The economics of nature-based solutions.

Deliverable 2.1: Value categories and approaches to assess NBS economic and financial performance

WP2 (Task 2.1 and Task 2.2)

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[1] *PU = Public*

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

ACRONYM	DESCRIPTION
CCA	Climate change adaptation
DRR	Disaster risk reduction
ESVD	Ecosystem Services Valuation Database
NBS	Nature-Based Solutions
NCA	Natural Capital Accounting
R&I	Research and Innovation
TEV	Total Economic Value

EXECUTIVE SUMMARY

The potential of Nature-Based Solutions (NBS) in addressing diverse societal challenges, including climate change adaptation (CCA) and disaster risk reduction (DRR), is widely recognized in both scientific and policy domains. However, a significant gap exists in our understanding of the economic implications of NBS, which is crucial for informed resource allocation and financing decisions by policymakers and practitioners. This report aims to bridge a part of this knowledge gap by providing a comprehensive exploration of NBS typologies across six distinct landscape types and thematic areas, along with an inventory of valuation methods. It delves into the costs and benefit categories associated with NBS, and examines various methodological approaches for capturing the diverse values attributed to NBS benefits.

This report organizes NBS, societal challenges, benefits, and costs into generic and specific categories. NBS actions are categorized into three types based on the level of ecosystem intervention and stakeholder involvement: i) protection/conservation of high-quality or critical ecosystems and/or sustainable management of healthy ecosystems, ii) modification of existing ecosystems e.g., restoration/rehabilitation of degraded ecosystems, and iii) creation/establishment of new ecosystems. These types are further classified into six landscapes or thematic areas: coastal areas, mountain areas, agriculture, forests, water management, and urban areas. NBS actions within each landscape are therefore grouped into three generic categories, with further disaggregation into specific NBS interventions. Six generic societal challenges are identified: climate adaptation, climate mitigation, natural hazards, environmental management, noise pollution, and socio-economic challenges, each with specific sub-challenges. Furthermore, ecological processes that underpin the delivery of multiple benefits are identified for each specific challenge.

To address these challenges effectively, it is essential to focus on multiple benefits, including those for biodiversity and society. Benefits are organized into generic and specific categories, with overarching categories aggregating a range of specific benefit categories that result from addressing each distinct societal challenge. Meanwhile, cost categories for NBS are also organized into generic and specific categories, mirroring traditional project budget groups but with the inclusion of trade-offs, indirect costs, disservices, and opportunity costs related to competing land uses.

Additionally, the report provides an extensive inventory of valuation methods for assessing the economic, environmental, and social costs and benefits of NBS, encompassing quantitative and qualitative approaches. It emphasizes the importance of considering various factors when selecting an economic valuation method, including scope, objectives, ecosystem services to be assessed, data quality, and context. The report recommends a combination of methods and integrated approaches for a holistic NBS assessment, including qualitative methods alongside quantitative ones. Furthermore, the report explores risk assessment approaches, decision support strategies, and the integration of NBS with natural capital accounting and climate data statistics to effectively address climate change challenges. Building on these insights, Invest4Nature aims to extend the total economic value (TEV) framework, incorporating uncertainties related to climate risks and impacts on disaster risk reduction, to develop an integrated assessment of NBS.

While primarily serving as a guiding framework within Invest4Nature, this deliverable also offers valuable insights to a broader audience, including practitioners seeking a deeper understanding of NBS and their economic implications. This report equips researchers and practitioners with an inventory for navigating the complex landscape of NBS, emphasizing a

multifaceted, context-aware approach to evaluate and harness their full potential in addressing pressing societal challenges.

1. INTRODUCTION

In recent years, regions across the globe, including Europe, have grappled with an ever-increasing occurrences and intensity of various societal challenges. Among these, perhaps the most pervasive and critical is the profound influence of climate change. The repercussions of climate change have become increasingly evident, with extreme weather events, including heavy rains, storms, and heatwaves, occurring more frequently and with greater intensity. Two disparate yet interconnected instances in the summer of 2023 vividly exemplify the far-reaching impact of climate change, taking place in Slovenia and southern Europe such as Portugal, Greece, Turvey, Croatia, Italy, Spain and Cyprus.

Slovenia bore the brunt of unprecedented floods during this summer. These floods caused havoc, impacting 181 out of the total 212 municipalities. Around 8,000 individuals had to be evacuated to the homes of relatives or other accommodation facilities, and tragically, six lives were lost as a consequence of the disaster. Over 170 landslides remained active, posing an ongoing threat to homes, infrastructure, and the electricity supply. According to initial estimates from the Slovenian Ministry of Defence, more than 400 buildings, including some with multiple housing units, were either destroyed or declared uninhabitable. The aftermath of this catastrophe, encompassing the loss of assets, homes, businesses, livestock, crops, and infrastructure, is projected to have a profound and enduring impact on job security and livelihoods (Copernicus EMS, 2023; IFRC, 2023).

Concurrently, southern Europe including Portugal grappled with devastating wildfires that engulfed vast areas, also during the summer. Over half of Portugal found itself on maximum wildfire alert, necessitating the evacuation of 1,400 individuals and causing extensive damage. These wildfires took a severe toll on 19 villages, leaving 16,600 acres of land charred, emphasizing the widespread impact of these destructive blazes. The partial closure of the A1 highway between Lisbon and Porto disrupted critical transportation networks, adding to the complexity of the situation. Tragically, at least nine firefighters were injured while bravely combatting the fires, vividly illustrating the immense dangers they confronted (BBC, 2023; Deutsche Welle, 2023; Reid, 2023).

In the face of these formidable challenges, there is a growing recognition of the transformative potential inherent in Nature-Based Solutions (NBS). These solutions, as defined by the European Commission, are inspired by and rooted in nature. They are cost-effective, offering simultaneous environmental, social, and economic benefits while strengthening resilience. NBS bring more nature and natural processes into cities, landscapes, and seascapes through locally adapted, resource-efficient, and systemic interventions. NBS must therefore benefit biodiversity and support the delivery of a range of ecosystem services. NBS represent innovative approaches that harness nature's inherent power to provide sustainable solutions to our most pressing problems. They manifest in various forms; for example, green infrastructure, such as urban parks and green roofs, not only mitigates heat, reduces pollution and aids in water management but also enhances overall community quality of life. The restoration and preservation of wetlands extend beyond flood mitigation, playing a crucial role in climate change mitigation by sequestering carbon dioxide and other greenhouse gases. Moreover, wetlands provide habitat for diverse species, store and delay run-off and improve water purification processes. Similarly, reforestation efforts combat the escalating threat of wildfires while concurrently sequestering carbon, protecting drinking water resources and safeguarding essential ecosystems.

What sets NBS apart is their multifaceted impact. They not only bolster resilience against climate impacts, natural disasters and enhance environmental quality but they also generate a host of benefits, from enriching biodiversity to enhancing air and water quality and nurturing community well-being. As societies worldwide confront the mounting challenges posed by climate change, biodiversity loss, and pollution, NBS emerge as a holistic and sustainable approach. They offer not only solutions but also a path forward toward harmonious coexistence with nature. It is increasingly evident that embracing and investing in NBS is a vital step toward securing a resilient and sustainable future for our planet and for generations yet to come.

The European Commission (EC) has been actively involved in promoting NBS since 2013 through consultations, expert groups and dialogues to define NBS and its place in ecosystem-based approaches (Faivre et al., 2017). These efforts led to the development of an R&I agenda for NBS, including calls for large-scale demonstration projects. Over the last decade, the European Union (EU) has significantly advanced NBS in its policies and strategies and has positioned itself as a global leader in promoting and implementing NBS (Davies et al., 2021; Faivre et al., 2017). The EU has integrated the 'working with nature' and “innovating with nature” approach into several sectoral policies, including flood protection, climate change adaptation, biodiversity, water retention and disaster risk management. These approaches align with the European Green Deal (EC 2019), a set of policy initiatives to steer the EU towards a green transition, with the aim of reducing net greenhouse gas emissions by 55% compared to 1990 by 2030 and becoming climate neutral by 2050. Implementing NBS across all landscapes is seen as key to enhance biodiversity and to make Europe more resilient to climate change. According to EEA (2021), the EU Biodiversity Strategy 2030, the EU Adaptation Strategy, the EU Green infrastructure strategy, the EU action plan on the Sendai Framework for disaster risk reduction and the Floods Directive provide strong support for NBS and explicitly mention NBS in connection with CCA and/or DRR in the policy text. The EU actively engages in policy dialogues and outreach initiatives at both European and global levels to promote NBS and enhance their widespread adoption.

At the global level, there was significant international recognition and incorporation of nature-based solutions into key intergovernmental agreements in 2022 (EC, 2023). The United Nations 5th Environment Assembly in 2022 formally adopted a definition of NBS (UNEA, 2022) and the UNFCCC COP27 recognized the potential of NBS to address climate change and biodiversity loss (UNFCCC, 2022). Moreover, NBS were integrated into the Kunming-Montreal Global Biodiversity Framework, emphasizing the importance of NBS in achieving a world living in harmony with nature by 2050 (Biodiversity Convention, 2023). Both the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2023) and the Intergovernmental Panel on Climate Change (IPCC, 2023) acknowledge the importance of nature-based solutions in addressing biodiversity and climate crisis.

Recent EU publications highlight the potential benefits and challenges associated with NBS. Notable reports include the European Environment Agency's (2021) examination of “Nature-based solutions in Europe: Policy, knowledge, and practice for climate change adaptation and disaster risk reduction”, the European Commission's (EC 2022) report on “The Vital role of Nature-Based Solutions in a Nature Positive Economy”, and the European Investment Bank's

(2023) investigation into "Investing in nature-based solutions". Despite these valuable insights, a significant knowledge gap persists in our understanding of the economic dimensions of NBS. To make well-informed decisions regarding NBS investment and financing, policymakers and practitioners require a comprehensive grasp of the economic implications of NBS, encompassing both costs and benefits, as well as the methods used for their evaluation.

The primary objective of this deliverable is to bridge a part of the knowledge gap. It provides an overview of the typology of NBS across six landscape types/thematic areas, delves into the costs and benefits of NBS, and explores methodological approaches to capture the diverse values associated with NBS benefits. While this deliverable serves as a framework for future tasks within Invest4Nature, it also offers valuable insights for a broader audience, including practitioners, seeking a deeper understanding of nature-based solutions and their economic implications.

CONTRIBUTIONS OF PARTNERS

The following depicts the main contributions from project partners in the development of this deliverable.

Table 1: Contributions of Partners

PARTNER SHORT NAME	CONTRIBUTIONS
AU	Writing of Sections 1, 2, 3, 4, 5, 7; Read and edit entire report
JR	Writing of Sections 1, 2, 6, 7; Read and edit entire report
CMCC	Writing of Section 4
Living Lab Partners (NIVA, AAKS, UMP, KBT, EMAC)	Discussion and validation of NBS typology and categories of costs and benefits
NIVA	Contributing to mapping and assessing the qualitative and quantitative approaches for valuing and evaluating NBS (Section 6); classification of cost categories (Section 5), Review and edit the entire report

2. OVERALL APPROACH

This deliverable covers outputs from Tasks 2.1 and 2.2. Task 2.1 is carried out by AU with inputs from technical partners (CMCC, JR) and the Living Lab partners. The Living Lab partners provide key inputs into the description of the different NBS interventions covered by each of the Living Labs. The LL partners also play important roles in the process of validating the cost and benefit categories. Task 2.2 is undertaken by JR with inputs from technical partners namely AU and NIVA.

The deliverable encompasses a diverse range of facets, necessitating the use of multiple approaches. These approaches encompass desktop reviews, iterative discussions, and exchanges with both technical/scientific partners and partners from the living labs within Invest4Nature. Additionally, we conducted purposive and semi-systematic reviews of pertinent literature and EU publications. Here we describe the approaches used for each of the different components.

To define the NBS typologies, we adapted the typology proposed by Eggermont et al. (2015). To this end, we classify NBS actions into three generic groups: i) protection/conservation of a high-quality or critical ecosystem and/or sustainable management of healthy ecosystem, ii) modification of existing ecosystems e.g., restoration/rehabilitation of a degraded ecosystem, and iii) introduction/establishment of a new ecosystem. We then compile the three general types of NBS in the following six landscapes/thematic areas in accordance with the report by the European Environment Agency (2021): water management, forests (and forestry), agriculture (and agroforestry), urban areas, coastal areas, and mountains. The draft was then presented during various occasions to the project partners (e.g., monthly WPL+ meetings, Aarhus workshops, bilateral meetings with Living Lab partners) and further refined.

To characterize the cost categories of NBS, we draw some inspirations from a number of reports (e.g., Emerton, 2017; Neumann & Hack, 2022; Panduro et al., 2021), and database from a completed H2020 project – Climate Resilient Infrastructures and Cities[2]. The cost categories include establishment, maintenance, monitoring, financing, opportunity cost, indirect costs. The cost categories were initially discussed within AU team. Then two rounds of validation were carried out. First validation process was done through online bilateral meetings with some Living Labs. Second validation process took place during the workshop in Aarhus in June 15th to 16th 2023 where representatives from all I4N Living Labs were present.

To characterise the multiple benefits of NBS, we draw inspirations from a report by the Expert Working Group on Nature-Based Solutions from the EKLIPSE (Establishing a European Knowledge and Learning Mechanism to improve the Policy-Science-Science Interface on Biodiversity and Ecosystem Services) project (Raymond et al., 2017) and the European Environment Agency (2021). Similar to the cost categories, the list of NBS multiple benefits was initially discussed within AU team. Two rounds of validation were then carried out. First validation process was done through online bilateral meetings with some Living Labs. Second validation process took place during the workshop in Aarhus where representatives from all I4N Living Labs were present.

To elucidate societal challenges, our approach was anchored in the EKLIPSE report (Raymond et al., 2017), which served as a valuable source of inspiration for identifying the broad range of societal challenges commonly addressed by NBS initiatives. These encompass climate change mitigation, climate change adaptation, natural hazard mitigation, environmental management, and the enhancement of socio-economic well-being. Our approach also involved consulting various relevant EU publications and reports, complemented by iterative internal discussions among the partners participating in Task 2.1. Subsequently, a preliminary draft was presented for review and feedback to the consortium during one of the WPL+ meetings, and additional input was gathered from our LL partners through dedicated bilateral meetings.

To describe the ecological processes that underpin NBS interventions to address the different societal challenges, encompassing four broad groups: climate change mitigation, climate

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[2] http://www.resin-cities.eu/home/

change adaptation, natural hazards and environmental management. Within each group, we addressed multiple specific challenges and described not only the key underlying ecological processes but also the benefits. We derived insights from targeted, purposive review of selected scientific and grey literature.

To compile an inventory of quantitative and qualitative assessment approaches to assess the value of NBS, we conducted an extensive literature review that involved a thorough examination of both peer-reviewed academic literature and grey literature sources. This encompassed a detailed review of reports, including key sources such as EEA (2021), Raymond et al. (2017), Dumitru & Wendling (2021) and van Zanten et al. (2023), among others, as well as the exploration of completed and ongoing EU HORIZON projects such as NAIAD[3], REGREEN[4], Naturance[5], Naturvation[6], and Nature4Cities[7]. Starting with a comprehensive case study analysis, we identified the economic evaluation methods employed in actual NBS projects, followed by an evaluation of these methods, including their strengths and weaknesses. Further, our analysis extended to the examination of the state-of-the-art in the development of advanced NBS assessment methods.

3. NBS CONCEPT, TYPOLOGY AND INTERVENTIONS

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[3] https://naiad2020.eu/
[4] https://www.regreen-project.eu/
[5] https://www.naturanceproject.eu/
[6] https://naturvation.eu/
[7] https://www.nature4cities.eu/

Network Nature

Source: Network Nature

To elucidate NBS concept, we begin by presenting various definitions of NBS sourced from the literature. Since the inception of nature-based solutions to address sustainability challenges, an ongoing debate has persisted. This debate arises, in part, due to the ambiguity surrounding the scope and categorization of interventions that qualify as NBS.

Section 3.1 synthesizes existing definitions and provides clarification of the NBS terminology. Section 3.2 presents a framework delineating NBS typologies. Here NBS actions are categorized into three distinct types, which are further applied to six thematic areas, as detailed in Section 3.3. These areas have been identified as pertinent for NBS within the European context.

The development of NBS concepts, typologies, and interventions builds on the result of scientific as well as grey literature, complemented by internal discussions and consultations with Invest4Nature partners and Living Labs. These interactions occurred through online meetings, email exchanges, and on-site meetings. The insights derived from these discussions and consultations were promptly uploaded and shared within a unified working platform (Nextcloud) for further validation by our partners and LLs. This process was replicated for identifying the societal challenges and subsequently describe the associated ecological processes, as presented in Section 4.

3.1. THE CONCEPT OF NATURE-BASED SOLUTIONS

The concept of NBS emerged in 2008 as a response to the quest for innovative approaches in managing natural systems, with the goal of harmonizing the benefits bestowed by nature with the well-being of society (World Bank, 2008). In 2015, the European Commission first officially defined NBS as "*actions inspired by, supported by or copied from nature, aimed to help societies address a variety of environmental, social and economic challenges in sustainable ways*". The European Commission elaborates further on the concept stating, *"Some (NBS) involve using and enhancing existing natural solutions to challenges, while others are exploring more novel solutions, for example mimicking how non-human organisms and communities cope with environmental extremes"* (EC, 2015).

In 2012, the International Union for Nature Conservation (IUCN) defined NBS as *"actions to protect, sustainably manage and restored natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits''* (IUCN, 2012) Furthermore, in 2020 the IUCN developed a Global Standard as a framework for the verification, design and scaling-up of NBS. More recently in 2022, the United Nations Environment Assembly defined Nature-Based Solutions 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, ecosystem services and resilience and biodiversity benefits"* (UNEA, 2022).

There is a growing demand to implement NBS triggered by concerns on global warming, biodiversity loss and human health. As a result, a more concise definition is necessary to determine which green and blue interventions should be regarded as NBS (Sowińska-Świerkosz & García, 2021). Moreover, the concept needs further clarification in relation to the scope of the intervention. A systematic review of 200 papers was conducted by Sowińska-Świerkosz and García (2022) identifying core features of NBS and formulating exclusion criteria to distinguish NBS actions from other green, blue or hybrid interventions. NBS actions can be identified as *those inspired and powered by nature, which address societal challenges, provide multiple benefits (including biodiversity), and are of high effectiveness and economic efficiency*. The same study by Sowińska-Świerkosz and García formulates a preliminary criteria to exclude green/blue infrastructure from the set of NBS: (1) an action “inspired by nature” is necessary but not sufficient to constitute a NBS; (2) green and hybrid actions must be deliberate and not random; (3) NBS should target problems detected *a priori*; (4) NBS must enhance biodiversity; (5) a NBS action cannot solely provide the same benefits as grey infrastructure alone; (6) NBS should provide simultaneous benefits to the environment and human well-being, or analogously, NBS should limit trade-offs and at the same time ensure the fair distribution of benefits and costs between the environment and society; (7) NBS should not be framed as a solution that is based on a previous successful solution, without having first adapted it to local conditions; (8) NBS should address issues identified through a transparent process actively involving all affected stakeholders, i.e., NBS are not solutions that lack social acceptance (hence, risk failing implementation), even if their conservation objectives are fully realized; (9) NBS should follow iterative learning and an adaptive management approach flexible to apply changes to unintended, unforeseen and/or undesirable factors; (10) NBS ought to be cost-effective, thus financial expenses cannot be disproportionate to benefits (e.g., this avoids economic failure); and (11) NBS should not be managed in isolation, but ought to account for the interactions (for instance, among inhabitants and ecosystems) that occur at a landscape level.

3.2. NBS TYPOLOGIES

We classify NBS actions into three groups of **generic NBS actions** associated with different types of ecosystem interventions: i) protection/conservation of high-quality or critical ecosystems and/or sustainable management of healthy ecosystems, ii) modification of existing ecosystems e.g., restoration/rehabilitation of degraded ecosystems, and iii) creation/establishment of new ecosystems. This categorization is inspired by the typology proposed by Eggermont et al. (2015), which defines three types of NBS:

- **Type 1** consists of no or minimal intervention in ecosystems, with the objectives of maintaining or improving the delivery of ecosystem services both inside and outside of these preserved ecosystems.

- **Type 2** corresponds to the definition and implementation of management approaches that develop sustainable and multi-functional ecosystems and landscapes (extensively or intensively managed), which improves the delivery of ecosystem services in relation to a more conventional intervention.

- **Type 3** consists of managing ecosystems in very intrusive ways or even creating new ecosystems.

3.3. NBS INTERVENTIONS BY SECTORS, LANDSCAPES AND THEMATIC AREAS

We compile the three groups of generic NBS actions across the **landscapes/thematic areas** selected in the report of the European Environment Agency *“nature-based solutions in Europe: Policy, knowledge and practice for climate change adaptation and disaster risk reduction”* (EEA, 2021). The EEA report analyses the multiple benefits, potential trade-offs and limitations of NBS for six relevant sectors, landscapes and thematic areas in Europe. Moreover, it builds on the increasing integration of NBS in the global and EU policy frameworks that are relevant for resilience to climate change, biodiversity conservation and restoration. The selection of these sectors and thematic areas is based on a review of projects on Nature-Based Solutions for climate change adaptation and disaster risk reduction across Europe by McVittie et al. (2018). These are:

1. Coastal areas
2. Mountain areas
3. Agriculture
4. Forest and forestry
5. Water management
6. Urban areas

The above mentioned three levels of **generic NBS actions** are identified for each thematic area. Each generic level corresponds to one of the NBS types defined in 3.2. Then each generic NBS action can be further divided into multiple **specific NBS actions** which produce multiple benefits simultaneously, including environmental, socio-cultural and economic benefits.

3.3.1. COASTAL AREAS

Coastal areas

Source: Network Nature

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Coastal areas are vulnerable to several coastal hazards such as extreme storm surges, sea level rise, droughts, heat waves, landslides and ocean acidification. This can cause land loss, coastal erosion, flooding and saltwater intrusion (EEA, 2017). NBS can help reduce the vulnerability towards such climate events as well as to reduce the negative impacts. For example, the formation of vegetation, barrier islands, dunes and beaches reduce impact of coastal erosion, serving as natural barriers to waves and capable of recovering rapidly after a storm (Bridges et al., 2015).

Generic NBS actions identified for coastal areas comprise: (i) protection/conservation of intact coastal ecosystems, (ii) modification of coastal ecosystems, and (iii) creation of a new coastal ecosystem.

Protection/conservation of coastal ecosystems encompasses for example the protection of barrier islands, sea grasses, seafloor vegetation, salt marshes, coastal vegetation, various marine species and distinct coastal landscapes. These types of coastal ecosystem can reduce the impact of coastal hazards and coastal erosion (Morris et al., 2018). Vegetation and natural barriers retain sediments and support erosion control (Gracia et al., 2018). Coral and oyster reefs provide protection by dissipating wave energy (Ferrario et al., 2014), improving biodiversity, enhancing carbon sequestration, and maintaining (fish) habitats essential to secure fish biomass and hence food supply. Unfortunately, most of coastal ecosystems have been heavily degraded.

Modification of coastal ecosystems comprises three different specific actions: i) managed realignment of coastal areas, ii) restoration of coastal habitats, and iii) near-shore enhancement of coastal morphology. Managed realignment of coastal areas relates primarily to removing or moving further inland flood defences or built coastal structures. This is to open room for the coastal ecosystems that act as natural coastal protection (e.g., salt meadows) leading to increased nutrient retention, improved water regulation, reduced coastal erosion, enhanced carbon sequestration and an increased potential for eco-tourism and recreation (MacDonald et al., 2020).

Restoration of coastal habitats includes for example the restoration of seagrasses, wetlands, saltmarshes, dunes, and reef species. The restored ecosystems contribute to reduced wind speed, wave attenuation during severe storms, enhanced carbon storage and sequestration (Renaud et al., 2013), nursery habitats, water filtration, species abundance and biodiversity (Chen et al., 2022; Hynes et al., 2021).

Near shore enhancement of coastal morphology involves beach nourishment, dune reconstruction, cliff stabilisation, and the restoration of natural barriers. This entails benefits such as sediment stabilisation in shallow coastal areas, reduced risk of storm surge events, and limiting habitat and nutrient losses. Both restoration of coastal habitats and near shore enhancement involve natural defence barriers for the mitigation of shoreline retreat, shoreline erosion and shoreline flooding (Bridges et al., 2015; Charbonnel et al., 2011; Taal et al., 2016).

Creation of new coastal ecosystems refers to engineered hybrid solutions, that is, natural solutions combined with built structures as green dykes, wooded fences, and vegetated levees. New coastal ecosystems can provide benefits that range from increasing biodiversity to enhancing resilience against climate hazards such as storm surges, coastal erosion and landslides. Table 2 lays out the generic and specific NBS actions for coastal areas.

Table 2: Generic and specific NBS actions for coastal areas

GENERIC ACTION	NBS TYPE	SPECIFIC ACTION
Protection/conservation of coastal ecosystems	1	Protection of barrier islands, sea grasses (seafloor vegetation), salt marshes, coral & oyster reefs, and coastal vegetation
Modification of coastal ecosystems	2	Managed realignment of coastal areas
		Restoration of coastal habitats in transitional waters, e.g., dunes, seagrasses, wetlands, saltmarshes, oyster & reef species
		Near-shore enhancement of coastal morphology, e.g., restoration of barrier islands, beach nourishment, dune reconstruction, cliff stabilisation
Creation of new coastal ecosystems	3	Engineered hybrid solutions: Natural solutions combined with built structures, such as, green dikes, wooded fences and vegetated levees, which are combined with structural dykes

3.3.2. MOUNTAIN AREAS

Mountains are highly vulnerable to the effects of climate change. Repercussions include decreased rainfall and higher temperatures at high elevations. These factors increase risk of rockslides, snow avalanches, floods and water scarcity. Moreover, lower precipitation and higher temperatures at high elevations can allow for example vectors to inhabit new areas and, as a result, spread diseases to the population (Mallet et al., 2021).

Generic actions for mountain areas are: (i) protection of high-quality mountain ecosystems (NBS type 1), (ii) modification of mountain ecosystems (NBS type 2), and (iii) creation of new mountain ecosystems (NBS type 3).

Protection of mountain ecosystems is mainly focused on the maintenance of protection forests, which can prevent a recognized potential damage of an existing natural hazard or reduce the associated risks. Protective forests can enhance the conservation and ecological connectivity of Alpine Space ecosystems, stabilize slopes, and protect against surface run-off, erosion, rockfalls, landslides and avalanches. For instance, the Engadin Region's project in Switzerland[8] and the GreenRisk4Alps project in five European countries (Austria, Germany, Italy, Slovenia, and Switzerland)[9] have respectively developed risk assessment methodologies and decision support tools to assess protective functions of forest ecosystems against natural hazards and climate change impacts.

Modification of mountain ecosystems involves (but it is not limited to) two specific actions which can be implemented jointly: i) terracing slopes, and ii) revegetation and/or reforestation. The first action is to terrace steep slopes, which can entail reinventing or rescuing old

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[8] Project in the Engadin Region, Switzerland: Nature-based measures against rockfalls over forests in the Engadin Region, Switzerland — English (europa.eu)

[9] GreenRisk4Alps Project description: https://www.alpine-space.eu/project/greenrisk4alps/

techniques of erosion control. For example, since 2019 the Phusicos project in the Pyrenees[10] has proposed using old terracing techniques combined with natural materials (timber and stone walls), revegetation with local organic soil, and plant species to stabilize slopes, and to prevent landslides and flooding. The second action is revegetation and/or reforestation to reduce the intensity of potential hazards such as flooding, torrents, rockfalls, landslides, debris flows and snow avalanches. For instance, the Phusicos project in the Kaunertal valley in Austria[11], which currently experiences glacier retreat decreasing the slope stability in the proglacial. The project area serves as a pilot concept to prove the stabilizing effect of vegetation and the growth-promoting effects of bacteria to enhance plant traits that most strongly contribute to slope stability. Both Phusicos projects, i.e., in the Pyrenees and in Kaunertal valley, seek to reduce the impact of potential hazards on the ecology and biodiversity in the area, to enable water absorption towards the aquifers, to up-scale NBS and to increase the well-being of communities. The positive impact ought to account for vegetation types, drainage systems, land use change and the support and engagement of local communities.

Creation of new mountain ecosystems refers to two main specific actions: i) afforestation of (arid) mountain areas, and ii) the construction and installation of green flood barriers. Concerning the first action, afforestation allows greater water retention to enable infiltration, percolation and recharge of aquifers, which consequently increases pollutant trapping, reduces peak flows to maintain base flows, and enhances biodiversity and gene-pool conservation in riparian areas. The second action entails the installation of retention basins or green flood barriers which reduce soil erosion, sediment deposition, nutrients, seeds and pesticides. The project in the broader area of Ancient Olympia, Elia, Greece[12] is a case example that integrates the two main specific actions in mountain ecosystems. The project involves the afforestation of mountain areas to help stabilizing hill slopes, as well as the temporary installation of structures utilizing locally available timber in order to increase water retention. The installation of the timber structures has been fixed parallel to the contours of the hills slopes in order to retain water. They were constructed from the cutting trunks of burned Aleppo Pine (Pinus helepensis) and Cypress (Supressus semprervirens) and they were secured on wooden stakes. This construction method was chosen to prevent major landscape intervention and to keep the ecological balance of the ecosystem. The potential for water retention must be balanced against the increased evapotranspiration and pollutant trapping that may be associated with forests. Table 3 presents the generic and specific NBS actions for mountain areas.

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[10] Phusicos Project in the Pyrenees (Andorra, France and Spain): The Pyrenees, Spain-France - PHUSICOS R&D project to reduce risk in mountain landscapes

[11] Phusicos project in the Kaunertal valley, Austria: Kaunertal valley, Austria - PHUSICOS R&D project to reduce risk in mountain landscapes

[12] Water retention management in the broader area of Ancient Olympia, Elia, Greece: NWRM-CS-GR-01

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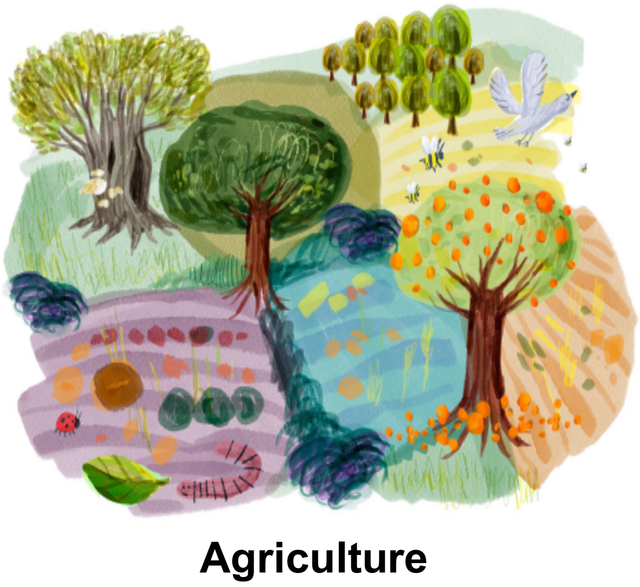
Table 3: Generic and specific NBS actions for mountain areas

GENERIC ACTION	NBS TYPE	SPECIFIC ACTION
Protection of mountain ecosystems	1	Maintenance of protection forests (a forest that can prevent a recognized potential damage due to an existing natural hazard or reduce the associated risks)
Modification of mountain ecosystems	2	Terracing with drainage/ Slope stabilization / Revegetation of steep slopes
		Reforestation and/or revegetation of mountain areas
Creation of new mountain ecosystems	3	Afforestation of mountain areas
		Green flood barriers

3.3.3. AGRICULTURE



Source: Network Nature

Agriculture is a sector regularly threatened by climate hazards. Heat stress can cause crop and livestock loss, increase the risk of pests and disease outbreaks, and exacerbate the water scarcity of droughts. In addition, flooding can cause damage to crop yields, transport and infrastructure. To reduce vulnerability to hazards, Nature-Based Solutions have been developed with the principle of increasing (or at least maintaining) crop yield through the diversification of ecologically based interventions (EEA, 2021). Such interventions contribute to improved soil (structure) and water management.

Generic NBS actions for climate change adaptation in the agriculture sector in Europe are: (i) the protection of an ecosystem to adapt a farming practice to climate change, (ii) the modification of an existing agricultural ecosystem, and (iii) the creation of a new ecosystem. The specific NBS actions encompass multiple farming systems aiming to mitigate the impacts of heat waves, droughts and heavy rainfall while ensuring food security, and reducing the risk of flood and erosion.

Protection of ecosystems to adapt agriculture to climate change can include multiple measures: i) the protection of trees in forests and wetlands, ii) soil moisture conservation, and iii) conservation agriculture. The first relates to the maintenance of tree-based farming systems and of forests in agricultural landscapes. The protection of trees can both enhance biodiversity and help crop production by protecting key species for pollination and by supporting natural predators of crop pests (Borah & Sunderland, 2021). On the other hand, soil moisture conservation techniques aim to minimize water loss through evaporation (i.e., from the soil), through transpiration (i.e., from plants), or through evapotranspiration (i.e., from both, the soil and the plants). Finally, conservation agriculture promotes the maintenance of soil organic cover, minimum soil disturbance (i.e., minimum or no tillage), and diversification of crop species (FAO, 2022).

Modification of agricultural ecosystems involves land management practices of which we mainly identify the following: i) paludiculture, including peatland restoration and wetland restoration, ii) no or minimum tillage, iii) crop diversification and rotation, and iv) mulching and use of cover crops. Paludiculture is an agricultural practice on peatlands to produce biomass (Tanner et al., 2015), which can contribute to improving water quality, provide habitat for rare and threatened species, and reduce the risk of droughts and flooding. Similarly, wetland restoration can lessen the impact of flooding and reduce nutrient leaching from farming practices (see the Tullstorpså project: www.tullstorpsan.se). No or minimum tillage can increase soil productivity and reduce soil erosion, however the environmental performance will depend on the soil type as well as the need for using pesticides (EEA, 2021). Crop diversification and rotation comprise mixed cultivation and intercropping, which generally lead to increased resistance to extreme weather events (Ratnadass et al., 2012), and greater crop yield stability in the long run (Altieri et al., 2015). Furthermore, crop diversity spreads the risk of pathogen attacks, as well as allowing for the diversification of farm income sources. Finally, cover crops (and mulching) aim to improve soil fertility to augment crop performance. Such enhancements help to reduce the impact of strong winds, extreme radiation and heavy rainfall (Vignola et al., 2015). Cover crops can be sold later as feedstocks and generate supplementary revenues to the farm; however, crop yields can be negative in the short term (Blanco-Canqui et al., 2015). Table 4 displays the generic and specific NBS actions for agriculture.

Table 4: Generic and specific NBS actions for agriculture

GENERIC ACTION	NBS TYPE	SPECIFIC ACTION
Protection of agricultural ecosystems	1	Protection of trees in forests and wetlands
		Soil moisture conservation e.g., using plants for shading
		Conservation agriculture
Modification of an existing agricultural ecosystem management	2	Paludiculture (including peatland and wetland restoration)
		No or minimum tillage
		Crop type diversification and rotation
		Mulching and use of cover crops
Creation of new agricultural ecosystems	3	Agroforestry
		Mixed crop-livestock systems
		Creation of micro-relief, and construction of floodplains for rainwater harvesting

Creation of new agricultural ecosystems mainly refers to: i) agroforestry, ii) mixed-crop-livestock systems, and iii) measures of water infiltration such as the creation of micro-relief. Agroforestry solutions integrate trees, crops and livestock into the same plot. For instance, it can consist of farming systems where intercropping (e.g., cereal, wheat, forage) and grazing (e.g., sheep, goats) are combined with tree crops (e.g., oak trees, walnut trees). This helps to mitigate erosion by creating a permanent soil cover, and to reduce the impact of extreme climate events by using windbreaks and hedgerows with trees and shrubs. Similarly, mixed crop-livestock farming involves the production of crops and livestock on the same site. This potentially improves nutrient cycling, soil fertility, and carbon sequestration (through cover crops) whilst reducing chemical inputs. At the same time, the beneficial interaction of crops and livestock can enhance biodiversity and increase pest control through species interaction. Examples of mixed crop-livestock actions can encompass silvo-pastoral practices and improved pasture management (EEA, 2019). Lastly, the creation of micro-relief, as well as the construction of floodplains close to farms, enhances water storage and improves water quality during droughts.

Note that some specific NBS actions can overlap across generic NBS actions. For example, conservation agriculture can belong to the first generic action (Eggermont type 1) because it implies minimum soil disturbance (e.g., no tillage). However, conservation agriculture can also entail management measures modifying the agricultural ecosystem (Eggermont type 2), such as the diversification and rotation of crop types. Moreover, some NBS measures can be considered intrusive depending on the scale of the intervention. As a result, a specific NBS action can fall under more than one Eggermont type. Similarly, there are specific actions that can be introduced as part of another specific action, for example, mixed crop-livestock systems can partake in agroforestry systems.

Two important challenges of agricultural NBS can be their complexity for implementation, and their potential lower profitability (or, increased costs incurred by farmers) compared to more conventional systems (EIP-AGRI Focus Group, 2017).

3.3.4. FOREST AND FORESTRY

Forest

Source: Network Nature

Forests are fundamental for the mitigation and adaptation to climate change. The protection, restoration and maintenance of forests contribute to the regulation of water flows, the control of pests and diseases, the stabilization of slopes, the enhancement of biodiversity, the promotion of recreation and landscape aesthetics, among others. Forest-related actions can reduce the impact of floods by water absorption, can help to mitigate climate change through carbon sequestration (Watson et al., 2018), and can reduce the impact of heat waves by providing shade and by cooling surroundings through transpiration (Krofcheck et al., 2019).

Nature-Based Solutions can be applicable at different levels: tree, stand and landscape. Landscape-based interventions can imply measures involving different ecosystems and overlapping with other landscapes and sectors, e.g., floodplain and river catchment restoration through reforestation. On the other hand, tree-based interventions have a lesser spatial extent yet still provide important environmental benefits. For example, the creation of hedges can act as noise pollution filters and wind barriers.

Generic NBS actions for forest and forestry are: (i) the protection of forest ecosystems, (ii) the modification of an existing forest ecosystem in accordance with sustainable forest management measures, and (iii) the creation of a new forest ecosystem.

Protection of forest ecosystems allows for biodiversity conservation, and the rich species composition make natural forests more resilient to unpredictable weather events. NBS involving the protection of forests. The total area of undisturbed natural forests in Europe is less than 4% (Forest Europe, 2020).

Modification of forest ecosystems is generally aligned with sustainable forest management practices. Sustainable forest management seeks to ensure that forests supply goods and services to meet the needs of present and future generations and contribute to the sustainable development of communities (FAO, 2022). Specific NBS actions to modify forest ecosystems can for example comprise: i) restoration of degraded forests, ii) maintenance of forests in riparian buffers and headwater areas, and iii) reforestation. All three specific NBS actions can overlap with each other and can vary depending on the management practice. The first specific NBS action relates to restoring degraded forests and enriching existing forests to re-establish forest functions. Evidence suggests that the sustainable restoration of forests can be cost-effective and generate long term savings (De Groot et al., 2013; Jongepierová-Hlobilová, 2012). The second specific NBS action intersects with water management measures. Riparian forest buffers are areas of trees, shrubs and vegetation along water streams (rivers) and water bodies (wetlands, lakes). The maintenance of forests in (such) water ecosystems helps to enhance water flow regulation, trap sediments and pollutants from other land use activities, improve habitat quality and diversity, enhance landscape connectivity and mitigate water scarcity during droughts (Reberski et al., 2017). The third specific NBS is reforestation, which refers to forest regrowth in previously forested land. The benefits of reforestation can vary depending on the goal of the NBS action as well as the ecosystems involved. For example, revegetation in mountain areas is effective in reducing erosion and consolidating slopes, which ultimately reduces the intensity of climate hazards. Reforestation can provide multiple benefits including the conservation of biodiversity, and the improvement of air and water quality. However, the efficiency (i.e., the effectiveness and the time it takes) of reforestation and rewilding forests for climate mitigation and adaptation still needs further research (Morecroft et al., 2019).

Creation of new forest ecosystems includes essentially two specific NBS: i) afforestation, and ii) the integration of trees and forests in other landscapes or sectors. First, afforestation is the plantation of trees in an area without any previous tree cover. The establishment of newly forested land serves as carbon sinks (World Economic Forum, 2021), stabilize steep slopes, and provide cooling for humans and animals (Cariñanos et al., 2018). Large scale interventions provide protection against erratic weather events, floods and landslides (Martin et al., 2016). Similarly, the introduction of trees and forests (i.e., afforestation[13]) supports climate change adaptation and disaster risk reduction in other landscapes and sectors. For instance, forests improve air quality and health in urban areas (Ferreira et al. 2020), improve soil conditions in agroforestry systems (Schoeneberger et al., 2012), and reduce flood risk in mountain and coastal areas. However, land ownership across landscapes can make it difficult to coordinate multiple stakeholders, and as a result, decision-making may become challenging. Table 5 lays out the generic and specific NBS actions for forest & forestry.

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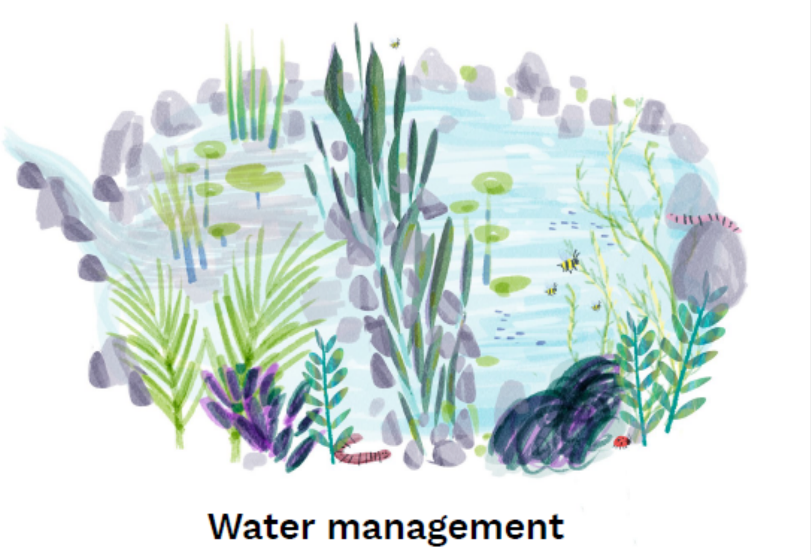
[13] Note that the second specific NBS action of NBS type 3 also entails afforestation. This second NBS action emphasizes the overlap of afforestation measures across landscapes and sectors.

Table 5: Generic and specific NBS actions for forest & forestry

GENERIC ACTION	NBS TYPE	SPECIFIC ACTION
Protection/conservation of forest ecosystems	1	Protection/conservation of primary and old-growth forests
Modification of an existing forest ecosystem / Sustainable forest management	2	Restoration of degraded forests
		Maintenance of forests in riparian buffers and headwater areas
		Reforestation / revegetation (e.g., regrowth of deciduous trees to reduce risks of future diebacks)
Creation of new forest ecosystems	3	Afforestation
		Integrating trees and forests into other landscapes (e.g., urban areas) or sectors (e.g., agroforestry)

The regulation and maintenance of (ecosystem) services of forests entail environmental benefits that can involve trade-offs with provisioning (ecosystem) services. Extraction of timber and biofuel feedstocks provide important revenues and jobs to different forest and bioenergy companies; however, these economic activities can hinder carbon storage, biodiversity and spaces for recreation. Synergies should be identified and developed to minimize systemic trade-offs (Eggermont et al., 2015).

3.3.5. WATER MANAGEMENT



Source: Network Nature

Sustainable water management is one of the main objectives of the Water Framework Directive. Water management is a thematic area integrating different landscapes and sectors involving water flows or water ecosystems. Climate change is changing precipitation patterns in terms of intensity and frequency, resulting in more torrential rains, floods and droughts (OECD, 2023). Freshwater ecosystems are impacted, affecting water quality and quantity.

Nature-Based Solutions have been identified to exert an important impact on water management and water availability, and to contribute to sustainable practices under climate change. Water management measures depend on the size of the NBS intervention. Large-scale NBS intersect different ecosystems and entail coordinated strategies across different actors. One example is the restoration of river streams by extending floodplains or by changing the natural form of the water stream. Small-scale NBS normally involve one landscape and are implemented in one location, for example, retention ponds for rainwater harvesting and/or for phytoremediation.

Generic NBS actions for water management include: (i) protection of intact hydrology and of existing high quality groundwater resources, (ii) modification of an existing hydrological ecosystem (e.g., water streams, riverbeds), and (iii) creation of a new water ecosystem.

Protection of hydrology and of existing groundwater resources include essentially the preservation and maintenance of safe physical environments to support natural processes that promote hydrogeological stability.

Modification of an existing hydrological ecosystem involves four specific NBS actions that may overlap with other landscapes (e.g., forests, urban areas) or sectors such as agriculture: i) rehabilitation of rivers (and river buffers), floodplains, basins, ponds, wetlands, lakes and aquifers, ii) water-sensitive forest management, and iii) groundwater management.

The rehabilitation and restoration of rivers and floodplains are commonly designed to mitigate flood risk and provide protection against drought. Multiple interventions are associated to the first specific NBS action, including reconstruction of river channels, sediment dredging, changing the natural form of rivers, re-meandering, restoration of river buffers, and extending or reconnecting floodplains. An important aim is to trap sediments and pollutants from agriculture or other land uses, decrease the speed of water flows, increase water storage, and enhance water quality (Bridgewater, 2018; Reberski et al., 2017)[14].

Water-sensitive forest management or ecohydrological-based forest management refers to measures that modify the forest cover and/or tree species composition. Examples of such measures include the opening of the canopy, the reduction of the density of the forest stand (pruning), and the selection of species.

Large-scale groundwater management options comprise injecting surface waters into the groundwater system through wells, managed aquifer recharge, forested infiltration areas or by filling recharge basins to allow percolation downwards. Such measures allow to increase groundwater availability, prevent saltwater intrusion in coastal regions, and serve agriculture as well as natural vegetation by maintaining water tables.

Creation of new water-related ecosystems is associated with measures mainly related to three specific NBS actions: i) rainwater harvesting, ii) phytoremediation, and iii) urban green space and corridors. Specific NBS actions can be used in agriculture, urban and peri-urban areas to mitigate flood risk, water scarcity and water quality deterioration. Rain harvesting measures include retention ponds, swales, rain gardens and green roofs. Phytoremediation measures, such as riparian vegetation, retention ponds and constructed (namely, artificial) wetlands, are used for waste treatment and water purification (Wild, 2020a). Urban green

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[14] The rehabilitation of river buffers can imply afforestation measures (as opposed to reforestation) that can fall under the third generic NBS category, e.g., establishment of vegetation strips, shrubs and trees adjacent to the river ecosystem.

space and corridors refer to parks, trees, hedgerows and green corridors, which allow percolation into soil and support flood control during (extreme) heavy rainfall events. Table 6 presents the generic and specific NBS actions for water management.

Table 6: Generic and specific NBS actions for water management

GENERIC ACTION	NBS TYPE	SPECIFIC ACTION
Protection of hydrology and of existing groundwater resources	1	Maintenance of safe physical environments to promote hydrogeological stability
Modification of an existing hydrological ecosystem	2	Rehabilitation and restoration of rivers, floodplains, basins, wetlands, ponds, lakes and aquifers
		Water-sensitive forest management
		Groundwater restoration and management
Creation of new water-related ecosystems	3	Rainwater harvesting
		Phytoremediation
		Urban green space and corridors

There are interventions of water-sensitive forest management and groundwater management which can be categorized as NBS type 2 or NBS type 3. For example, afforestation, riparian vegetation and/or planting of hardwood species entail the creation of new water ecosystems for water-sensitive forest management. Similarly, NBS interventions for groundwater recharge enhancement and improvement of groundwater quality are more object-based (e.g., building) or within a specific site (e.g., street or plot). These can include permeable paving of footpaths, parking lots and playgrounds, porous asphalt, infiltration basins, constructed wetlands and vertical greening systems (e.g., green facades and green walls). Moreover, the rehabilitation of river buffers can entail the establishment of vegetation buffers which can also fall under NBS type 3.

An evident challenge for water management is the coordination across different stakeholders, hence potential communication gaps may arise between researchers, engineers, politicians, managers and the general public (Fletcher et al., 2015).

3.3.6. URBAN AREAS

Urban ecosystems

Source: Network Nature

Urban ecosystems are natural systems within a city or a densely populated area. Blue-green infrastructure is a key strategy for climate change adaptation and mitigation in urban areas. For example, the urban heat island effect can be reduced significantly by enhancing transpiration and shading with street trees, green roofs, and parks (McPhearson et al., 2018). Vegetation contributes to mitigation by capturing CO_2 through photosynthesis and helps to increase rainwater infiltration (storm water absorption), reduce water pollution, and decrease the level of stress to citizens.

Generic NBS actions identified for urban areas comprise: (i) protection of urban ecosystems (NBS type 1), (ii) modification of urban ecosystems (NBS type 2), and (iii) creation of a new urban ecosystem (NBS type 3). All generic actions involve green and blue infrastructure.

Protection of high-quality urban ecosystems encompasses the protection of two specific NBS actions: i) protection of green infrastructure, and ii) protection of blue infrastructure. The protection of green infrastructure refers to maintaining urban trees, urban forests, urban greenspace and urban forest parks. This offers multiple benefits lowering air temperatures because of shading and evapotranspiration (Armson et al., 2012), and as a result, mitigating heat stress and the urban heat island effect. For instance, grass surfaces are 2-4 degrees Celsius cooler than concrete surfaces, and larger parks have a greater cooling effect than built-up areas (Bowler et al., 2010a). Other important benefits are urban biodiversity support and connectivity improvement between urban and rural areas (Naumann & Davis, 2020). Furthermore, stormwater regulation and flood hazard mitigation are crucial benefits of urban green infrastructure. A forested landscape typically loses about 13% of rainfall while urban landscapes of rainfall to surface run-off (Pataki et al., 2011). On the other hand, the protection of blue infrastructure refers to maintaining urban infrastructure related to water, such as, wetlands, lakes, streams and riverbanks. In urban environments, blue infrastructure can also be referred to as blue-green infrastructure. It can improve the water quality and quantity of water resources, remove pollutants from urban run-off and reduce the impact of sewer overflows (Wild, 2020). Both specific NBS actions may offer quantifiable benefits to society including job creation, savings of energy costs, increased housing prices, avoided damage costs, and reduced costs of mental and physical healthcare (hence, providing increased benefits to human health and well-being).

Modification of urban ecosystems comprises three different specific actions: i) restoration of green infrastructure, e.g., urban green space, corridors, parks, trees and habitats, ii) reforestation of urban and peri-urban forests, and iii) restoration and rehabilitation of blue infrastructure, e.g., ponds, wetlands, bioswales, rain gardens. Besides the abovementioned benefits of protecting green infrastructure, restoration can provide new habitats and new green corridors for biodiversity (Vojinovic, 2020). Restored green infrastructure reduce stormwater run-off during heavy precipitation, and improve the microclimate by reducing air temperatures, reducing solar radiation, relative humidity, glare and reflection (Bowler et al., 2010b; Calfapietra, 2020).

Reforestation of urban and peri-urban forests enhance carbon sequestration and mitigate heat. It improves air quality as trees and plants remove pollutants, e.g., ozone, fine particulate matter, nitrogen oxides and sulphur dioxide (Grantz et al., 2003; Nowak et al., 2014). Plants and trees can also emit pollen and biogenic volatile organic compounds with negative health effects. However, it is possible to maximise the services and minimize the disservices by selecting the right species (Calfapietra, 2020). At a larger spatial level, reforestation can also facilitate and enhance landscape (ecological) connectivity between urban and peri-urban areas.

Restoration and rehabilitation of blue infrastructure imply interventions addressing water management in urban environments. These entail the modification of urban ecosystems: basins, ponds, channels, rills, detention basins, filter strips, infiltration basins, permeable surfaces, retention ponds, sediment capture ponds, sustainable drainage systems (SUDS), temporary floodwater storage, wetlands, bioswales, and rain gardens. These interventions can also be created (versus modified), therefore, water management in urban areas can also imply creation of new blue infrastructure (NBS type 3).

Creation of new urban ecosystems refers to two specific NBS actions: i) creation of new green infrastructure, ii) creation of new blue infrastructure, and iii) greening the building envelope. Creation of new blue and green infrastructure vary with size and impact of the NBS intervention. Interventions range from the single-object level (NBS objects such as buildings and parking lots) to the city or peri-urban level (NBS systemic approach such as large urban parks and urban forests).

New blue-green infrastructure includes green building envelopes, which are systems in urban areas providing a wide range of ecosystems services. They essentially deliver local benefits for water and heat management. Green roofs, green walls, green facades, vegetated surfaces and vertical greening systems retain greater amount of water, delay water run-off, reduce air temperature, and contribute to reducing the urban heat island effect by reflecting more light because of higher albedo (up to 30%) than artificial surfaces (5%; Perini & Rosasco, 2013). Green roofs can reduce energy demand for air-conditioning up to 60% (Mazzali et al., 2012), can cool neighbouring streets up to 3 degrees Celsius (L. Francis & Jensen, 2017), can reduce peak flow volume of heavy rain up to 96% and can reduce run-off up to 70% (Ruangpan et al., 2020). Table 7 displays the generic and specific NBS actions for urban areas.

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Table 7: Generic and specific NBS actions for urban areas

GENERIC ACTION	NBS TYPE	SPECIFIC ACTION
Protection of high-quality urban ecosystems (green and blue)	1	Protection of green infrastructure, e.g., urban trees, urban forests, urban greenspace, and urban forest parks
		Protection of blue infrastructure, e.g., wetlands, lakes, streams, riverbanks
Modification of urban ecosystems (green and blue)	2	Rehabilitation and restoration of urban habitats, urban green space and corridors
		Rehabilitation and restoration of blue infrastructure / Water management in urban areas
		Reforestation of urban and peri-urban forests
Creation of new urban ecosystems (green and blue)	3	Creation of new green infrastructure, e.g., parks, urban forest, street trees, vegetable gardens, vineyards // Greening the building envelope, e.g., green roofs, green facades, roof gardens, vertical greening systems
		Creation of new blue infrastructure, e.g., retention ponds, sediment capture ponds, temporary flood water storage, detention (and infiltration) basins, filter strips, SUDS, daylighting of streams, canals and rills

Based on the EEA report (2021), we identify four scale levels of NBS in urban areas as reference: object, neighbourhood, city and peri-urban. The levels can seemingly overlap as they depend on the size and impact of the NBS intervention. Examples include:

Table 8: Scale levels of NBS in urban areas

OBJECT	NEIGHBOURHOOD	CITY	PERI-URBAN
Buildings Eco-treets/green roads Green and pocket car parks Green roofs, walls and facades Rain gardens Green playgrounds/school grounds Vegetation dells	Tree corridors Rebuilding a water stream System of small canals linked to a river Greening river banks Redesign/redevelop former industrial/residential areas	Green roofs at a systemic scale Blue-green city corridors	Confluence parks combining river restoration with recreation Forests

Investments in urban NBS have proved challenging because the benefits take time to manifest (Bulkeley et al., 2020). Moreover, data on assessments of the relative performance of NBS, e.g., cost-effectiveness compared with traditional grey infrastructures, are urgently needed.

4. SOCIETAL CHALLENGES AND ECOLOGICAL PROCESSES

NBS are actions involving nature to address societal challenges on an economic, social and environmental level. By using the Eklipse report (Raymond et al., 2017) as primary source of literature, we have synthesised challenges that NBS seek to address into generic and specific challenges: 1. climate change adaptation (flooding, heat, storms, drought), climate change mitigation (GHG emissions), natural hazards (avalanches, landslides, earthquakes), environmental management (pollution of air and water, water scarcity, erosion, and biodiversity loss), noise pollution, and socio-economic challenges (unemployment, inequality, health & wellbeing, social segregation and economic efficiency). Table 9 shows the generic challenges disaggregated by specific challenges.

Table 9: Generic and specific societal challenges

GENERIC CHALLENGES	SPECIFIC CHALLENGES
Climate change adaptation	Flooding: Riverine, pluvial, coastal
	Heat stress (UHI, microclimate, thermal cooling)
	Adaptation to storms
	Adaptation to droughts
Climate change mitigation	Carbon and GHG emissions
Natural hazards	Avalanches, landslides, earthquakes
Environmental management	Air pollution
	Water pollution
	Water physical scarcity
	Coastal erosion, soil erosion
	Biodiversity loss
Noise pollution	Noise pollution
Socio-economic challenges	Unemployment
	Inequality
	Health & well-being
	Social segregation
	Economic efficiency

For each specific challenge, we identify ecological processes that will deliver the benefits addressing these challenges. In collaboration with CMCC, AU finalised a description of ecological processes by which NBS can contribute to addressing these challenges. The addition of ecological processes can have multiple usages throughout the project for practitioners in the Living Labs, for stakeholders, for dissemination and for embedding socio-economic research in a physical context.

4.1. ECOLOGICAL PROCESSES OF CLIMATE ADAPTATION

4.1.1. RIVER FLOOD REGULATION

River flooding occurs when the flow of water increases up to filling the riverbed and overtopping its banks. In a healthy and balanced river, flood mitigation occurs mostly in floodplains, flat area next to the river that provide space for the retention of water. Here, the flow of water is collected and can move small sediments that contribute to maintain river shape and structure. Main processes involve the retaining of excess temporary water and runoff, which helps reduce peak flows (Ferreira et al., 2020; The World Bank, 2017). By maintaining floodplains hydrologically connected with lands compatibly used with flooding (e.g., forests, pasture, open space), downstream flood levels can potentially be reduced, and damages from flooding can be limited or eliminated (Opperman & Galloway, 2022; Vouk et al., 2021). Allowing natural river and floodplain functions to have sufficient space can decrease the exposure of people and infrastructure to flood hazards, while also creating room for water to flow. Moreover, re-meandering rivers - which involves restoring the original curves of a river - increases the length of the river channel (in a nonlinear way), thus decreasing flow conveyance and water speed. Consequently, floodplain storage capacity is enhanced and flood protection increased (EEA, 2017).

Within floodplains, ponds, depression, and vegetation can also help to store and slow the flow of water to river channels, and enhance ground infiltration, while also promoting the retention of sediment, pollutants, and nutrients, soil stabilization and erosion reduction (Blackwell et al., 2006; Vouk et al., 2021). Floodplains and buffer reduce runoff by filtration through the substrate in the trench and subsequently through soil (Zeleňáková et al., 2017).

Infiltration retention processes underlying flood regulation can contribute to water management in wider perspective, addressing drought at the same time (see drought section).

- **Benefits:**

Studies reported that a 10m vegetated buffer strip can reduce runoff by 50% (NWRM, 2013). The capacity of buffer strips to control runoff widely depends on the vegetation planted: willow buffer strips can reduce the total turnoff by 49%, deciduous woodland buffer strips by 46%, grass buffer strips by 33% (Dunn et al., 2022).

Natural infrastructure or natural water management measures, aimed to river and floodplain restoration, has shown positive impacts for flood control. In North Carolina, in the Neuse River basin, wetlands and river basin afforestation resulted to reduce runoff by 6-9% and to reduce peak flow by 5% at the sub-watershed level (Kurki-Fox et al., 2022). In a 25km^2 catchment in the New Forest (UK) the results of a monitoring study found river restoration led to a 21% reduction in flood peak for 2year recurrence event (Sear et al., 2006). Similarly, river restoration in Eddleston Water (Scotland) flood risk downstream by 30% by planting trees and cross-slope hedgerows in the upper catchment, building log dams across side-streams, re-meandering the river and removing embankments to reconnect it to the floodplain (NBS Initiative, 2021).

It should be noted that although many studies have addressed the potential of Nature-Based Solutions in water management, there is currently limited information on their effectiveness in flood mitigation (Watkin et al., 2019). The performance of NBS in flood protection is strongly influenced by specific local conditions, such as soil type and NBS design (Kalantari et al.,

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2020). Therefore, a universal approach cannot be applied, as different contexts require tailored solutions (Ferreira et al., 2020; The World Bank, 2017).

4.1.2. COASTAL FLOOD REGULATION

Coastal flooding usually occurs during seasonal high tides and storms that push water toward the shore. However, as sea levels are rising, floods in coastal communities are increasingly occurring. Coastline vegetation, barrier islands, dunes and beaches serve as natural barriers to water (Bridges et al., 2015). Specifically, dunes and coastal vegetation act as protective buffers against coastal floods due to storm surge, waves, and erosion of the hinterland, by reducing wave energy and lowering wind speed (Sigren et al., 2014).
As well, tidal marshes, mangroves, coral reefs, and shellfish reefs possess natural capacities to reduce storm waves, storm surges, and adapt to sea-level rise through the accumulation of sediments (Temmerman et al., 2013).
Mangroves, in particular, contribute to erosion reduction and sediment deposition due to their vegetation, which decreases wave energy, slows water flow over the soil surface, and facilitates sediment settlement (University of Cambridge, 2014).
Wetlands also play a role in flood reduction by capturing and storing floodwaters from surface runoff, enhancing soil infiltration and groundwater recharge. They can act as natural 'sponges', slowing the general run-off and improving hydraulic resistance through their water absorption capacity (EEA, 2017). The vegetation in wetlands creates resistance to flow, slowing down water movement within the floodplain and attenuating runoff (Bullock & Acreman, 2003).

The general processes mitigating coastal floods can address coastal storms and coastal erosion (see storm and coastal erosion sections).

- **Benefits:**

Dunes and coral reefs mainly act as a physical barrier to water, waves and wind. Particularly, dunes contribute up to 60% of wave attenuation during storm events (EEA, 2021) and the presence of mature plant roots in dunes double the amount of time before structural failure occur and increase the cumulative shear required to break down sediment by 180% (Sigren et al., 2014). Coral reef provide substantial coastal protection by dissipating up to 95 % of wave energy and significantly reduce wave height (Ferrario et al., 2014).

Wetlands act by collecting waters and absorbing it with the help of its vegetation. A 1% increase in wetland roughness caused by vegetation could decrease storm surge by 15.4% to 28.1% (Barbier et al., 2013). A hectare of wetland can store up to 9,400 -14,000 m3 of floodwater (GFDRR, 2022).

4.1.3. PLUVIAL FLOOD REGULATION

Pluvial floods occur when rainwater is not absorbed by ground drainage systems, especially in cities. Intense and spatially concentrated precipitation events in densely developed urban areas can result in excessive water flow which can cause sizeable damage to tangible assets. Water-sensitive urban planning and designing buildings, to reduce water run-off, attenuating flood peaks and enhancing groundwater recharge are example of small-scale NBS for water management and flood risk reduction (EEA, 2021) . In this group are included different green infrastructure such as: restored river, bioswales, retention and detention basins (or bioretention cells/filters), (constructed) wetlands, rain gardens, permeable pavements, riparian vegetation strips and green roofs, parks, gardens, trees, urban forests etc. Their capacity to decrease run-off volumes and timing, while increasing water retention, enables the reduction of flooding risk during heavy rainfall events (EEA, 2021). They can act as storage for water volume and with the help of vegetation, which is increasing porosity and permeability of the soil, allow water to percolate in the ground. Urban parks and forests can regulate storm water thus mitigating flood hazards by intercepting rainfall, which subsequently evaporates, infiltrates the ground or is otherwise delayed in contributing to run-off (Berland et al., 2017).

The processes underlying urban NBS functioning contribute to water management both in a context of water scarcity and flood (see water scaricity section).
NBS are often combined to increase their effectiveness. For example, wetlands may be combined with other green infrastructure, such as rain gardens and porous pavements to increase water infiltration and reduce storm runoff (Opperman & Galloway, 2022).

- **Benefits:**

Studies on the role of vegetation in urban environments showed that trees are estimated to intercept 6.7 m^3 water per year, which can help to reduce the frequency and severity of combined sewage water overflow events (Berland & Hopton, 2014). A Korean case study estimated that the presence of parks in an upstream river could decrease the flood peak downstream decreases by 30–83%, in scenarios of rainfall duration with a return period of 1 in 100 years (Meng, 2022; Ngo Thy Thuy, 2016). The stormwater benefits from urban trees can be also translated into economic terms; for example, a study from Lisbon estimated an economic benefit of USD 47.80 per tree, due to its ability to reduce stormwater run-off (EEA, 2021; Soares et al., 2011).

In particular, bioretention systems, such as ponds, swales and rai gardes, are effective in peak discharge control, with an average reduction above 40% (P. A. Davis et al., 2009). Regarding green roofs, the retention rate may range from 29 to 100%, with an average retention just under 78 percent, depending on the depth of the rainfall (Rasmussen, 2006). Permeable material may as well be used to build permeable pavements and reduce water run-off. Porous pavements may lead to a significant reduction of 30-65% of water run-off.

The implementation of NBS for flood prevention has been experimented in some cities in China with the aim of creating the so-called Sponge City. The vegetated area could store more rainwater than hard surface in a heavy rainstorm, which reduces runoff loss and the risk of flooding. The total volume of rainwater runoff reduced by Beijing's urban green spaces, for example, has been estimated to be 154 million cubic meters, and the amount of reduced runoff per hectare green space was 2494 cubic meters (Zhang et al., 2012). In Yixing, the runoff regulation capacity of green spaces resulted to be greater in the built-up areas, at approximately 3.9 × 107m3yr-1 of rainwater runoff, while green spaces outside the built-up areas made a relatively minor contribution to rainwater runoff reduction (only 1.4 × 107m3yr−1) (Yang et al., 2015).

4.1.4. THERMAL CONTROL AND COOLING

Urban heat islands and heat stress occur in cities, where the natural land cover is replaced by concrete pavements, dense concentrations buildings, and other surfaces that absorb and retain heat. Vegetation plays a crucial role in shaping urban microclimates by providing shading and evapotranspiration services, which contributes to cooling and regulating surface and atmospheric temperatures (Price et al., 2015). During summer, a part of the sun's energy

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is absorbed by leaves and used for photosynthesis or reflected back into the atmosphere. As a result, the area beneath vegetation remains considerably cooler (EPA, 2005). At the same time, water absorbed by roots is released through leaves, where it evaporates, utilizing heat from the surrounding air. This evaporation process, being endothermic (meaning it is absorbing energy, as heat in this case), lowers the surrounding temperatures (Menon & Sharma, 2021).

When placed on rooftops, vegetation provides additional benefits. Firstly, it reduces heat transmission into buildings by blocking sunlight from reaching the roof surface, acting as thermal insulation. Secondly, it reduces the heat that would otherwise be emitted into the atmosphere, while also creating an additional layer of stagnant air, known as the insulation effect (EPA, 2005; Menon & Sharma, 2021; Perini et al., 2011; Price et al., 2015).

Green walls, covering larger areas compared to green roofs, potentially amplify their benefits connected to the shading effect. Additionally, green walls shade adjacent buildings, further lowering air temperatures and the heat absorbed by nearby paved surfaces, such as streets and lower positioned roofs (Price et al., 2015). Additionally, also green walls contribute to save energy through thermal insulation and the process of evapotranspiration (Balogun et al., 2014; Menon & Sharma, 2021; Price et al., 2015). However, it is important to note that the insulation effect can also have disadvantages, as bare walls cool down much faster than greened ones (Gillefalk et al., 2021).

By reducing energy demand, vegetation indirectly contributes to the reduction of greenhouse gas emissions, thereby mitigating the effects of climate change. Urban vegetation and coastal wetlands play as well a crucial role in greenhouse gas reduction through carbon sequestration (see carbon sequestration section), acting as carbon sinks or sources for dissolved organic carbon (Melton et al., 2013).

Lastly, vegetation can provide additional societal benefits, especially from a health perspective. The reduction of greenhouse gases helps decrease the incidence of heat-related health issues such as heat cramps, exhaustion, heatstroke, and heat-related fatalities (Price et al., 2015). While the capacity of absorbing pollutants and clean the air (see air pollution section) contribute to limit possible long-term health effects, as hearth and respiratory diseases.

- **Benefits:**

It has been demonstrated that trees have a positive impact on urban temperature. Across Europe, the surface temperature the presence of trees, compared to continuous urban fabric, is on average 0-4 °K lower in Southern Europe, and 8-12 K lower in Central Europe (Schwaab et al., 2021). A study conducted in Berlin, estimated a significant contribution of the shading effects of green facades to the overall cooling effect, accounting for up to 81.5% of the measured cooling effect (Gillefalk et al., 2021). Furthermore, on average, green walls were cooler than bare walls, with temperature differences ranging from -4.4 to -2.2 degrees Celsius. The insulation effect of green facades showed a reduction of the heat flux from 64.5 and 43.9 W/m produced by bare walls to 36.5 and 34.1 W/m^2 generated by green walls.

Positive results were also showed by an earlier study were the oasis effect was proved to diminish the temperature of a plant's surrounding air to as much as 8 °C (Price et al., 2015).

Several studies have also estimated the potential energy consumption savings - at a national level - resulting from the implementation of urban green infrastructures. In the US, tree plantation and the implementation of green roofs and facades could lead to a possible 20% reduction in U.S. national energy consumption, equivalent to $10 billion in energy use (Akbari et al., 2001). In the Mediterranean climates, green buildings could reduce the energy demand for air-conditioning by 40-60% in Mediterranean climates (Perini & Rosasco, 2013).

Furthermore, studies investigate the contribution of vegetation on heat-related mortality. Cities with high greenspace value resulted to have the lower heat-mortality relative risk, and an increase of 20% of greenspace is associated with a decrease of heat-related mortality of 9% (Choi et al., 2022).

4.1.5. MITIGATE WIND SPEED AND WAVE ENERGY IN COASTAL ECOSYSTEMS

Storms in coastal areas can be characterized by strong winds, heavy precipitation and increasing wave energy, that can lead to storm surge, coastal floods and coastal erosion and turn also into cyclones, hurricanes, and typhoons, according to different geographical areas.

Coastline vegetation and mangroves forest, barrier islands and coral reefs, dunes and beaches serve as natural barriers to wind and waves, contributing also to mitigate impacts associated with sea level rise, coastal erosion, and floods (EEA, 2021).

On the coast, dunes provide a natural barrier of sand that erodes during storm conditions and dissipates wave energy in the process. A wide, lower dune performed better during longer moderate storms while a tall, narrow dune provided more protection during intense storms (Itzkin et al., 2021). Vegetation is abundantly present in most coastal dunes and may enhance the capability of the dune to withstand erosion, increasing the mechanical strength of non-cohesive sediment (Figlus et al., 2014; Sigren et al., 2014). Vegetation helps to trap windblown sand, building dune volumes and increasing dune's ability to act as a buffer from storm waves, erosion, and flooding. Salt-tolerant plants also contribute to hold sediment with their roots, stabilizing areas where they are planted, and to absorb water, to break the impact of raindrops or wave-splash, to physically slow the speed and to diffuse the flow of overland runoff, reducing runoff erosion (Massachusetts Office of Coastal Management, 2013). In this way, dunes act as sand storage areas, supplying sand to eroded beaches.

Similarly, mangrove forests and marshes act in reducing wave energy and slows the flow of water over the soil surface. They reduce the water's capacity to dislodge sediments and carry them out of the mangrove area, and the slower water flows can allow already suspended sediments to settle out from the water, resulting in increased deposition of sediment (University of Cambridge, 2014).

Similarly, processes characterizing coastal vegetation actions can contribute to mitigate coastal floods and erosion (see costal erosion and coastal flood sections).

In the oceans, coral reefs are an effective natural barrier from waves because of their ability to break waves offshore, thus limiting the energy impacting the coastline (Cuttler et al., 2018; EEA, 2021). The high structural complexity of coral reefs results in high hydraulic roughness and greater frictional dissipation of waves when compared to other coastal settings (Harris et al., 2018).

- **Benefits:**

The rehabilitation of terrestrial coastal habitats and ecosystems in transitional waters provides key ecological benefits, as vegetation is responsible for about 60 % of wave attenuation during storms events (EEA, 2021)._Experiments with live plants showed that they can significantly reduce the volume of dune erosion and the dune scarp retreat rate by over 30%. The presence of mature plant roots doubled the amount of time before structural failure occurred and increased the cumulative shear required to break down sediment by 180% (Sigren et al., 2014). Additionally, a 1% increase in wetland roughness caused by wetland vegetation will decrease storm surge by 15.4% to 28.1%. These estimates suggest that storm surge will be reduced by 1 m per 9.4 to 12.6 km of additional wetlands along the transect we analyze (Barbier et al., 2013). Coastal vegetation and mangroves contribute also to create and preserve unique habitat for flora and fauna % (Sigren et al., 2014), promote fisheries production by providing an indispensable habitat for juvenile fish, shellfish and crustaceans, and act as sinks for atmospheric CO_2 and therefore contribute to climate change mitigation (Temmerman et al., 2013).

Coral reefs provide substantial protection against natural hazards by reducing wave energy by an average of 97%. Reef crests alone dissipate most of this energy (86%), while reef flats dissipated 65% of the remaining wave energy (Ferrario et al., 2014). Additionally, there are up to 197 million people that live both below 10m elevation and within 50km of a reef who may receive risk reduction benefits from reefs.

4.1.6. WATER STORAGE, WATER INFILTRATION AND EVAPOTRANSPIRATION

Natural processes that increase water infiltration into the soil, enhance evapotranspiration, provide storage areas for rainwater, and slow the release of water contribute to maintain and improve water availability, water quality, and reduce risks associated with water-related disasters and climate change, as droughts (OECD, 2020). Increasing green spaces and vegetation cover can support these processes in different environments (EEA, 2021). Vegetation reduces the impact of rainfall on soil, slowing the run-off and the open structure of healthy soils facilitates the infiltration of water into the ground, contributing to groundwater recharge through increased infiltration periods (Bonthron et al., 2022; United Nations Environment Programme et al., 2018).

In agricultural land, both smaller interventions, such as creating hedges, tree lines or grass strips alongside crops, and management practices, such as mulching and the use of cover crops, have been demonstrated to enhance water infiltration rates and water content in the soils, to reduce surface run-off, alleviate drought stress and reduce soil compaction and erosion risk (EEA, 2021). Cover crops, such as grass or legumes in rotation between regular crops, can help alleviate drought stress by increasing water infiltration rates and soil moisture and by maintaining the evapotranspiration balance and reducing the effects of extreme radiation, extreme rainfall and strong winds. This act as insulating layer, diminishing the temperature of the surface soil and eliminates the effect of wind, while the heat from the sun is only slowly transmitted from the surface of the residues through the air trapped within the layer of residues to the soil surface. Consequently, the soil surface remains cooler and the rate of evaporation of soil water is slowed down. Hot winds may lead to excessive crop transpiration, increasing water uptake by pants or crops, limiting soil moisture reserve. Wooded vegetation acting as windbreaks could therefore significantly reduce wind speed and reduce crop transpiration rates and the unnecessary loss of soil water (Shaxson & Barber, 2003). Additionally, they can also improve soil quality by increasing soil organic matter and reducing erosion (EEA, 2021).

Floodplains and buffer areas also provide protection against drought and water scarcity by retaining and slowly releasing water discharges and enhancing groundwater recharge (EEA, 2021). Infiltration trenches reduce runoff rates and volumes and can help replenish groundwater and preserve base flow in rivers. They treat runoff by filtration through the substrate in the trench and subsequently through soil (Zeleňáková et al., 2017).

Water-sensitive forests' management (e.g., reducing the density of trees in a stand, shortening the cutting cycles, planting hardwood species, afforestation) can enhance water flow regulation, reduce surface run-off during heavy rainfall events and mitigate water scarcity during drought (EEA, 2021). It has to be underlined that this overview strongly indicates the dominance of local factors, i.e., soil conditions in the Mediterranean playing a more significant role on runoff conditions compared to forests in other regions. This could depend by local conditions as the influences of soil genesis in forested catchments reducing the permeability and retention capacity (EEA, 2015).

Vegetation ecological processes can widely contribute to water management, both in terms of water scarcity and flood regulation (see section on water scarcity and flood).

- **Benefits:**

Vegetation can positively influence the regulation of surface runoff due to their retention potential, storing water in the substrate and making it available for evapotranspiration process. Studies showed that water interception is highest in trees and shrub, while trees and grass transpired around 30% more than shrubs. This can be explained by a higher interception capacity of shrubs compared to grass and by a deeper root depth of trees compared to shrub to sustain transpiration. Additionally, soil evaporation was highest under grass, due to the lower LAI and the deep shading under the trees and shrub canopies, but this remained only a small part of the total evapotranspiration losses (5 %) (Gillefalk et al., 2021).

The introduction of perennials (grasses, agroforestry, managed forestry) or cover crops lead to an increase of infiltration rates by around 60% and 35% respectively (Basche & DeLonge, 2019). Buffer areas and filter strips also provide protection against drought and water scarcity by retaining and slowly releasing stormwater, with a reduction of the overflow up to 50% on average. Performance can be improved following some key design criteria for filter strips. For example, the longitudinal slope should be 1 to 5%, runoff should be evenly distributed and the minimum width should be 6m to obtain good performance values for filter strips (Kõiv-Vainik et al., 2022). A six meter wider buffer strip of trees and shrubs resulted to reduce runoff by 78% compared to no buffer strip (Borin et al., 2010).

Additionally, water retention potential tends to increase along with the extent of forest cover in a water basin. Compared to basins with a forest cover of 10%, total water retention is 25% and 50% higher in water basins where the forest cover is more than 30% and 70%, respectively (EEA, 2015). When a forest cover exceeds 30% of the area of the subbasin, each additional increase of 10% in forest cover decreases runoff by 2–5%, and thus increases water retention by forests. In addition, when forest cover exceeds 70% of the subbasin's area, forests retain 50% more water than subbasins where forest cover is only 10%. Forests decrease runoff by almost 25% more in summer than in winter (EEA, 2015). Coniferous forests in general retain 10% more water than broadleaved forests or mixed forests (EEA, 2015).

4.2. ECOLOGICAL PROCESSES OF CLIMATE MITIGATION

4.2.1. CARBON SEQUESTRATION IN TERRESTRIAL ECOSYSTEMS

Terrestrial carbon refers to carbon, both organic and inorganic, stored in soils and carbon in the vegetation supported by the soil and includes both living and dead forms of biomass. Terrestrial habitats take up and store atmospheric carbon, partly mitigating the increase in atmospheric CO_2 concentration.

Wetlands store the largest amount of carbon per unit area, although this varies widely, followed by forests (EEA, 2021). Peat soils in terrestrial wetland habitats are important carbon pools. Their long-term carbon storage capacity is partly because wetlands rarely burn compared with drier habitats. However, if they are drained, these habitats turn into sources of greenhouse gases, as aerobic conditions lead to the decomposition of the organic substances in the soil. Forests provide large carbon stocks owing to the high carbon content of the above and below ground biomass. The carbon stocks strongly depend on individual habitats and therefore vary within each biogeographical region and across Europe. Carbon is captured not only in tree biomass but also in forest soils. Forest ecosystems cover large parts of the terrestrial land surface and are major components of the terrestrial carbon (C) cycle. Most important, forest ecosystems accumulate organic compounds with long C residence times in vegetation, detritus and, in particular, the soil by the process of C sequestration. Trees, the major components of forests, absorb large amounts of atmospheric carbon dioxide (CO_2) by photosynthesis, and forests return an almost equal amount to the atmosphere by auto- and heterotrophic respiration. However, a small fraction of C remaining in forests continuously accumulates in vegetation, detritus, and soil. Thus, undisturbed forest ecosystems are important global C sinks.

In contrast to wetlands and forests, the carbon storage of agricultural land can be improved using management practices to increase the organic carbon content of soil. However, for heathlands, shrub and semi-natural grasslands, measures to increase carbon storage would reduce their high value for biodiversity, leading to further losses of species richness and abundance. Carbon storage in sparsely vegetated land is highly variable, as it comprises a wide variety of different habitats. Tundra covers only small areas of the EU-27 territory. Through the process of photosynthesis, plants capture atmospheric carbon dioxide and store the carbon in their living tissue, both above and below the ground. Some of this organic carbon becomes part of the soil as plant parts die and decompose, and some is lost back to the atmosphere as gaseous carbon emissions through plant respiration and decomposition. Herbaceous grassland plants contribute to grassland carbon stores primarily by the growth and sloughing of roots, a cyclical process in the case of perennial species and especially when grazed. When such a plant is pruned back, as with grazing, a roughly equivalent amount of roots dies off (adding carbon to the soil) because the remaining top growth can no longer photosynthesize enough food to feed the plant’s entire root system.

The main drivers controlling C fluxes are largely scale dependent and most are related to some aspects of hydrology. At a local scale the depth of the unsaturated zone together with vegetation composition (plant functional type, and leaf area index) are promising predictors for soil respiration through their effects on the availability of electron donors (organic matter) and electron acceptors. At an ecosystem scale vegetation composition is in turn controlled by water level, nutrient availability and pH. At the landscape and regional scale, the percentage of land cover (e.g., peatlands, woodlands, grasslands, etc.), as well as their connections to other ecosystem types through subsurface and surface hydrology and topography affect C export to water and atmosphere. The above illustrates the scale-dependency of the main drivers, making full integration across scales difficult.

Vegetation ecological processes underlying carbon sequestration can contribute also to air pollution and heat stress mitigation, especially in urban environments (see heat stress and air pollution sections).

- **Benefits:**

The carbon sequestration potential of terrestrial ecosystems vary by ecosystem types. For example, peatlands cover <3% of the world's surface, they hold two times global forest biomass pool, and represent more than 30% of the total global soil carbon store. The long-term ability of peatlands to absorb carbon dioxide is dependent on changing climate or management, which can alter peatland hydrological processes and pathways for water movement across and below the peat surface (driving carbon storage and flux) (EEA, 2021; Holden, 2005).

The potential of restoration and management of forests range from 0.4–5.8 Gt CO_2 yr−1 from avoided deforestation and land degradation, as well as a carbon sequestration potential of 0.5–10.1 Gt CO_2 yr−1 in vegetation and soils from afforestation/reforestation". Restoring tree cover to 900 mha could 'draw down' some 200 Gt of carbon at full maturity, and that even if 10% of such an opportunity could be realized restoring forests offers a significant NBS for climate mitigation. Existing forests may have the capacity to sequester carbon of the equivalent of up to 13% of total EU greenhouse gas emissions from the burning of fossil fuels (Seddon et al., 2019).

Meanwhile, grassland ecosystems cover an area of 52.5 million km^2, accounting for ~40.5% of the Earth's land surface excluding Greenland and Antarctica. Grasslands store approximately one third of the global terrestrial carbon stocks and can act as an important soil carbon sink. They also store ~34% of the terrestrial carbon stock (1), with ~90% of their carbon stored belowground as root biomass and soil organic carbon (SOC), thus playing a vital role in soil carbon sequestration. The estimated carbon sequestration potential of world soils lies between 0.4 to 1.2 Gt per year which includes 0.01-0.30 Gt per year from grasslands. Recent studies show that plant diversity increases soil organic carbon (SOC) storage by elevating carbon inputs to belowground biomass and promoting microbial necromass contribution to SOC storage. In grassland ecosystems, ~60% of net primary productivity is allocated belowground. Belowground carbon inputs are more often incorporated into SOC than aboveground inputs because of their chemical composition (e.g., aliphatic compounds and root exudates) and their presence in the soil. On average, root carbon inputs have a SOC stabilization efficiency that is five times greater than aboveground carbon inputs (Bai & Cotrufo, 2022).

4.2.2. CARBON SEQUESTRATION IN AQUATIC ECOSYSTEMS

Aquatic ecosystems from headwaters to the deep ocean are major players in the global carbon cycle. Aquatic carbon sequestration refers to the long-term (century-scale) storage of atmospheric carbon in sediments, biomass and/or water. This includes not only storage of organic carbon in local biomass and vegetated sediments, but also carbon transported away from the source to be stored elsewhere in lakes, rivers, glaciers, groundwaters, and the ocean.

Aquatic ecosystems acting as in carbon sequestration includes mangrove forests, saltmarshes, seagrass meadows, and macroalgal forests, lakes, wetlands, estuaries, coastal blue carbon habitats, and deeper water marine systems. While some ecosystems such as lakes, tidal wetlands, and the ocean store large amounts of carbon, other ecosystems such as rivers and streams may represent long-term sources of carbon dioxide to the atmosphere.
Soils and sediments are often considered the predominant long-term carbon reservoir in aquatic ecosystems, especially in lakes and coastal environments. Carbon sequestration can also occur as alkalinity, dissolved inorganic and organic carbon (DIC and DOC) as well as detritus export beyond the habitat where carbon is fixed. Groundwater and porewater flows can release some of the soil and sediment carbon back to the water column as alkalinity, DOC, CO_2, and methane. The net carbon sequestration ability of aquatic ecosystems depends not only on the net uptake of CO_2 via primary production, but also on the emissions of the powerful greenhouse gases methane (CH_4) and nitrous oxide (N_2O).

Of the biologically ‘fixed’ carbon in marine habitats, marl beds have by far the highest carbon stocks. Lophelia reefs and seagrass beds also have high carbon stocks, whereas flame shell beds, blue mussel beds, brittle star beds and faunal turfs all have low carbon stocks. One of the best-studied benthic habitats in terms of carbon storage and sequestration is seagrass beds, where carbon is stored in the plants and the underlying sediments. Accumulation rates and storage depend on the species, sediment characteristics, depth range of the habitat, age of the seagrass bed, depth of the sediment being sampled and remineralization rates. Carbon storage capacity also varies considerably between geographical areas.
Carbon sequestration in aquatic ecosystems can only take place if photosynthesis exceeds respiration over long-time scales. Measuring this net effect is extremely challenging because photosynthesis and respiration do not necessarily occur at the same place and time and are naturally variable. Indeed, much of the fixed carbon in aquatic ecosystems is transported away from the source, respired along the way, and only a small fraction is stored locally over long-time scales. Global and regional scale impacts such as climate change and eutrophication modify the rates of both photosynthesis and respiration, and thus the net carbon sequestration capacity of aquatic ecosystems. The type of sediment has a significant influence on carbon storage: subtidal sediments that have a high mud fraction have the greatest potential to store carbon. Anthropogenic activities, such as fishing, dredging and installing offshore structures that affect the mixing of sediments, including disturbing the infauna, will affect carbon storage in shelf sea sediments. Unlike rooted coastal vegetation, macroalgae do not directly transfer carbon to marine sediments. Nevertheless, seaweed detritus can deliver carbon to sedimentary sites and may provide a source of refractory dissolved organic carbon. Recent studies indicate that globally important amounts of carbon may be involved in these processes.

- **Benefits:**

The climate mitigation potential of aquatic ecosystems differs across ecosystem types. To illustrate, marine ecosystems are the largest long-term sink for carbon in the biosphere, storing and cycling an estimated 93% of the Earth's CO_2. Most of the carbon in the oceans is inorganic carbon in the form of bicarbonate, carbonate, dissolved CO and carbonic acid. The highest concentrations of inorganic carbon are found in the North-east Atlantic Ocean, which is estimated to store around 23% of anthropogenic CO_2. A much smaller proportion is organically bound, biologically fixed carbon, i.e. carbon in living organisms or decaying matter in organic compounds in water or in sediments. Approximately 1% of the total organic carbon production at the sea surface is estimated to be buried in the sediment, where it can be stored for thousands and even millions of years.

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4.3. ECOLOGICAL PROCESSES OF NATURAL HAZARDS

4.3.1. SLOPE STABILISATION

Avalanches and landslides are associated with mass movement of snow, rock or soil on sloping terrain. Improving stability of slopes and sites, reducing velocity of mass movements and reducing surface runoff are key measures to contrast and limit the risk and impact of landslides and avalanches phenomena.

Retaining and restoring forest cover, especially on steep slopes, are beneficial for the maintenance of safe physical environments, while also encouraging maintenance or growth of vegetation (EEA, 2021). Forests prevent and mitigate gravitational natural hazards by retaining solid material on site, therefore limiting mass displacement that could initiate avalanches or landslide initiation, and by breaking down, narrowing laterally and eventually reducing the propagation of the mass movement (Perzl et al., 2021). The breakage, uprooting and overturning of trees as well as the entrainment of coarse woody debris and snow deposition behind trees may cause a loss of energy and reduce runout lengths of medium to large avalanches originating from sites above the timberline or from large clear-cuts (Gubler & Rychetnik, 1990; Perzl et al., 2021; Schneebeli & Bebi, 2004; Teich et al., 2012).

In case of avalanches, both standing and fallen trees stabilise the snowpack, preventing avalanches or at least reducing the size of the slab that is released. In the forest, snow falls from the trees, and vegetation canopy can change the energy balance of the snow surface. As a consequence of these factors, the forest snowpack is subject to small-scale inconsistencies, and the weak layers that play a critical role in the release of avalanches can form less easily. Furthermore, the forest is able to stem and stop small avalanches (Teich et al., 2012).

For landslides mitigation, deep-rooted trees and shrubs have a primary role in reducing the occurrence of shallow, strengthening soil layers and improving drainage. The effectiveness of vegetation in protecting slopes depends on the architecture of the root system, rooting depth and the roots' density and distribution. Branching, root elasticity and strength, and root-soil cohesion also affect the roots' reinforcement properties. Root depth and distribution are the most important properties for slope stabilization because the deeper the tree roots extend (ADPC, 2020). However, the root-soil cohesion decreases rapidly as water saturation increases. In shallow soils, roots may penetrate the entire soil depth, providing anchors into more stable layers while dense lateral roots stabilize soil surface layers against landslides. Therefore, forests can play a role in slowing and blocking smaller debris flows and rock falls by forming a physical barrier. Additionally, transpiration via extensive root systems also reduces soil water content and landslide risk (Forbes & Broadhead, 2013). The beneficial hydrological effects of vegetation relate to its ability to extract water from the soil and intercept rainfall, allowing rain to evaporate before reaching the soil. Vegetation cover can help to drain excess water from and to reduce pore-water pressures within the slope by extracting water from the roots and transpiring through the leaves (ADPC, 2020). Similarly, enhancing groundwater management can promote soil compaction and reduce peat oxidation. However, deep landslides resulting from continuous heavy rainfall or earthquakes are less likely to be prevented by vegetation (Hamilton et al., 2008).

More in general, the vegetation roots action for slope stabilization can address soil erosion control (see soil erosion section).

- **Benefits:**

Forest conditions that reduce likelihood of avalanche releases include a crown coverage of >30%, the absence of gaps >25 m in length, and an increased terrain roughness associated with lying or standing trees that exceed snow-depth (Bebi et al., 2009).

The protective effect of forests is more dependent on stem density and surface roughness than clearly connected to the canopy cover, for which most of the guidelines report the need of a stem density higher than 15% (Perzl et al., 2021). Forest density is characterized by the number of stems per hectare and has a significant impact on avalanche runout for the class of trees with a mean diameter at breast ranging between 1 and 15 cm. Small trees seem to be especially important in the starting zone and on the first 200 m of the avalanche path for limiting avalanche runout. Smaller bending stresses and the complete deflection of such trees consume avalanche energy resulting in a significant deceleration of small avalanches Additionally, the type of forest can influence differently the avalanche developments. Deciduous coniferous forests have lower effects than evergreen coniferous and mixed forests, which usually contain a high number of small diameter stems, because of an increased crown biomass, higher interception effects, and, therefore, less snow entrainment in the avalanche path (Teich et al., 2012).

For landslides risk mitigation, vegetation resulted to play a key role. Studies in different parts of the world showed how vegetation reinforced slope stability, increasing the factor of safety (FOS) by 22–34% (Emadi-Tafti et al., 2021; Tsige et al., 2020; Zayadi et al., 2022). This is particularly effective when vegetation coverage is uniformed and provided by mixed species, while is less effective at the increase of slope angle.

4.4. ECOLOGICAL PROCESSES OF ENVIRONMENTAL MANAGEMENT

4.4.1. AIR PURIFICATION

Air quality is linked to a series of complex interaction between land and atmosphere, where vegetation plays a key role (EPA, 2015). Vegetation can act as a filter for many pollutants, such as carbon monoxide, ozone, particulate matter or nitrogen oxides. Vegetation act through its metabolism, which is based on the gas exchange between plant tissues and the environments (Wróblewska & Jeong, 2021). Plants can take up of gaseous and particulate matter from the atmosphere through their absorption into plan biomass, metabolizing them into non-hazardous forms (Biswal et al., 2022; Bolan et al., 2011; Lamb et al., 2014). The main processes carried out by vegetation are photosynthesis and respiration. They absorb air through their stomata, uses gaseous substances for their metabolism, and release again processed and clean air through the stomata.

Similar processes are also underlying the carbon sequestration potential of vegetation (see carbon sequestration section).

These biochemical processes work in combination with dispersion and deposition processes, in which vegetation is acting as a physical barrier that decrease and trap air pollutants concertation (Barwise & Kumar, 2020; Biswal et al., 2022; Janhäll, 2015; Morakinyo & Lam, 2016). Dispersion mechanisms mainly refers to the changes of trajectory and velocity of gasses and particular matter through plants physical structure (Diener & Mudu, 2021). Dry deposition refers to the deposition of pollutants on plant surfaces, such as leaf, where stomata uptake substances and, reacting with water, start metabolism processes (Janhäll, 2015; Price et al., 2015; Pugh et al., 2012). Additionally, some species can act through bioaccumulation of pollutants and heavy metals, particularly critical in industrial areas, i.e. by retaining these substances into their tissues (Menon & Sharma, 2021).

A number of studies highlighted that the interactions between individual plants and air quality are complex and that species and vegetation distribution can differently influence the effects (Churkina et al., 2015; Sæbø et al., 2012; Willis & Petrokofsky, 2017). Deposition is largely determined by related variation in plant macromorphology and in the range of traits (including leaf physiology and micromorphology) that contribute toward surface resistance (Barwise & Kumar, 2020). As well, filtration vegetation barriers must be dense enough to offer large deposition surface area and porous enough to allow penetration, instead of deflection of the air stream above the barrier. The choice between tall or short and dense or sparse vegetation determines the effect on air pollution from different sources and different particle sizes (Janhäll, 2015).

- **Benefits:**

The action of vegetation for air purification is particularly relevant in urban areas. Here air pollution has been linked both with a reduction of urban greenery and increase of various health impacts such as cardiovascular diseases, premature mortality and children's health issues (Menon & Sharma, 2021).

Increasing vegetation in urban areas can include different actions (e.g. green roofs, vegetation roads, urban parks) and has shown positive impacts on air pollution. Generally, the capacity of urban vegetation in reducing typical air pollutant concentrations resulted to be around 16-27% for particulate matter (PM), 14-36% for nitrogen oxide and 20-48% for sulfur dioxide (Gong et al., 2023). Literature seems to agree on the benefits of green infrastructure in cities, which is locally expected to reduce the ambient PM10 by 26% (Wróblewska & Jeong, 2021). Studies on roadside vegetation particularly observed and estimated reduction of fine particulate matter between 30 and 60% and reduction of nitrogen dioxide up to 40% (Al-Dabbous & Kumar, 2014; Pugh et al., 2012). Although, the exposure reductions through dispersion can vary greatly with the exact location of exposure measurement, and spatial concentration patterns can be strongly affected by the local wind. Using long-term averages, the highest dispersion values have been found for PM1 (52%), PM 2.5 (44%) and PM10 (35%) (Ottosen & Kumar, 2020), and PM1 resulted to be blocked most effectively compared to PM10 and PM2.5 (Abhijith & Kumar, 2019). As well, recent studies found reductions of up to 63% for black carbon and 14% for PM2.5 (Abhijith & Kumar, 2019; Santiago et al., 2019).

Referring to PM concentrations, vegetation can also act as a physical barrier. It has been noticed a close relationship between source of contaminants and the presence of vegetation, showing a reduction of PM levels at distance of 7-12 m for oblique winds and 8-18m for perpendicular winds (Wróblewska & Jeong, 2021).

Where wider strategies and plans for regreen urban areas has been implemented, positive impacts on air quality have been registered. For example, 39% of Stuttgart's territory is protected under nature conservation orders (Urban Climate Stuttgart, 2008); more than 60% of the city surface is green; they planted around 100.000 trees in parks, open spaces, and along the streets; they created 5000ha of forest and woodland and 300.000 m2 of green roofs, as well as kilometers of green tram tracks. In the recent year, the environmental quality increased. The exceedance level of NO_3 and PM10 in the air decreased in the last years, as well as the day of high heat stress.

4.4.2. WATER POLLUTION REDUCTION

Water pollution is the contamination of water sources by substances which make the water unusable for drinking, agricultural production (irrigation) and recreational activities, as well as undermining habitat quality and biodiversity. As for air purification, vegetation can play a key role in cleaning water by bioretention and buffering processes in different environments.

Plants are viable for use in the remediation of both organic and inorganic pollutants, by the so-called phytoremediation process. Through phytoremediation, plants and microbes volatilize, immobilize, extract, and degrade the contaminants in soil and water. This process implies different mechanisms performed by different parts of the plant: i) phytodegradation, in which plant tissues degrade organic pollutants by enzymatic action; ii) phytovolatilization, is the contaminant removal carried out via plant transpiration; iii) phytostabilization, that allow the bioavailability and mobility of contaminants by their absorption onto roots; iv) rhizofiltration, that imply the absorption and sequestration of pollutants by roots in aquatic media; iv) phytoextraction or phytoaccumulation, that imply the uptake of harmful metals by roots and their deposit into plant cells or tissues (Delgado-González et al., 2021; Kristanti & Hadibarata, 2023). Phytoremediation capacity of a plant depends, however, on molecular and physiological mechanisms, that can influence the tolerance to pollutants and accumulation capacity of plants.

At wider scales, the use of different solutions based on vegetation contribute to water quality by means of phytoremediation processes.

In freshwater ecosystems, vegetation buffer strips and wetlands purify water by reducing water flow velocity and absorbing substances and nutrients through plants roots. Particularly vegetation buffers along agricultural channels and crops contribute to removing fertilizers and pesticides, especially trapping and assimilating nitrates and phosphorous, by reducing surface runoff form fields and filtering surface, ground water, and stream runoff (Borin et al., 2010; Lovell & Sullivan, 2006). Extensive root systems of perennial plants (in buffer area) hold soil in place, allow greater infiltration of water, and trap the sediment entering from cultivated areas. Windbreaks containing woody plants also help minimize soil loss from fields by reducing wind current (Nordstrom & Hotta, 2004). Wetlands purify water through flow velocity reduction, microbial degradation of organic matter, microbial transformation, and nutrient retention and uptake by plants (Vymazal, 2011). Main processes are driven by the soil/sediment moisture regime and vegetation present which can enable nutrient fluxes to be retained and/or transformed. Key retention mechanisms are related to clay and organic adsorption, iron and aluminium co-precipitation in acid soils and calcium crystallization in neutral conditions. Under aerobic conditions, organic nitrogen can be mineralized, while under anaerobic conditions, nitrification is repressed and ammonium accumulates in soils or sediments (B.-M. Vought et al., 1995).

Agroforestry can address both point and non-point agricultural pollution sources, since they are able to reduce leaching to groundwater aquifers and also absorb pollutants from unsaturated or saturated-low depth zone through their tree roots (Jose, 2009). Other studies support that water infiltration and soil retention of quantity and quality of agricultural leaching and drainage to groundwater are improved in agroforestry systems (Bharati et al., 2002; Pavlidis & Tsihrintzis, 2018). Poplar and willow trees are generally known and have been reviewed for their ability to absorb pollutants, including pesticides and their degradation products, and immobilize them in woody parts of the tree (Licht & Isebrands, 2005).

- **Benefits:**

The contribution of buffers and wetlands for water quality has been primarily investigated for the removal of nutrients, such as nitrate and phosphorus. Wetland and buffers can reduce nitrate concentration in a range between 40 and 94% before entering a stream. Phosphorus runoff can be reduced in vegetated buffer strips, but removal rates vary greatly (from 25 to 95%) depending on the percentage of soil-bound versus soluble phosphorus, length of buffer strip, plant cover, and hydrologic conditions (Lovell & Sullivan, 2006). This is also true for pesticides that have different mobility and binding properties. When properly maintained, buffers can remove up to 97% of soil sediment before it enters a stream (Lee et al., 2003; Lowrance & Crow, 2002).

Numerous laboratory-scale and field-scale experiments have been carried out to examine the effectiveness vegetation as bioretention system for removal of diverse pollutants, as total suspended solids, nutrients (total nitrogen and total phosphorous), heavy metals and organics from stormwater. Promising results showed removal capacity above 40% for suspended solids and nitrogen, above 70 % for phosphorous and above 30% for organic matter (Biswal et al., 2022).

Bioretention systems are widely used also in urban areas on roadside, where their contribution in removing of suspended solids, nitrogen and phosphorous could be quite high, around 91 - 97%, 38 - 57%, and 86 - 94%, respectively (Shrestha et al., 2018). Studies also showed the potential of bioretention systems to remove metals as Cu and Pb (around 90%) and other contaminants as PCBs (above 45%) (Gülbaz et al., 2015). Together with bioretention systems, green roofs and constructed wetlands could also contribute to water quality, potentially removing nitrogen above 50%, phosphorous above 25-30% and heavy metals above 60%, according to different cases (Biswal et al., 2022).

4.4.3. WATER STORAGE AND GROUNDWATER RECHARGE

Improving aquifer recharge and rainfall interception and storage help to alleviate water stress and scarcity.

The presence of vegetation can enhance these processes. The combination of channels and ponds, that can collect and store water when available, with trees and shrubs coverage can enhance the infiltration capacity of the soil. Root growth increase the permeability of the soils that can absorb and retain water and facilitate the percolation of water to the aquifer. In agricultural land, forested infiltration areas or managed aquifer recharge can support this function, while limiting the needs of water for irrigation and acting also as carbon sink (Agostinetto et al., 2013; Mezzalira et al., 2014).

Similarly, in urbanized areas, public and private green space can increase water storage capacities. The run-off of concrete surface events accounts for nearly 95% of the total precipitation (Zölch et al., 2017). Water-sensitive urban planning (e.g. permeable paving of footpaths, car-parking areas and playgrounds, linked to underground storage tanks, infiltration basins, retention ponds, rain gardens, porous asphalt, constructed wetlands and vertical greening) helps to reduce water run-off, attenuating flood peaks and enhancing groundwater recharge by converting to green impermeable surfaces. Urban vegetation and permeable surfaces intercept rainfall, which is slowed as it flows through roots and a drainage layer. Some of the rainwater is stored in the drainage layer and taken up by the vegetation.

Processes underlying small NBS functioning for water scarcity mitigation can contribute similarly to urban pluvial flood control (see pluvial flood section).

Rainwater harvesting measures, including ponds, swales, rain gardens, green roofs linked to storage cisterns, are used in both agricultural areas and urban environments to mitigate both flooding and water scarcity, enhancing the availability and quality of water (EEA, 2021). Ponds can serve to collect and store water during precipitation events, providing additional storage capacity to retain runoff and release this at a controlled rate once the risk of flooding has passed (Zölch et al., 2017). Ponds can also uptake water from rivers during winter, when usually water is available, to be used during dry or irrigation season, without undermining minimum ecological conditions of the rivers (Staccione et al., 2021).

Ecological processes contributing to water scarcity issues can also address droughts on a larger scale (see drought section).

- **Benefits:**

Vegetation and Nature-Based Solutions could increase water retention during rain events, both in agricultural and urban environments.

In agricultural land, studies estimated that forested infiltration areas realized in Northern Italy can infiltrate around 5.000 m3 of water per hectare per day, and almost 1 million m3 of water in one year (Agostinetto et al., 2013; Mezzalira et al., 2014). Natural water retention ponds increase the volume of water availability for irrigation, by maintaining the minimum ecological flow in the river, also in worsen climate change conditions. A 1Mm3 natural water pond could support a surface of almost 200 ha of high-water-demanding crops (Pistocchi, 2022; Staccione et al., 2021).

In urban areas, water retention capacity is strictly related to the climatic conditions and Nature-Based Solution used, contributing both to contrast water scarcity and run-off. Small-scale systems have been found to decrease runoff by 30-65% for porous pavements, up to 100% for rain gardens or up to 56% for infiltration trenches (Ruangpan et al., 2020). Permeable pavements show higher water retention capacity of pervious pavements in warm and wet climatic conditions, where average reduction of water run-off is around 80% (Kõiv-Vainik et al., 2022). Bioswale capacity could range between 19 and 85%, depending on climatic conditions, season, swale type and design, with a potential runoff reduction of 23-48% (Kõiv-Vainik et al., 2022). Water retention capacity of green roofs can be largerly above 50% (Meng, 2022; Whittinghill et al., 2015). A heavy rain event of short duration (e.g. 30 min) could be completely retained by a dry green roof and in general reduce runoff volume by up to 70 % and peak flow volume by up to 96% (Ruangpan et al., 2020). Additionally, soil conditions can influence the retention capacity. When rainfall intensity is low and the roof substrate is dry, there is almost no runoff and the retention rate is up to 100%, while when rainfall is intensive and the substrate is already saturated with water – runoff will be instantaneous, and the runoff retention rate could be very small (Kõiv-Vainik et al., 2022).

4.4.4. COASTAL EROSION CONTROL

Coastal erosion is the process by which local sea level rise, strong wave, and coastal flooding wear down or carry away rocks, soils, and/or sands along the coast. The shores' resistance to erosion can be increased by nature-based coastal protection measures, such as planting vegetation or adding sediment, that stabilize costal structure and enhance the natural ability of shorelines to absorb and dissipate storm and wave energy without interfering with natural coastal processes.

Terrestrial coastal vegetation restoration strengthens the stability of the coastal morphology: roots and reefs retain soil and stabilise sediments in shallow coastal areas (EEA, 2021). Root systems play a major role for the anchorage of vegetal organisms, while also functioning as soil stabilization. The intricate network created by the tree roots below the surface has been demonstrated to stabilize the sediment and reduce landslide erosion by retaining soil particles and increasing shear strength the soil medium (Perricone et al., 2023). This action is particular important in the dune system. Dunes are a protective feature that provide sand buffer and protect the land from waves and flooding, acting also as sand storage areas, supplying sand to eroded beaches. Dune grass and other vegetation can help stabilize the shoreline. The roots of these plants will absorb rainwater and help stabilize the sand, lessening the effects of erosion (Figlus et al., 2014).

Underwater vegetation, such as seagrasses, can retain sediments and support erosion control (EEA, 2021). Hence, the restoration of coastal habitats (e.g. seagrass beds, wetlands, intertidal mudflats, saltmarshes, coral reefs) act as a natural defense against shoreline erosion and flooding. Seagrasses are subtidal plants that can build large meadows. Seagrass provides a potential Nature-Based Solution to reduce wave-generated erosion and extend the timespans for coastal benefits at nourishment sites. Seagrass beds are ecologically important marine habitats that stabilize sandy substrates through the binding effects of their roots and rhizomes and, through the hydrodynamic buffering capabilities of their leaves, dissipate wave energy, tidal currents and storm surges (W. Chen et al., 2022). At the same way, macroalgal communities and halophytic reeds have also been found to perform erosion protection by modifying near-surface current (Feagin et al., 2019). In the oceans, both coral and oyster reefs constitute an effective defense from erosion by the attenuation of wave energy, the production and retention of sands, increasing sediment deposition behind the reef, stabilizing the shoreline. The reef ability in wave attenuation depends on its height and roughness: taller crests can mitigate higher waves, and coral species with rough texture are able to reduce wave energy more than smooth-textured ones (Perricone et al., 2023).

Lastly, near-shore enhancement of coastal morphology contributes also to ensure soil stability, greater dissipation of wave energy and resistance to erosion, while providing opportunities for recreation, water purification and biodiversity conservation (EEA, 2021). The placing of additional sand on the beach serves as a buffer against erosion, the deposited sand will be transported to and along the shore, providing an input to the coastal sediment budget.

- **Benefits:**

Vegetation resulted to reduce wave run up erosion by approximately 40% for dunes (Feagin et al., 2019). Mangrove species with dense vegetation and aerial roots are most effective at reducing wave height, with a reduction between 13–66% over a 100-m-wide mangrove forest and 50–100% over a 500-m-wide mangrove forest (Perricone et al., 2023).

A dense seagrass meadow is able to reduce wave height by 40% during storm events. The combination of shoreface nourishment and seagrass planting significantly reduced the wave height, with higher effects when seagrass meadows coincide with the wave breaking zones, with a reduction of wave height up to 1.3m (around 80%), leading to a sand erosion reduction of around 40% (W. Chen et al., 2022). The presence of seagrass meadows of Zostera marina produces an average attenuation of 32 % of the storm peak with a maximum attenuation of 89 % in incoming wave height, reducing beach erosion volumes up to 55 % (Unguendoli et al., 2023).

Healthy coral reefs have been discovered to dissipate 97% of wave energy and 84% of wave height. Major reductions are provided by the crest (i.e. the tallest part of the reef) due to the wave breaking phenomena, while the remaining energy and height is mitigated by the reef flat (i.e. the first hundred meters after the crest). Oyster reefs are capable of 51–90% reduction in wave height and 76–99% reduction in wave energy at shore (Perricone et al., 2023).

4.4.5. SOIL EROSION CONTROL

Soil erosion is the deterioration of land due to the removal of its particles, by dislodgement, transportation, and sedimentation. This occurs when soil is left bare and exposed to wind and water that can erode it. Sediments are transported to storm drains and surface waters and can choke aquatic life, increase water temperatures and degrade water quality. The loss of soil leads to a decline in organic matter and nutrient content, a breakdown of soil structure, and a reduction of the available soil water. Nutrient and carbon cycling can be significantly altered by mobilization and deposition of soil (Quinton et al., 2010).

Soil erosion can be particularly intense in agricultural landscapes and affecting the watercourses due to anthropogenic pressures (Eurostat, 2021). Here, soil management strategies that are focused on reaching a healthier soil, like organic farming, aim to improve soil organic matter content and structure to facilitate higher infiltration rates and lower runoff and erosion. Other practices, such as mulching, no tilling farming, intercropping and the use of cover crops, are more focused on the conservation of soil surface (Keesstra et al., 2018). They contribute to increase infiltration rates and the water content in agricultural soils, alleviate drought stress and reduce soil compaction and erosion risk, support agricultural productivity while also benefiting groundwater recharge, soil fertility and disease regulation (EEA, 2021).

Mulching consists in the application of organic material on the soil surface and is extremely important to preserve soil quality and conservation, halting land degradation. Mulching reduces rainfall kinetic energy, preventing sediment detachment, contributing to soil erosion control.

Organic mulch, when decomposing, mainly increases the soil organic matter and can strongly influence the physical properties. A short-term application does not impact soil bulk density, while high doses of organic mulches or their long-term application significantly reduce soil compaction. These changes are due to the soil organic matter increase, that makes the soil aggregates persistent to external forces and groups them into larger clods. This helps also to control soil dust. In these soils, water infiltration is high, and sediment and water losses are reduced. Finally, mulch mitigates the loss of nutrients, organic matter, soil coarsening, soil productivity decline, and more severe problems like microplastic pollution (Bogunović & Filipović, 2023; Keesstra et al., 2018). Mulching is using in combination with no-tilling farming, a conservation practice that grows crops without disturbing the soil when planting seeds.

Cover crops (grass or legumes in rotation between regular crops) can help alleviate drought stress by increasing water infiltration rates and soil moisture. They can also improve soil quality by increasing soil organic matter and reducing erosion. Cover crops help reduce the effects of extreme radiation, extreme rainfall and strong winds, limiting the soil losses (EEA, 2021).

Planting and keeping trees next to farmland can protect crops from erosion due to heavy rain. Vegetation ate margin of crops and along water channels create buffer strips, that are vegetated areas consisting of bands of multi-annual herbaceous species and/or tree and shrub. Buffer strips limit soil erosion, trap sediments, and enhance the filtration of potential nutrients or pollutants flowing into water bodies and contribute to improve water quality and the ecological status of lakes and surrounding areas (Climate-ADAPT, 2022). Vegetation buffers have been used for many years to reduce soil loss by wind and water erosion. Conservation buffers employ perennial plants to combat this problem. Extensive root systems of perennial plants hold soil in place, allow greater infiltration of water, and trap the sediment entering from cultivated areas. Windbreaks containing woody plants also help minimize soil loss from fields by reducing wind current (Lovell & Sullivan, 2006). Strips with perennial vegetation, such as grasses, trees and/or shrubs, can counter soil erosion via filtration of larger sediment particles, and by increasing soil stability through increased root density (Haddaway et al., 2018).

Similarly, on hill and mountain slope, vegetation roots action can contribute to slope stabilization and reduce landslides risk (see slope stabilization section).

- **Benefits:**

When properly maintained, vegetation buffers can remove up to 97% of soil sediment before it enters a stream (Lovell & Sullivan, 2006). Studies showed that runoff and sediment reduction both increased as the vegetation coverage increased and tended to be stable when vegetation coverage exceeded 60%. Vegetation provided a greater benefit for sediment reduction than for runoff control under intense rainfall. Grasslands were generally more effective in reducing sediment than other vegetation types. Forests, grasslands, and scrublands were most efficient in soil erosion control on 20°–30°, 0°–25° and 10°–25° slopes respectively. Grasslands and scrublands generally performed better with respect to soil erosion control on moderately coarse soils, whereas forests were most effective on medium-textured and moderately fine soils (Wu et al., 2020).

Mulching and no-till farming can reduce soil erosion by more than 80 percent, which has the added benefit of protecting water quality by keeping sediments on the land and out of bodies of water (Bertram et al., 2017).

Natural flood management interventions and ponds can trap masses of sediment, phosphorus, and organic carbon. Analysis showed that, even with a footprint <1% of the catchment area, they can drain 44% of the total land area and capture the equivalent of 15% of the total suspended sediment yield, 10% of the total phosphorus yield, and 8% of the particulate organic carbon (Robotham et al., 2023).

4.4.6. HABITAT/ECOSYSTEM CONDITION

Environmental degradation undermines biodiversity by reducing biological diversity, resources and habitats availability and quality. Protecting and restoring habitat, while maintaining and supporting habitat varieties, contribute to maintain biodiversity and ecological functions in different environments.

In agricultural land, the use of vegetation buffer along crop fields contribute to increasing biodiversity of both flora and fauna, providing habitat for wildlife and supporting pollination, as well as by maintain water and soil quality. This can be an be features such as fallow land, terraces, field margins, hedges, trees, buffer strips and land sown with catch crops or nitrogen-fixing crops (Pe'er et al., 2017). Vegetation in riparian areas can help regulate light and temperatures, allowing wildlife access to food and water and creating a wide variety of habitats—all contributing to ecological diversity (Lovell & Sullivan, 2006). In addition to improving the ecological conditions for terrestrial species, riparian buffers, particularly those containing trees, can also contribute to the health of aquatic species by cooling stream waters, providing food and habitat, and increasing the dissolved oxygen in water (P. Davis & Hitchings, 2000). Similarly, the implementation of natural water retention ponds for agricultural irrigation has shown benefits for biodiversity in several cases, serving as refugee for birds and wildlife animals, as well as for fishes, mollusks and pollinators (Staccione et al., 2021). Restored and constructed wetlands have the have the potential to increase local biodiversity by providing food and breeding sites (Sebastián-González et al., 2010; Semeraro et al., 2015).

In coastal areas, salt marshes, aquaculture fishponds, mine impoundments, gravel pits, or irrigation ponds are able to provide alternative or substitute habitats for waterbirds communities as well as for amphibians, plants or invertebrates. Wetlands and reefs promote fisheries production by providing important habitats for juvenile fish, shellfish and crustaceans (Temmerman et al., 2013). Wetlands are home to vegetation, fish and amphibians, besides being used for reproduction by insects and birds. More than two thirds of the fish consumed in the EU rely on coastal and inland wetland areas for their existence (EEA, 2017).

In the urban environments, the creation and restoration of green spaces are key actions for biodiversity. Vertical greening systems, green walls and green roofs have vital function in high density urban areas, becoming a food source, nesting or breeding opportunity for birds, like sparrows, blackbirds and greenfinches (Perini & Rosasco, 2013). As well, in the face of global habitat loss, green spaces in cites may provide an important haven for biodiversity and may benefit both locally extirpated as well nationally threatened species (Ives et al., 2016; Soanes & Lentini, 2019). Increasing the richness, cover or density of native plants in urban green spaces has been repeatedly linked to increases in animal biodiversity (Berthon et al., 2021; Parsons et al., 2006; Wilkinson, 2006).

Benefits:

Funded by
the European Union

The restoration of terrestrial ecosystems resulted to increase biodiversity by an average of 20% compared to unrestored sites, but decreasing its variability by an average of 14% (Atkinson et al., 2022). Restoration of semi-natural (e.g. sites subjected to thinning, burning, mowing) and agricultural land produced higher mean biodiversity increases (compared with degraded unrestored systems) than other past land-uses. Particularly, the restoration of agroecosystems (such as patches/strips of wildflowers, creating habitats on riparian margins and on the edges of crop fields, organic farming, and revegetating with native species) contributed to an overall biodiversity increase for all organism types by an average of 68% worldwide, ranging from 54% for vertebrates to 79% for invertebrates; the recovery levels for soil microfauna and vascular plants fell within the same range (Barral et al., 2015). At smaller scales, Nature-Based Solutions like urban park development and river restoration can lead to an estimated 67% increase in species richness (Jorgman et al., 2022; Key et al., 2021).

Protected areas resulted to play a key role for biodiversity conservation globally. Species richness in protected areas is 10.6% higher and abundance 14.5% higher compared to unprotected sites (Gray et al., 2016). However, the higher positive influence seems to be related to differences in land use between protected and unprotected sites.

4.4.7. ECOLOGICAL CONNECTIVITY AND FUNCTIONALITY

Changes in land use and the expansion of infrastructures and urban areas led to the loss of many habitats, deterioration in the quality of the remaining habitats and increased fragmentation of the landscape. As a result, both the movement of animals and the dispersal of plants have become more restricted and the connectivity between habitat patches has been reduced, with a consequent reduction of populations' size and genetic variability, a lower resilience in facing environmental changes and an increase in extinction risk (Travers et al., 2021).

In an increasingly fragmented and degraded natural environments, another way to promote ecosystem quality and functioning, in order to support biodiversity, is to restore and maintain landscape and habitat connectivity. Building ecological networks, with multiple, diverse and interconnected corridors across the landscape would allow species and materials movements and dispersal throughout the space and at different scales.

Corridors can benefit populations by increasing the gene flow between isolated populations and facilitate the re-colonization of habitat patches where species have become locally extinct. However, concerns on possible negative effects of corridors have been raised, since they could facilitate the spread of diseases and of invasive species, produce edge effects and even create barriers between habitats (Travers et al., 2021).

Corridors are widely used in conservation practice at a range of spatial scales from tens of meters to hundreds of kilometers. Several interventions have been planned to create habitat corridors on national, international and continental scales. As well, landscape-scale conservation is starting to replace the protection of isolated patches with conservation of corridors and connection among protected areas (EC, 2020; Keeley et al., 2019; Staccione et al., 2023). Conservation buffers can promote wildlife health by providing corridors that connect wildlife habitats and allow safe movement between fragmented patches of natural areas, crossing roads and urbanized areas (Henry et al., 1999; Schuller et al., 2000).

Reconnection of habitats could refer also to river ecosystems, meant as the reconnection of rivers with its floodplains or with a system of channels. Restoring river network allows to enhance riverine processes, making the ecosystem healthier and maintaining natural functions that are critical to the well-functioning of the ecosystem. These measures can increase infiltration of flood waters, which raise the water table, improving riparian forest health; create riparian habitat for wildlife, including birds, and inundated habitat for invertebrates and fish; improve abiotic and biotic functioning, as well as climate regulation functions; and promote biogeochemical functions associated with floodplains as water purification and nutrient cycling. Such corridors can also be found in coastal ecosystems such as MPA networks.

- **Benefits:**

Corridors could increase movement between habitat patches by approximately 50% compared to patches that are not connected with corridors, and this is especially for the movement of invertebrates, nonavian vertebrates, and plants than they were for birds (Gilbert-Norton et al., 2010).

Connected urban vegetation and parks resulted to positively influence biodiversity, by increasing species richness across many taxa, especially in comparison to isolated gardens or green spaces (Beninde et al., 2015). In Singapore, The Connector Park project, creating vegetated corridor system connecting various urban parks, attracted 550 species of birds and butterflies to the area (Newman, 2014).

A study a larger scale, in the Savannah River in South Carolina, monitored the effects unconnected and connected habitats, reporting 2% lower extinction rates and 5% higher colonization rates in the connected habitats (Damschen et al., 2019).

Projects on the restoration and reconnection of rivers and floodplains demonstrated how riparian and aquatic ecosystems can respond to increased floodplain connectivity. Measures as the partial removal and setback of levees renewed flooding enhanced flow diversity across the floodplain, which in turn promoted riparian vegetation establishment (Serra-Llobet et al., 2022).

4.5. ECOLOGICAL PROCESSES OF NOISE POLLUTION MITIGATION

4.5.1. NOISE MITIGATION

Environmental noise is a pervasive pollutant that adversely affects the health and well-being of European citizens and wildlife (EEA, 2020). The World Health Organization (WHO) defines noise above 65 decibels (dB) as noise pollution, but effects can start to appear at levels as low as 40 dB(A) for terrestrial. Anthropogenic noise pollution is a threat to terrestrial and marine wildlife causing a range of physiological and behavioral responses. Terrestrial and marine species rely on acoustic communication for important aspects of life, such as finding food or locating a mate. Anthropogenic noise sources can potentially hinder these functions, and as a result, negatively affect species diversity, population size and population distribution (EEA, 2020).

Noise may cause changes for wildlife in sleep patterns, space use, movements, efficiency of foraging and provisioning, vocal communication, mating behavior, territorial defense, vigilance, and predator avoidance behavior. For example, there is substantial evidence that noise affects many behavioral responses in birds as they have been shown to avoid sites with loud traffic.

Singing behavior is altered close to noise sources. In particular, birds' dawn chorales were found to begin earlier in areas close to airports and roads (Dominoni et al., 2016). Other effects on their singing include singing shorter songs and raising the frequency of their calls to reduce acoustic masking (Gentry et al., 2017). Not only their singing but also their ability to predict other birds' aggressive intent has been found to be affected by noise (Kareklas et al., 2019).

Negative behavioral and physiological responses have been documented in marine species. The effects observed in marine mammals include changes in vocalization, stress, changes in respiration, increased swimming speed, orientation away from the sound source, sudden and longer dives, shifts in migration paths, strandings, changes in foraging and breeding behavior, and auditory physiological damage (ETC/ICM, 2019). Chronic exposure to noise affects fish and invertebrates in a similar way and can result in impaired growth and reproductive processes, stress, an increase in heart rate, increased motility, migration and hearing loss (Weilgart, 2018). These physiological and behavioral responses can lead to reduced reproductive success, increased mortality risk and emigration, resulting in reduced population densities (C. D. Francis & Barber, 2013). However, the effects of traffic noise on animals vary markedly among individuals as well as within species, owing to a variety of factors, including age, sex, sensitivity and prior exposure. Likewise, the impacts also depend on noise characteristics, such as noise intensity, duration, noise frequency and the type of noise.

Therefore, as a result of these differences between species and between noise characteristics, it has been difficult to set a noise level that avoids ecological consequences, although, at least for terrestrial environments, effects have been documented for low levels of environmental and transport noise starting between 40 and 50 dB(A) (Shannon et al., 2016). Studies also indicate that biological responses of marine wildlife can occur at noise levels commonly emitted by underwater sources, such as shipping, oil and gas prospection, sonars, pile driving, dredging devices, naval exercises and offshore windmills (Shannon et al., 2016). However, despite observed differences in impacts on different species and across different noise sources, there is substantial evidence that anthropogenic noise not only affects a few species regarded as sensitive to noise but a wide range of terrestrial and aquatic species that inhabit very different ecosystems (Kunc & Schmidt, 2019).

- **Benefits:**

Reducing environmental noise is a key objective under the Seventh Environment Action Programme (7th EAP) and the Environmental Noise Directive. Mitigation of noise pollution contributes to decrease the negative effects on wildlife. For example, noise mitigation can help to avoid reducing reproductive success, and prevent increments in mortality, in emigration and in lower population densities.

Measures to target air pollution in European cities often offer co-benefits in terms of reducing environmental noise. However, not all interventions are equally effective for both stressors. Nevertheless, cost-benefit estimations for mitigation measures can be more favourable if the positive impacts of addressing both air quality and noise are considered. This calls for effective coordination between communities of policymakers and stakeholders working to address noise and air pollution. In urban areas, more than 50% of measures to reduce and manage noise focus on mitigating noise at source. Measures at source are extensively used to reduce and manage noise in areas outside cities that are affected by major railways (52%), major airports (70%) and major roads (39%).

The Environmental Noise Directive recognizes the need to preserve areas of good acoustic environmental quality, referred to as 'quiet areas', to protect the European soundscape (EEA, 2020). It distinguishes between two types of quiet areas. Noise pollution is caused by a variety of sources and is widely present not only in the busiest urban environments but also in natural environments. Quiet areas offer low sound levels from traffic and human activities, providing relief from environmental stress and opportunities to rest and relax. Apart from the physical and mental health benefits for humans, quiet areas are also important for animals.

5. NBS BENEFIT AND COST CATEGORIES

This section presents benefit and cost categories relevant to NBS. The categories have been determined based on the literature and knowledge summary in sections 3 and 4, namely, NBS typologies for six landscapes, and societal challenges with associated ecological processes. Benefit and cost categories have been identified and defined with validation from Living Labs and project partners.

5.1. NBS BENEFIT CATEGORIES

Whilst addressing societal challenges, NBS simultaneously provide multiple benefits for biodiversity and human well-being. Essentially, the benefits arise from the societal challenges being addressed; hence, the formulation of NBS benefit categories is inspired by the selection of societal challenges, building on the Eklipse expert report on NBS (Raymond et al., 2017). The benefit categories are an adaptation of the generic and specific societal challenges targeted in section 4 and are also based on the benefits delivered by the ecological processes recorded in that section. Table 10 lays out the benefit categories for NBS actions.

Adaptation to climate change: This refers to the capacity to react and respond to the sharp variations and shifts in temperatures and weather patterns. The enhancement of this capacity through NBS actions gives rise to reducing local temperatures, hence mitigating heat stress and urban heat island effects (Fioretti et al., 2010). Another example of an expected impact of climate change adaptation is an increased flood regulation at national (meso-level) or local (micro-level) scales (Pregnolato et al., 2016). This translates into benefits for different ecosystems, for instance, reduced flood risks in rivers, in wetlands and in coastal areas. Similarly, the creation of NBS for flood regulation can help to enhance urban and coastline resilience to climate change. The creation of NBS measures that enhance water infiltration, water retention and rainwater storage entail benefits resulting in a reduced depletion of freshwater resources and a reduced impact of both storms and droughts.

Mitigation of climate change: This is the potential to reduce greenhouse gas emissions (GHG), carbon emissions in particular, through the implementation of NBS at different spatial scales. NBS actions for mitigation span from the micro-scale (e.g., a single building), the meso-scale (e.g., city) and the macro-scale (e.g., planet). Reducing GHG emissions or removing carbon from the atmosphere can be achieved with NBS actions enhancing carbon storage and sequestration, and avoiding carbon loss. The specific benefits of these actions are multiple and ultimately result in a reduced impact of climate change: enhancing carbon sequestration in vegetation and soil (Z. G. Davies et al., 2011), reducing the temperature at a mesoscale or a microscale (Akbari, 2002), and improving air quality (Baró et al., 2014). Additional specific benefits that overlap with other generic benefits can be heatwave risk reduction and increased energy savings from reduced energy consumption.

Disaster risk reduction: NBS can contribute to mitigate the effects of natural hazards by enhancing the presence of natural resources and by maintaining healthy ecosystems. Multiple benefits emerge from the reduced risk of natural hazards. These are very similar to the benefits of "adaptation to climate change": reduced damage value of buildings and inventory, reduced damage on infrastructure, reduced damage value of habitats, reduced cleaning up costs after natural hazards, reduced costs of evacuation, reduced costs of temporary rehousing, reduced health risks, reduced agricultural crop loss, reduced potential loss of transportation time, reduced health risks, and reduced costs of permanent relocation of buildings and infrastructure. Furthermore, the benefits of reducing the likelihood of avalanches and landslides are mostly associated with those of reduced erosion by implementing NBS actions for slope stabilisation.

Improved environmental quality: This generic category comprises five specific categories. Reduced (coastal and soil) erosion damages or reduced erosion risks overlap substantially with those of "climate change adaptation" and "disaster risk reduction" related to landslides and avalanches. Overall, reduced erosion decreases surface runoff speed, maintains soil integrity, controls pollutants and sediments, and maintains habitats and biodiversity. Such benefits lead to even more specific benefits, such as reduced loss of soil carbon, reduced loss of grazing productivity, reduced disruption and damage to road infrastructure, buildings and residential areas.

Improved air quality implies reduced air pollution risks, as well as reduced health risks and avoided productivity loss. In terms of health benefits and savings of the healthcare system, NBS actions can entail reduced cases of pollution-related diseases (e.g., chronic bronchitis, asthma exacerbation), avoided costs of medical treatments, reduced infant and adult mortality rates, reduced number of hospital admissions and emergency visits. Concerning reduced productivity loss, air quality improvement potentially avoids lost work days, avoids lost school days and reduces loss in fish populations and in fish yields. In addition, reduction of air pollutants can help to mitigate stormwater runoff, regulate microclimate through shading, increase habitat quality and maintain biodiversity, provide noise shielding, recreational and cultural services (Mullaney et al., 2015).

Reduced water pollution has several benefits including: avoided costs of future restoration of water systems (i.e., prevention of degradation is less costly than restoring an already degraded ecosystem), cost savings of avoided removal of contaminants, increased recreation and tourist use of waterbodies (i.e., water streams with improved water quality can generate revenues from recreational activities and tourism), increased premium of housing prices because of nearby high-quality waterbodies, increased crop production (e.g., wild rice), increased fish production (e.g., walleye), increased revenues from economic activities, avoided costs of medical care related to water pollution, avoided costs of productivity loss, lower mortality rates of infants and adults, and increased intangible values of water resources such as aesthetics, cultural significance, non-use and existence value.

Reduced loss of biodiversity and improved habitat quality help to maintain vital ecosystem functions that yield further specific benefits which translate into welfare gains to society. Such benefits are, among several others, enhanced structural and functional connectivity of green and blue space, increased ecological integrity and resilience, increased abundance and (genetic) diversity of functional groups, reduced number of invasive species, increased natural insurance value (provisioning, regulating, cultural), and greater crop and timber yield stability.

Lower noise levels bring about specific benefits mainly to human health and wildlife. Human health benefits comprise reduced environmental stress, fewer sleep disturbances, and reduced noise-related diseases (e.g., hypertension, ischemic heart disease, anxiety). Regarding wildlife species, benefits relate to avoided negative behavioural and physiological responses, e.g., changes in respiration, higher stress levels, disorientation, impaired reproductive processes, hearing loss, alteration in migration patterns, and increased mortality risk (Weilgart, 2018).

Socio-economic benefits: The majority of NBS projects implemented across Europe yield attractive social returns on investment (Bockarjova et al., 2022) and have the potential to maximize the benefits for provision of economic services (Raymond et al., 2017). We identify seven core specific benefits arising from NBS which generate social and economic value to people:

- Improved economic possibilities and jobs: Nature-Based Solutions can reduce social vulnerabilities and promote inclusive economic growth by creating green jobs and "green business" opportunities (OECD, 2013), which includes the adaptation of existing and innovative practices based on traditional or local knowledge. NBS projects that promote job diversification will further reduce social vulnerability and foster economic resilience. For instance, crop type diversification and agroforestry systems can decrease farmers' dependence on one single source of income.

- Reduced economic challenges: NBS can contribute to reducing economic challenges by fostering equitable access to food production, enhancing food security, improving attachment to natural spaces, reducing costs of healthcare, enhancing opportunities for (eco-)tourism, increasing natural capital, increasing social return on investments, and reducing insurance premiums.

- Improved health and well-being: A fundamental specific benefit category of NBS is the positive effect on physiological and psychological outcomes. Studies have identified improved public health and well-being through stress relief (Roe et al. 2013), reduced depression (Bratman et al., 2015), improved mental health (Hartig et al., 2014), more opportunities for physical activity (Sugiyama & Thompson, 2007), reduced cardiovascular morbidity and mortality (Gascon et al., 2016), reduced obesity (Kim et al., 2014), reduced diabetes (Maas et al., 2009), and improved functioning of children's immune system (Lynch et al., 2014). Moreover, NBS involving tree plantings and vegetation can reduce heat-related morbidity and mortality (D. Chen et al., 2014).

- Improved equality, integration, environmental justice and social inclusion, including improved security and reduced crime rates: Specific socio-economic benefits integrating social justice span from improved equality, environmental justice and social cohesion and inclusion. In line with this, a specific NBS benefit category should acknowledge the presence of diverse and of excluded social groups, and support processes that enable fairness, inclusiveness and distributional justice of environmental qualities, both socially and spatially (Raymond et al., 2017). Correlated benefits are manifold: increased sense of community, trust and acceptance, increased equality of access to green-blue areas, improved equitable access to community gardens, improved relationships between and within similar and different social groups in the community, and increased community engagement, empowerment and participation. This includes also improved security and reduced crime rate. Research studies have shown that urban greening and tree canopy programs reduce violent crime (Kondo et al., 2017). As a result, NBS investments are beneficial to improving perception of reduced risk, to supporting safe communities, to enhancing public safety in the neighbourhood, to improving the built environment, and to fostering a sense of community.

- Increased awareness and education: Furthermore, the introduction of NBS can motivate improvements in awareness and education. If Nature-Based Solutions lead to an improved understanding of (urban) nature, local communities are more likely to embrace higher ownership of NBS as well as to harness the benefits of implementation. Greater awareness and experiential learning can enable improved creativity and innovation in the community, greater motivation for a sustainable lifestyle, increased environmental education activities, increased pro-environmental behaviour, improved nutritional habits, and improved connection to nature.

- Reduced energy-related challenges: Investment in NBS can offer benefits associated with improved sustainable food consumption, reduced fuel poverty, increased energy savings due to reduced energy consumption and hence potentially reduced energy prices. We also include in this category the benefits from sustainable transport patterns, that is, reducing vehicle use as well as reducing transport distances.

Table 10: Generic and specific benefit categories

GENERIC BENEFITS	SPECIFIC BENEFITS
Adaptation to climate change	Reduced flood risks (rivers, wetlands, sea-level)
	Heat mitigation (Urban Heat Island)
	Alleviation of storm impacts
	Reduced incidents of droughts and water scarcity
Mitigation of climate change	Reducing impacts of climate change
Disaster risk reduction	Reduced damage from avalanches, landslides, earthquakes
Improved environmental quality	Reduced erosion
	Improved air quality
	Improved water quality
	Enhanced biodiversity
	Improved noise pollution
Socio-economic benefits	Improved economic possibilities and jobs
	Reduced economic challenges
	Improved health and well-being
	Improved equality, integration, environmental justice, social inclusion, including improved security and reduced crime rates
	Increased awareness and education
	Reduced energy-related challenges, sustainable transport patterns

5.2. NBS COST CATEGORIES

NBS actions presuppose financial costs incurred by different stakeholders ranging from (potential) funding bodies to the community in general. NBS costs equate to the funds required to cover the expenses, investments and transactions to deliver and sustain the NBS intervention over time.

The cost categorization is primarily based on Panduro et al. (2021) who provide an overview of costs for nature areas that can serve as NBS, and lay out applications of cost estimates in cost-effective analysis for potential NBS in urban areas. More sources of reference are Emerton (2017), Neumann and Hack (2022), among other grey literature. The categories were discussed internally in the AU team and shared online to Living Labs and project partners for further validation. NBS categories were further validated and consolidated following the workshop organized by AU on diagnostic framework of the total economic value (TEV) and cost categories (MS1 report) in the Living Lab Aarhus (Denmark) from June 15th to 16th 2023.

NBS cost categories are organized into generic and specific. Generic cost categories group specific cost categories (potentially) relevant for nature-based projects. The generic cost categories encompass I) costs of establishment, II) costs of maintenance, administrative, and operation, III) monitoring costs, IV) financing costs, V) opportunity costs, and VI) indirect costs.

Costs of establishment are initial investments and expenses incurred before starting project operations. Specific cost categories for costs of establishment consist of: a) fundraising campaigns, events and meetings with (prospective) funding bodies and the community in general, b) feasibility, technical and planning studies to assess risks and cost-analyses prior to execution, c) architectural and engineering design, d) research and development (R&D) and activities aimed towards innovation, e) Site or land acquisition, f) costs of construction, installation and implementation of the NBS project, such as excavation or the creation of blue-green infrastructure, g) allowance for contingencies and unexpected costs occurring during construction or installation, h) relocation/removal of existing land-use infrastructure, i) labour costs (namely, wages and benefits) and training personnel, j) expenses related to stakeholder involvement, such as workshops, meetings, interviews, surveys, food, accommodation, and promotional and educational activities, k) acquisition of capital equipment, facilities, machinery and office supplies (e.g., software, hardware, trademarks, furniture, chairs), and l) expenses on utilities, namely electricity, water, waste disposal, heating, air conditioning, sewage, etc.

Maintenance, administrative and operational costs are regular expenses (i.e., running costs) and those incurred after starting the operation of the project. These are: a) labour wages and training staff on-site and off-site, b) insurance policies (e.g., health, life) and taxes (e.g., property), c) ongoing research and development (R&D) and activities aimed towards innovation, d) expenses related to (continued) stakeholder involvement comprising promotion, participation, engagement and education, e) rent payments of land, f) maintenance, repair and replacement of capital assets, e.g., IT equipment, machines, intangibles, software license fees, furniture, office supplies, and other physical endowments, g) capital depreciation, h) utilities, i) travel and transport expenses, j) legal counselling, audit and supporting staff, including audit fees and external staff salaries.

Monitoring costs refer to costs of observation and tracking the performance and impact of the NBS intervention. Monitoring implies the collection of information, data or field measurements, which can be gathered, recorded and updated on a timely basis for analytical purposes and sampling surveys. Moreover, there can exist costs related to the development of monitoring protocols.

Financing costs are those charges connected to credit loans, such as interests, commissions, fees, transaction costs and lease payments. Opportunity costs equals the foregone benefits associated with other land uses such as housing developments, industrial activities, sports, recreation, and other competing land uses. Indirect costs are the costs of disservices, side effects and unintended impacts of the NBS project, for instance: a) residual damages, b) agricultural loss, and c) reduced air/water/soil quality. Table 11 illustrates and synthesizes the generic and specific NBS cost categories:

Table 11: NBS cost categories

GENERIC COST CATEGORIES	SPECIFIC COST CATEGORIES
I) Costs of establishment	a) Fundraising
	b) Feasibility and planning studies
	c) Architectural and engineering design
	d) Research and development (R&D)
	e) Site and/or land acquisition
	f) Construction and installation
	g) Allowance for contingencies
	h) Relocation and/or removal of existing land-use infrastructure
	i) Labour and training
	j) Stakeholder involvement
	k) Capital (Equipment, facilities, machinery, and office supplies)
	l) Utilities
II) Maintenance, administrative and operation costs	a) Labour and training
	b) Insurance and taxes
	c) Ongoing research and development (R&D)
	d) (Continued) Stakeholder involvement
	e) Land rent
	f) Capital (Equipment, facilities, machinery, and physical endowments)
	g) Capital depreciation
	h) Utilities
	i) Transport and travel expenses
	j) Legal counselling, audit and supporting staff
III) Monitoring costs	*[Costs of tracking and observation ex-ante and ex-post]*
IV) Financing costs	a) Interests
	b) Fees, transactions costs and commissions
	c) Lease payments
V) Opportunity costs	*[Foregone benefits associated with other land uses such as housing developments, industrial activities, sports, recreation, and other competing land uses]*
VI) Indirect costs	a) Residual damages
	b) Agricultural loss
	c) Reduced air / water / soil quality

6. ASSESSMENT OF QUALITATIVE AND QUANTITATIVE APPROACHES FOR VALUING AND EVALUATING NBS

The following chapter provides an inventory of existing economic valuation approaches to assess the economic, environmental, and social costs and benefits of Nature-Based Solutions. These approaches help to analyse tangible but also intangible, and non-market values associated with ecosystems, like flood protection, water purification, and erosion control. The use values, i.e. direct, indirect, and option values associated with NBS are considered as well as non-use values, i.e. existence, altruistic, and bequest values. Recognising and incorporating both, use and non-use value, is important for a comprehensive assessment of the benefits provided by NBS. The framework also considers costs, including implementation costs, maintenance costs, and opportunity costs associated with NBS (for more details see Chapter 5). These costs are weighed against the economic benefits to determine the overall net value of NBS projects.

By assigning monetary values, these methods help to raise awareness of the importance of preserving and managing ecosystems sustainably, considering their contributions to human well-being and economic prosperity. It enables the comparison of NBS with alternative solutions, such as grey infrastructure. This broader perspective allows decision-makers to capture the full range of economic, environmental, and social benefits associated with NBS when making informed choices and policies regarding implementation and conservation. Additionally, it highlights the multiple dimensions of value provided by NBS, going beyond traditional market-based assessments and emphasising the importance of non-market values in decision-making processes.

In the first sub-chapter 6.1, economic valuation methods are described. The aim is not to provide a detailed description of the methods, but to provide an overview of the methods, including their strengths and weaknesses. This overview is intended to simplify the choice of the most suitable method in practice. A checklist summarises some relevant points to consider when selecting a method. The second sub-chapter 6.2 deals with risk assessment approaches, followed by decision-supporting approaches in 6.3, which can be applied to weigh up the costs and benefits. Sub-chapter 6.4 contains the results of the analysis of two databases for the valuation of ecosystem services examined within I4N. Finally, the last sub-chapter (6.5) examines the link between NBS and natural capital accounts and climate data statistics.

6.1. ECONOMIC VALUATION METHODS

The various economic valuation methods are listed below. As explained above, this list is intended to provide an inventory of the variety of available methods. The relationship between ecosystem services, types of value and methods is illustrated. The following diagram (Figure 1) shows the three levels and their linkages.

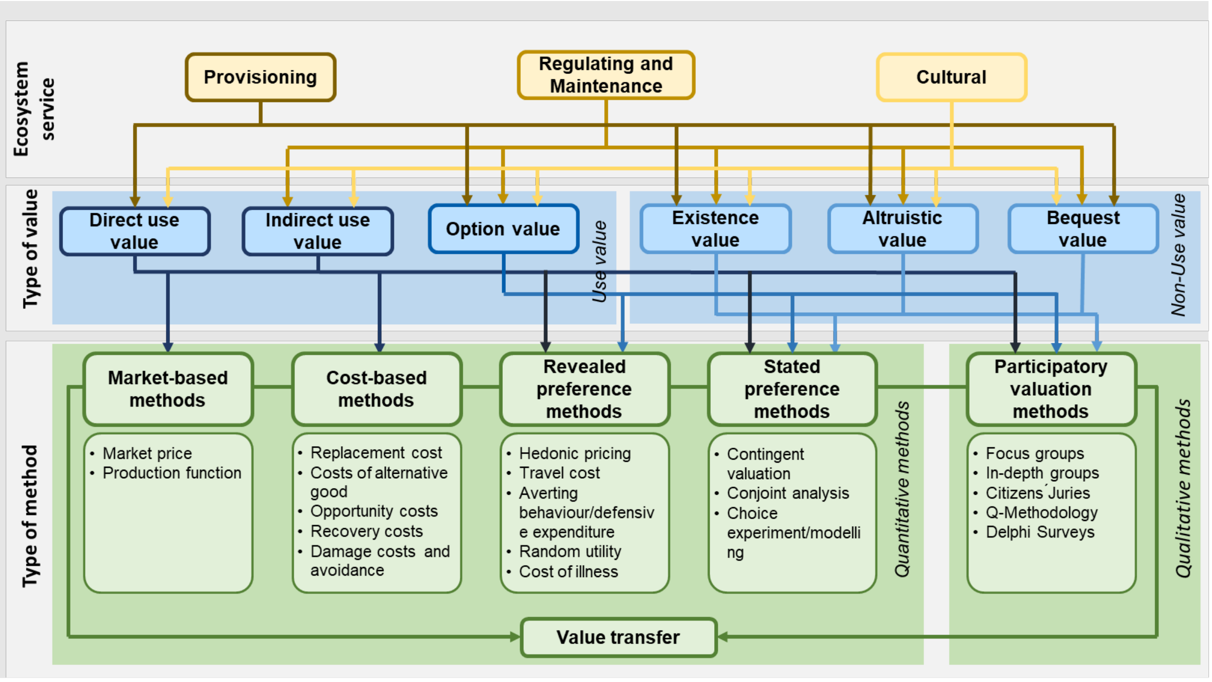


Figure 1: Economic valuation method cluster

(Source: Croci & Lucchitta, 2021; DEFRA, 2007; Hynes et al., 2021)

At the level of ecosystem services, according to CICES V5.1 (Haines-Young & Potschin, 2018), three ES are distinguished.

- **Provisioning** (e.g., wood, food, fresh water, fibre, genetic resources, medicinal plants)
- **Regulating and Maintenance** (e.g., climate regulation, water purification, disease regulation, maintenance of physical conditions)
- **Cultural** (e.g., recreation, tourism, education, aesthetic value, spiritual value, religious value)

The second level shows the subdivision of values into use values and non-use values. **Use values** are the value that people derive from the direct, indirect, or optional use of a good.

- **Direct economic values** encompass the market-based benefits derived from NBS, including tangible goods and services that have a market price, for example, the value of timber, agricultural products, or water supply services generated by an NBS.
- **Indirect economic values** capture the benefits that are not traded in markets but still have an economic impact. This includes the value of ecosystem services provided by NBS, such as carbon sequestration, water purification, and climate regulation.
- **Option values** denote the willingness to pay for the existence of NBS as a future resource. For example, a person might hope to visit the Great Barrier Reef at some point in the future and would therefore be willing to pay something towards the conservation of the area to preserve that opportunity.

Non-use values represent the intangible benefits that individuals derive from NBS, even if they do not directly utilise or interact with them.

- **Existence values** are intrinsic values that people attach to the existence of NBS for ethical or moral reasons.

- **Altruistic values** refer to the individual's willingness to pay for the preservation of an asset or resource that they do not use themselves so that others can use it.
- **Bequest values** include the value placed by the current generation on preserving biodiversity and ecosystem functioning for future generations.

This is followed by the economic methods, which are divided into quantitative and qualitative methods. In the following two sub-chapters, the individual methods are briefly described, and the relationship between ES, value, and method is explained.

6.1.1. QUANTITATIVE VALUATION METHODS

Quantitative economic valuation methods are based on the analysis of data and facts to determine the monetary value of ecosystem services. These include for example determining the value of forests for timber production, the pollination of plants by bees, or the purification of water by wetlands.

Several economic valuation methods can be used to assess the value of various ecosystem services. The most common methods are presented below and the three most important advantages and disadvantages of each are described. In addition, recent examples from the literature on the application of the methods in the context of NBS are given:

- **Market-Based Methods:** These methods estimate the value of ecosystem services by examining market prices and transactions related to similar goods or services. For example, the value of timber harvested from a forest can be a direct measure of its economic contribution. Examples of market-based methods are the market price method and the production function (Burningham & Davies, 2004). In the study by Hérivaux and Grémont (2019), for example, the value of standing timber was estimated based on market prices for different timber products and end uses, considering tree species and the contributions of local actors. Factors such as stemwood prices for different and their respective uses (fuel, construction, furniture) were taken into account to quantify the economic contribution of forests.
    - Strengths:
        1. Quantifiable: Market-based methods utilise actual market transactions and prices, making them easier to understand and communicate. They provide concrete and quantifiable values based on the economic exchange of goods and services related to NBS.
        2. Market preferences: These methods capture the preferences and values of market participants as expressed through their actual purchasing decisions. Market prices are determined by supply and demand dynamics, reflecting their relative importance.
        3. Efficient allocation of resources: By assessing market values, market-based methods can help to identify the most economically efficient allocation of resources. They provide information on the economic viability and profitability of NBS, facilitating resource allocation decisions and investment planning.
    - Weaknesses:
        1. Non-market value exclusion: Market-based methods may only capture a subset of the total value of NBS, focusing primarily on goods and services with existing market prices. This can lead to an underestimation of the broader social, cultural, and non-market values associated with

        NBS. Important dimensions of NBS value may be overlooked, leading to an incomplete assessment.
        2. Market failures: Market-based methods assume well-functioning markets without externalities, market power, or other market failures. However, NBS might address market failures, such as environmental externalities, and their value may not be fully reflected in market prices alone.
        3. Data limitations: The availability of reliable and comprehensive market data can be a limitation, especially for emerging NBS. Limited data can hinder the accuracy and robustness of market-based valuation results.

- **Cost-Based Methods:** Cost-based methods involve assessing the economic value of Nature-Based Solutions by estimating various costs associated with their implementation and the consequences of their absence. It involves estimating the expenses of alternative engineering or technological interventions. For instance, comparing the cost of building and maintaining water treatment facilities to the value of water purification services provided by wetlands. Examples of this type of method include replacement costs, costs of alternative goods, opportunity costs, recovery costs, damage costs, and damage avoidance (Barbier & Heal, 2006). For example, in their study, Capotorti et al. (2019) examined the influence of green infrastructure on ecosystem services by estimating the potential beneficiaries of enhanced air quality and quantifying the benefit on human health through calculating avoided costs on human health damages.
    - Strengths:
        1. Quantifiable: Cost-based methods provide concrete and measurable values by assessing the costs associated with implementing or replacing NBS. These costs can be easily quantified, making it straightforward to communicate and compare across different options or alternatives.
        2. Decision support: By evaluating the costs of engineering or technological interventions needed to replicate the services provided by NBS, cost-based methods help identify cost-effective approaches and support resource allocation decisions.
        3. Market independence: Cost-based methods can also be used if no or insufficient market prices are available for the goods or services provided by the NBS.
    - Weaknesses:
        1. Excluding values: Cost-based methods often focus solely on the costs involved in replicating NBS rather than capturing their full value. This can lead to an incomplete assessment of the benefits and ecosystem services provided by NBS, neglecting non-market values and intangible benefits.
        2. Difficulty in monetizing non-market values: Cost-based methods struggle to monetize non-market values associated with NBS, such as cultural, aesthetic, or spiritual benefits. These non-market values are challenging to quantify in monetary terms and may be overlooked in cost-based assessments.
        3. Data limitations: Accurate cost estimation requires reliable and comprehensive data, which may be limited or difficult to obtain.

Insufficient data can undermine the accuracy and reliability of cost-based valuation results.

- **Revealed Preference Methods:** These methods analyse people's behaviour in related markets to infer their preferences for ecosystem services. This can include studying changes in property values, travel costs, or recreational visitation rates to estimate the value of scenic landscapes, recreational services, or tourism opportunities. Examples are hedonic pricing, travel costs, averting behaviour/defensive expenditure, random utility and the cost of illness. Mutlu et al. (2023), for example, conducted a case study examining homeowners' willingness-to-pay for NBS that offer flood safety and environmental benefits. Using hedonic price modelling, the study estimated homeowners' willingness to pay by analysing property value changes over time and evaluating evolving flood risk discounts associated with NBS implementation.
    - Strengths:
        1. Real-world preferences: Revealed preference methods rely on observed behaviour and choices made by individuals in related markets. They capture real-world preferences and values as reflected in people's actions.
        2. Trade-offs: These methods enable the examination of trade-offs between NBS-related benefits and other goods or services that individuals consume or engage with. By analysing how individuals allocate their resources and make choices, revealed preference methods capture the relative importance and value of NBS.
        3. Flexibility and adaptability: Revealed preference methods consider the specific context and characteristics of the market being studied. This allows for a more tailored and contextually relevant assessment of the value of NBS, considering local preferences and conditions.
    - Weaknesses:
        1. Excluding values: Revealed preference methods rely on market transactions and behaviours, which may not fully capture the complete value of NBS. Non-market values may be overlooked as they are not reflected in observable market choices.
        2. Market failures: Market imperfections, such as externalities or incomplete information, can lead to biased or incomplete valuation results. These methods may not fully account for the social and environmental externalities associated with NBS, potentially underestimating their true value.
        3. Lack of accessibility: In some cases, data on market behaviour and choices related to NBS may be limited or challenging to obtain. Accessibility issues can hinder the application of revealed preference methods, thereby affecting the accuracy and reliability of the valuation results.

- **Stated Preference Methods:** Stated Preference Methods involve surveying individuals and asking them about their willingness to pay (WTP), or willingness to accept (WTA) compensation for the benefits derived from NBS. This approach provides insights into people's preferences and perceptions of value and helps capture non-use values such as existence and bequest values. Examples of Stated Preference Methods are contingent valuation, which includes WTP and WTA, conjoint analysis, and choice experiment (Hanley et al., 2001).

For example, Haque et al. (2022) conducted a case study using the contingent valuation method, specifically the payment card approach, to assess the willingness of a low-income marginal population to pay for the conservation and restoration of pond landscapes and blue ecosystem services. The respondents were presented with different payment options on a card, and they indicated how much they were willing to pay for the preservation of these ecosystem services.

- Strengths:
  1. Non-use values: Stated preference methods can capture non-use values, such as existence, altruistic or bequest value, by assessing individuals' willingness to pay or accept compensation for the preservation or provision of NBS.
  2. Societal and ethical considerations: Stated preference methods enable the inclusion of broader societal and ethical considerations in the valuation process.
  3. Flexibility and adaptability: These methods offer flexibility in designing surveys and scenarios to capture different dimensions of NBS value. They can be tailored to specific contexts and issues, accommodating diverse stakeholder perspectives and preferences.
- Weaknesses:
  1. Hypothetical bias: Stated preference methods rely on respondents' responses to hypothetical scenarios, which can introduce bias. Individuals may not always provide accurate or realistic responses when faced with hypothetical situations, leading to a gap between stated preferences and actual behaviour.
  2. Sample bias: Stated preference surveys rely on a sample of respondents, and the composition of the sample can introduce biases. The sample may not be fully representative of the population of interest, leading to potential selection bias. This can limit the generalizability and applicability of the findings. In addition, respondents may exhibit social desirability bias, where they provide answers that they perceive as socially acceptable or desirable.
  3. Complex Systems: Stated preference methods may not capture the complexity and interdependencies of natural systems or ecosystem services. Respondents may have limited knowledge or understanding of the ecological processes and functions involved, leading to a potential misrepresentation of values or preferences.

- **Value Transfer:** This method utilises existing economic valuation studies and applies their values to similar contexts or locations. It involves transferring economic values estimated in one study to another area or ecosystem, with necessary adjustments made to account for contextual differences. A distinction can be made between function transfer and unit value transfer (Quintas-Soriano et al., 2016).
  - Strengths:
    1. Cost and time efficiency: Benefit transfer leverages existing economic valuation studies and their results, allowing for cost and time savings compared to conducting new primary valuation studies. It can provide a

quick estimation of the value of NBS by applying values from similar studies.

        2. <u>Data generation</u>: Benefit transfer can address data scarcity issues in situations where primary valuation data for a specific NBS or location are limited or unavailable. It allows for the use of value estimates from studies conducted in similar contexts or ecosystems.
        3. <u>Policy and decision support</u>: Benefit transfer provides valuable information for policy and decision-making by transferring knowledge and economic values across different contexts. It can inform resource allocation, planning, and policy development related to NBS by providing estimated values for decision-makers.
    - Weaknesses:
        1. <u>Contextual and site-specific variability</u>: The transferability of values through benefit transfer is dependent on the similarity of the contexts and sites between the study being transferred from and the target NBS. Differences in ecological, socio-economic, and cultural contexts can lead to inaccuracies in the transferred values.
        2. <u>Quality of source studies</u>: The reliability and applicability of the source studies used for benefit transfer are crucial. The quality of the original study, including its methodology, data quality, and relevance to the target NBS, directly affects the accuracy of the transferred values.
        3. <u>Large potential bias</u>: Benefit transfer relies on previously conducted studies, which might contain biases, limitations, or outdated information. The transferred values may not reflect current market conditions or changes in societal preferences, potentially leading to inaccuracies in the assessment.

Understanding these strengths and weaknesses of different methods is crucial for a comprehensive assessment of NBS. Complementing approaches with other valuation methods can help capture a broader range of values and ensure a more holistic evaluation of NBS benefits. Combining, for instance, stated preference methods with other valuation approaches and considering multiple perspectives can help mitigate potential biases and provide a more robust understanding of NBS values. It is also recommended to include qualitative methods alongside quantitative approaches, more on this in the following sub-chapter.

6.1.2. QUALITATIVE VALUATION METHODS

Qualitative methods are important to understand and take into account people's perceptions and attitudes towards specific ecosystem services. By involving stakeholders and local communities, these approaches capture local knowledge, preferences, and aspirations, ensuring that NBS align with the needs and values of the people they aim to benefit. Qualitative methods make it possible to include subjective evaluations and assessments in the valuation of NBS, especially regarding the social and cultural impacts of ecosystem-related decisions that cannot always be captured by quantitative methods.

- **Participatory valuation approach:** This approach can assess both the use value and the non-use value of natural resources or ecosystem services. Examples of participatory valuation approaches are focus groups, in-depth groups, citizens′ juries, Q-methodology, or Delphi surveys.

The study by Strand et al. (2017), for example, assessed the economic value of protecting the Amazon rainforest, a global environmental public good using a qualitative method. Through the application of the Delphi method, over 200 environmental valuation experts from 37 countries were tasked with predicting the results of a contingent valuation survey aimed at determining the willingness to pay for Amazon Forest conservation in their respective countries. The Delphi method involves several rounds of interviews and feedback to reach consensus among the experts.

- Strengths:
  1. Comprehensive assessment: Qualitative methods can provide a holistic understanding of the multiple benefits and values associated with NBS. They allow for a comprehensive assessment of the social, environmental, and economic dimensions that may not be captured by purely quantitative approaches.
  2. Stakeholder engagement: These methods often involve stakeholder participation, allowing for the inclusion of diverse perspectives and values. They promote engagement with local communities, decision-makers, and experts, leading to more inclusive and participatory processes.
  3. Flexibility and adaptability: Qualitative methods can be flexible and adaptable to different NBS scenarios, making them suitable for a wide range of situations. They can be customised to focus on specific dimensions or objectives and can accommodate emerging themes or issues during the valuation process.
- Weaknesses:
  1. Subjectivity and bias: Qualitative methods are more prone to subjective judgements and biases due to their reliance on qualitative data and interpretation. The valuation outcomes may vary depending on the perspectives and values of the stakeholders involved, potentially leading to inconsistent or contested results. These methods often focus on specific case studies or localised contexts, which may limit their generalizability to other NBS projects or regions. The findings may not be directly transferable or applicable to different settings, reducing their wider applicability.
  2. Limited quantification: Qualitative methods often lack the precision of quantitative techniques, making it challenging to translate gathered insights into concrete monetary values, which may be required for certain decision-making processes.
  3. Time- and resource-intensive: Qualitative economic valuation methods can be time-consuming and require significant resources, including expertise, data collection, and analysis. The involvement of multiple stakeholders and the need for qualitative data interpretation can further contribute to the complexity and duration of the process.

In conclusion, qualitative methods offer valuable insights into the multifaceted values of NBS. They provide a more nuanced understanding of the benefits and engage stakeholders effectively. However, they should be used alongside quantitative approaches to ensure a more comprehensive and robust assessment of the economic value of NBS.

6.1.3. GUIDANCE ON THE SELECTION OF APPROPRIATE VALUATION METHODS

The selection of the most appropriate valuation method depends clearly on the specific context, data availability, type of ecosystem service and type of benefit and cost-categories being assessed. Employing a combination of methods and integrated approaches often leads to a more robust and comprehensive valuation of ecosystem services. This allows the consideration of various economic, social, and environmental factors to assess the overall benefits and costs associated with implementing NBS projects. The choice of methods often depends on the available budget. Therefore, when deciding on the economic valuation method, several factors should be considered to ensure an accurate and comprehensive assessment, see Figure 2.

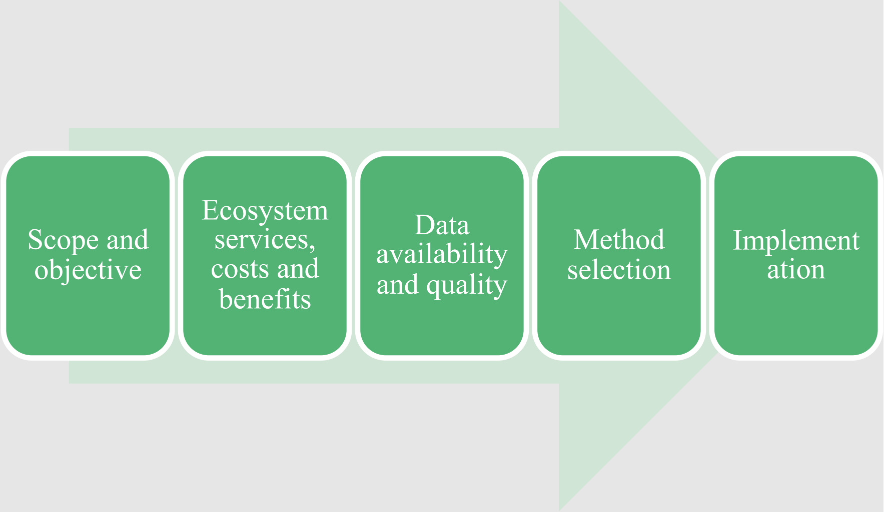


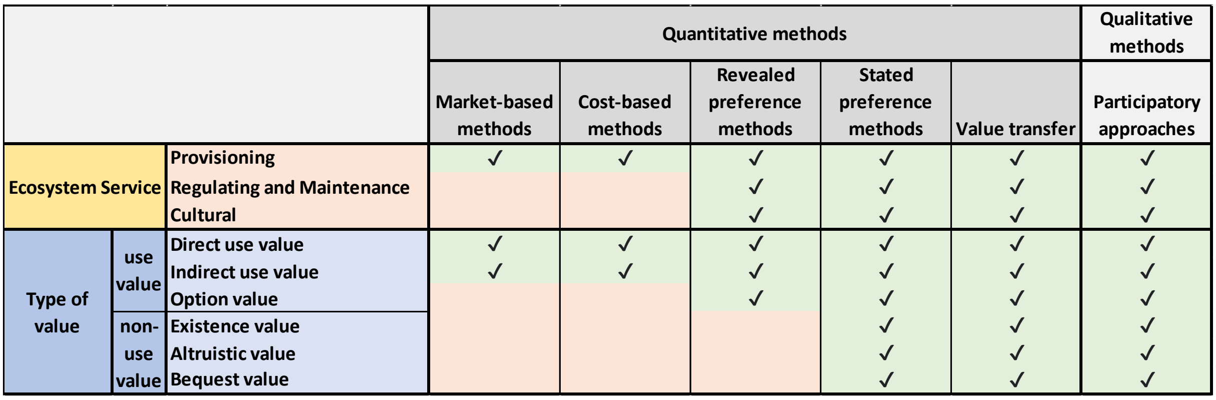
Figure 2: Step-by-step guide to selecting an appropriate valuation method

These factors include:

1. **Define the scope and objectives:**
   Clearly define the scope, objectives and purposes of the economic valuation. Determine what aspects of the NBS you want to assess and the specific ecosystem services you want to include in the valuation.
2. **Identify relevant ecosystem services, costs and benefits:**
   Identify the range of ecosystem services provided by the NBS. This may involve conducting a literature review, consulting experts, or engaging stakeholders to ensure a comprehensive understanding of the services. Determine costs and benefit categories (use values, non-use values). Also, consider risk reduction benefits as well as potential trade-off between benefits.
3. **Assess data availability and quality:**
   Assess the availability and quality of the data required for economic valuation. This includes data relevant to the NBS and its impacts. This can be economic, environmental, social, technical, hydrological, physical, chemical, etc. Determine if the necessary data can be collected or if existing data sources can be utilised.
4. **Select appropriate valuation methods:**
   Consider a range of economic valuation methods that are suitable for capturing the values associated with the identified ecosystem services. Based on a comparative

analysis of the methods, the economic valuation method(s) that best align with the objectives, data availability, feasibility, and practicality of the assessment can be selected.

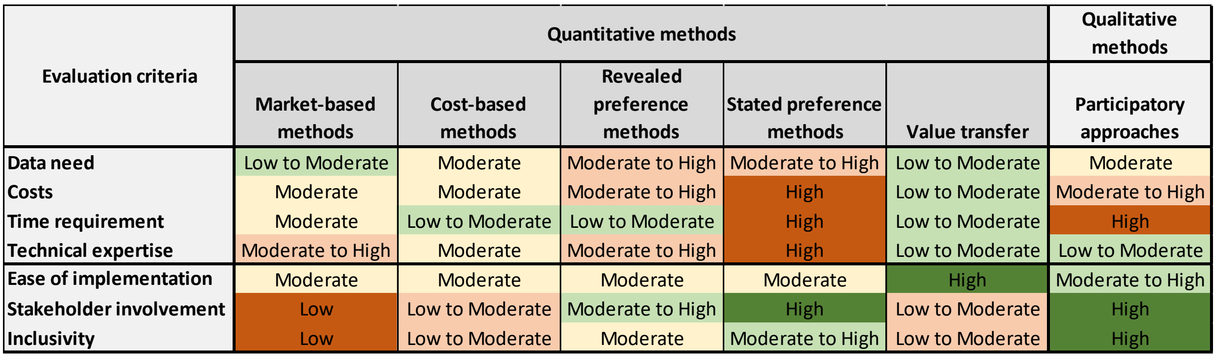
Depending on which ecosystem services and type of value are to be captured, some economic methods can already be excluded. The following diagram (Figure 3) illustrates this relationship:



			Quantitative methods					Qualitative methods
			Market-based methods	Cost-based methods	Revealed preference methods	Stated preference methods	Value transfer	Participatory approaches
Ecosystem Service		Provisioning	✓	✓	✓	✓	✓	✓
		Regulating and Maintenance			✓	✓	✓	✓
		Cultural			✓	✓	✓	✓
Type of value	use value	Direct use value	✓	✓	✓	✓	✓	✓
		Indirect use value	✓	✓	✓	✓	✓	✓
		Option value			✓	✓	✓	✓
	non-use value	Existence value				✓	✓	✓
		Altruistic value				✓	✓	✓
		Bequest value				✓	✓	✓

Figure 3: Comparative analysis of the methods considering ecosystem services and types of value

In addition, other criteria can be used to compare the methods in order to select those that best match the requirements, demands and objectives. In Figure 4, some criteria for the different method categories are rated on a scale ranging from low to high.



Evaluation criteria	Quantitative methods					Qualitative methods
	Market-based methods	Cost-based methods	Revealed preference methods	Stated preference methods	Value transfer	Participatory approaches
Data need	Low to Moderate	Moderate	Moderate to High	Moderate to High	Low to Moderate	Moderate
Costs	Moderate	Moderate	Moderate to High	High	Low to Moderate	Moderate to High
Time requirement	Moderate	Low to Moderate	Low to Moderate	High	Low to Moderate	High
Technical expertise	Moderate to High	Moderate	Moderate to High	High	Low to Moderate	Low to Moderate
Ease of implementation	Moderate	Moderate	Moderate	Moderate	High	Moderate to High
Stakeholder involvement	Low	Low to Moderate	Moderate to High	High	Low to Moderate	High
Inclusivity	Low	Low to Moderate	Moderate	Moderate to High	Low to Moderate	High

Figure 4: Comparative analysis of the methods considering further evaluation criteria

Also, consider using a combination of methods to capture different dimensions of value and cross-validate the results.

However, it needs to be considered that rating economic valuation methods based on the criteria is subjective and can vary depending on specific contexts and applications.

5. **Implement the chosen method(s):**
   Design and implement the selected economic valuation method(s) according to established guidelines and best practices. Collect the necessary data, conduct analyses, and estimate the economic values associated with the identified ecosystem services.

For further support in selecting methods, the following sources can be consulted:

- The ETC/CCA Technical Paper provides a step-wise framework for designing NBS assessments, covering purpose and goal setting, definition of assessment characteristics, selection of assessment elements and finally approaches for NBS assessments (Veerkamp et al., 2021).

- The IPBES methodological assessment report can be used, as the formation of valuation method families and evaluation according to criteria such as relevance, resources and robustness provide more certainty as to which methods are suitable (*Summary for Policymakers of the Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Service*, 2022).
- In addition, online tools can be used, such as the Method Navigator from ValuES. The method database offers support in finding a suitable method by working with filters to narrow down methods. Furthermore, the database contains extensive information on methods by which ES can be assessed, when and how the methods can be applied, which resources are necessary, case studies, etc. (Kosmus & von Bertrab, 2014).

6.2. RISK ASSESSMENT APPROACHES

Nature-Based Solutions play a vital role in mitigating a wide range of challenges that pose risks to communities, ecosystems, and economies. These challenges include in generic terms climate change adaptation, climate change mitigation, natural hazards, environmental management, noise pollution and socio-economic challenges (for more details see chapter 4 "Societal challenges and ecological processes). NBS offer innovative strategies to reduce these risks by harnessing the protective and regenerative capacities of natural ecosystems.

Risk assessment is a fundamental process for evaluating and managing potential hazards and their associated impacts. The risk assessment formula, often expressed as *Risk = Hazard × Exposure × Vulnerability*, provides a conceptual framework for understanding and quantifying risk. *Hazard* represents the probability or likelihood of an adverse event occurring, *exposure* accounts for the extent of potential impact (including people, assets or ecosystems), and *vulnerability* encompasses the sensitivity or capacity of the exposed elements to withstand or recover from the hazard (Doswald et al., 2021).

Some common risk assessment approaches are:

Table 12: Description of risk assessment approaches

Risk assessment approaches	*Description*
Quantitative risk assessment	Quantitative risk assessment is a systematic approach that involves numerical analysis of potential hazards, exposures, and vulnerabilities to quantify risks accurately. By simulating different scenarios, risk models help estimate the expected benefits in terms of avoided damages, reduced loss of lives, or minimised economic disruptions resulting from NBS implementation. QRA utilises mathematical models, data analysis, probabilistic methods and statistical methods to estimate the reduction in risks and associated benefits.
Risk-benefit analysis	Risk-benefit analysis considers both the risks and benefits associated with ecosystem services, aiming to balance the potential gains against the potential losses when making

	decisions that may affect ecosystems, allowing for a comprehensive evaluation of trade-offs and supporting sustainable resource management strategies.
Scenario analysis	Scenario analysis explores various plausible future scenarios, often under different conditions or assumptions, to understand how NBS can influence outcomes. This method uses modelling techniques, such as hydrological or climate models, to simulate the performance of NBS under various risk scenarios. By comparing the outcomes of different scenarios, decision-makers can assess the effectiveness of NBS in reducing risks and estimate the associated benefits.
The insurance value of ecosystems	The insurance value of ecosystems quantifies the value of ecosystems in providing risk reduction and insurance-like services, such as flood regulation, storm protection, or water purification, by estimating the costs that would be incurred if those services were to be replaced by built infrastructure or other alternatives.
Value-at-Risk approach	Value-at-Risk is a quantitative method used in finance to estimate potential losses under adverse conditions. The VaR approach assesses the extent to which NBS can mitigate losses associated with natural disasters or environmental degradation, providing a valuable metric for risk reduction.

Subsequently, the strengths and weaknesses of risk assessment approaches in a general context will be outlined:

- Strengths:
    1. Objective evaluation: These approaches often rely on data, models, and standardized criteria, reducing the influence of subjectivity and personal bias in risk assessments.
    2. Risk communication: They offer a structured framework and language for communicating risks to stakeholders, promoting a shared understanding of the challenges and facilitating cooperation in risk management efforts.
    3. Diverse scenarios: Risk assessment approaches provide the capability to explore a range of potential future scenarios, enabling organizations to anticipate and prepare for a diverse array of possible outcomes.
- Weaknesses:
    1. Data limitations: Many risk assessment approaches require extensive and accurate data, which may not always be available, especially for emerging or complex risks.
    2. Simplification: These approaches often oversimplify the complexities of real-world risks, potentially leading to underestimation or neglect of certain aspects of risk.
    3. Assumptions: The accuracy of risk assessments is contingent on the validity of assumptions made during the modelling process, which could introduce uncertainties.

To offer a practical illustration of the risk assessment methods, a case study is presented as an example. In Miguez et al. (2019) case study, the authors quantified flood risk, assessed resilience, and evaluated economic feasibility by initially utilizing a hydrodynamic model to simulate flood maps across various return periods. Subsequently, the study employed a multicriteria flood risk index, an integrated flood resilience index, and conducted a benefit-cost analysis to compare two design alternatives aimed at addressing urban flood risks.

While these approaches provide an objective and structured means of quantifying risks and facilitating risk communication, they are also dependent on data availability, may oversimplify complex realities, and hinge on the validity of underlying assumptions, often requiring detailed modelling of physical processes. As we continue to explore the integration of NBS into risk mitigation strategies, it is imperative to acknowledge and address these nuances to make informed decisions that prioritize the resilience and sustainability of our communities and environments.

6.3. DECISION-SUPPORTING APPROACHES

Once the economic, environmental and social costs and benefits have been quantified, the next step is to evaluate, rank or compare the costs and benefits. Making a decision between alternative investment options requires balancing competing objectives. This section provides an overview of methods for evaluating project alternatives and scenarios that are commonly used in a range of decision-making contexts:

- **Cost-benefit analysis (CBA):** One common method is the cost-benefit analysis, which compares the costs of implementing and maintaining NBS projects with the benefits they generate to determine the overall feasibility and desirability of the intervention. This approach considers both market values, such as increased property values or reduced healthcare costs, and non-market values, such as improved recreational opportunities or enhanced biodiversity.
    - Strengths:
        1. <u>Objective evaluation</u>: CBA provides a structured and objective framework to assess NBS projects by comparing their costs and benefits in monetary terms. This helps decision-makers make rational and evidence-based choices.
        2. <u>Comprehensive assessment</u>: CBA allows for the consideration of various economic, social, and environmental impacts of NBS, leading to a more holistic understanding of the project's overall value.
        3. <u>Resource allocation</u>: CBA helps prioritise NBS projects based on their net benefits, ensuring efficient allocation of resources to projects that offer the highest societal gains.
    - Weaknesses:
        1. <u>Valuation challenges</u>: Assigning monetary values to all impacts, especially non-market and intangible benefits, can be difficult and subject to varying interpretations.
        2. <u>Temporal considerations</u>: CBA relies on discounting future costs and benefits, which can lead to conflicts between short-term and long-term objectives, raising ethical and fairness concerns.
        3. <u>Distributional effects</u>: CBA may not fully account for the distributional impacts of NBS, potentially overlooking disparities in benefits and costs among different social groups.

- **Cost-effectiveness analysis (CEA):** The cost-effectiveness analysis focuses on identifying the most cost-effective NBS option for achieving specific environmental objectives. It compares the costs of different NBS alternatives and assesses their effectiveness in delivering desired outcomes, such as greenhouse gas emissions reduction or erosion control.
    - Strengths:
        1. Resource optimisation: CEA focuses on identifying the most cost-effective NBS interventions, maximising the achievement of desired outcomes while minimising costs.
        2. Transparent comparison: CEA allows for direct comparison of different NBS interventions based on their costs and achieved outcomes, aiding decision-makers in selecting the best options.
        3. Efficiency-oriented: CEA provides a pragmatic approach to decision-making, particularly when resources are limited, as it prioritises interventions that deliver the most significant impact per unit of cost.
    - Weaknesses:
        1. Limited scope: CEA often considers only a narrow set of outcomes, potentially neglecting important non-monetary and long-term effects of NBS.
        2. Outcome quantification: Quantifying some NBS outcomes in monetary terms can be challenging, leading to a potential underrepresentation of certain benefits.
        3. Goal conflict: Focusing solely on cost-effectiveness may result in overlooking NBS projects that address multiple objectives but may be less cost-effective for a specific outcome.
- **Decision making under uncertainty (DMU):** Decision making under uncertainty refers to the process of making choices when the outcomes and probabilities of different options are uncertain or unknown. In this approach, decision-makers consider a range of possible scenarios and their associated uncertainties before selecting a course of action.
    - Strengths:
        1. Risk management: Decision-making under uncertainty considers potential risks and uncertainties associated with NBS, enabling decision-makers to develop robust strategies.
        2. Flexibility: This approach allows for adjustments and adaptations of NBS interventions in response to changing conditions and new information.
        3. Scenario analysis: Decision making under uncertainty often involves scenario analysis, which helps explore different potential futures and their implications on NBS performance.
    - Weaknesses:
        1. Data limitations: Uncertainty in NBS evaluation may arise due to insufficient data or uncertainties in projections, potentially affecting the accuracy of decision-making.
        2. Complex analysis: Decision making under uncertainty can involve complex probabilistic modelling and analysis, requiring specialised expertise and computational resources.

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        3. Decision paradox: Dealing with uncertainty can lead to decision-making paralysis or overly conservative choices, which may hinder bold and innovative approaches to NBS.
- **Multi-criteria analysis (MCA):** Multi-criteria analysis as an economic valuation method of NBS involves considering multiple criteria, such as economic, social, and environmental factors, to assess and compare different NBS options and determine the most favourable alternative based on a holistic evaluation. Each alternative is then assessed against these criteria, usually through a systematic scoring or weighting process.
    - Strengths:
        1. Inclusivity: MCA incorporates diverse stakeholder perspectives and values by considering multiple criteria, promoting transparency and collective decision-making.
        2. Flexibility: MCA allows for the customization of evaluation criteria based on the specific context and objectives of NBS, accommodating various stakeholder interests.
        3. Trade-off analysis: MCA facilitates the explicit exploration of trade-offs between different criteria and enables decision-makers to identify compromise solutions.
    - Weaknesses:
        1. Subjectivity: MCA involves assigning weights to criteria, which can be subjective and may lead to varying outcomes based on stakeholder preferences.
        2. Data aggregation: Aggregating diverse criteria into a single evaluation metric can be challenging, potentially oversimplifying complex decision contexts.
        3. Complexity: MCA can be complex, requiring specialised expertise in decision analysis and data interpretation, which may limit its widespread use in some contexts.
- **Life-cycle analysis (LCA):** Life-cycle analysis for ecosystem service valuation is a comprehensive approach that assesses the environmental impacts and resource use associated with the production, use, and disposal of goods and services, allowing for a holistic understanding of their contribution to ecosystem services and facilitating informed decision-making for sustainable resource management.
    - Strengths:
        1. Comprehensive assessment: LCA considers the entire life cycle of NBS providing a holistic view of environmental effects.
        2. Impact identification: LCA helps identify potential hotspots and environmental impacts throughout the life cycle of NBS, aiding in the development of targeted mitigation strategies.
        3. Comparison tool: LCA allows for the comparison of different materials, technologies, and design options to identify the most environmentally sustainable alternatives for NBS.
    - Weaknesses:
        1. Data-intensive: Conducting an LCA requires extensive and reliable data, which may not always be available, especially for emerging or unique NBS interventions.

2. Boundary setting: Setting the system boundaries and defining the functional unit can influence the LCA results and raise questions about the accuracy and comparability of the assessment.
3. Impact weighting: LCA involves assigning weights to different environmental impacts, which can be subjective and raise concerns about the influence of value judgements on the results.

Table 13 presents and briefly describes additional decision-supporting approaches:

Table 13: Description of additional decision-supporting approaches

Decision-supporting approaches	*Description*
Corporate Ecosystem Valuation (CEV)	Evaluates the value of ecosystem services for businesses, aiding corporate decision-making by integrating nature's benefits and risks
Cost-minimization analysis (CMA)	Identifies the least costly approach to achieving desired ecosystem service outcomes, optimizing resource allocation.
Cost-utility analysis (CUA)	Assesses the economic efficiency of ecosystem services by weighing costs against the overall societal well-being they generate.
Ecosystem accounting (EA)	Quantifies and integrates ecosystem services into economic frameworks, enhancing policy formulation with a comprehensive view of nature's contributions.
Environmental Impact Assessment (EIA)	Quantifies and integrates ecosystem services into economic frameworks, enhancing policy formulation with a comprehensive view of nature's contributions.
Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST)	Spatially explicit modelling tool that quantifies and maps the benefits provided by ecosystems while considering trade-offs among different services.
Robust Decision Making (RDM)	Utilizes scenarios and models to make ecosystem service-related decisions that are resilient to uncertainties and future changes.
Social Return on Investment (SROI)	Measures the broader social, environmental, and economic impacts of ecosystem services, providing a comprehensive assessment of their value.
Strategic environmental assessment (SEA)	Integrates environmental considerations into strategic planning processes to ensure the incorporation of ecosystem services in long-term policies and projects.

The decision-support approach most frequently used in case studies is cost-benefit analysis. In the study by Le Coent et al. (2021), cost-benefit analysis was applied to assess the economic efficiency of NBS for water-related risks. This analysis involved quantifying the costs associated with NBS implementation and maintenance, as well as estimating benefits, including the reduction of potential damages and the monetary valuation of co-benefits, such as improved biodiversity and enhanced recreational opportunities. The study used cost-benefit analysis as a fundamental method to determine the cost-effectiveness and overall economic viability of NBS in mitigating water-related risks.

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Overall, these decision-supporting approaches are not mutually exclusive, and in practice, multiple approaches may be combined to provide a more comprehensive assessment of the costs and benefits of NBS. The specific choice depends on the project's context, available data, and the goals of the evaluation. It is essential to understand these strengths and weaknesses when using decision support frameworks for NBS assessments. Adapting and customising the frameworks to specific contexts, improving data availability, and incorporating stakeholder engagement can help address some of the limitations and enhance the effectiveness of the decision-making process.

6.4. ANALYSIS OF ECOSYSTEM SERVICE VALUATION DATABASES

In this sub-chapter, we will examine existing databases and repositories containing information on ecosystem service valuation to get an overview of applied economic valuation methods and prioritised methods per ecosystem service and landscape category in practice. For this purpose, the *Ecosystem Service Valuation Database (ESVD)*[15] and the *Blue Value Database*[16], both focusing on ecosystem service valuations, were selected. In addition, both databases haven been matched with the *Oppla database*[17], which deals specifically with NBS case studies, to assess the coverage of these. It shows, that the ESVD and the Blue Value Database have almost no overlap with the OPPLA database. In some cases, the same ecosystems or ecosystems in the vicinity are addressed, but not the NBS cases of the OPPLA database directly. But both selected databases can give an insight on the link between applied valuation methods, landscape category and ecosystem services. The geographical distribution of the case studies in the three databases is for Europe illustrated in Figure 5.

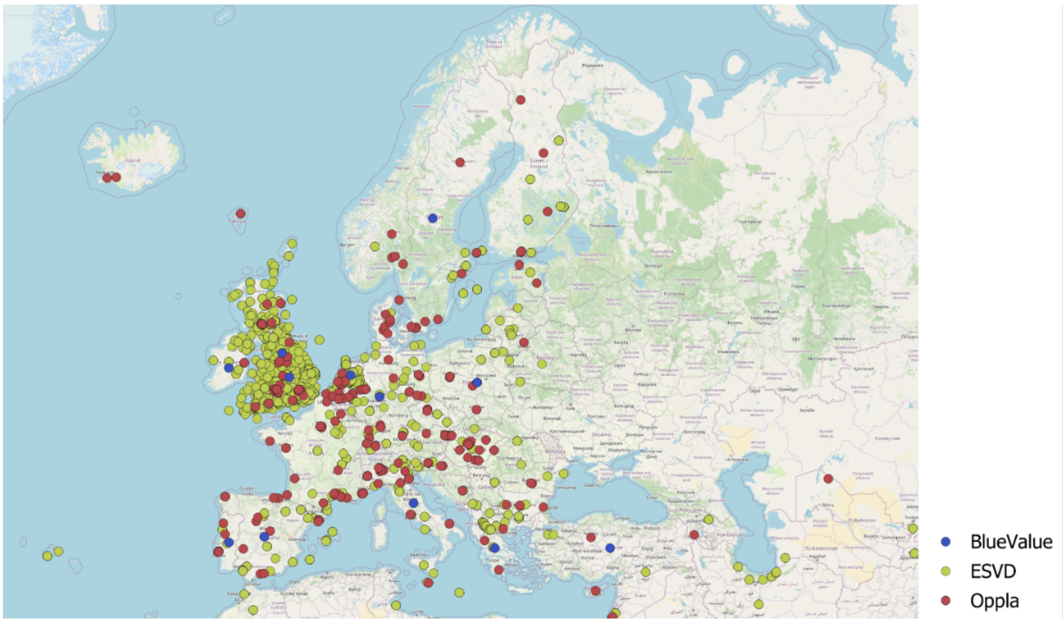

Figure 5: Geographic distribution of the case studies in the three databases

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[15] https://www.esvd.net/

[16] https://www.bluevalue.org/

[17] https://oppla.eu/case-study-finder

6.4.1. ECOSYSTEM SERVICE VALUATION DATABASE

General information:

The Ecosystem Service Valuation Database (Brander et al., 2023) is a comprehensive global repository that catalogues and consolidates economic valuation studies on ecosystem services, providing detailed information and standardized monetary values for various ecosystem types, services, locations, valuation methods, and beneficiaries. It is developed and hosted by the Foundation for Sustainable Development (FSD) and Brander Environmental Economics (BEE), with support from the Ecosystem Services Partnership (ESP) (Grammatikopoulou et al., 2023).

- 9,500 values from over 30 years of peer-reviewed academic research and official reports on monetary valuation of ecosystem services
- 70% standardized in Int$2020/ha/year
- Repository of valuation studies contains over 2000 studies
- 42% values externally reviewed
- Organized in 106 columns with information on e.g., Biomes/Ecosystems, Country, Protection Status, TEEB ES Services, CICES ES Service, Valuation Method, etc.
- Data from 1970-2023 (see Figure 6 below)

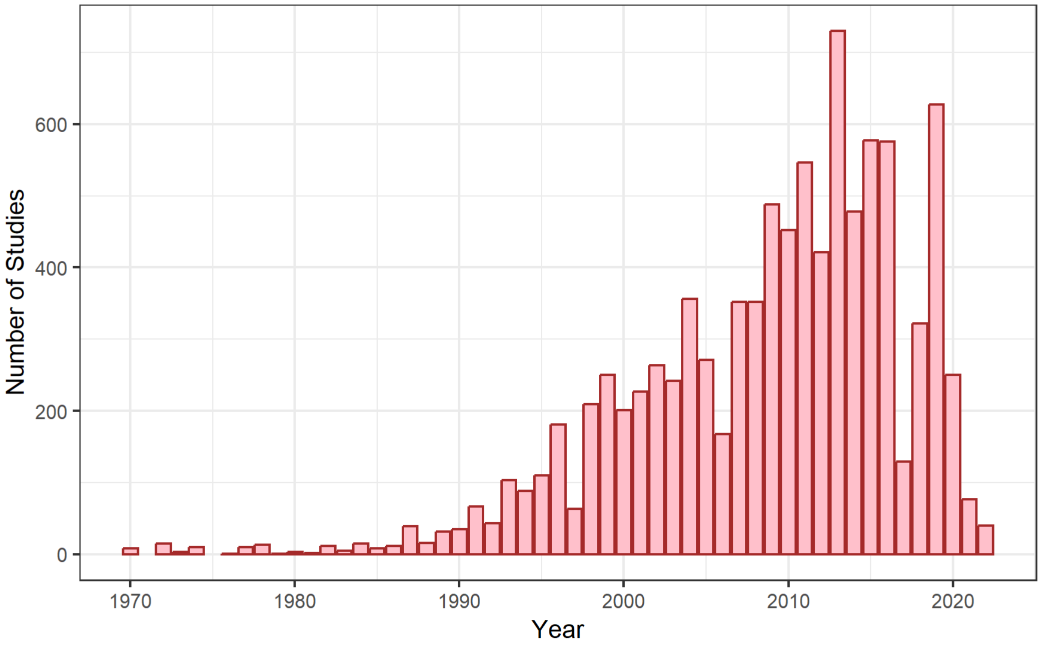

Figure 6: Year of value collection, ESVD

Data set preparation:

The database was adjusted in the following way:

- Exclusion of cases where values do not correspond to the unit international $/ha/year (international dollars are a hypothetical currency unit designed to facilitate cross-country comparisons by accounting for differences in price levels and inflation rates)
- Exclusion of non-European cases

- Due to the strong focus on the United Kingdom and the very high number of values, the following two studies, which contained a significant proportion of cases in the UK (364 and 124 cases respectively), were excluded to ensure that our results are applicable to the broader European context:
    - Pollution Removal by Vegetation (UKCEH & eftec, 2019)
    - The value of potential marine protected areas in the UK to divers and sea anglers (Kenter et al., 2013)
- Exclusion of outliers: Removal of two highest values of each landscape category

Due to the reasons for exclusion just explained, the database was reduced from 9,500 to 1,688 cases. For more details on the preparation of the dataset, such as the allocation and mapping of I4N landscape categories and ecosystem services, see the Appendix I.

Analysis:

The boxplot (Figure 7) illustrates the distribution of values in international dollars per hectare per year ($/ha/yr) across the landscape categories defined within the project (no case studies in the category Mountainous). The landscapes are arranged in a descending order based on their median value. The case studies in Water management exhibit the highest median value with approx. 1,530, yet they also display significant dispersion, with values reaching a maximum of almost 40,000 $/ha/yr. Urban landscapes rank second in terms of median values with about 850, while Coastal and marine landscapes secure the third position with 270. The median of Agriculture is fourth, followed by Forest and forestry, which has the smallest median and the smallest range of all five landscape categories. There is a high difference between the maximum values in Water Management compared to the other four landscapes with a maximum smaller than 5,000.

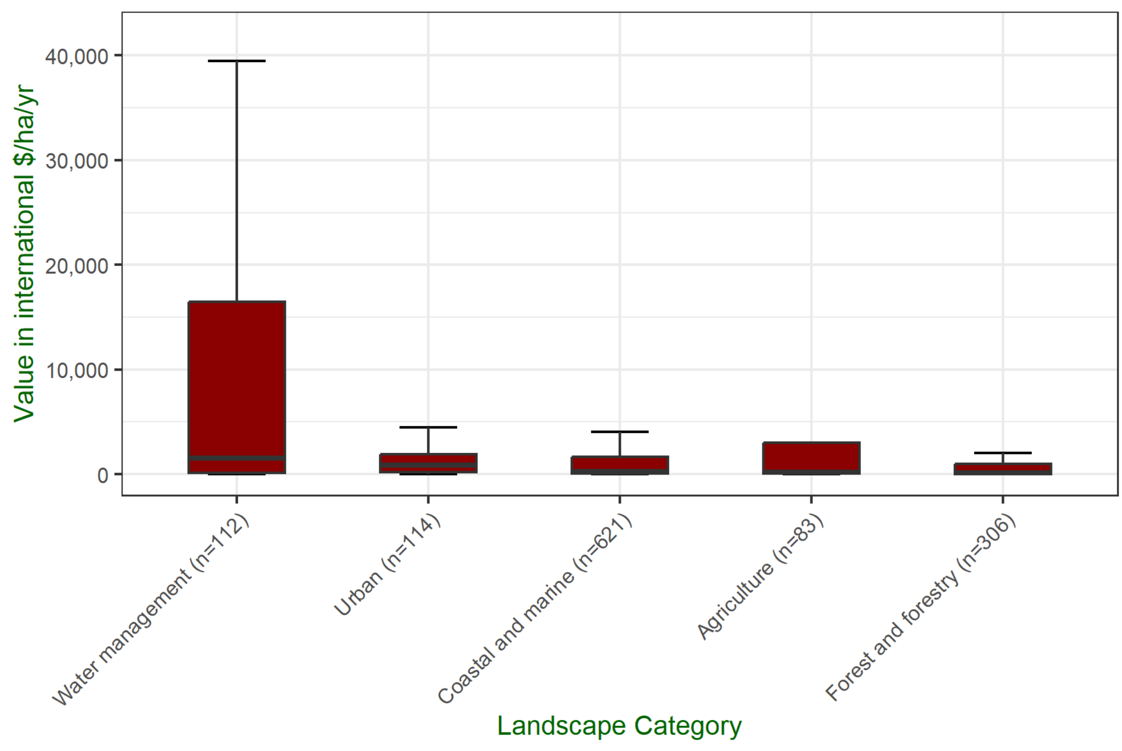

Figure 7: Distribution of values per landscape, ESVD

(n=1,236; “Multiple landscape categories” and “Other” excluded)

The following boxplot (Figure 8) shows the distribution of values in international dollars per hectare per year ($/ha/yr) across the different ecosystem services, ordered by their median value. The ecosystem service Cultural (Mdn.=304) has the highest median value, the ecosystem service Regulating and maintenance (Mdn.=127) has the second highest median value and Provisioning (Mdn.=35) ranks third in median value. In terms of the range, Cultural has the largest span with values up to over 4,000 $/ha/year. The highest value for Regulating and Maintenance is 2,000 and for Provisioning 800.

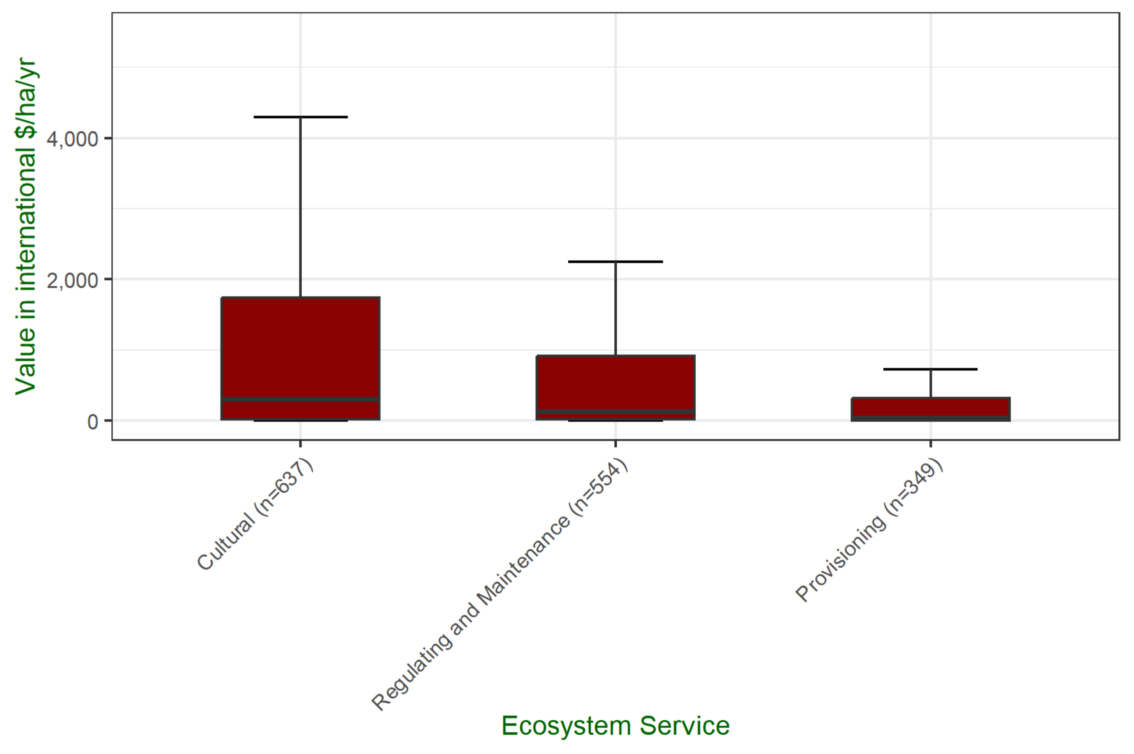

Figure 8: Distribution of values per ecosystem service, ESVD

(n=1,540; “Multiple Ecosystem Services” excluded)

The bar chart, Figure 9 below, illustrates the distribution of ecosystem services across the different landscapes based on the number of studies conducted. The studies assigned to Coastal and Marine include the largest proportion, over 50%, of cultural values, the majority of these deal with the subservice Recreation and tourism. More than 25% of the studies assess values in Regulating and Maintenance, and the remaining 20% relate to Provisioning. Studies concerning the forest ecosystem can be assigned to the three ecosystem services in approximately three equal parts. Water Management related studies have the majority of measured values, 75%, in the ecosystem service culture. More than 60% of the urban studies are related to the evaluation of values in Regulating and Maintenance and more than 50% of the studies in the field of agriculture focus on cultural values.

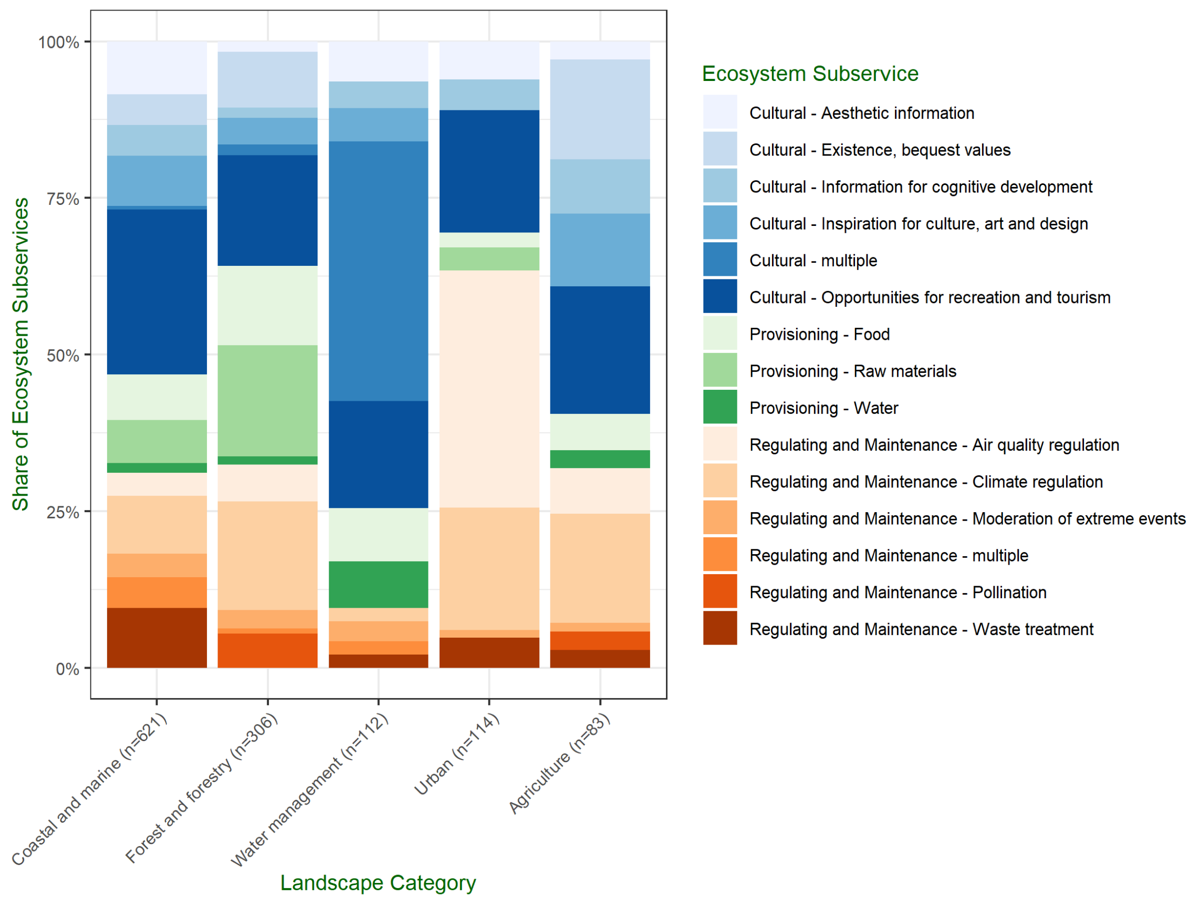

Figure 9: Percentage of ecosystem subservices in studies per landscape, ESVD
(n=1,236; “Multiple landscape categories” and “Other” excluded)

The bar chart below (Figure 10) presents the distribution of applied methods across various landscape categories. In Coastal and marine as well as Forest and forestry studies, the predominant methods used for determining values are market-based and stated preference methods. In the landscape categories of Water management and Agriculture the focus is strongly on the use of stated preference methods, with a share of 60 % and 75 %, respectively. Within the urban landscape, studies are markedly reliant on cost-based methods, accounting for almost 60% of the assessment methodologies.

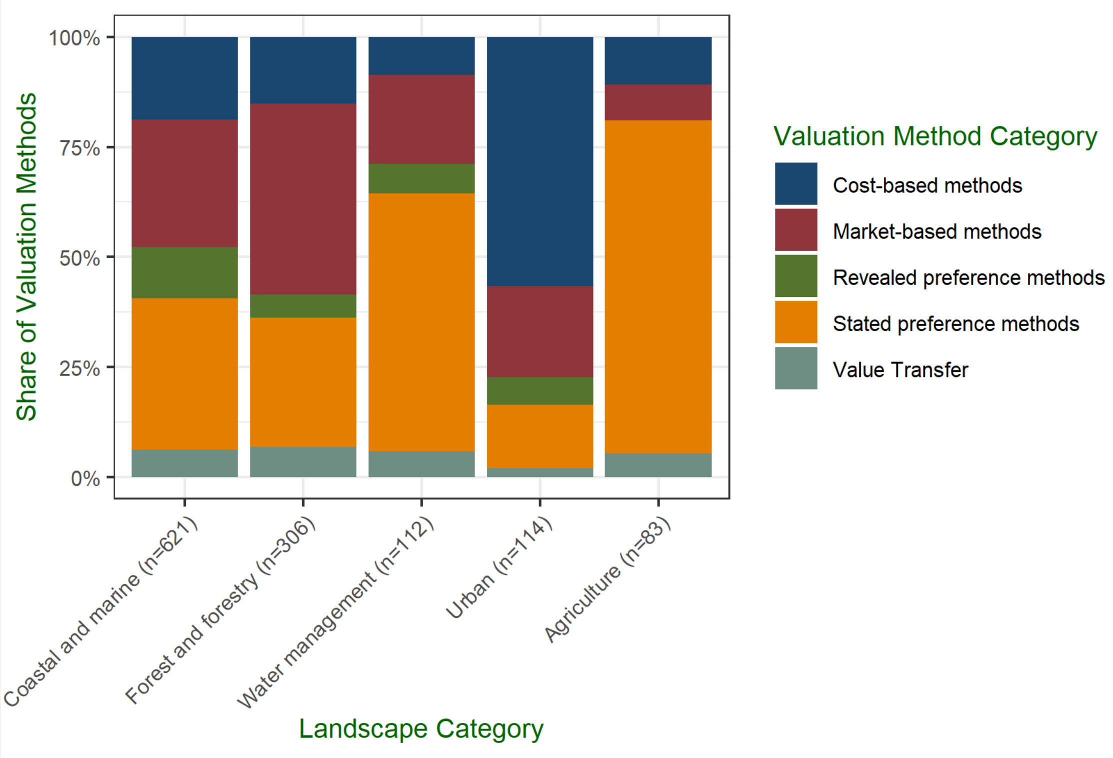

Figure 10: Percentage of applied methods per landscape category, ESVD
(n=1,236; “Multiple landscape categories” and “Other” excluded)

The diagram below (Figure 11) shows the distribution of applied methods across different ecosystem services. Around 70% of the methods used to analyse Provisioning services are market-based methods, another 20% use stated preference methods and the remaining studies applied cost-based methods as well as value transfer. For the Regulating and maintenance services, 50% of the values are assessed using cost-based methods, 25% stated preference method and almost 25% market-based methods. For studies assessing the cultural service, a significant proportion, almost 50%, is assessed using stated preference methods, while 25% use market-based methods and 20% are based on revealed preference approaches. For all three ecosystem services, a small, negligible proportion of the studies used value transfer.

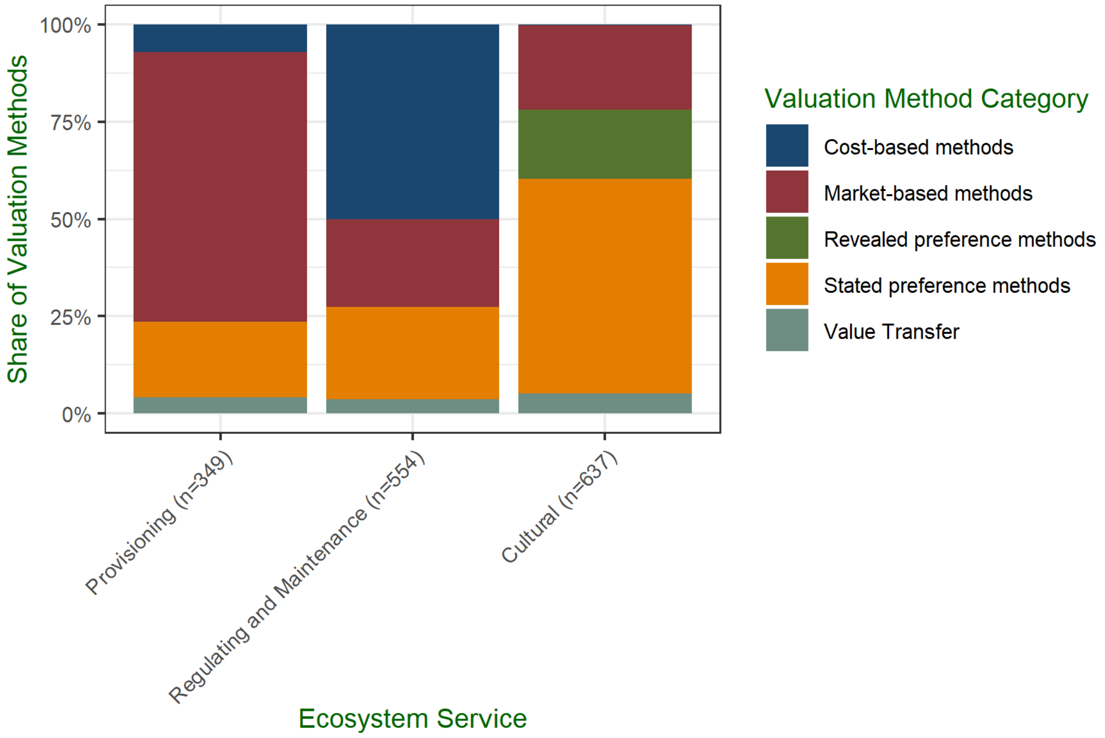

Figure 11: Percentage of applied methods per ecosystem service, ESVD
(n=1,540; "Multiple Ecosystem Services" excluded)

6.4.2. BLUE VALUE DATABASE

General information:

The Blue Value database provides a comprehensive collection of studies and data, offering insights into the monetary worth of marine and aquatic resources, such as coastal habitats, fisheries, water purification, and recreation. BlueValue is a project of the Socio-Economics Group at the Harte Research Institute for Gulf of Mexico Studies at Texas A&M University-Corpus Christi.

- 1,219 values of peer-reviewed academic research and official reports on monetary valuation of ecosystem services
- 60% standardized in Int$2020/ha/year
- Organized in 10 columns with information on Habitat, Ecosystem service, Value, Country, State and Valuation Method

Data set preparation:

The database underwent modification as follows:

- Exclusion of cases where values do not correspond to the unit international $/ha/year (international dollars are a hypothetical currency unit designed to facilitate cross-country comparisons by accounting for differences in price levels and inflation rates)
- Exclusion of non-European cases

Due to the reasons for exclusion just explained, the database was reduced from 1,219 to only 74 cases (without exclusion of non-European cases n = 735). For more details on the preparation of the dataset, such as the allocation and mapping of I4N ecosystem services, see the Appendix I.

Analysis:

The boxplot demonstrated in Figure 12 shows the distribution of values in international $/ha/year of all studies in the Coastal and marine landscape (n=74). The values range from 0 to 10,000, with a median of about 700.

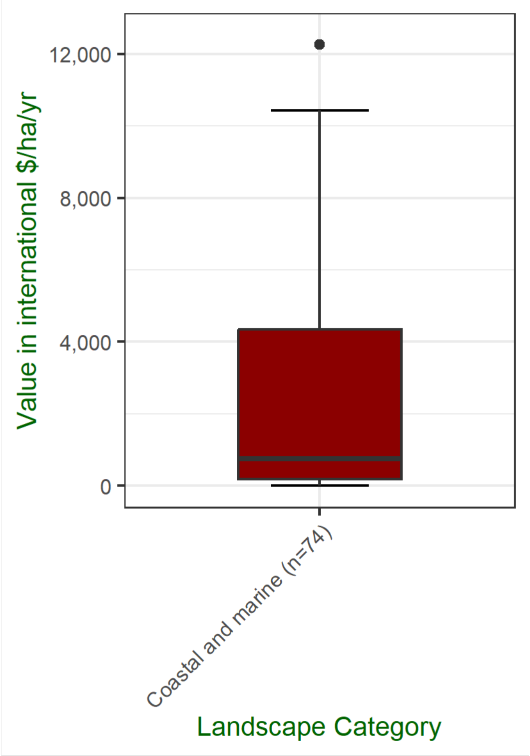

Figure 12: Distribution of values in the landscape "Coastal and marine”, Blue Value

Figure 13 demonstrates the share of valuation methods in all studies in the landscape Coastal and marine (n=75). Value transfer determined almost 75% of the studies. In addition, about 10% of the values were assessed via market-based methods. Cost-based methods, revealed preference methods and stated preference methods form the valuation method of the remaining percent, with a share of about 5% per method category.

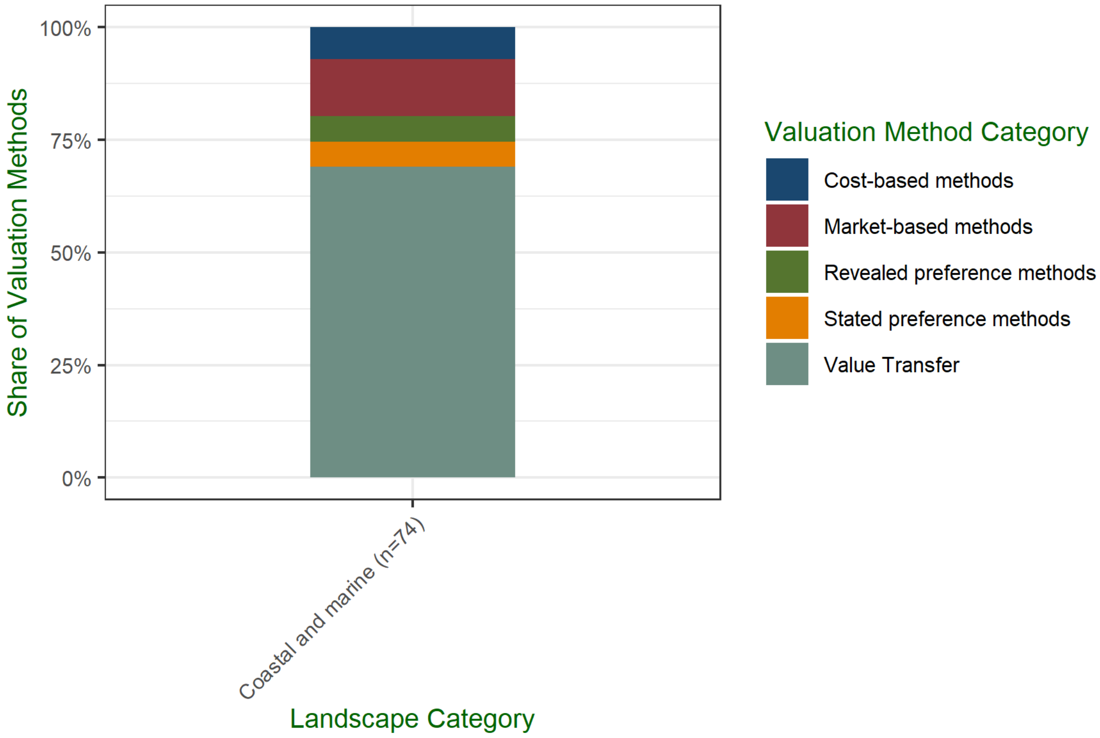

Figure 13: Percentage of applied methods per landscape, Blue Value

The bar chart, Figure 14 below, illustrates the distribution of ecosystem services across the different landscapes based on the number of studies conducted. The studies include the largest proportion, almost 50%, of values in Regulation and Maintenance, as well as 25% Provisioning and 25% Cultural. While Provisioning and Regulating include various sub-services, the largest share in Cultural lies in Recreation.

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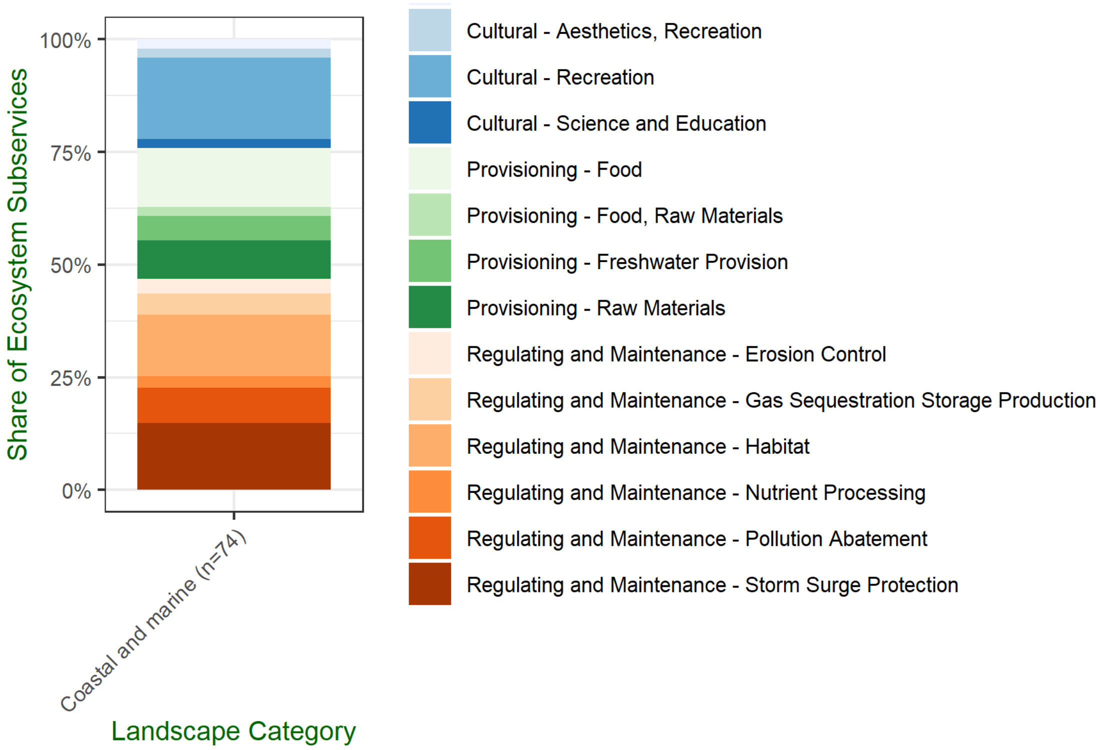

Figure 14: Percentage of ecosystem subservices in studies per landscape, Blue Value

The evaluation of the Blue Value Database shows that only limited data for the European countries and ecosystems. In the filtered dataset, the majority of studies draw on value transfer, but at least some examples of cost-based, market-based, revealed preference and state preference methods can be found. The list of subservices also shows relevant benefit categories.

6.5. LINK TO NATURAL CAPITAL ACCOUNTING AND CLIMATE DATA STATISTICS

Natural capital accounting (NCA) is a comprehensive accounting framework aimed at systematically measuring and reporting on the stocks and flows of natural resources and ecosystems, recognizing the environment as an asset that requires management and integration of its contributions into established accounting systems (EC, 2022). Linking NBS with natural capital accounting and climate data statistics enables a data-driven approach to understanding and addressing climate change challenges. There are several examples of NCA frameworks that have been developed and applied globally. Below, you will find some examples:

- **System of Environmental-Economic Accounting (SEEA):** SEEA is an international comprehensive framework developed by the United Nations for incorporating the value of natural capital, including ecosystem services, into economic accounting systems. It quantifies and measures the interactions between the environment and the economy, valuing environmental assets and their contributions to human well-being. SEEA enables the systematic integration of environmental data and indicators, including those related to NBS, into economic decision-making processes. The SEEA framework is a standardised assessment method that has been widely adopted and serves as a reference for national statistical agencies, policymakers, and researchers worldwide. It promotes consistency and comparability in natural capital accounting, enabling countries to measure and monitor their natural resources and environmental assets in a standardised and systematic manner (Grammatikopoulou et al., 2023).

The first version of SEEA was published in 1993. Since then, the SEEA has gone through several revisions and updates to enhance its methodology, expand its coverage, and align with international standards and guidelines. In 2021, the most recent version, the System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA), was published. SEEA EA is a comprehensive statistical framework that integrates spatial data to organise biophysical information about ecosystems. It facilitates the measurement of ecosystem services, monitoring changes in ecosystem extent and condition, the valuation of ecosystem services and assets, and the linkage of this information to economic and human activity indicators. Ecosystem accounting encompasses data presented in the form of maps and accounting tables, representing information in both physical and monetary units (United Nations et al., 2021).

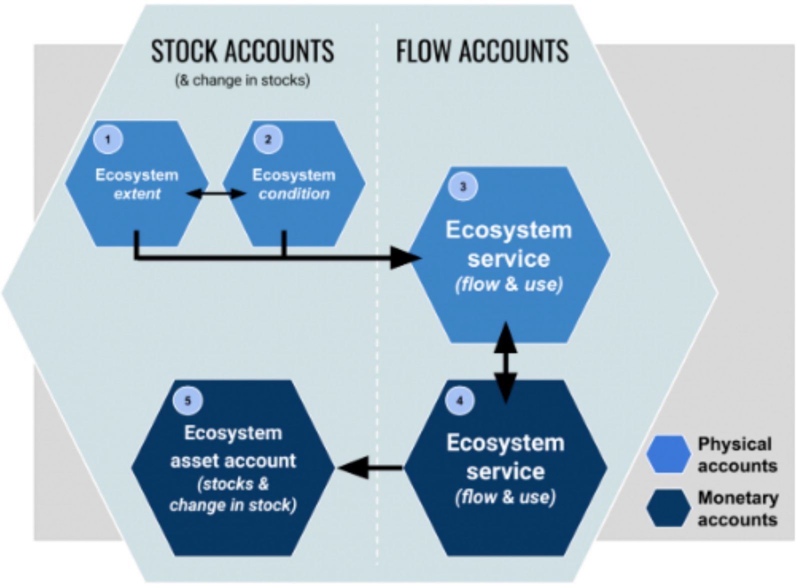

Figure 15: Ecosystem accounts and their interrelationships

(United Nations et al., 2021)

- **Inclusive Wealth Index (IWI):** The Inclusive Wealth Index was developed by a team of researchers from the United Nations Environment Programme (UNEP), the United Nations University International Human Dimensions Programme on Global Environmental Change (UNU-IHDP), and the World Bank in 2012. The IWI is a framework that measures the comprehensive wealth of a nation, including manufactured (e.g., infrastructure, buildings), human (e.g., education, skills), and natural capital. Natural capital encompasses the stock of renewable and non-renewable resources, ecosystems, and the services they provide. It assigns monetary values to natural capital to provide a holistic understanding of a country's wealth and sustainability (Managi & Kumar, 2018).

- **Natural Capital Protocol:** The Natural Capital Protocol, developed by the Natural Capital Coalition in 2016, is a standardised framework that enables businesses to identify, measure, and value their impacts and dependencies on natural capital. It provides guidance on assessing risks and opportunities associated with natural capital and supports the integration of natural capital considerations into business decision-making (Natural Capital Coalition, 2016).
- **Wealth Accounting and Valuation of Ecosystem Services (WAVES):** The WAVES initiative was developed by a partnership of organisations including the World Bank, the United Nations Environment Programme (UNEP), the United Nations Development Programme (UNDP), as well as the Natural Capital Project and was launched in 2010. WAVES supports countries in developing natural capital accounting frameworks. It provides technical assistance and guidance for integrating natural capital accounting into national accounting systems, enabling policy-makers to make informed decisions (The World Bank, 2021).
- **Accounting for Ecosystems and their Services in the European Union (INCA):** INCA is an initiative developed to assess and account for the contributions of ecosystems and their services in the European Union aiming to integrate environmental and economic information by valuing ecosystem services. It provides a framework for evaluating the impacts of policies, promoting sustainable resource management, and supporting evidence-based decision-making. INCA helps policy-makers and stakeholders understand the importance of ecosystems and their services for sustainable development in the European Union (Vysna, V. et al., 2021).
- **Environmental Profit and Loss (E P&L):** The EP&L is an accounting framework developed by PUMA in 2011 used by businesses to quantify and monetize the environmental impacts and dependencies associated with their operations. It enables companies to assess the costs and benefits of natural capital, such as water resources, land use, biodiversity, and greenhouse gas emissions, associated with their activities. The EP&L provides insights into a company's environmental performance and supports decision-making for more sustainable business practices. By integrating NBS into the E P&L framework, companies can account for the positive environmental contributions of their nature-based initiatives, allowing them to assess and communicate the value of these actions in terms of their environmental performance (Høst-Madsen et al., 2014).

Utilising climate data in the evaluation of NBS projects provides several benefits. By integrating **climate data statistics**, such as temperature records, precipitation patterns, and climate projections, NBS can be designed and implemented more effectively. This information helps identify vulnerable areas and prioritise nature-based interventions, such as reforestation, coastal restoration, or green infrastructure development, where they can have the greatest impact. By analysing historical climate data, decision-makers can identify the specific climate-related risks and vulnerabilities in a given area. This knowledge helps in designing NBS that can enhance climate resilience, such as creating green buffers, protecting natural water sources, or implementing agroforestry practices. Climate data statistics also assist in monitoring and evaluating the performance of NBS. By comparing pre- and post-implementation climate data, it becomes possible to assess the effectiveness of interventions in reducing greenhouse gas emissions, regulating temperature, or improving water management. Ultimately, linking NBS with climate data statistics helps optimise the allocation of resources and investments to tackle climate change. It empowers stakeholders to make informed choices, prioritise actions, and implement NBS that effectively contribute to climate resilience and sustainable development.

7. DISCUSSION AND CONCLUSIONS

This report provides a guiding framework and an overview of methodologies for valuing benefits and costs of Nature-Based Solutions. We begin by presenting the NBS concept and its definitions and distinct boundaries to enhance clarity and minimize ambiguity surrounding the NBS concept when compared to other green-blue interventions. We define a NBS typology consisting of three different types of generic NBS actions. Each NBS type essentially differs by the intensity of intervention carried out within an ecosystem of interest:

i) Protection/conservation of high-quality or critical ecosystems and/or sustainable management of healthy ecosystems,

ii) Modification of existing ecosystems e.g., restoration/rehabilitation of degraded ecosystems, and

iii) Creation/establishment of new ecosystems.

We categorize the three NBS types into six distinct landscapes, sectors, or thematic areas: coastal regions, mountainous terrain, agriculture, forests, water management, and urban settings. Within each of these domains, we associate each NBS type with a corresponding generic NBS action, resulting in three such actions per landscape, sector, or thematic area. Furthermore, each generic NBS action encompasses specific NBS actions that yield multiple benefits and costs.

Simultaneously, we consolidate five overarching environmental, social, and economic challenges that NBS can effectively address to promote sustainable development. These generic challenges encompass climate adaptation, climate mitigation, natural hazard mitigation, environmental management, and socio-economic challenges. For each of these societal challenges, we identify the ecological processes responsible for generating the benefits derived from addressing them.

The benefits, costs, and potential disservices arising from both generic and specific NBS actions, as well as the resolution of societal challenges, serve as essential inputs in defining relevant benefit and cost categories for NBS. The latest definition of NBS, as provided by the UN Environment Assembly in 2022, underscores their cost-effectiveness. This implies that the financial expenditures associated with NBS must not disproportionately outweigh the benefits, ensuring that NBS remain economically viable in comparison to other green-blue infrastructure solutions.

To assess whether a given NBS is indeed cost-effective, it becomes imperative to establish well-defined benefit and cost categories for NBS. This foundational step serves as a crucial basis for compiling evidence and knowledge pertaining to NBS, laying the groundwork for subsequent quantitative or valuation assessments. The establishment of these benefit and cost categories for NBS provides a guiding framework, facilitating the tailored adaptation of the Total Economic Valuation (TEV) framework across the six diverse landscapes and the five societal challenges.

We have characterized the multiple benefits and costs associated with NBS, which allows for meaningful comparisons between NBS and alternative (hybrid) interventions, taking into account several crucial factors: the specific challenges being addressed, the landscapes affected, the ecological processes harnessed, and the NBS typologies (i.e., types of NBS actions) employed. Nonetheless, it is important to emphasize that further research studies and empirical evidence are needed to map and quantify the synergies and trade-offs inherent in NBS implementation. For instance, consider agroforestry measures, which have the potential to yield numerous environmental and socio-economic benefits such as diversifying income sources, controlling erosion, and enhancing water storage. However, it is equally important to recognize the associated trade-offs: the management approaches required to realize these benefits can be costly, complex, and time-consuming for farmers. Consequently, it is essential to acknowledge both the number and magnitude of synergies and trade-offs to accurately assess the financial performance of NBS. In this context, trade-offs typically encompass negative consequences (i.e., disservices) or the opportunity costs (i.e., forgone benefits from alternative infrastructure or competing land uses) associated with the implementation of an NBS project. The generic NBS cost categories that we have developed account for these trade-offs, considering them as opportunity costs and indirect costs in the assessment process. On the other hand, the inclusion of synergies is an interesting avenue for future research, recognizing synergies as the added value ensuing from enhancement across multiple NBS benefit categories.

There remains an ongoing imperative to enhance and delineate the boundaries within the terminology and application of NBS. The lines of distinction between the three NBS types often prove challenging to define precisely, primarily due to the nuanced nature of NBS interventions that can take on hybrid forms that don't neatly fit into a single category. This complexity arises because these actions may straddle multiple NBS types or because determining the appropriate NBS type based on the extent, scale, and expected outcomes of the intervention can be a complex task. Furthermore, hybrid solutions may encompass or extend into multiple landscapes, impacting several geographical areas simultaneously. Consequently, the implementation of such NBS actions must take into account the scale and scope of these interventions, recognizing their potential to influence and traverse various landscapes.

In addition, the report provides a comprehensive inventory of the variety of valuation methods that can be used to assess the economic, environmental and social costs and benefits of NBS. It categorizes quantitative and qualitative valuation methods, provides case studies to illustrate their application and discusses their strengths and weaknesses. When selecting an economic valuation method, it is crucial to consider various factors, including scope, objectives, ecosystem services, costs and benefits, data availability and quality, and specific context, to ensure accuracy. However, also the available budget is a deciding factor. Employing a mix of methods and integrated approaches enables a more comprehensive assessment of NBS. It is also recommended to include qualitative methods alongside quantitative approaches, especially for NBS, which often encompass a wide range of benefits, costs, and tangible and intangible values, including use and non-use values. The overview of risk assessment approaches revealed the availability of various methods, although they often require extensive data and detailed modelling of physical processes. Additionally, the results and scenarios can enhance communication of risks to stakeholders. Although some applications in the context of NBS can be found, additional case studies would be helpful to facilitate transferability to different situations.

Decision support approaches help to evaluate, rank or compare the costs and benefits to provide decision-makers with tools for making informed decisions regarding the implementation of NBS. We further explore established databases such as the Ecosystem Service Valuation Database and the Blue Value database to offer insights into economic valuation methods and preferred practices for various ecosystem services and landscape categories. Although there are minor overlaps in the matching of valuation databases, they provide valuable insights into the relationship between applied valuation methods, landscape types, and ecosystem services. The paper underscores the importance of integrating NBS with natural capital accounting and climate data statistics to effectively tackle climate change challenges within economic systems.

In summary, the range of available methods is broad and method development in the field of valuation of ecosystem services has a long tradition. Recent applications of methods in the context of NBS can be found, along with guiding handbooks for method selection and NBS assessment design. The multi-benefit nature of NBS, where use and non-use values are relevant, requires an integrated assessment of different cost and benefit categories following a total economic value framework (TEV) that also considers disaster risk reduction and climate change adaptation aspects. Further efforts are necessary to refine these methods and tailor the assessments to specific contexts and landscapes. In addition, it is crucial to explore the synergies and trade-offs between NBS and other forms of climate change mitigation and adaptation strategies. As a next step, Invest4Nature aims to expand the TEV framework, with special emphasis on incorporating uncertainties with climate risks and impacts on disaster risk reduction.

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APPENDIX

PREPARATION OF DATABASES

Ecosystem Service Valuation Database

Landscape categories ESVD	**Landscape categories I4N**
Open sea/ocean	Coastal and marine
Coral reefs	Coastal and marine
Coastal systems (incl wetlands)	Coastal and marine
Inland wetlands	Water management
Rivers and lakes	Water management
Tropical forests	Forest and forestry
Temperate forests	Forest and forestry
Woodland & Shrubland	Forest and forestry
Grass-/Rangeland	Agriculture
Desert	Other
Tundra	Other
High mountain & Polar systems	Mountainous
Inland Un- or Sparsely Vegetated	Other
Cultivated areas	Agriculture
Urban Green and Blue Infrastructure	Urban
Other	Other

Ecosystem Service ESVD	**Ecosystem Sub-Service ESVD**	**Ecosystem Service I4N**
Food	Fish	Provisioning
	Meat	
	Plants / vegetable food	
	NTFPs [food only!]	
	Food [unspecified]	
	Other	
Water	Drinking water	
	Industrial water	
	Water Other	
	Irrigation water [unnatural]	
	Water [unspecified]	
Raw materials	Fibers	
	Timber	
	Fuel wood and charcoal	
	Fodder	
	Fertiliser	
	Other Raw	
	Raw materials [unspecified]	
	Sand, rock, gravel	

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	Biomass fuels	
Genetic resources	Plant genetic resources	
	Animal genetic resources	
	Genetic resources [unspecified]	
Medicinal resources	Biochemicals	
	Models	
	Test-organisms	
	Bioprospecting	
Ornamental resources	Decorative Plants	
	Fashion	
	Decorations / Handicrafts	
	Pets and captive animanls	
Air quality regulation	Capturing fine dust	Regulating and Maintenance
	Air quality regulation [unspecified]	
	UVb-protection	
Climate regulation	C-sequestration	
	MDS-production	
	Climate regulation [unspecified]	
	Microclimate regulation	
	Gas regulation	
Moderation of extreme events	Storm protection	
	Flood prevention	
	Fire Prevention	
	Prevention of extreme events [unspecified]	
Regulation of water flows	Drainage	
	River discharge	
	Natural irrigation	
	Water regulation [unspecified]	
Waste treatment	Water purification	
	Soil detoxification	
	Abatement of noise	
	Waste treatment [unspecified]	
Erosion prevention	Erosion prevention	
Maintenance of soil fertility	Maintenance of soil structure	
	Deposition of nutrients	
	Soil formation	
	Nutrient cycling	
Pollination	Pollination of crops	
	Pollination of wild plants	
	Pollination [unspecified]	
Biological control	Seed dispersal	
	Pest control	
	Disease control	
	Biological Control [unspecified]	
Maintenance of life cycles	Nursery service	
	Refugia for migratory and resident species	

Maintenance of genetic diversity	Biodiversity protection	
Aesthetic information	Attractive landscapes	Cultural
Opportunities for recreation and tourism	Recreation	
	Tourism	
	Ecotourism	
	Hunting / fishing	
Inspiration for culture, art and design	Artistic inspiration	
	Cultural use	
	Inspiration [unspecified]	
Spiritual experience	Spiritual / Religious use	
Information for cognitive development	Science / Research	
	Education	
	Cognitive [unspecified]	
Existence, bequest values	Existence value	
	Bequest value	

Valuation Methods ESVD	**Method Cluster I4N**
Choice Modelling (Discrete Choice Experiment; Conjoint Analysis)	Stated preference methods
Contingent Valuation	Stated preference methods
Damage Cost Avoided	Cost-based methods
Defensive Expenditure	Revealed preference methods
Group Valuation (Participatory Valuation)	Participatory valuation methods
Hedonic Pricing	Revealed preference methods
Input-Output Modelling	Cost-based methods
Market Prices (Gross Revenue)	Market-based methods
Net Factor Income (Residual Value; Resource Rent)	Market-based methods
Opportunity Cost	Cost-based methods
Production Function	Market-based methods
Public Pricing	Cost-based methods
Replacement Cost	Cost-based methods
Restoration Cost	Cost-based methods
Social Cost of Carbon	Cost-based methods
Travel Cost	Revealed preference methods
Value Transfer	Value Transfer

Blue Value Database

Ecosystem Service Blue Value Database	**Ecosystem Service I4N**
Freshwater provision	Provisioning
Food	
Raw materials	
Genetic resources	
Medicinal resources	

Ornamental resources	
Nutrient processing	Regulating and Maintenance
Primary production	
Pollination and seed dispersal	
Habitat	
Hydrological Cycle	
Gas sequestration, storage, and production	
Climate processes	
Storm surge protection	
Biological control	
Water flow	
Erosion control	
Pollution abatement	
Recreation	Cultural
Aesthetic	
Science and education	
Cultural, spiritual and historic	
Bequest	
Existence	
Option	

Valuation Methods Blue Value Database	**Method Cluster I4N**
Avertive or Mitigative Expenditures	Cost-based methods
Benefit Transfer (BT)	Value Transfer
Choice Experiment (CE) or Discrete Choice Experiment (DCE)	Stated preference methods
Contingent Valuation (CV)	Stated preference methods
Damage Cost Avoided (DCA or DC)	Cost-based methods
Debt for Nature Swap	Market-based methods
Delphi Panel	Qualitative methods
Demand Function	Revealed preference methods
Discrete Factor Method (DFM)	Revealed preference methods
Emergy	Cost-based methods
Energy Analysis (EA)	Cost-based methods
Expected Damage Function Approach (EDF)	Cost-based methods
Hedonic Price Method (HP)	Revealed preference methods
Market Price (MP)	Market-based methods
Meta-Analysis (MA)	Value Transfer
Opportunity Cost	Cost-based methods
Productivity Method (PM)	Market-based methods

Random Utility Model (RUM)	Revealed preference methods
Relative Ratings	Revealed preference methods
Replacement Cost (RC)	Cost-based methods
Revealed Preference	Revealed preference methods
Shadow Price (SP)	Cost-based methods
Stated Preference	Stated preference methods
Travel Cost Method (TC)	Revealed preference methods
Willingness-to-Pay (WTP)	Stated preference methods

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