



# The economics of nature-based solutions.

**Value categories and approaches to assess NbS economic and financial performance**

**WP2 (Task 2.1 and Task 2.2)**

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## ABBREVIATIONS AND ACRONYMS

| ACRONYM | DESCRIPTION                           |
|---------|---------------------------------------|
| CBA     | Cost-benefit analysis                 |
| CCA     | Climate change adaptation             |
| CEA     | Cost-effectiveness analysis           |
| DMU     | Decision making under uncertainty     |
| DRR     | Disaster risk reduction               |
| ES      | Expected Shortfall                    |
| ESVD    | Ecosystem Services Valuation Database |
| LCA     | Life-cycle analysis                   |
| MCA     | Multi-criteria analysis               |
| NbS     | Nature-based Solutions                |
| NCA     | Natural Capital Accounting            |
| R&I     | Research and Innovation               |
| TEV     | Total Economic Value                  |
| VaR     | Value-at-Risk                         |

## 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, Turkey, 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 5<sup>th</sup> 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 (2021a) 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.*

| PARTNER<br>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<br>Partners (NIVA,<br>AAKS, UMP,<br>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 |

*Table 1. Contributions of Partners*

## 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 (2021a): 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<sup>2</sup>. 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 (2021a). 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

<sup>2</sup> <http://www.resin-cities.eu/home/>

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 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 (2021a), 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<sup>3</sup>, REGREEN<sup>4</sup>, Naturance<sup>5</sup>, Naturvation<sup>6</sup>, and Nature4Cities<sup>7</sup>. 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.

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<sup>3</sup> <https://naiad2020.eu/>

<sup>4</sup> <https://www.regreen-project.eu/>

<sup>5</sup> <https://www.naturanceproject.eu/>

<sup>6</sup> <https://naturvation.eu/>

<sup>7</sup> <https://www.nature4cities.eu/>



### 3. NBS CONCEPT, TYPOLOGY AND INTERVENTIONS



Graphic 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

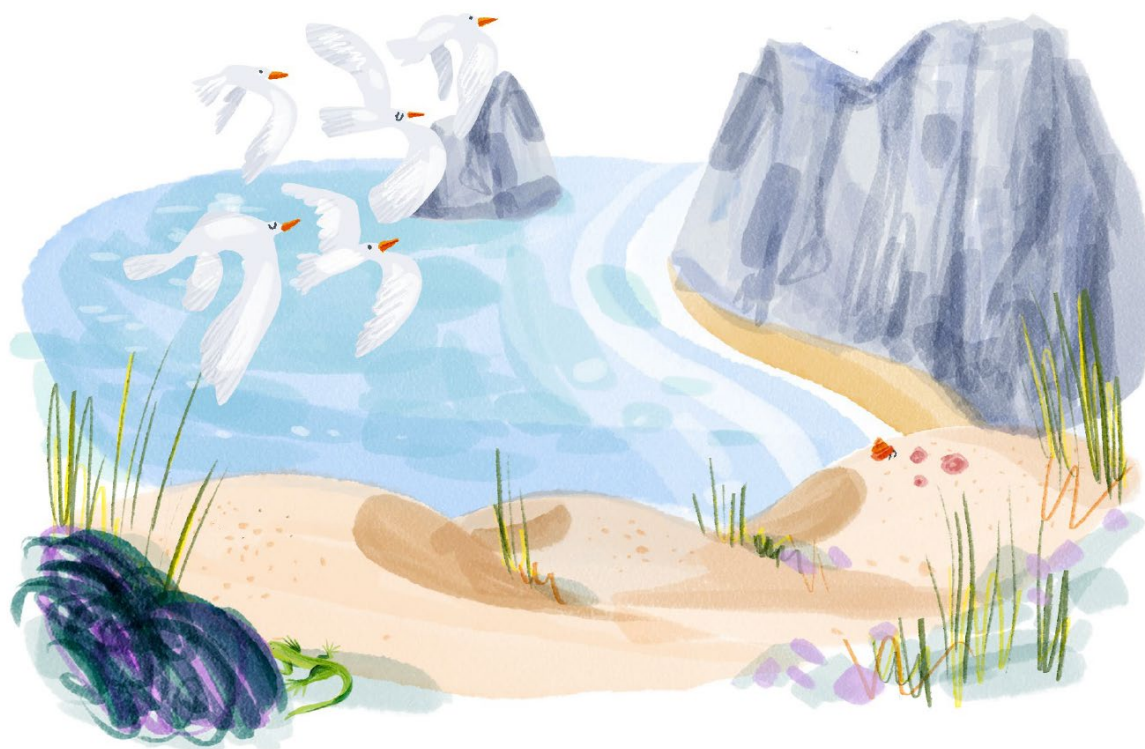
We compile the three groups of generic NbS actions across the **landscapes/thematic areas** selected in the report of the European Environment Agency “*nature-based solutions in Europe: Policy, knowledge and practice for climate change adaptation and disaster risk reduction*” (EEA, 2021a). The EEA report 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



Graphic source: Network Nature

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, 2017a). 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., 2014a), 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.

| 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 |

Table 2. Generic and specific NbS actions for coastal areas

### 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<sup>8</sup> and the GreenRisk4Alps project in five European countries (Austria, Germany, Italy, Slovenia, and Switzerland)<sup>9</sup> 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 techniques of erosion control. For example, since 2019 the Phusicos project in the Pyrenees<sup>10</sup> 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<sup>11</sup>, 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<sup>12</sup> is a case example that integrates the two main specific actions in mountain ecosystems. The project involves

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

<sup>9</sup> GreenRisk4Alps Project description: <https://www.alpine-space.eu/project/greenrisk4alps/>

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

<sup>11</sup> Phusicos project in the Kaunertal valley, Austria: [Kaunertal valley, Austria - PHUSICOS R&D project to reduce risk in mountain landscapes](#)

<sup>12</sup> Water retention management in the broader area of Ancient Olympia, Elia, Greece: [NWRM-CS-GR-01](#)

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 halepensis*) 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.

| 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   |

Table 3. Generic and specific NbS actions for mountain areas



### 3.3.3. AGRICULTURE



Graphic 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, 2021a). 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](http://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, 2021a). 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.

| 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 |

Table 4. Generic and specific NbS actions for agriculture

**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



Graphic 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<sup>13</sup>) 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.

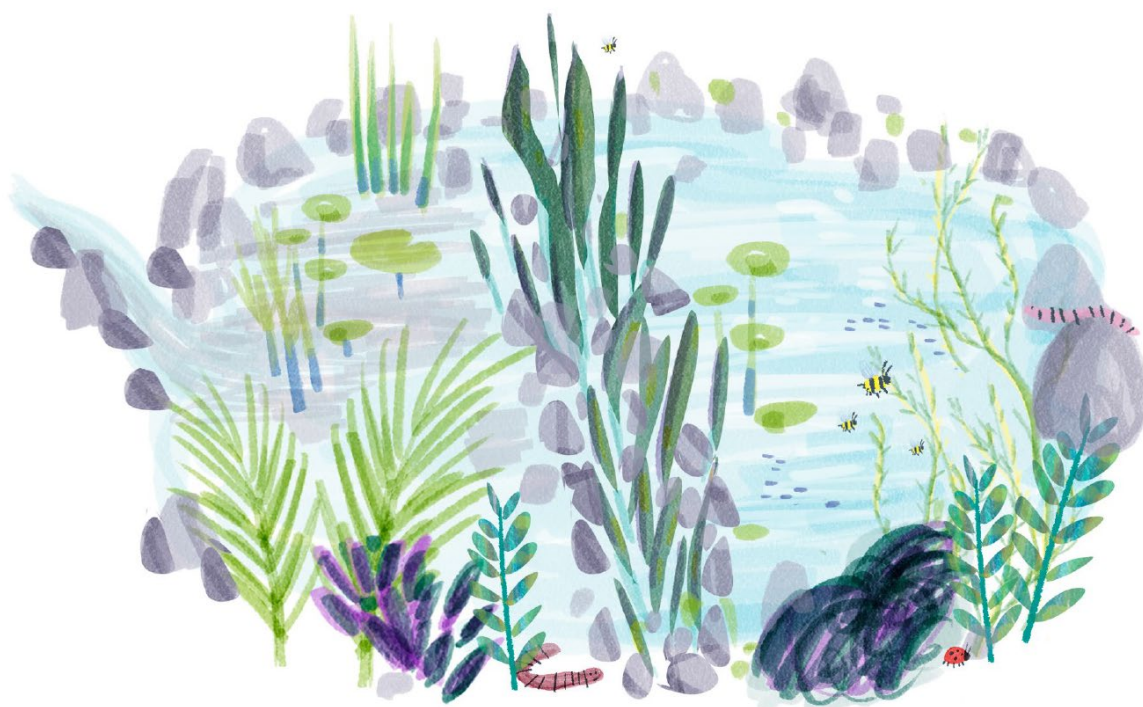
| GENERIC ACTION   | NBS TYPE | SPECIFIC ACTION   |
|--|----------|---|
| Protection/conservation of forest ecosystems                                 | 1        | Protection/conservation of primary and old-growth forests   |
| Modification of an existing forest ecosystem / Sustainable forest management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

<sup>13</sup> 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*

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



Graphic 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)<sup>14</sup>.

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 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.

| 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  |

Table 6. Generic and specific NbS actions for water management

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).

<sup>14</sup> 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.

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



Graphic 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<sub>2</sub> 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, Vojinovic, Sabatino, et al., 2020). Table 7 displays the 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    |

Table 7. Generic and specific NbS actions for urban areas

Based on the EEA report (2021a), 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 are included in table 8 below.

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

Table 8. Scale levels of NbS in urban areas

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 Eclipse 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.

| 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                                    |
| Environmental management  | Water pollution                                  |
|                           | Water physical scarcity                          |
|                           | Coastal erosion, soil erosion                    |
|                           | Biodiversity loss                                |
|                           | Noise pollution                                  |
| Socio-economic challenges | Unemployment                                     |
| Socio-economic challenges | Inequality                                       |
|                           | Health & well-being                              |
|                           | Social segregation                               |
|                           | Economic efficiency                              |

Table 9. Generic and specific societal challenges

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 water volume increases to the point where it fills the river bed and overflows its banks.

In a healthy and well-balanced river, flood mitigation occurs mainly in **floodplains**, flat areas next to the river that provide space for water retention. Here, the flow of water slows down, collects and moves sediments that help to maintain the shape, structure, and dynamics of the river. The main processes are the retention of temporary excess water and run-off, which helps to reduce peak flows (Ferreira et al., 2020; The World Bank, 2017a). Ensuring the hydrological connectivity of floodplains with flood-compatible land types such as forests, pastures, and open spaces has the potential to mitigate downstream flood levels and minimize or prevent flood damage (Opperman & Galloway, 2022; Vouk et al., 2021). Leaving sufficient space for natural rivers and floodplains can reduce the exposure of people and infrastructure to flood hazards, while creating space for the water to flow. Moreover, re-meandering rivers (i.e. restoring river natural meandering pattern by reintroducing bends, curves, and sinuosity) increases the length of the river channel, consequently reducing flow conveyance and water speed (EEA, 2017b).

Within floodplains, **water retention ponds and basins** can also act as natural buffers against floods by temporarily storing water, reducing the speed and volume of water entering downstream watercourses. They can also enhance groundwater infiltration, promote the retention of sediment, pollutants, and nutrients, soil stabilization and erosion reduction (Blackwell et al., 2006; Vouk et al., 2021).

Additionally, along water courses, **vegetated buffer strips** consist of plants with deep root systems that can 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 a wider perspective, addressing drought at the same time (see drought section).*

#### Examples of benefits:

##### River restoration (Floodplain restoration, re-meandering, water retention ponds):

Natural infrastructure aimed to river and floodplain restoration has shown positive impacts for flood control. For example, in North Carolina (USA), 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<sup>2</sup> catchment in the New Forest (UK) the results of a monitoring study found river restoration led to a 21% reduction in flood peak for 2-year recurrence event (Sear et al., 2006). Similarly, river restoration in Eddleston Water (UK) 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).

##### Vegetated buffer strips:

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

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

#### 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).

On the coast, **dunes and coastal vegetation** provide a protective buffer against coastal flooding by acting as physical barriers that absorb and dissipate the energy of storm surges, and lower the wind speed, reducing flood risk (Sigren et al., 2014). Coastal vegetation helps to stabilize and maintain the integrity of the dunes by binding sand and trapping new sediment, reducing erosion. Similarly, **mangroves** reduce coastal erosion by dissipating wave energy through their intricate network of roots, which slows the flow of water across the soil surface and facilitates the settlement and deposition of sediment. Mangrove roots obstruct wind passage, reducing wave heights. The combination of diminished wave energy and increased sedimentation effectively reduces coastal erosion (Perricone et al., 2023; University of Cambridge, 2014). Mangroves serve also as coastal buffer zones between the ocean and inland areas, acting as a first line of defence against storm surge and tidal inundation. **Wetlands** act as natural sponges, capturing storing floodwater, slowing surface runoff and improving the hydraulic resilience of the landscape (EEA, 2017b). Stored water is released gradually, helping to regulate water flows during both floods and droughts. In addition, wetland vegetation increases flow resistance, dissipates water energy and reduces erosion, attenuating runoff (Bullock & Acreman, 2003). As well, **tidal marshes** have been shown to reduce the height of wind waves (Möller et al., 2014) and storm surges through their vegetation, which increases surface roughness and reduces damages during extreme flood events (Barbier et al., 2013; Costanza et al., 2008).

In the ocean, **coral and shellfish reefs** are natural barriers against waves due to their ability to break waves offshore, limiting the energy impacting the coastline (Cuttler et al., 2018; EEA, 2021b). These have a high structural complexity, which leads to high hydraulic roughness and greater frictional dissipation of waves compared to other coastal settings (D. L. Harris et al., 2018). The crest, which is the tallest part of the reef, provides major reductions due to wave-breaking phenomena, while the remaining energy and height are mitigated by the reef flat, which is the first hundred meters after the crest (Perricone et al., 2023).

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

#### Examples of benefits:

##### Dunes and coastal vegetation:

Dunes can contribute up to 60% of wave attenuation during storm events (EEA, 2021b).

##### Mangrove forests:

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). Mangrove forests' attenuation potential varies with the geographical location of the site and its characteristics: 27% attenuation potential in Indonesia, 50% in Mexico, 29% in Myanmar, 47% in India, 28% in the Philippines,

and 22% in Cuba (Blankespoor et al., 2017). Mangroves can annually reduce property damage by more than \$US 65 billion and protect more than 15 million people (Menéndez et al., 2020).

#### **Wetlands and tidal marshes:**

The water storage capacity of wetlands is between 9,400 - 14,000 m<sup>3</sup> of flood water (GFDRR, 2022), while the 1% increase in wetland roughness because of vegetation could decrease storm surge by 15.4% to 28.1% (Barbier et al., 2013). Tides that exceed the marsh platform's peak water levels are typically reduced along the channels, with maximum attenuation rates of 5 cm/km for tides that flood the marsh platform by 0.5-1.0 m (Stark et al., 2015).

#### **Coral and shellfish reefs:**

Coral reefs provide substantial coastal protection by dissipating up to 95% of wave energy and significantly reducing wave height (Ferrario et al., 2014b). Healthy coral reefs have been found to dissipate 97% of wave energy and 84% of wave height (Perricone et al., 2023). Oyster reefs are capable of reducing wave height by 51-90% and wave energy at the shore by 76-99% (Perricone et al., 2023).

### **4.1.3. PLUVIAL FLOOD REGULATION**

Pluvial floods occur when rainwater is not absorbed by ground drainage systems, particularly in urban areas. Intense and spatially concentrated rainfall events in densely developed cities can result in excessive water flows that can cause significant damage to tangible assets.

Water-sensitive urban planning and building design, aimed at minimizing water runoff, mitigating flood peaks, and improving groundwater replenishment, can contribute to water management and pluvial flood risk mitigation (EEA, 2021b). **Urban water retention measures** include different green infrastructure, such as bioswales, retention and detention basins, (constructed) wetlands, rain gardens, permeable pavements, riparian vegetation strips and green roofs, parks, gardens, trees, urban forests. These measures help to increase the amount of permeable surface area through vegetation, which increases the porosity and permeability of the soil, allowing water to infiltrate into the ground. This reduces surface runoff and increases groundwater storage, thereby reducing the risk of flooding during heavy rainfall events (EEA, 2021b). **Urban parks and forests** can regulate storm water and mitigate flood hazards by intercepting rainfall, improving infiltration through deeper infiltration along root channels, or generally delaying the contribution to surface runoff (Berland et al., 2017).

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).

*The processes underlying urban NbS functioning contribute to water management both in a context of water scarcity and flood (see water scarcity section).*

#### **Examples of benefits:**

##### **Urban water retention measures:**

Bioretention systems, such as ponds, swales and raingardens, are effective in peak discharge control with an average reduction above 40% (P. A. Davis et al., 2009; Kõiv-Vainik et al., 2022a). The retention rate of green roofs, instead, may range from 29 to 100%, with an average retention just under 78 percent, depending on the depth of the rainfall (Rasmussen, 2006). Permeable pavements can reduce stormwater flow by around 75-80%, especially in warm and wet climate conditions (Kõiv-Vainik et al., 2022a). In China, the implementation of NbS for flood prevention at city scales created the so-called Sponge Cities. Here, 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 m<sup>3</sup>, and the amount of reduced runoff per hectare green space was 2494 m<sup>3</sup> (Zhang et al., 2012). In Yixing, the runoff regulation capacity of green spaces resulted to be greater in the built-up areas, at approximately  $3.9 \times 10^7$  m<sup>3</sup>yr<sup>-1</sup> of rainwater runoff, while green spaces outside the built-up areas made a relatively minor contribution to rainwater runoff reduction (only  $1.4 \times 10^7$  m<sup>3</sup>yr<sup>-1</sup>) (Yang et al., 2015).

#### Urban parks and forests:

Studies on the role of vegetation in urban environments have shown that trees can intercept an estimated 6.7 m<sup>3</sup> of water per year, helping to reduce the frequency and severity of combined sewage water overflow events (Berland & Hopton, 2014). In a Korean case study, it was estimated that the presence of parks in an upstream river could reduce downstream flood peak by 30–83%, in 1-in-100-year return period rainfall scenarios (Meng, 2022a; Ngo Thy Thuy, 2016). The stormwater benefits of urban trees can be also translated into economic terms; for example, a study in Lisbon estimated an economic benefit of USD 47.80 per tree, due to its ability to reduce stormwater runoff (EEA, 2021b; Soares et al., 2011).

#### 4.1.4. THERMAL CONTROL AND COOLING

Urban heat islands and heat stress occur in cities, where the natural green cover is replaced by concrete pavements, buildings, and heat-absorbing surfaces. For urban population, these effects contribute to increasing energy costs for cooling and heat-related health issues.

**Vegetation** plays a crucial role in influencing urban microclimates by providing shading and evapotranspiration services, contributing to reduce and regulate surface and atmospheric temperatures (Price et al., 2015). During summer, a part of the sun's energy is absorbed by plant leaves and used for photosynthesis or reflected back into the atmosphere, cooling the area below (EPA, 2005). At the same time, the water absorbed by roots is released through the leaves, where it evaporates, utilizing heat from the surrounding air. This evaporation process is endothermic (i.e. it is absorbing energy, as heat in this case), resulting in a reduction of temperatures in the surrounding areas (Menon & Sharma, 2021). By reducing energy demand, vegetation indirectly contributes to the reduction of greenhouse gas emissions, thereby mitigating the effects of climate change

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). Green walls can also 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).

*The processes underlying urban vegetation contribute to carbon sequestration and air purification (see carbon sequestration and air purification sections).*

#### Examples of benefits:

##### Urban vegetation:

It has been demonstrated that trees have a positive impact on urban temperature. Across Europe, the surface temperature in presence of trees is lower compared to concrete urban surfaces: 0–4°K lower in Southern Europe and 8–12°K lower in Central Europe (Schwaab et al., 2021). Positive results were also showed by an earlier study where the oasis effect was proved to



diminish the temperature of a plant's surrounding air of 8 °C (Price et al., 2015). Furthermore, vegetation can help to reduce heat-related mortality. Cities with high greenspace value resulted to have the lower relative risk of heat-related mortality, and a 20% increase in green space is associated with a 9% decrease in heat-related mortality (Choi et al., 2022).

#### Green roofs and green walls:

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 °C. Green roofs can help improve thermal comfort, reducing the Human thermal index by up to 5.88°C (Santana et al., 2023). The insulating properties of green roofs can reduce heat flux between the external environment and the buildings, reducing the need for air conditioning load by 10% to 30% (EPA, 2018). The insulation effect of green facades showed a reduction of the heat flux from 64.5 and 43.9 W/m<sup>2</sup> produced by bare walls to 36.5 and 34.1 W/m<sup>2</sup> generated by green walls. 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 planting and the implementation of green roofs and facades could lead to a possible 20% reduction in US 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% (Perini & Rosasco, 2013b).

#### 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, 2021b).

On the coast, **dunes** provide a natural barrier of sand that erodes during storm conditions, dissipating wave energy. The effectiveness of dunes varies: wider, lower dunes perform better during longer moderate storms, while taller, narrower dunes offer greater protection during intense storms (Itzkin et al., 2021). Vegetation on coastal dunes 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, augmenting dune volumes and increasing dune's ability to mitigate 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, replenishing eroded beaches. Similarly, **mangrove forests and wetlands** 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 transport them away from the mangrove area. Furthermore, the decreased speed of water flow enables previously suspended sediments to settle, leading to enhanced sediment deposition (University of Cambridge, 2014).

In the oceans, **coral reefs** serve as a proficient natural defence against waves by breaking them offshore, reducing the energy reaching the coastline (Cuttler et al., 2018; EEA, 2021b). The high structural complexity of coral reefs leads to high surface roughness, causing greater frictional dissipation of waves when compared to other coastal environments (D. L. Harris et al., 2018).

*The processes characterizing coastal vegetation actions can contribute to mitigate coastal floods and erosion (see coastal erosion and coastal flood sections).*

## Examples of benefits:

### Vegetated dunes:

In terrestrial coastal habitats and ecosystems in transitional waters provides, vegetation is responsible for about 60 % of wave attenuation during storms events (EEA, 2021b). Experiments with live plants have demonstrated a notable reduction in both the volume of dune erosion and the rate of dune scarp retreat rate by more than 30%. The roots of mature plants are more effective against structural failure and sediment degradation (Sigren et al., 2014). Additionally, 1% increase in wetland roughness caused by wetland vegetation is associated with a reduction in storm surge ranging from 15.4% to 28.1% (Barbier et al., 2013).

### Mangrove forests and wetlands:

Coastal vegetation and mangroves contribute also to create and preserve unique habitat for flora and fauna (Sigren et al., 2014). Additionally, they support fisheries production by providing an indispensable habitat for juvenile fish, shellfish and crustaceans, and act as sinks for atmospheric CO<sub>2</sub> and contributing to climate change mitigation (Temmerman et al., 2013). In addition, mangrove 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).

### Coral reefs:

Coral reefs provide significant protection against natural hazards by reducing wave energy by an average of 97%. The majority of this energy reduction (86%) is attributed to reef crests, while reef flats dissipate 65% of the remaining wave (Ferrario et al., 2014b)

## 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 contributing 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, 2021b). 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; UN Environment-DHI et al., 2018). 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 (i.e. water absorbed by the roots is released through the leaves using the heat of the air). Water interception is highest in trees and shrub, while trees transpiring 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 leaf cover and the deep shading under the trees and shrub canopies (Gillefalk et al., 2021).

**Vegetated buffer areas** can provide protection against drought and water scarcity by retaining and slowly releasing water runoff and enhancing groundwater recharge (EEA, 2021b). Buffer areas play a role in reducing the rate of runoff and help recharge groundwater, preserving the minimum ecological flow in rivers. They can treat runoff by filtration through the substrate in the vegetated strips and subsequently through soil (Zelevánková et al., 2017). These measures also help to diminishing surface runoff and mitigate the risk of soil compaction and erosion (EEA, 2021b).

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 soil moisture level, to reduce surface run-off, alleviate drought stress and reduce soil compaction and erosion risk (EEA, 2021b). **Mulching** contributes to increased water infiltration rates and soil moisture retention in agricultural soil, thereby

maintaining soil moisture levels (Keesstra et al., 2018). **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. Acting as an insulating layer, they lower surface soil temperature and mitigate wind effects, reducing soil water evaporation. By mitigating hot wind impact, excessive crop transpiration and water uptake are minimized, preserving soil moisture reserves (Bergtold et al., 2019; Vignola et al., 2015). **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, 2021b).

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, 2021b). 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, 2015a).

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

### Examples of benefits:

#### Vegetated buffer areas:

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., 2022a). 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).

#### Agroforestry and sustainable agricultural practice:

Introducing perennials (grasses, agroforestry, managed forestry) or cover crops can increase water infiltration rates by about 60%, while cover crops contribute to a 35% increase (Basche & DeLonge, 2019). Cover crops can increase cumulative water infiltration by 52% to 68%, depending on the season, compared land management without cover crops (Haruna et al., 2022). Cover crops can increase water storage by 6% at a soil depth of 30cm (Wang et al., 2021). Hedgerows can decrease wind speed more than 50% per year compared to open fields (Böhm et al., 2014).

#### Forest management:

Studies have shown that water interception is highest in trees and shrubs, whit trees transpiring around 30% more than shrubs (Gillefalk et al., 2021). Furthermore, compared to basins with 10% of forest cover, the total water retention increases by 25% and 50% in water basins where the forest cover exceeds 30% and 70%, respectively (EEA, 2015a). When forest cover exceeds 30% of the sub-basin area, each additional 10% increase in forest cover reduces runoff by 2-5%, increasing water retention by forests. Furthermore, in sub-basins where forest cover exceeds 70%, forests retain 50% more water than in sub-basins with only 10% forest cover. In particular, forests can reduce runoff in summer by almost 25% more than in winter (EEA, 2015a). Coniferous forests generally have a 10% higher water retention capacity than broadleaved or mixed forests (EEA, 2015a).



## 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 vegetation, and includes both living and dead forms of biomass. Terrestrial habitats absorb and store atmospheric carbon, partly mitigating the rise in atmospheric CO<sub>2</sub> concentrations.

Wetlands and peatlands store the largest amount of carbon per unit area followed by forests (EEA, 2021b). **Peat soils** are important carbon pools. Their long-term carbon storage capacity is partly due to their high-water content, which makes them less likely to burn than drier habitats. However, when drained, these habitats become sources of greenhouse gases through the decomposition of organic matter in the soil. **Forests** provide large carbon stocks due to the high carbon content of the above and below ground biomass (EEA, 2021b). Carbon (C) is not only stored in tree biomass but also in forest soils. Forest ecosystems cover large parts of the terrestrial land surface and are important components of the terrestrial carbon cycle. Forests accumulate organic compounds sequestering carbon for long time in vegetation, detritus and soil. Trees absorb large amounts of atmospheric carbon dioxide through photosynthesis, and forests return almost the same amount to the atmosphere through respiration. But a small fraction of the remaining carbon continues to accumulate in vegetation, detritus, and soil.

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. In shrub and semi-natural **grasslands**, plants capture atmospheric carbon dioxide and store the carbon in their living tissue, both above and below the ground (photosynthesis process). 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 primarily contribute to carbon storage through the growth and shedding of roots, which is a cyclical process. When these plants are pruned, such as through grazing, a similar number of roots also dies off, adding carbon to the soil (Bai & Cotrufo, 2022; Ghosh & Mahanta, 2014).

*The 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).*

#### Examples of benefits:

##### Peatlands and wetlands:

Peatlands cover <3% of the world's surface and they hold two times global forest biomass pool, that is more than 30% of the total global soil carbon store (EEA, 2021b; Holden, 2005). Overall, Wetlands can retain up to 40% or more of the soil carbon reserves (Nahlik & Fennessy, 2016). Tropical and subtropical wetlands, with an average net carbon sequestration of 118 g-C m<sup>-2</sup> year<sup>-1</sup>, account for the majority of global wetland carbon sequestration (Mitsch et al., 2013). Boreal and subarctic peatlands comprise a carbon pool of 455 Pg (billions of tons) that has accumulated during the postglacial period (Gorham, 1991).

##### Forest:

Existing forests can sequester carbon up to 13% of total EU greenhouse gas emissions from the burning of fossil fuels (Seddon et al., 2019). Additionally, upon reaching full maturity, approximately 900 million hectares of restored forest have the capability to draw down a substantial 200 Gt of carbon. Globally, forests play a crucial role as net carbon sinks, removing approximately  $-7.6 \pm 49$  Gt of CO<sub>2</sub>eq yr<sup>-1</sup>. This includes both gross carbon removals, which amount to  $-15.6 \pm 49$  Gt of CO<sub>2</sub>eq yr<sup>-1</sup>, and gross emissions resulting from deforestation and other disturbances, which account for  $8.1 \pm 2.5$  Gt of CO<sub>2</sub>eq yr<sup>-1</sup> (N. L. Harris et al., 2021). Responsible forest management increases the carbon sink potential. Avoided deforestation and land degradation increases carbon storage by up to 0.4-5.8 GtCO<sub>2</sub> yr<sup>-1</sup>, while carbon

sequestration through afforestation/reforestation potentially increases carbon storage to 0.5-10.1 Gt CO<sub>2</sub> yr<sup>-1</sup> (Bastin et al., 2019; Seddon et al., 2020).

### **Grassland:**

Grassland ecosystems cover an area of 52.5 million km<sup>2</sup>, and store approximately one third of the global terrestrial carbon stocks acting as an important soil carbon sink. Almost 90% of the carbon stock is stored below ground as root biomass and soil organic carbon (SOC). The soil carbon sequestration potential is estimated to be between 0.4 and 1.2 Gt CO<sub>2</sub> yr<sup>-1</sup> (Meena et al., 2020). The carbon sequestration potential of grasslands is part of this potential, ranging from 0.01 to 0.30 Gt CO<sub>2</sub> yr<sup>-1</sup> (Ghosh & Mahanta, 2014).

## **4.2.2. CARBON SEQUESTRATION IN AQUATIC ECOSYSTEMS**

**Aquatic ecosystems** acting as 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 (Hendriks et al., 2022).

Aquatic carbon sequestration encompasses to long-term storage of atmospheric carbon in sediments, biomass and/or water. This process involves not only the retention of organic carbon within local biomass and vegetated sediments achieved through photosynthesis but also the transportation of carbon away from its source to be stored in various aquatic environments such as lakes, rivers, glaciers, groundwaters, and the ocean (EEA, 2021).

Carbon can be sequestered through various chemical and physical processes. The presence of alkaline conditions (i.e. capacity of water to resist acidification) may facilitate the precipitation of carbon in the form of calcium carbonate, dissolved organic and inorganic carbon, which can be absorbed by water or accumulated in sediments. Additionally, carbon can be sequestered through plant photosynthesis or as simple physical sedimentation, where organic and inorganic materials settle at the bottom of water bodies. (Alonso et al., 2012)

In lakes and coastal environments, soils and sediments can be considered as the dominant long-term carbon reservoir in aquatic ecosystems. Carbon accumulation and storage capacity in seagrass meadows varies depending on species, sediment characteristics, depth of the habitat and remineralisation rates. In addition, storage capacity can vary significantly between geographical areas or be affected by anthropogenic activities (EEA, 2021).

### **Examples of benefits:**

#### **Marine ecosystems:**

Marine ecosystems are the largest long-term sink for carbon in the biosphere, storing and cycling an estimated 93% of the Earth's CO<sub>2</sub>. North-east Atlantic Ocean is estimated to store around of 23 % of anthropogenic CO<sub>2</sub> (inorganic carbon), while a much smaller proportion of organic carbon - approximately 1% - is estimated to be buried in the sea sediment resulting from millions of years of deposition. Marl beds and sea grass beds stand out for having the highest carbon stocks, while Lophelia reefs and seagrass beds also exhibit substantial carbon stocks. In contrast, flame shell beds, blue mussel beds, brittle star beds, and faunal turfs have lower carbon stocks (EEA, 2021).

## 4.3. ECOLOGICAL PROCESSES OF NATURAL HAZARDS

### 4.3.1. SLOPE STABILISATION

Avalanches and landslides pose significant risks associated with the mass movement of snow, rock, or soil on sloping terrain. Maintaining and restoring **forest** cover serves as a crucial strategy for preventing and mitigating these hazards by retaining solid material on-site, limiting mass movements (EEA, 2021b; Perzl et al., 2021). Deep-rooted trees and shrubs play a primary role in reducing the occurrence of shallow landslides by strengthening soil layers and enhancing drainage. Additionally, the extensive root systems facilitate transpiration, which lowers soil water content and decreases landslide risk (Forbes & Broadhead, 2013). However, the effectiveness of vegetation in slope protection depends on the architecture of the root system, including rooting depth, density, distribution, elasticity, and strength. While vegetation can stabilize shallow soils and soil surface layers against landslides, it may be less effective in preventing deep landslides caused by prolonged heavy rainfall or seismic activity (Hamilton et al., 2008).

In the case of avalanches or landslides, the breakage, uprooting, and overturning of trees, along with the entrapment of coarse woody debris and snow deposition behind trees, dissipate energy and shorten the runout lengths of medium to large avalanches originating from sites above the timberline or large clear-cuts (Gubler & Rychetnik, 1990; Perzl et al., 2021; Schneebeli & Bebi, 2004; Teich et al., 2012). Both standing and fallen trees play a critical role in stabilizing the snowpack during avalanches, effectively mitigating their risk or reducing the size of released slabs. Forests have demonstrated their ability to intercept and arrest small avalanches, as supported by research findings (Teich et al., 2012).

*The processes underlying slope stabilisation can contribute also to soil erosion control (see soil erosion section).*

#### Examples of benefits:

##### Forests against avalanches:

Forest characteristics influence the ability to reduce avalanche runout: canopy cover >30%, absence of gaps >25 m in length, and an increased terrain roughness associated with lying or standing trees above the snow depth were found to be particularly effective (Bebi et al., 2009). Forest density has a substantial influence on avalanche runout. Small trees, especially those with a mean diameter at breast height between 1 and 15 cm, are particularly important in the realising zone and within the first 200 meters of the avalanche track (Teich et al., 2012). Forest type can also influence differently the avalanche dynamics. Deciduous coniferous forests have a smaller effect compared to evergreen coniferous and mixed forests, due to the higher crown biomass and interception effects of evergreen coniferous and mixed forests, which typically contain a greater number of small-diameter stems (Teich et al., 2012). The protective effect of forests depends more on stem density and surface roughness than on canopy cover, for which most guidelines report the need for a stem density greater than 15% (Perzl et al., 2021).

##### Forests against landslides:

The protective effect of forests requires a density (i.e. number of stems per hectare) higher than 15% (Perzl et al., 2021). Across the world, vegetation resulted to mitigate landslides risk and reinforce 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 uniform and consists of mixed species. However, it tends to be less effective with an increase in slope angle.

## 4.4. ECOLOGICAL PROCESSES OF ENVIRONMENTAL MANAGEMENT

### 4.4.1. AIR PURIFICATION

Air quality is linked to a series of complex interactions between the land and the atmosphere, in which **vegetation** plays a key role (EPA, 2015). The role of vegetation for air purification is particularly important in urban areas. Here, air pollution has been associated with both a reduction in urban greenery and an increase in various health impacts such as cardiovascular diseases, premature mortality and child health issues (Menon & Sharma, 2021).

Vegetation, through its metabolism (photosynthesis and respiration), can act as a filter for many pollutants, such as carbon monoxide, ozone, particulate matter or nitrogen oxides (Wróblewska & Jeong, 2021). Plants absorb gaseous and particulate matter through their leaves, assimilate it into plant biomass and metabolise it into non-hazardous forms, finally releasing processed and clean air through the leaves again (Biswal et al., 2022; Bolan et al., 2011; Lamb et al., 2014).

These biochemical processes work in combination with dispersion and deposition processes, where vegetation acts as a physical barrier that reduces and traps air pollutants (Barwise & Kumar, 2020; Biswal et al., 2022; Janhäll, 2015; Morakinyo & Lam, 2016a). Dispersion mechanisms mainly refer to the changes in the trajectory and velocity of gases and particular matter through the physical structure of plants (Diener & Mudu, 2021). Deposition refers to the deposition of pollutants on leaves, where stomata take up substances and react with water to initiate metabolic processes (Janhäll, 2015; Price et al., 2015; Pugh et al., 2012). Additionally, some species can act retaining pollutants and heavy metals in their tissues, i.e. via bioaccumulation (Menon & Sharma, 2021).

Species and vegetation distribution can influence air purification processes in different ways (Churkina et al., 2015; Sæbø et al., 2012; Willis & Petrokofsky, 2017). Vegetation distribution and morphology can influence physical filtration processes of vegetation by increasing or decreasing deposition surface, penetration of substances and deflection of airflow (Barwise & Kumar, 2020; Janhäll, 2015).

*The processes underlying air purification can contribute also to carbon (see carbon sequestration section).*

#### Examples of benefits:

##### Urban vegetation:

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 sulphur dioxide (Gong et al., 2023; Wróblewska & Jeong, 2021). Roadside vegetation can contribute to reduce fine PM by 30-60%, PM<sub>2.5</sub> around 14%, nitrogen dioxide up to 40%, black carbon up to 63% (Abhijith & Kumar, 2019; Al-Dabbous & Kumar, 2014; Pugh et al., 2012; Santiago et al., 2019).

Pollutant reduction through dispersion can vary greatly depending on the exact location of exposure measurement, and spatial concentration patterns, which can be strongly affected by the local wind. PM<sub>1</sub> (52%) have the highest dispersion values, followed by PM<sub>2.5</sub> (44%) and PM<sub>10</sub> (35%) (Ottosen & Kumar, 2020). However, PM<sub>1</sub> can be blocked most effectively compared to PM<sub>10</sub> and PM<sub>2.5</sub> (Abhijith & Kumar, 2019).

Vegetation can also act as a physical barrier to PM concentrations. Potential reduction depends on distance from pollution sources, up to 7-18 m according to the wind direction (Wróblewska & Jeong, 2021).

### Urban green space:

Where wider strategies and plans for regreen urban areas has been implemented, positive impacts on air quality have been registered. the city of Stuttgart protected under nature conservation orders 39% of its territory, regreening more than 60% of the city surface (around 100.000 trees; 5000 ha of forest and woodland; 300.000 m2 of green roofs, kilometres of green tram tracks) (Urban Climate Stuttgart, 2008). In the recent year, the environmental quality increased. The exceedance level of NO<sub>3</sub> and PM<sub>10</sub> 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 defined as the contamination of water sources by substances which make water unusable for drinking purpose, agricultural production (irrigation) and recreational activities, as well as undermining habitat quality and biodiversity. As with air purification, vegetation can play a key role in cleaning water through bioretention and buffering processes in different environments.

In particular, **vegetation buffers** along agricultural watercourses and crops contribute to the removal of fertilisers and pesticides, especially by trapping and assimilating nitrates and phosphorus, by reducing surface runoff from fields and by filtering surface, groundwater and stream runoff (Borin et al., 2010; Jose, 2009; Lovell & Sullivan, 2006). The extensive root systems of perennial plants play a key role by holding soil in place, allowing greater infiltration of water and trapping sediment runoff from cultivated areas.

**Wetlands** purify water by reducing flow velocity, and through phytoremediation processes, involving microbial degradation of organic matter, microbial transformation, and nutrient retention and uptake by plants (Vymazal, 2011). Processes are driven by the soil water content and the presence of vegetation, which can allow nutrient fluxes to be retained and/or transformed. Under aerobic conditions (presence of oxygen), organic nitrogen can be mineralized, while under anaerobic conditions (absence of oxygen), nitrification is repressed and ammonium accumulates in soils or sediments (Vought et al., 1995).

**Agroforestry** system contribute to improve water infiltration and soil retention capacity, contributing to water and ground water quality (Bharati et al., 2002; Pavlidis & Tsihrintzis, 2018). Agroforestry help to reduce agricultural pollutants leaching to groundwater aquifers and absorbing pollutants from unsaturated or saturated-low depth zone through tree roots (Jose, 2009). Particularly, poplar and willow trees are known for their ability to absorb pollutants, including pesticides and their degradation products, and immobilize them in woody parts of the tree (Licht & Isebrands, 2005).

**Phytoremediation** involves plants and microbes to remove contaminants from soil and water. This includes phytodegradation, where plant tissues break down pollutants enzymatically; phytovolatilization, where contaminants are removed through plant transpiration; phytostabilization, which reduces the mobility of contaminants by absorbing them onto roots; rhizofiltration, where roots absorb and sequester pollutants in water; and phytoextraction or phytoaccumulation, where roots take up harmful metals and store them in 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.

### Examples of benefits:

#### Vegetated buffers strips and wetlands:

Wetlands and buffers can reduce nitrate concentrations in the range of 40% to 94% before entering a stream, while phosphorus removal by vegetated buffer strips can vary widely. Phosphorus removal by vegetated buffer strips can vary widely, from 25 to 95 per cent, depending on factors such as the percentage of soil-bound versus soluble phosphorus, length of buffer strip, plant cover and hydrological conditions (Lovell & Sullivan, 2006). This also applies



to pesticides, which 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).

#### Agroforestry:

The contribution of agroforestry to nitrate reduction from groundwater ranges from 60% to 90% for nitrates and 24% to 81% for phosphorus (Mayer et al. 2005; Schoonover et al. 2003). Agroforestry buffers demonstrated to reduce 62% of total suspended solids, 25% of nitrate–nitrite, 64% total nitrogen and 23% of total phosphorus from watershed (Salceda-Gonzalez et al., 2024).

#### Vegetation (phytoremediation):

Numerous studies have shown that the removal capacity of vegetation is above 40% for suspended solids and nitrogen, above 70 % for phosphorous and above 30% for organic matter (Biswal et al., 2022). Ponds can also trap large amounts of sediment, phosphorus and organic carbon. Analysis has shown 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). In urban areas, bioretention systems act as phytoremediators and help to reduce suspended solids, nitrogen, phosphorous, metals as Cu and Pb, contaminants as PCBs by approximately 91-97%, 38-57%, and 86-94%, 90% and 45%, respectively (Gülbaz et al., 2015; Shrestha et al., 2018). 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; Mezzalana et al., 2014).

Similarly, in urbanized areas, a wide variety of structures, from public and private parks and gardens and permeable surfaces, can increase water storage capacities. **Urban vegetation and permeable surfaces** intercept rainfall, slow water runoff and make the water flow through the underlying drainage layers, where it is partially stored and used by the vegetation itself when needed. 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. **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, 2021b). Ponds can serve to collect and store water during precipitation events, providing additional storage capacity to retain runoff and release when the risk of water overflow ceased (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).

*The processes underlying water scarcity mitigation can contribute also to urban pluvial flood control and droughts (see pluvial flood and drought sections).*

### Examples of benefits:

#### Groundwater recharge:

In agricultural land, forested infiltration areas realized in Northern Italy can infiltrate around 5.000 m<sup>3</sup> of water per hectare per day, and almost 1 million m<sup>3</sup> of water in one year (Agostinetto et al., 2013; Mezzalana et al., 2014). 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., 2022a).

#### Urban green spaces (permeable surface):

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., 2022a). A heavy rain event of short duration 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, Vojinovic, Di Sabatino, et al., 2020). The water retention capacity of green roofs can be largely above 50% (Meng, 2022a; Whittinghill et al., 2015). 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, Vojinovic, Di Sabatino, et al., 2020).

#### Rainwater harvesting measures:

In urban areas, 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., 2022a). Water retention capacity of green roofs can be largely above 50% (Meng, 2022a; Whittinghill et al., 2015). In agricultural land, 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 1Mm<sup>3</sup> natural water pond could support a surface of almost 200 ha of high-water-demanding crops (Pistocchi, 2022; Staccione et al., 2021).

### 4.4.4. COASTAL EROSION CONTROL

Coastal erosion occurs when sea level rise, strong waves, and coastal flooding remove rocks, soils, and/or sand along the coast. Coastal resilience to erosion can be enhanced by nature-based coastal protection measures, such as planting vegetation or adding sediment, which stabilize coastal structure and enhance the natural ability of the coastline to absorb and dissipate storm and wave energy by maintaining the natural coastal processes.

**Terrestrial coastal vegetation** strengthens the stability of the coastal morphology. Vegetation root systems are critical for anchoring plants, retaining and stabilising soils (EEA, 2021b; Perricone et al., 2023). This action is particularly important in the dune system. Dunes are a protective feature that provide a sand buffer and protect the land from waves and flooding, acting also as sand storage area, supplying sand to eroding beaches. Dune grass and other vegetation can help stabilize and absorb the sand shoreline, limiting the effects of erosion (Figlus et al., 2014).

Underwater vegetation, such as **seagrasses**, can retain sediments and support erosion control (EEA, 2021b). Seagrasses live below the tidal line and can create large meadows. Through their roots and leaves, they stabilize sandy substrates, dissipate wave energy, tidal currents and storm surges, while enhancing the potential for beach nourishment (W. L. Chen et al., 2022). At the same way, macroalgal communities provide erosion protection by modifying near-surface current (Feagin et al., 2019). In the oceans, both **coral and oyster reefs** constitute an effective protection against erosion by attenuating

wave energy, producing and retaining sands, increasing sediment deposition behind the reef, and stabilizing the shoreline. The ability of the reef to attenuate waves depends on its height and roughness. Taller crests and rougher texture of the reef, higher and stronger the waves that can be reduced (Perricone et al., 2023).

### Examples of benefits:

#### Vegetated dunes:

Dune vegetation has been shown to reduce wave run-up erosion by approximately 40% (Feagin et al., 2019). The volume of dune sediment erosion can be reduced by 6.6% for every additional 100mg/l of dry fine roots, while the rate of scarp retreat can be reduced by 4.6% (Figlus et al., 2022). Vegetated dunes can reduce dune erosion volume and dune scarp retreat rate by more than 30%. Furthermore, mature plants can increase the cumulative shear necessary for sediment breakdown by 180% (Sigren et al., 2014).

#### Underwater vegetation:

A dense seagrass meadow is able to reduce wave height by 40% during storm events. When combined with beach nourishment, planting seagrass in proximity with the wave breaking zones can reduce wave height up to 1.3 m (around 80%), resulting in a reduction of around 40% of sand erosion (W. L. Chen et al., 2022). The presence of *Zostera marina* (seagrass specie) can reduce the peak storm by an average of 32 %, with a maximum attenuation in wave height of 89% and a reduction in beach erosion volume up to 55% (Unguendoli et al., 2023).

#### Coral and oyster reef:

Healthy coral reefs can 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 the waves, while the remaining energy and height is mitigated by the reef flat (i.e. the first hundred meters after the crest). In Mexico, a reduction of 51–90% in wave height and 76–99% in wave energy at the shore has been attributed to the action of oyster reefs (Perricone et al., 2023).

### 4.4.5. SOIL EROSION CONTROL

Soil erosion occurs when land degrades due to the displacement, transport, and deposition of its particles. This process is exacerbated when soil is left bare and exposed to the erosive forces of wind and water. The sediments can be discharged into water, where they can harm aquatic life, raise water temperatures, and reduce water quality. Soil loss also leads to a decline in organic matter and nutrient contents, a deterioration in soil structure, and a reduction in the soil water content (Quinton et al., 2010).

Due to anthropogenic pressures, soil erosion can be particularly intense in agricultural landscapes with impacts on watercourses (Eurostat, 2021). In this context, soil management strategies that focus on soil quality, such as organic farming, can enhance the content and structure of soil organic matter. This improvement aims to increase infiltration rates and decrease runoff and erosion. Other practices, including mulching, no-till farming, intercropping, and the use of cover crops, focused instead on conserving the soil surface (Keesstra et al., 2018). These practices not only enhance infiltration rates and water retention in agricultural soils, alleviating drought stress and reducing soil compaction and erosion risk, but they also support agricultural productivity (EEA, 2021b). **Mulching** consists in the use of organic material on the soil surface, important to preserve soil quality. Mulching reduces rainfall energy, preventing sediment detachment and controlling soil erosion. Decomposing, the organic mulch mainly increases the soil organic matter (SOM) and strongly influence the soil physical properties. However, this process require time to be effective. With the increase of soil organic matter, soil aggregates, is more compacted and structured, limiting also soil dust. Mulching increase also water infiltration, and sediment and water losses are reduced. Finally, mulching avoids the loss of nutrients and the decline of soil productivity decline, limiting also soil pollution (Bogunović & Filipović, 2023; Keesstra et al., 2018). Mulching can be used in combination with no-tilling farming and cover crops.

No-tilling is a conservation practice that grows crops without disturbing the soil when planting seeds. Cover crops uses vegetation (e.g. grass or legumes) between regular crops.

Planting and preserving trees along fields can protect crops from erosion due to heavy rain. Bands of multi-annual herbaceous species and/or tree and shrub at the margin of crops and along water channels create **vegetated buffer strips**. 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 surrounding areas (Climate-ADAPT, 2022). Vegetation buffers have been used to reduce soil loss by wind and water erosion. Extensive root systems of perennial plants hold soil and trap the sediment entering from cultivated areas (Haddaway et al., 2018). Woody plants act also as windbreaks, minimising soil loss from fields by reducing wind current (Lovell & Sullivan, 2006).

*On hill and mountain slopes, the processes underlying soil stabilisation can contribute to slope stabilization and reduce landslides risk (see slope stabilization section).*

### Examples of benefits:

#### Vegetated buffers:

When properly maintained, vegetation buffers can remove up to 97% of soil sediment (Lovell & Sullivan, 2006). Runoff and sediment reduction are related to the vegetation coverage, resulting particularly effective when coverage exceeded 60%. Vegetation types perform differently for soil erosion control. Grasslands generally resulted more effective than other vegetation types. Efficiency of forests, grasslands, and scrublands in soil erosion varies also with surface slopes and soil type. Grasslands and scrublands typically perform better in controlling soil erosion on moderately coarse soils, while forests are more effective on fine soils (Wu et al., 2020).

#### Mulching, no-tillage farming:

Mulching and no-tillage reduce soil erosion by more than 80% and also benefit water quality by retaining sediment on the land (Bertram et al., 2017). No-tillage can reduce soil loss by 0.42 Mg ha<sup>-1</sup> compared to conventional tillage. On the other hand, tillage and mulching were found to have a positive correlation interaction, in fact mulching can reduce soil organic matter loss by 47.2 kg ha<sup>-1</sup> in the tilled plots, which is almost eight times greater reduction than in the no-till plots (Chalise et al., 2020). Conservation tillage (no post-harvest tillage) with stubble retention has been shown to significantly reduce soil erosion compared to conventional tillage (Gao et al., 2016).

#### 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 diversity, contribute to maintain biodiversity and ecological functions in different environments.

In agricultural land, the use of **vegetation buffer strips** along crop fields contribute to increasing biodiversity of both flora and fauna, providing habitat for wildlife and supporting pollination, in addition to maintaining water and soil quality (Pe'er et al., 2017). Similarly, the implementation of natural water retention ponds for agricultural irrigation has shown benefits for biodiversity in several cases, serving as refuge for birds and wildlife animals, as well as for fishes, molluscs and pollinators (Staccione et al., 2021). Along water courses, vegetated buffers can help regulate light and temperatures, allowing wildlife access to food and water and creating a wide variety of habitats, contributing to ecological diversity (Lovell & Sullivan, 2006). In addition to improving the ecological conditions for terrestrial species, riparian buffers 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).

In coastal areas, **salt marshes, aquaculture fishponds, gravel pits, or irrigation ponds** are able to provide habitats for water birds, 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, increasing local biodiversity by providing food and breeding sites (Sebastián-González et al., 2010; Semeraro et al., 2015). More than two thirds of the fish consumed in the EU rely on coastal and inland wetland areas for their existence (EEA, 2017b).

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, 2013b). As well, in the face of global habitat loss, green spaces in cities 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).

### Examples of benefits:

#### Protected areas:

Globally, species richness is 10.6% higher and abundance 14.5% higher in samples taken inside protected areas than outside (Gray et al., 2016). The higher positive influence seems to be related to differences in land use between protected and unprotected sites.

#### Agricultural ecosystems:

Agroecosystems restoration such as patches/strips of wildflowers create habitats on riparian margins and on the edges of crop fields, organic farming, and revegetating with native species, contributed to a global average 68% increase in biodiversity for all species, ranging from 54% for vertebrates to 79% for invertebrates. The recovery rates for soil microfauna and vascular plants were in the same range (Barral et al., 2015). Restoration of terrestrial ecosystems increase biodiversity by an average of 20% compared to unrestored sites, however it has also decreased its variability by an average of 14% (Atkinson et al., 2022).

#### Coastal ecosystems:

Restored degraded wetlands have the potential to increase biodiversity by 19%: +53% in vertebrates diversity, +45% in vascular plants diversity, +17% in terrestrial and +15% in aquatic invertebrates diversity (Meli et al., 2014). Research on biodiversity trends in restored mangroves is limited due to differences in site characteristics. However, there is evidence of recovery of animal species in restored sites, with fish populations returning to similar composition and densities to reference sites within five years (Bosire et al., 2008). Mangrove forests worldwide have been found to be home to numerous species, including 853 vertebrate species: 790 species of birds, 40 species of mammals, 20 species of reptiles and 3 species of amphibians. This is probably an underestimate, as it only includes terrestrial species (Luther & Greenberg, 2009). Coral reef restoration using new techniques of coral fragment planting has produced positive results in coral restoration, with survival rates reaching 70% (Pancrazi et al., 2023).



## Urban ecosystems:

Urban park development and river restoration can lead to an estimated 67% increase in species richness even at a small scale (Jorgman et al., 2022; Key et al., 2021). For example, a 10-30% increase in understorey vegetation in Melbourne (Australia) was associated with a 30-120% increase in the abundance of bats, native birds, beetles and bugs, while a 10-30% increase in native vegetation was associated with a 10-140% increase in the abundance of all native taxa (Threlfall et al., 2017).

### 4.4.7. ECOLOGICAL CONNECTIVITY AND FUNCTIONALITY

Changes in land use and the expansion of built up cause the loss of many habitats, deterioration in the quality of the remaining habitats and increased fragmentation of the landscape. As a result, the connectivity between habitat patches has been reduced limiting both the movement of animals and the dispersal of plant seeds. This can have negative impacts on the populations' size and genetic variability, lowering resilience in facing environmental changes and an increase in extinction risk (Travers et al., 2021).

In an increasingly fragmented and degraded natural environment, one 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 the movements and dispersal of species and materials across space and scales (Mitchell et al., 2013; Staccione et al., 2022). Corridors can benefit populations by enhancing the gene flow and recolonization of habitat. However, can also facilitate the spread of disease and of invasive species, create 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 meters to hundreds of kilometres. Several interventions have been planned to create habitat corridors at national, international and continental scales. Landscape-scale conservation is more often combined with the protection of isolated patches, establishing and protecting corridors and connection between existing protected areas (EC, 2020b; Keeley et al., 2019; Staccione et al., 2023). Conservation corridors can promote wildlife health by providing safe routes between habitat patches, including across roads and urbanized areas (Henry et al., 1999; Schuller et al., 2000).

Reconnection of habitats could also refer to river ecosystems, meant as the reconnection of rivers to their floodplains or to a channel system. By restoring the **river network**, river processes can be improved, making the ecosystem healthier and maintaining natural functions that are critical to the proper functioning of the ecosystem. These measures can i) increase infiltration of flood waters, raising the water table and improving the health of riparian forests health; ii) provide riparian habitat for wildlife, including birds, and aquatic habitat for invertebrates and fishes; iii) improve abiotic and biotic functioning and climate regulation; iv) and promote biogeochemical functions associated with floodplains, such as water purification and nutrient cycling. Such corridors can also be found in coastal ecosystems such as marine protected area networks (Serra-Llobet et al., 2022).

## Examples of benefits:

### Terrestrial corridors:

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 and small vertebrates (Gilbert-Norton et al., 2010). Connected urban vegetation and parks have been found to have a positive impact on biodiversity, increasing species richness across many taxa, especially compared 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).

### River network:

River restoration can lead to an estimated 67% increase in species richness (Jorgman et al., 2022; Key et al., 2021). 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 enhanced flow diversity across the floodplain, which in turn has promoted riparian vegetation establishment (Serra-Llobet et al., 2022). A study at a larger scale, in the Savannah River in South Carolina (US), monitored the effects disconnected and connected habitats and reported 2% lower extinction rates and 5% higher colonization rates in the connected habitats (Damschen et al., 2019).

## 4.5. ECOLOGICAL PROCESSES OF NOISE POLLUTION MITIGATION

### 4.5.1. NOISE MITIGATION

Environmental noise, a widespread pollutant, has detrimental effects on the health and well-being of both European citizens and wildlife (EEA, 2020). The Environmental Noise Directive recognizes the importance of preserving ‘quite areas’, i.e. areas of good acoustic environmental quality (EEA, 2020). Quiet areas offer minimal sound disturbance from traffic and human actions, offering relief from environmental stress and chances for rest and relax. Beyond the advantages for human physical and mental well-being, quiet areas are also important for animals.

From an ecological/environmental perspective, the World Health Organization (WMO, 2009) defines noise above 65 decibels (dB) as noise pollution, but for terrestrial species, effects can begin at levels as low as 40 dB. Anthropogenic noise pollution is a threat to terrestrial and marine wildlife causing a range of physiological and behavioural responses. Terrestrial and marine species rely on acoustic communication for finding food or a mate. Anthropogenic noise sources can potentially interfere with these functions, and negatively affect species diversity, population size and population distribution (EEA, 2020). The effects of noise on animals vary markedly among individuals and species and depend on noise characteristics, such as noise intensity, duration, noise frequency and the type of noise. However, an overall noise threshold that avoids ecological consequences in terrestrial environments have been set between 40 and 50 dB (Shannon et al., 2016). While for marine wildlife, biological responses can occur at noise levels commonly emitted by underwater sources, such as shipping, oil and gas exploration, sonars, dredging devices, and offshore wind turbines (Shannon et al., 2016).

Noise pollution can significantly impact wildlife behaviour, including sleep patterns, spatial utilization, movement patterns, foraging efficiency, communication, mating behaviour, territorial defence, vigilance, and predator avoidance. Birds, for instance, alter their behaviour in response to noise, such as avoiding areas with loud traffic and adjusting their singing behaviour near noise sources (Dominoni et al., 2016; Gentry et al., 2017; Kareklas et al., 2019). Negative behavioural and physiological responses have been documented also in marine species. The effects in marine mammals include changes in vocalization, stress, altered respiration, increased swimming speed, orientation loss and shifts in migration paths, changes in foraging and breeding behaviour (ETC/ICM, 2019). Chronic exposure to noise affects fish and invertebrates in a similar way and can result also in impaired growth and reproductive processes, increased mortality risk and emigration, reducing population densities (C. D. Francis & Barber, 2013; Weilgart, 2018).

Restoring and maintain **vegetation buffers** around noise sources can mitigate the impacts of noise pollution on wildlife. Vegetation buffers can be placed along roads and highways, can surround urban areas acting as a green belt, can create a barrier between anthropic landscapes and natural habitats. In

urban areas, the concrete surfaces can heavily reflect and amplify the sound, while trees leave and branches are able to reduce noise by absorbing, deflecting, or refracting sound waves. Additionally, the porous nature of soil within green areas contributes to sound absorption. Implementing a buffer strip composed of dense and diverse vegetation can be an effective strategy for reducing noise levels. Alternative nature-based solutions can include vegetation covers of walls and barriers, berms, vegetated belts and tree lines, urban forests and green spaces (Van Renterghem et al., 2015).

### **Examples of benefits:**

#### **Urban green buffers:**

Urban green space can act as noise buffers. Lines of trees and shrubs can reduce noise by 5-10 dB for every 30m width of vegetated coverage. This can be translated in a reduction of around 50% for human ears. In the city of Shenzhen (China) a green belt has been created around roads, finding that for every 1% increase in vegetation coverage, noise resulted to be reduced by 0.2 - 1.0 dB according to the type of road (Van Renterghem et al., 2015).

## 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 Eklipe 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 (Pregnotato 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.

| 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  |

Table 10. Generic and specific benefit categories

## 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:

| 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                               | <i>[Costs of tracking and observation ex-ante and ex-post]</i>  |
| IV) Financing costs                                 | a) Interests  |
|   | b) Fees, transactions costs and commissions   |
|   | c) Lease payments   |
| V) Opportunity costs                                | <i>[Foregone benefits associated with other land uses such as housing developments, industrial activities, sports, recreation, and other competing land uses]</i> |
| VI) Indirect costs                                  | a) Residual damages   |
|   | b) Agricultural loss  |
|   | c) Reduced air / water / soil quality   |

Table 11. NbS cost categories

## 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.

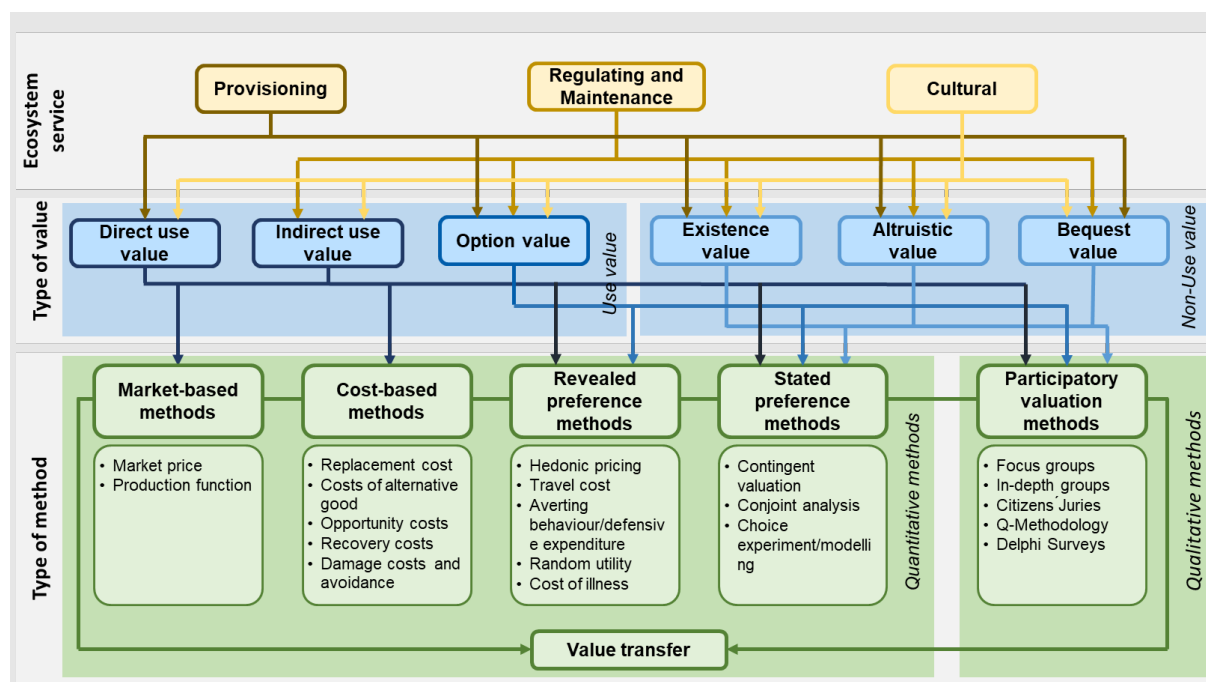


Figure 1. Economic valuation method cluster  
(Source: Croci & Lucchitta, 2021; DEFRA, 2007; Hynes et al., 2021)

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. Data generation: 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. Policy and decision support: 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. Contextual and site-specific variability: 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. Quality of source studies: 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. Large potential bias: 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.

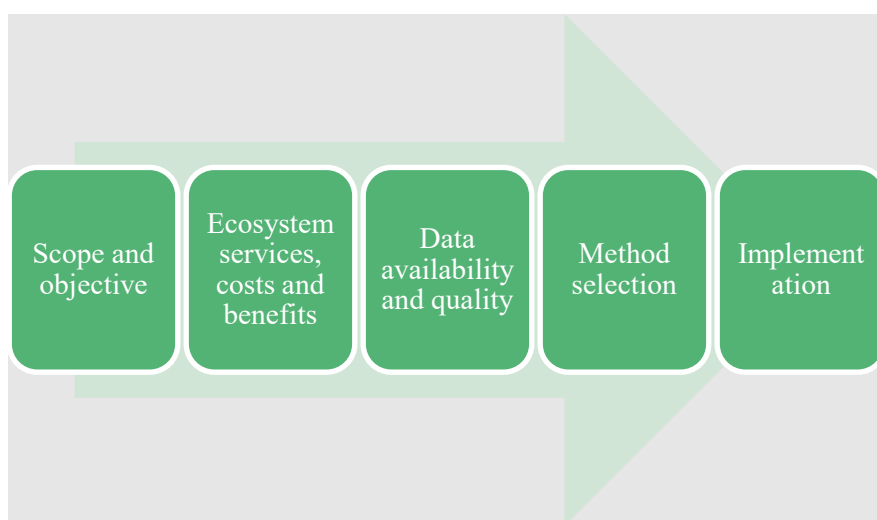


Figure 2. Step-by-step guide to selecting an appropriate valuation method

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  $Risk = Hazard \times Exposure \times Vulnerability$ , 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).

Building upon this understanding, various assessment methods are utilised to evaluate and manage risks. One such method is Value-at-Risk (VaR), a statistical measure commonly employed by investment and commercial banks to quantify potential financial losses over a specific time frame, providing a valuable tool for assessing risk exposure.

Stemming from the origins of portfolio theory, the concept of VaR dates back to the mid-20th century, where the VaR was proposed as an indicator to measure market risks. In the 1990s, the VaR became popular in the investment banking sector, where it was promoted as the preferred risk indicator for market risks by the Basel 2 and 3 Accord, which forms a worldwide basis on regulations for the banking sector (Adamko et al., 2015). The VaR is used to calculate the greatest possible loss for a specific time span. Statistically, it represents a predefined quantile of an estimated distribution function. The 1%-VaR

represents the 99th quantile and corresponds to the impending loss from a 100-year event. Also, the Conditional VaR (CVaR) or Expected Shortfall (ES) is a common risk indicator that is similar and gives the expected value above a given quantile.

Although the VaR has already been used in other thematic fields, it is currently hardly used in the area of NbS. According to the EEA (2023), the VaR has the potential to create a common methodical basis with the investment sector and subsequently unlock investments for NbS, but there is still a lack of VaR tools in the valuation of nature and ecosystem services. Therefore, Invest4Nature will work on the integration of the VaR concept and portfolio effects into an extended TEV framework, which will be applied within deep dive cases within the Living Labs. This will be further investigated in T2.3, to be reported in Invest4Nature Deliverable 2.2. Some other common risk assessment approaches are listed in Table 12 below.

| RISK ASSESSMENT APPROACHES         | DESCRIPTION   |
|------------------------------------|---|
| Quantitative risk assessment (QRA) | QRA 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.  |

Table 12. Description of other common risk assessment approaches

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. **Objective evaluation:** 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. **Comprehensive assessment:** 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. **Resource allocation:** 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. **Valuation challenges:** Assigning monetary values to all impacts, especially non-market and intangible benefits, can be difficult and subject to varying interpretations.
    2. **Temporal considerations:** 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. **Distributional effects:** 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.
    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 overleaf presents and briefly describes 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. |

Table 13. Description of additional decision-supporting approaches

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.

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)*<sup>15</sup> and the *Blue Value Database*<sup>16</sup>, both focusing on ecosystem service valuations, were selected. In addition, both databases have been matched with the *Oppla database*<sup>17</sup>, 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.

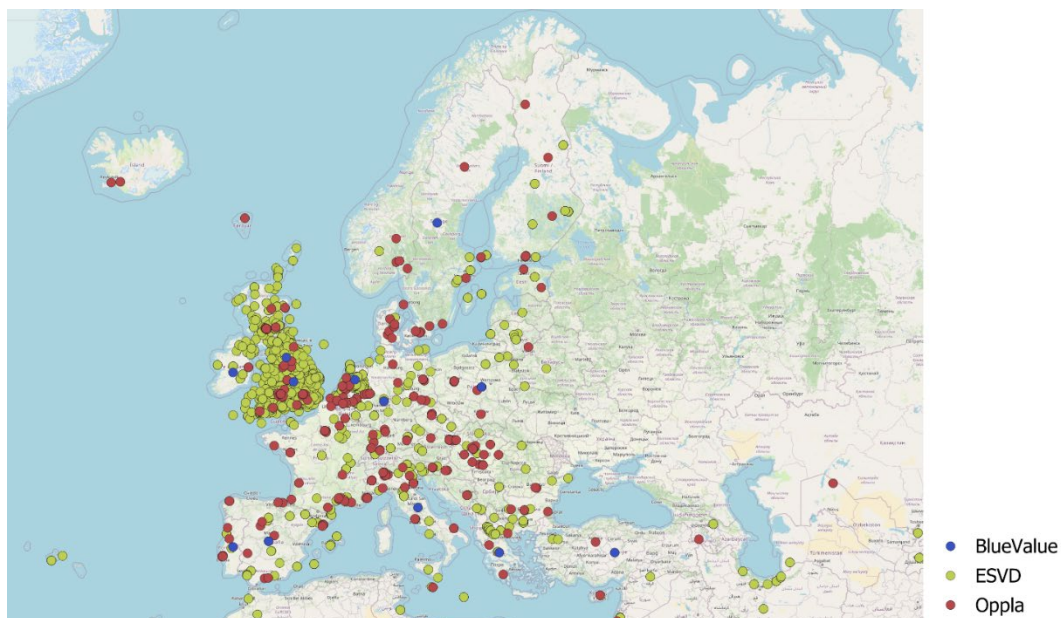


Figure 5. Geographic distribution of the case studies in the three databases

### 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).

<sup>15</sup> <https://www.esvd.net/>

<sup>16</sup> <https://www.bluevalue.org/>

<sup>17</sup> <https://oppla.eu/case-study-finder>

- 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)

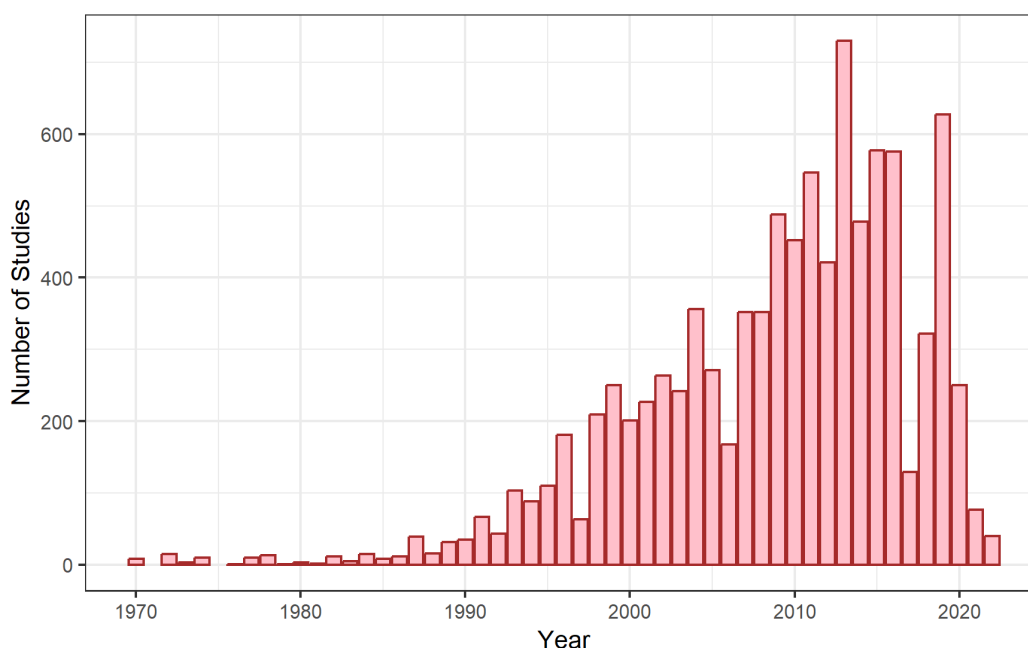


Figure 6. Year of value collection, ESVD

### 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 & efttec, 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.

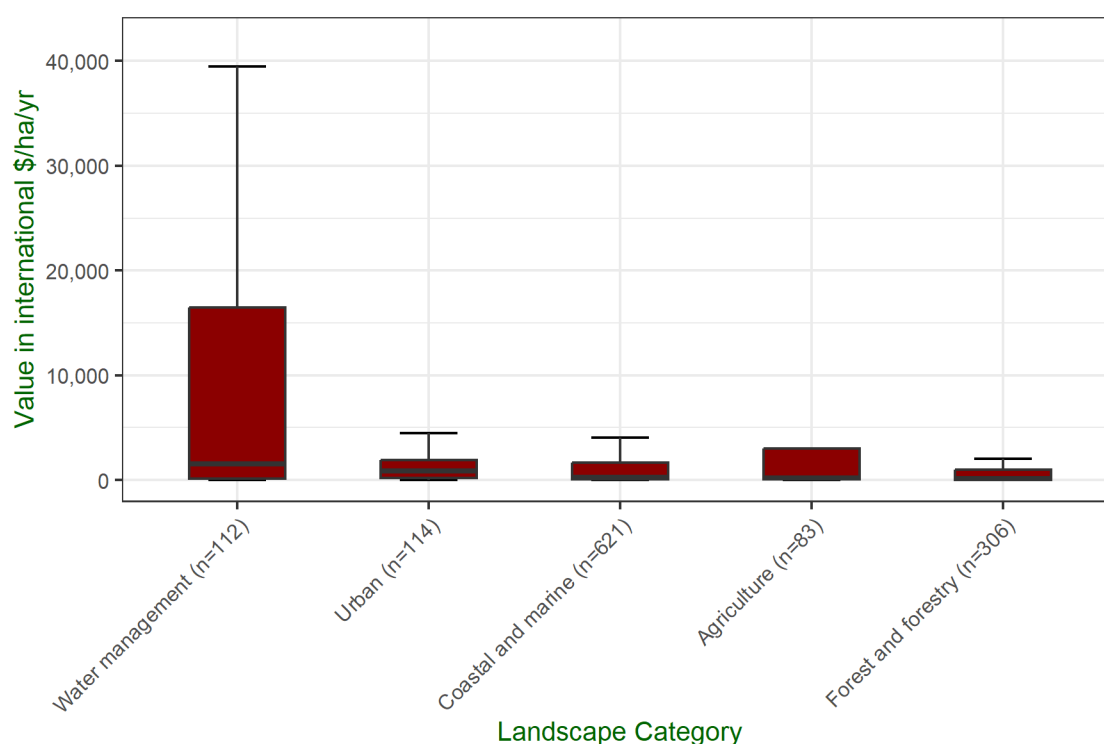


Figure 7. Distribution of values per landscape, ESVD  
(n=1,236; “Multiple landscape categories” and “Other” excluded)

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.



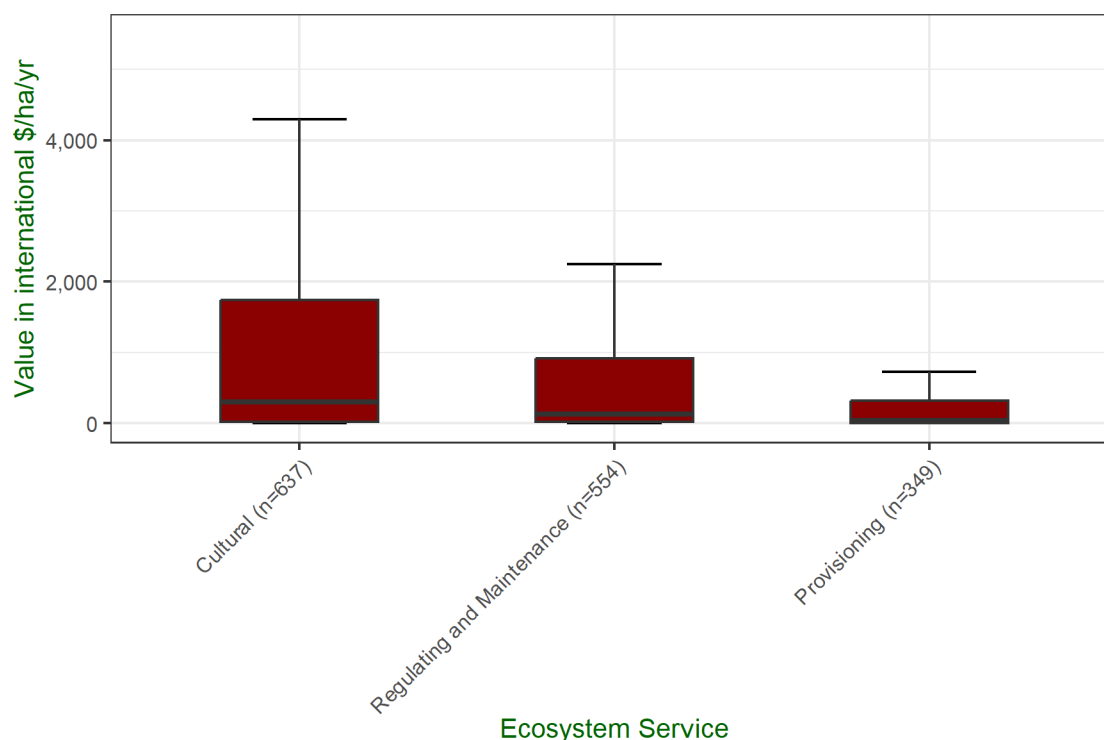


Figure 8. Distribution of values per ecosystem service, ESVD  
(n=1,540; “Multiple Ecosystem Services” excluded)

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.

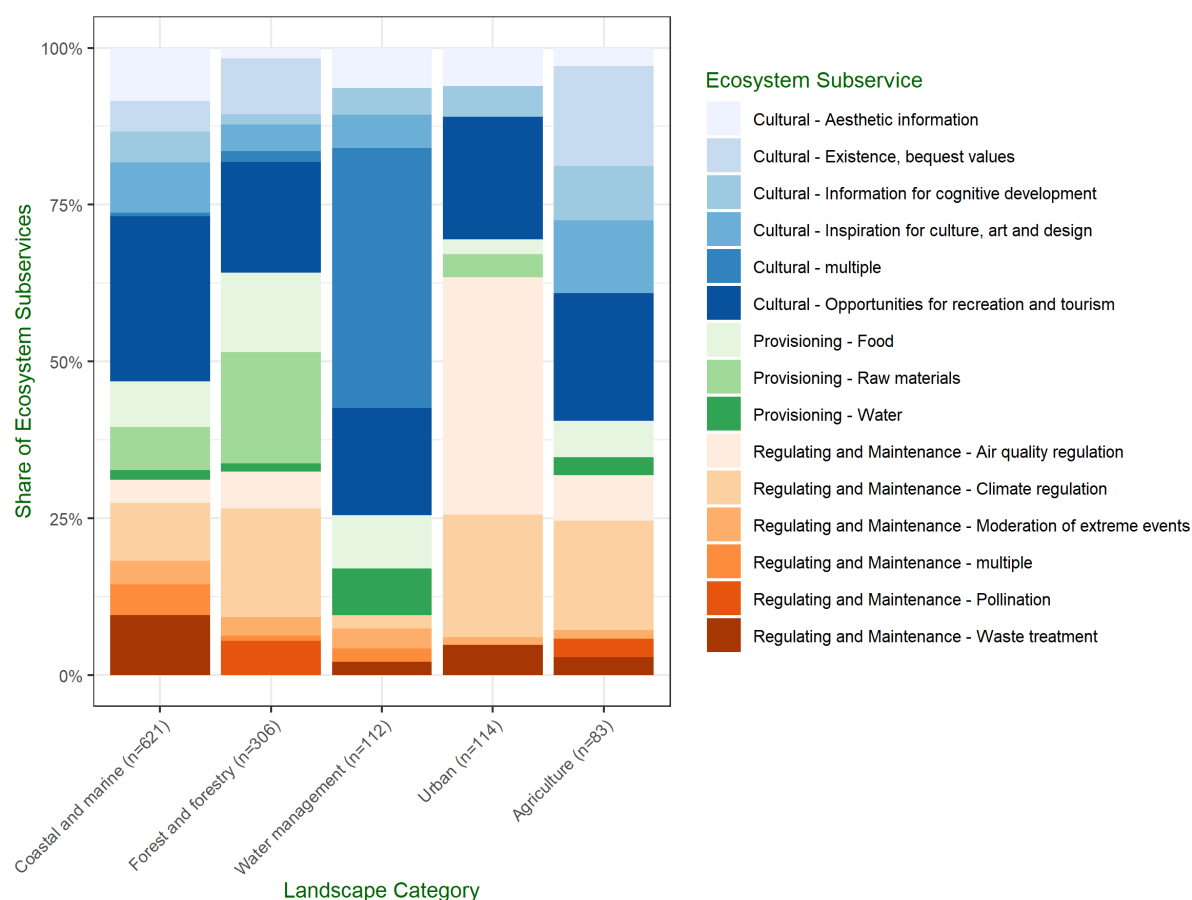


Figure 9. Percentage of ecosystem subservices in studies per landscape, ESVD  
(n=1,236; "Multiple landscape categories" and "Other" excluded)

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.

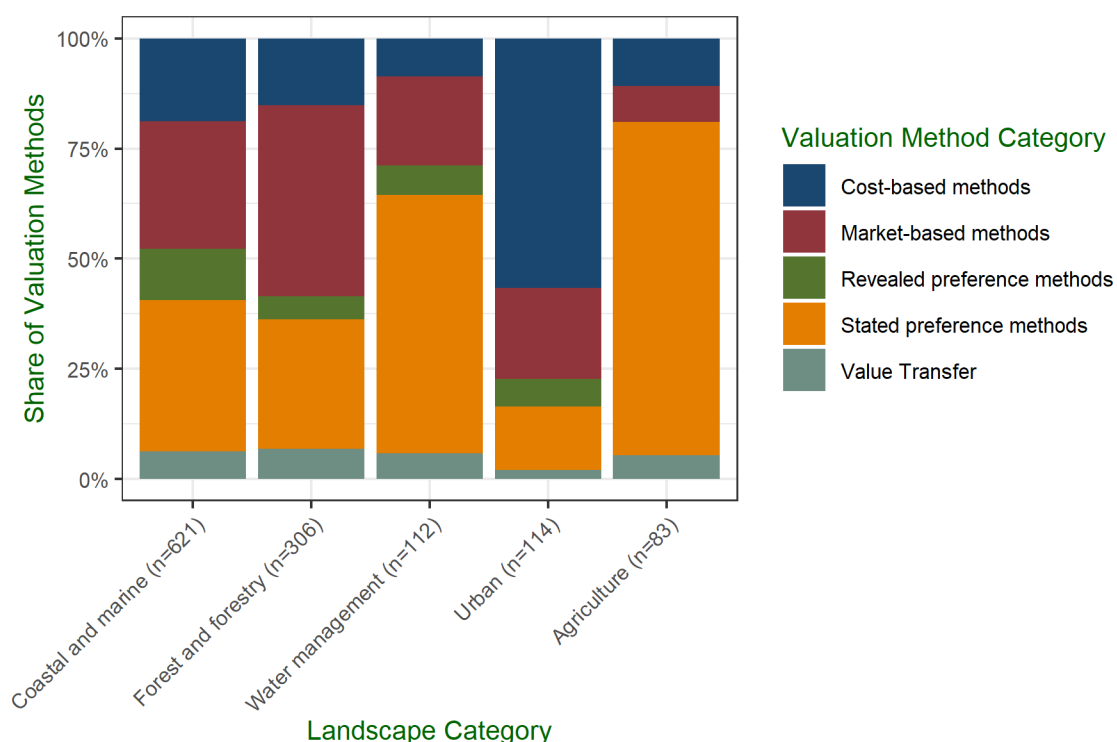


Figure 10. Percentage of applied methods per landscape category, ESVD (n=1,236; “Multiple landscape categories” and “Other” excluded)

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.

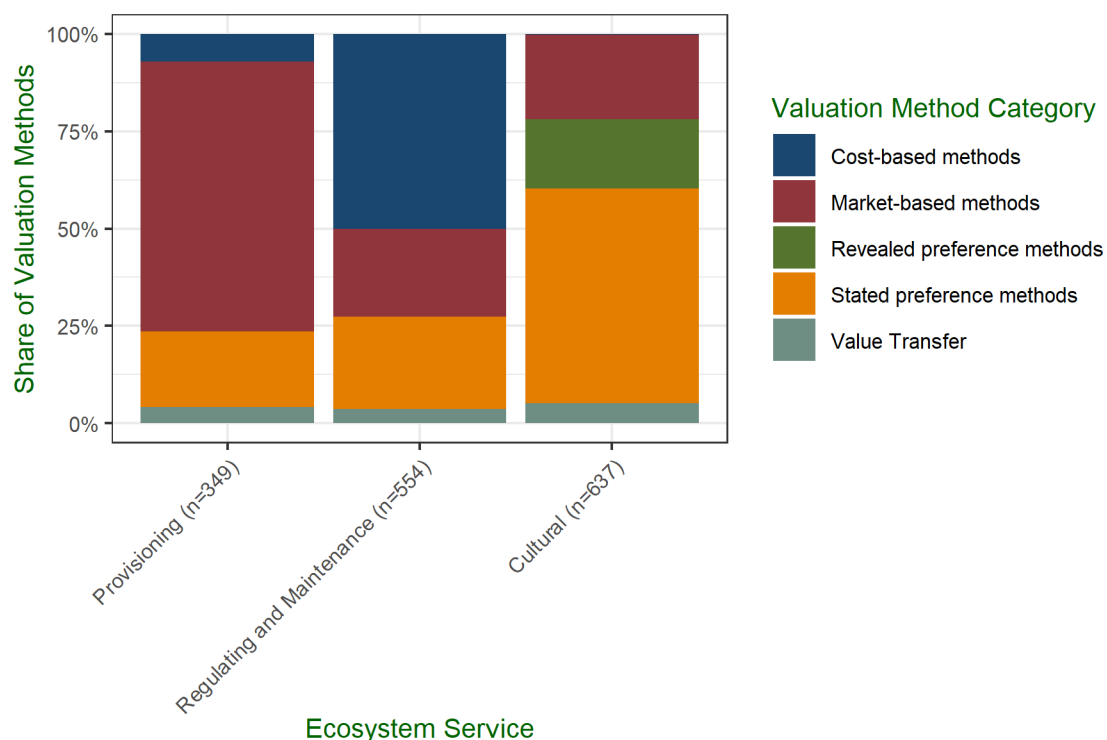


Figure 11. Percentage of applied methods per ecosystem service, ESVD (n=1,540; “Multiple Ecosystem Services” excluded)

## 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.

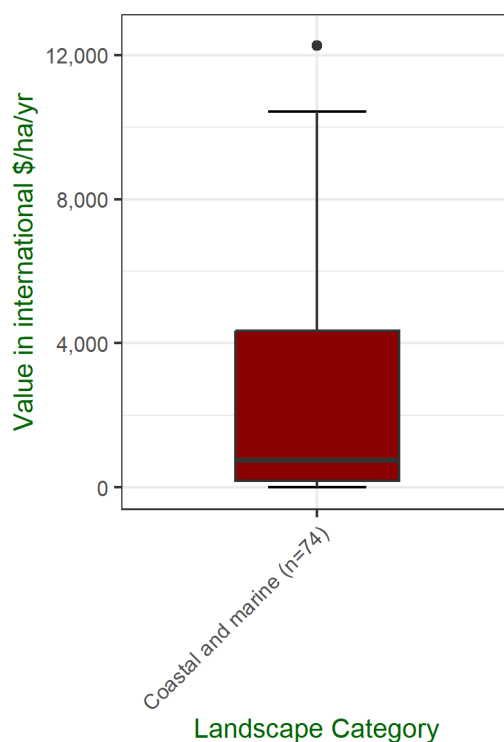


Figure 12. Distribution of values in the landscape "Coastal and marine", Blue Value

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.

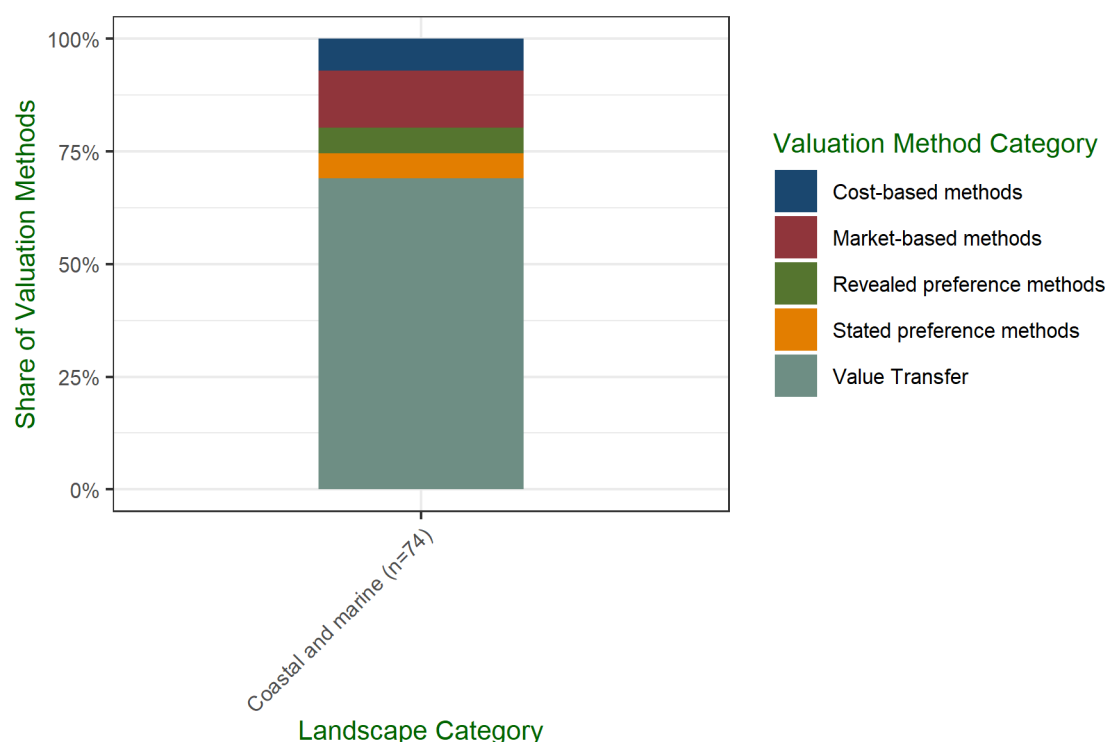


Figure 13. Percentage of applied methods per landscape, Blue Value

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.



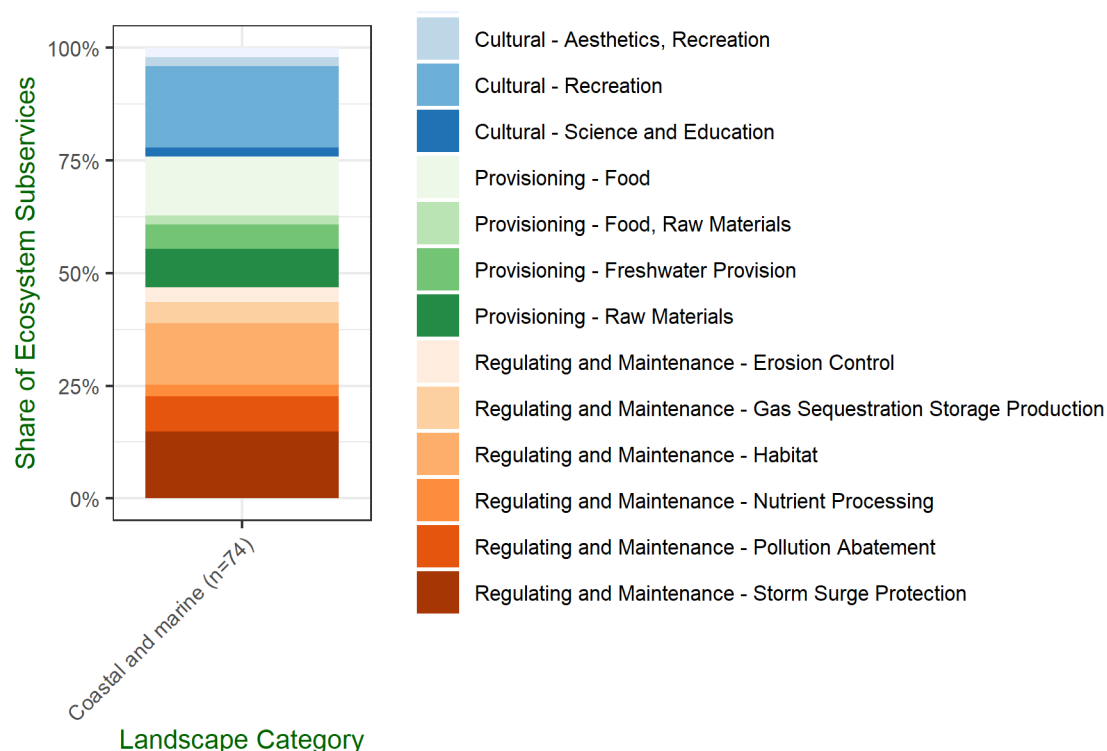


Figure 14. Percentage of ecosystem subservices in studies per landscape, Blue Value

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).

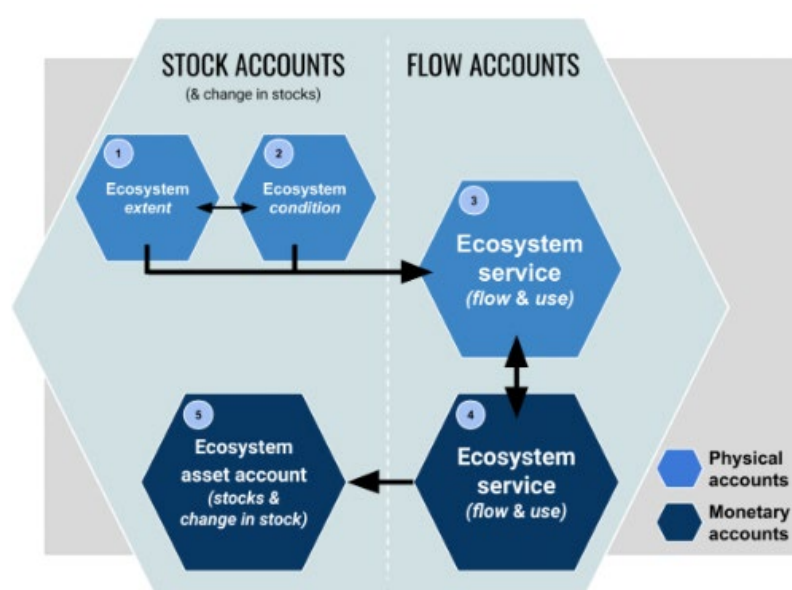


Figure 15. Ecosystem accounts and their interrelationships  
(Source: United Nations et al., 2021)

- 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           |                       |
|                        | Biomass fuels                |                       |

| Ecosystem Service ESVD        | Ecosystem Sub-Service ESVD                 | Ecosystem Service I4N      |
|-------------------------------|--|----------------------------|
| 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 animals                   |                            |
| 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 |                            |

| Ecosystem Service ESVD                   | Ecosystem Sub-Service ESVD | Ecosystem Service I4N |
|--|----------------------------|-----------------------|
| Maintenance of genetic diversity         | Biodiversity protection    | Cultural              |
| Aesthetic information                    | Attractive landscapes      |                       |
| 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 |

| Valuation Methods Blue Value Database | Method Cluster I4N        |
|---------------------------------------|---------------------------|
| Willingness-to-Pay (WTP)              | Stated preference methods |

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