land reclamation is the process of creating new land from the sea. The simplest method of land reclamation involves simply filling the area with large amounts of heavy rock and/or cement, then filling with clay and soil until the desired height is reached. Draining of submerged wetlands is often used to reclaim land for agricultural use. (Stauber et al., 2016)	
Polder or coastal land-reclaimation area		Originally meaning silted-up land or earthen wall, and generally used to designate a piece of land reclaimed from the sea or from inland water. It is used for a drained marsh, a reclaimed coastal zone, or a lake dried out by pumping. (Eisma, 2014)	

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Appendix 3: Biodiversity

Definition: Living components of the biosphere. We use this term irrespective of the scale of aggregation to which we refer (i.e., organism, population, community or ecosystem).

Table 8. *Identified biodiversity component.* We use EUNIS categories *(list 1)* to list biodiversity at t*he habitat level. It has been expanded to EUNIS level two in those habitats where further disaggregation is considered important to characterise their interaction in the provision of services.* https://eunis.eea.europa.eu/habitats-code-browser-revised.jsp?expand=23466,20955,23186,23539#level_23539

Type	Biodiversity - EUNIS Level 1	Level 2
Natural ecosystems	Marine benthic habitats	
	Pelagic water column	
	Ice-associated marine habitats	
	Coastal habitats	Coastal dunes and sandy shores
		Coastal shingle
		Rock cliffs, ledges and shores, including supralittoral
	Inland waters	
	Wetlands	
	Grasslands and lands dominated by forbs, mosses or lichens	
	Heathland, scrub and tundra	
	Forest and other wooded land	
	Inland habitats with no or little soil and mostly with sparse vegetation	
Novel ecosystems	Vegetated man-made habitats	Arable land and market gardens
		Cultivated areas of gardens and parks
		Artificial grasslands and her dominated habitats
		Hedgerows
		Shrub plantation
		Tree dominated man-made habitats

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Appendix 4: Ecosystem Services

Definition: direct and indirect benefits that people derive from the ecological functioning of ecosystems (De Groot et al., 2002). Depending on the type of the biophysical interactions that drive the ES, ES are more closely related to one of the following socio-ecological components:

A- Intensity of abiotic flows: abiotic provisioning and regulating ES where biodiversity acts by mediating (e.g., reducing or concentrating) an abiotic flow.

B- Biodiversity pattern: biotic provisioning and regulating ES (those originally considered as supporting ES; see in Reid et al., 2005) narrowly driven by physical, chemical, and biological transformations of matter and energy that involves a specific organism and their interactions with abiotic flows and other organisms.

F- Ecosystem functioning: regulating ES related to the sum of multiple ecological processes involving interactions between ecosystems or several of their components.

C- Cultural: ES that are, above all, context-dependent on the social and cultural perception and configuration of a society.

Table 9. List of ecosystem services. We have used the European Commission and CICES classifications to define ecosystem services. In the case of the CICES classification, the service group appears in italics, while in normal type at the class level. Numerical codes refer to the CICES class.

ES type	Ecosystem services (EC 2015)	Ecosystem services (CICES 5.1)	Biophysical type	Related ecosystem function	Main ecosystem implied in ES provision
Provisioning	Raw materials provision	*Cultivated terrestrial plants for nutrition, materials or energy* (1.1.1.1, 1.1.1.2, 1.1.1.3)	B	Biomass production (growth)	-Vegetated man-made habitats
		Cultivated aquatic plants for nutrition, materials or energy (1.1.2.1, 1.1.2.2, 1.1.2.3)			-Inland waters -Wetlands -Pelagic water column -Coastal habitats
		Reared animals for nutrition, materials or energy (1.1.3.1, 1.1.3.2, 1.1.3.3)			-Vegetated man-made habitats -Grasslands and lands dominated by forbs, mosses or lichens -Heathland, scrub and tundra
		Reared aquatic animals for nutrition, materials or energy (1.1.4.1, 1.1.4.2, 1.1.4.3)			-Inland waters -Wetlands -Marine benthic habitats -Pelagic water column

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					-Coastal habitats
		Wild plants (terrestrial and aquatic) for nutrition, materials or energy (1.1.5.1, 1.1.5.2, 1.1.5.3)			Natural ecosystems
		Wild animals (terrestrial and aquatic) for nutrition, materials or energy (1.1.6.1, 1.1.6.2, 1.1.6.3)			Natural ecosystems
		Mineral substances used for nutrition, materials or energy (4.3.1.1, 4.3.1.2, 4.3.1.3)	A	Interactions with material flows	-Inland waters
	Food provision	*Cultivated terrestrial plants for nutrition, materials or energy* (1.1.1.1, 1.1.1.2, 1.1.1.3)	B	Biomass production (growth)	-Vegetated man- nade habitats
		Cultivated aquatic plants for nutrition, materials or energy (1.1.2.1, 1.1.2.2, 1.1.2.3)			-Inland waters -Wetlands -Pelagic water :olumn -Coastal habitats
		Reared animals for nutrition, materials or energy (1.1.3.1, 1.1.3.2, 1.1.3.3)			-Vegetated man- nade habitats -Grasslands and ands dominated by 'orbs, mosses or ichens -Heathland, scrub ınd tundra
		Reared aquatic animals for nutrition, materials or energy (1.1.4.1, 1.1.4.2, 1.1.4.3) -			-Inland waters -Wetlands -Marine benthic ıabitats -Pelagic water :olumn
		Wild plants (terrestrial and aquatic) for nutrition, materials or energy (1.1.5.1, 1.1.5.2, 1.1.5.3)			Natural ecosystems
		Wild animals (terrestrial and aquatic) for nutrition, materials or energy (1.1.6.1, 1.1.6.2, 1.1.6.3)			Natural ecosystems

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	Energy provision	*Cultivated terrestrial plants for nutrition, materials or energy* (1.1.1.1, 1.1.1.2, 1.1.1.3)	B	Biomass production (growth)	-Vegetated man-made habitats
		Cultivated aquatic plants for nutrition, materials or energy (1.1.2.1, 1.1.2.2, 1.1.2.3)			-Inland waters -Wetlands -Pelagic water column -Coastal habitats
		Reared animals for nutrition, materials or energy (1.1.3.1, 1.1.3.2, 1.1.3.3)			-Vegetated man-made habitats -Grasslands and lands dominated by forbs, mosses or lichens -Heathland, scrub and tundra
		Reared aquatic animals for nutrition, materials or energy (1.1.4.1, 1.1.4.2, 1.1.4.3)			-Inland waters -Wetlands -Marine benthic habitats -Pelagic water column
		Wild plants (terrestrial and aquatic) for nutrition, materials or energy (1.1.5.1, 1.1.5.2, 1.1.5.3)			Natural ecosystems
		Wild animals (terrestrial and aquatic) for nutrition, materials or energy (1.1.6.1, 1.1.6.2, 1.1.6.3)			Natural ecosystems
		Mineral substances used for nutrition, materials or energy (4.3.1.1, 4.3.1.2, 4.3.1.3)	A	Interactions with water-energy flows	-Inland waters -Wetlands -Pelagic water column -Coastal habitats
		Non-mineral substance or ecosystem properties used for nutrition, materials or energy (4.3.2.1, 4.3.2.2, 4.3.2.3, 4.3.2.4, 4.3.2.5)			
	Water provision	*Surface water used for nutrition, materials or energy* (4.2.1.1, 4.2.1.2, 4.2.1.3, 4.2.1.4)	A	Interactions with water flows	-Inland waters -Forest and other wooded land

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		Ground water for used for nutrition, materials or energy (4.2.2.1, 4.2.2.2, 4.2.2.3)			Pelagic water column
	Biodiversity provision and genetic diversity maintenance	Genetic material from all biota, including seed, spore or gamete production (1.2.1.1, 1.2.1.2, 1.2.1.3, 1.2.2.1, 1.2.2.2, 1.2.2.3)	B	Biotic interactions and flows	Natural and novel ecosystems
Regulating	Climate regulation	*Regulation of chemical composition of atmosphere and oceans (2.2.6.1)*	F	Interactions in the carbon cycle	-Inland waters -Wetlands -Marine benthic habitats -Pelagic water column -Forest and other wooded land -Tree dominated man-made habitats
		Regulation of temperature and humidity, including vegetation and transpiration (2.2.6.2)	A	Regulating solar energy flow and water flow	
	Air quality regulation	*Bio-remediation by micro-organisms, algae, plants, and animals (2.1.1.1)*	B	Transformation of an organic or inorganic substance by organisms	Natural and novel ecosystems
		Filtration/ sequestration/ storage/ accumulation by micro-organisms, algae, plants, and animal (2.1.1.2)	A	The fixing and storage of an organic or inorganic substance by organisms	
		Smell reduction (2.1.2.1)		Retention and dissipation of odorous particles	
		Noise attenuation (2.1.2.2)		Sound wave interception	
	Erosion control	*Control of erosion rates (2.2.1.1)*	A	Soil protection, particle retention and slowing of transport through the interaction of vegetation	-Forest and other wooded land
		Buffering and attenuation of mass movement (2.1.2.2)			
	Water flow regulation	*Hydrological cycle and water flow regulation, Including flood control, and*	A	Regulation of water flows by the vegetation dynamics	-Forest and other wooded land

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		coastal protection (2.2.1.3)			
	Water quality regulation	*Regulation of the chemical condition of freshwaters by living processes (2.2.5.1)*	F	Maintenance of the chemical condition of waters by the activity and interaction of ecosystem components via food webs	-Forest and other vooded land Inland waters
		Regulation of the chemical condition of salt waters by living processes (2.2.5.2)			-Wetlands -Marine benthic ıabitats Pelagic water :olumn
	Biological control	*Pest control, including invasive species (2.2.3.1)*	B	Biological interactions	Natural ecosystem
		Disease control (2.2.3.2)			
	Natural hazard regulation	*Wind protection (2.2.1.4)*	A	Regulation of abiotic and biotic flows that may trigger an environmental hazard	Hazard-dependent
		Fire protection (2.2.1.5)			
		All the ES previously considered in the regulating category			
	Soil formation	*Weathering processes and their effect on soil quality* (2.2.4.1)	B - F	Interaction via biological decomposition	-Forest and other vooded land -Grasslands and ands dominated by orbs, mosses or ichens -Heathland, scrub ınd tundra
		Decomposition and fixing processes and their effect on soil quality (2.2.4.2)			
	Biogeochemical cycles	Mainly, all the ES previously considered in the regulating category	A – B – F	Ecosystem functioning	Natural and novel ecosystems
	Pollination	*Pollination, or 'gamete' dispersal in a marine context* (2.2.2.1)	B	Biological interactions	Natural ecosystems
		Seed dispersal (2.2.2.2)			
	Habitat creation	*Maintaining nursery populations and habitats, Including gene pool protection* (2.2.2.3)	B	Biological facilitation	Natural ecosystems
		Visual screening (2.2.2.3)	B	Physical barrier	-Tree dominated nand-made habitats -Forest and other wooded land
Cultural		*Characteristics of living systems that*	C		Natural and novel ecosystems

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	Educational value	*enable scientific investigation or the creation of traditional ecological knowledge* (3.1.2.1)		*Multiple. It is not relevant to specify*	• Urban
		Characteristics of living systems that enable education and training (3.1.2.2)			
	Aesthetic value	*Characteristics of living systems that enable aesthetic experiences* (3.1.2.4)			
	Social relations	*Elements of living systems that have symbolic meaning* (3.2.1.1)			
		Elements of living systems that have sacred or religious meaning (3.2.1.2)			
	Recreation / Tourism	*Elements of living systems used for entertainment or representation* (3.2.1.3)			
	Cultural heritage	*Characteristics of living systems that are resonant in terms of culture or heritage* (3.1.2.3)			
	Therapeutic benefits	Physical and experiential interactions with natural environment (3.1.1.1; 3.1.1.2)			
	Sense of place	*Characteristics or features of living systems that have an existence value* (3.2.2.1)			
		Characteristics or features of living systems that have an option or bequest value (3.2.2.2)			
	Social equity and environmental justice				

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Appendix 5: Nature-based Solutions

Table 10. Categories of nature-based solutions. The categories come from the catalogue initially developed by IHCantabria within the i-SANA project. Currently, the catalogue is being developed within the NBRACER project, so it is expected to produce a higher level of definition in the coming months.

Nature based Solutions- types	Subtypes
Protection/conservation measures	General protection measures
	Ecosystem-specific conservation
Restoration measures	General restoration measures
	Active restoration
	Passive restoration (rewilding)
Management measures	General management measures
	Good forestry practices
	Good agricultural practices
	Good livestock practices
	Changes in the habitat that favour the re-introduction of keystone species
	Water management (of natural ecosystems)
	Sustainable Urban Drainage Systems (SuDs)
Combination of interventions	Natural Water Retention Measures (NWRM)
	Soil and Water Bioengineering (SWB)
Creation and management of new ecosystems	Establishment of new ecosystems and their management
	Urban NbS
	Sustainable novel ecosystems
Urban NbS	Urban forests
	Terraces and slopes
	River and stream renaturation
	Building solutions
	Open green spaces
	Green corridors
	Urban farming/Community gardens
	Bioretention areas
	Natural inland wetlands

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	Constructed inland wetlands
	River floodplains
	Salt marshes (coastal urban areas only)
	Sandy shores (coastal urban areas only)

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Appendix 6: Key Community Systems

Definition: A system that meets important basic societal needs but that is increasingly impacted by climate change. A key community system is an area of innovation and transformation for the Mission, part of a larger interdependent system (European Mission, 2021).

Table 11. Identification of key community systems. The categories have been defined based on Aalmo et al. (2022), and subcategories have been added that are considered as interesting in the context of NBRACER.

Key community systems		Examples
Critical infrastructure	Critical infrastructure in an urban context	Educational establishments, schools, libraries or cultural and sports centres
	Critical infrastructure downstream at the catchment scale	
	Transportation-related structures	Airports, ports, railroads, subway lines, paved and unpaved roads or paths
	Energy transport	Power lines, oil pipelines, water transportation for energy production or gas pipelines
	Telecommunication infrastructure	Antennas, cabling or satellite receivers
	Power structures	Hydroelectrical dams, photovoltaic power station, wind farms or power plants
	Production / Secondary sector	Production and manufacturing sector, chemical sector or any type of factories
	Service sector	Food service, government facilities, educational centres, dump sites, emergency services, retail or professional services
	Human facilities	Housing, shelter, huts and other non-private facilities
Health & Well-being	Health centres	
	Hospitals	
	Clinics	
	Pharmacies	
	Recreational centres	
	Hotel industry	
	Structures related to religious beliefs	
Water management	Water collection	Surface water, groundwater, seawater intakes
	Water distribution	Distribution networks, piping (drinking water, grey water, black water, stormwater, agricultural water reuse), pumping facilities, storage tanks
	Water treatment and storage systems	Desalinization plants, drinking water and wastewater treatment plants, environmental buffers (lakes, rivers,

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		reservoirs, groundwater aquifer), nature-based treatment solutions
Primary production	Agriculture	Agricultural land, halls and other infrastructures related to agricultural, marine or inland waterway operations.
	Aquaculture	
	Fisheries	
	Non-timber forest production	
	Livestock	
	Forestry focused on timber production	
	Mineral extraction sites	

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Appendix 7: Integrating Climate Risk Impact Chains (CRICs) into NbS Planning

To further enhance the framework's effectiveness, it incorporates CRICs as a core analytical tool. CRICs provide a structured approach to analysing how risks propagate across the biophysical, social, and governance domains, helping to map interdependencies and understand how vulnerabilities can cascade through these interconnected systems.

By visualizing cause-effect relationships, CRICs enable stakeholders to gain a deeper understanding of systemic interactions and identify critical leverage points where interventions can effectively reduce risks. This insight is essential for informed decision-making, ensuring that resilience strategies address not only immediate threats but also their broader, long-term implications. A crucial component of establishing a baseline for NbS implementation is the integration of CRICs into the planning process. By assessing place-based vulnerabilities and mapping how climate risks evolve and interact, CRICs help ensure that NbS interventions are strategically placed to maximize resilience benefits and minimize systemic risks. The approach supports the design of interventions that are both context-specific and scalable, aligning with broader resilience objectives.

Understanding CRIC

- **Climate Hazards** – External stressors that threaten socio-ecological systems. Examples: Floods, droughts, storms, heatwaves, coastal erosion
- **Exposed Elements** – What is at risk?
  Includes ecosystems, infrastructure, and KCS (e.g., populations, businesses, healthcare, transportation networks)
- **Intermediate Impact Identification – Mapping Cascading Risks:** Climate hazards do not act in isolation but trigger secondary and tertiary impacts that worsen systemic risks.
- **Vulnerabilities** – Why are these elements at risk?
  Factors such as land degradation, socio-economic inequalities, and weak governance increase the likelihood of severe climate impacts
- **Risk** – Incorporating Place-Based Risk Assessments: Place-based risk assessments evaluate how risks vary spatially and contextually, ensuring risk analysis is location-specific rather than generalized.

This approach uses geospatial mapping, climate models, socio-economic data, and hazard exposure analysis to determine:

- ➢ Which areas are most vulnerable? (e.g., flood-prone urban centers, deforested catchments)
- ➢ Which populations are at the highest risk? (e.g., elderly communities near flood zones)
- ➢ Where NbS should be prioritized? (e.g., wetland restoration in high-risk watersheds)

Example: Heavy rainfall (hazard) → River overflow (direct impact) → Road network disruption (intermediate impact) → Economic losses & restricted emergency response (cascading impact).
Identifying intermediate impacts ensures NbS target critical failure points, such as riparian buffers to reduce runoff and prevent flooding.

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