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BIOFIN-EU

PROTECTING AND RESTORING BIODIVERSITY USING MAINSTREAM FINANCE

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Executive Summary

This report establishes a comprehensive framework for valuing biodiversity and ecosystem services (ES). This framework will support the development of financial solutions that address societal challenges through innovative funding approaches for Nature-based Solutions (NbS). The report provides an overview of how ecosystems provide various services to humans and how NbS and biodiversity impact these services.

The report begins with a discussion on the values that biodiversity and ecosystems bring to humans, introducing NbS as an institution that relies on protecting, developing, and creating ecosystems. It then explores different economic approaches to measure these values, highlighting the critical aspects of each method. The report also addresses specific aspects of biodiversity and their implications for the valuation of ecosystem services and the provision and funding of NbS.

Furthermore, the report presents the state-of-the-art assessment tools for ecosystem services and NbS, providing an overview of their impacts. It concludes with remarks on the importance of integrating these tools into decision-making processes to support more informed, nature-positive decisions.

This report sets the stage for the next steps in the BIOFIN-EU project, including the design of a dashboard that will facilitate financial decision-making and support the development of new financial products and instruments towards NbS.

Table of Contents

Funded by the European Union

List of Figures

List of Tables

Glossary of terms and abbreviations used

List of Abbreviations and Acronyms	
CE	Choice Experiment
ES	Ecosystems Services
CV	Contingent Valuation
HPM	Hedonic Pricing Method
NbS	Nature-based Solutions
PF	Production Function
TCM	Travel Cost Method
WTA	Willingness to Accept
WTP	Willingness to Pay
RP	Revealed Preference
SP	Stated Preference

1. Introduction

BIOFIN-EU aims to establish a comprehensive framework and technology that fosters the necessary conditions for nature-positive investments. BIOFIN-EU is actively innovating and experimenting with novel approaches for capturing, aggregating, and analysing biodiversity and ecosystem services (ES) data. The goal is to minimise transaction and reporting costs associated with finance that supports the protection and restoration of biodiversity. The project will develop financial solutions to address societal challenges, including through innovative funding approaches for Nature-based Solutions (NbS).

A key aspect of this is an understanding of what values NbS provides. NbS are key for protecting biodiversity and ecosystems, where actions that leverage the ecosystem's abilities are used to achieve various goals such as protecting biodiversity (Swedish Environmental Protection Agency, 2022). There are several definitions of NbS, but they all have in common that they are solutions relying on protecting, developing, and/or creating ecosystems. We have seen an increased interest in NbS in society. The contexts of NbS vary immensely, from urban green spaces to wetland restoration, and the scale can range from very small, such as green roofs, to large, such as forest conservation. This diversity of contexts and scales in which NbS are applied presents significant challenges to decision-making, driving the development of numerous assessment tools for NbS and ES. To understand how these tools are integrated, both individually and collectively, in decision-making processes, there is a clear need to map existing tools, supporting more informed, nature-positive decisions. This mapping will help understand the tools' current capabilities, identifying potential gaps, and guide future development initiatives to improve the capability of stakeholders to effectively deploy those assessment tools. This is evident in areas such as lending and capital allocation, where the integration of NbS into decision-making processes is still limited.

In this report, we provide an overview of how ecosystems provide various ecosystem services to humans, and how NbS and biodiversity affect these services. We begin with a discussion about what values biodiversity and ecosystem bring to humans and then introduce NbS as an institution that rely on protecting, developing, and creating ecosystems, and hence generate values for humans. We then discuss different economic approaches to measure these values, as well as their critical aspects. There are several options and methods to measure values, and several approaches might be needed in many cases. Next, we discuss several aspects that we are particular for biodiversity, and what implications these have for the valuation of ecosystem services and for the provision and funding of NbS . We then turn to the actual empirical assessment of ecosystem system services and NbS. We begin with presenting the state of the art when it comes to assessment tools, and then we provide an overview of NbS impacts. Finally, we provide some concluding remarks.

2. The value of biodiversity

Biodiversity is the diversity of living organisms at different levels of organization, from genes to species to ecosystems. It is also the diversity within species, between species and of ecosystems. It relates to both fauna (all animal life e.g. mammals, birds, reptiles, insects and aquatic species) and flora (e.g. trees, shrubs, grasses, mosses, and algae). Biodiversity provides various benefits for humans, such as food, medicine, recreation, cultural identity, and ecosystem services. However, biodiversity is threatened by habitat loss, overexploitation, climate change, and pollution, all caused by human behaviour (Pereira et al., 2012). Biodiversity is declining today faster than ever in human history (IPBES, 2019). Economists typically characterize biodiversity as a public good. The public-good characteristics[1] often result in a so-called market failure where the societal value of biodiversity is not appropriately reflected in market prices. This means that consumers will not have incentives to pay, and suppliers will not have incentives to supply. Policies are therefore needed to protect and restore biodiversity appropriately. The design of policies and investment choices could depend on the societal values that biodiversity creates, and the values associated with biodiversity losses. Given these unpriced societal values, markets alone cannot accurately capture the full worth of biodiversity, underscoring the need for policy intervention. Policies can set the agenda for what needs to be achieved, such as the Biodiversity Strategy for 2030 (European Commission, 2020) and the Water Framework Directive (European Commission, Directive 2000/60/EC.) Policies can also result in more specific policy tools such as offsetting and putting requirements on investors to compensate for biodiversity loss (McKenney and Kiesecker, 2010; Lambooy and Levashova, 2011; Benabou, 2014), biodiversity-relevant subsidies, taxes, and fees (OECD, 2020). These policy tools are necessary to protect biodiversity. According to (OECD, 2020) governments spend larger amounts supporting activities that is potentially harmful to biodiversity than their total spending for protecting biodiversity. One example of harmful support is the support for fossil fuels that contribute to climate change, which is the third largest direct driver of global biodiversity loss (IPBES, 2019).[2]

It is a daunting task to talk and write about the value of biodiversity. We will primarily focus on an anthropocentric view of values. Thus, our focus is on the human values arising from biodiversity and ecosystems.

2.1. The societal value of biodiversity

Ecosystems primarily benefit people through so-called ecosystem services. The Common International Classification of Ecosystem Services (CICES) defines three broad categories of ecosystem services:

[1] Non-rival in consumption: One person´s consumption of the public good does not reduce the amount available for others. Non-excludible: Technically infeasible to keep users from enjoying the good, i.e. it is not possible to supply the good only for those who choose to pay for it. It could also be possible to exclude from consumption but too costly to do so.

[2] This is linked to "greening finance,' i.e. directing financial flows away from private and public projects with negative impacts on biodiversity and ecosystems to projects that mitigate the negative impacts (World Bank Group, 2020).

- **Provisioning services**: examples of provision services are food (e.g. fish and honey from fauna and fruits, vegetables and grains from flora), materials (e.g. wool, silk, and leather from fauna and timber, fibre and biofuels from flora), water, but also genetic resources. These services thus provide inputs for products that we use directly or as inputs in production processes.
- **Regulating and maintenance services**: examples from fauna are pollination by e.g. bees, butterflies, and birds, pest control from natural predators e.g. insects, seed dispersal by e.g. birds and insects, and nutrients cycling by e.g. worms. Examples from flora are climate regulation via shading and transpiration, carbon sequestration through the photosynthesis, water regulation and flood prevention by erosion control and slowing water runoff. These are thus services that regulate and maintain ecosystems.
- **Cultural services**: examples are spiritual and religious experiences and aesthetic and cultural aspects, involving experiential interaction with the environment for leisure. From the fauna we e.g. enjoy wildlife tourism while flora offers recreational values in gardens, parks, and natural landscapes.

Biodiversity is the variety of ecosystems or biological resources. The fauna and the flora are interconnected in providing ecosystem services. For example, bees and birds depend on plants for nectar, and plants depend on animals for fertilization and seed dispersal. The Convention on Biological Diversity defines biodiversity as "the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part" (Convention on Biological Diversity, Article 2). The question is where among the ecosystem services does biodiversity play a role, and what the values of ecosystems are.

It is informative to distinguish between four different values: direct and indirect use values, non-use values, and option values.

Direct use values: This is primarily the output from the ecosystem that is consumed directly, like food, but also amenity values from recreation and ecotourism, where thus biodiversity is a source of enjoyment for humans. The use value also includes productive use-values, i.e. goods that are inputs and are transformed in a production process, like paper, wood, and silk.

Indirect use values: There are also values from biodiversity that are so-called indirect use values that support human well-being without direct use and consumption. These include the regulating and maintaining services the ecosystems provide to reduce pollution, prevent erosion and floods, and climate regulation. This includes human existence values, i.e. that biodiversity loss can threaten human lives by causing pollution, landslides, or storms, and human health values by e.g. protection from pandemics (Dasgupta, 2021).

Non-use values: One important type of non-use values is existence values, i.e. that humans care about the existence of the ecosystems (Dasgupta, 2021). They are thus not dependent on the ecosystem's services. Instead, humans benefit from simply knowing that ecosystems are maintained, protected, and restored. This can concern whole ecosystems, but also specific species that are endangered. Another type of non-use value is linked to the welfare effect of actually supporting a public good through for example donation, and it refers to the feeling of warm glow that is enjoyed from the act of donating (Andreoni, 1990; Nunes and Schockaert, 2003). Furthermore, there are two more non-use values: "bequest value" and "altruistic value". Bequest value means that individuals can put a value on the preservation of an environmental asset for future generations. Altruistic value means that individuals value that biodiversity should be available for others in the current generation.

Option values: Biodiversity might also have a value that today is unknown to us. The option value of biodiversity is a type of use value for possible future use. An example connected to biodiversity is the value of maintaining biodiversity because it might provide benefits in the future that are unknown to us today. Another example is the value of prohibiting a loss in biodiversity to decrease future harm and environmental crises. For example, the loss of diversity in animals and plants, including genetic diversity, poses a serious risk to global food security by undermining the resilience of many agricultural systems to threats such as pests, pathogens and climate change (IPBES, 2020).

Use values are enjoyed foremost by the local population, in particular regarding provisioning services, while non-use values can easily extend to a much larger number of people, and ultimately be of global concern.

Many of the aspects of the values, in particular the indirect-use and non-use values are primarily so-called non-market values, while for several of the direct use-values markets could be in place. This has two important implications. 1. for goods/values where sufficiently well-functioning markets exist, there is less need for policies for biodiversity, and behaviour at the markets would give us information on the size of these values. 2. For non-market values policies could be needed to make the right amount of investment in biodiversity as markets do not include information about the values. As these values are not revealed in the market, economists have developed non-market valuation methods to provide estimates that can be used in a normative decision-making framework such as a cost-benefit analysis (CBA) to guide the decision on appropriate investment level in biodiversity. Not including these values in a CBA might severely underestimate the total value of biodiversity.

Note that we here do not include any intrinsic value of ecosystems, i.e. that biodiversity has value independent of how humans value it which means that it has a value beyond the instrumental value it provides to humans (Dasgupta, 2021). While we do acknowledge that such values could be important in policy we focus in this study on human well-being.

In Figure 1, we integrate the different aspects of ecosystems' value to humans, from ecosystems to biodiversity values.

		Ecosystem services	Examples	Values
		Provisioning services	Food, fuel	Direct use
			Freshwater	Indirect use
Ecosystems		Regulating and maintenance services	Disease regulation,	Direct use
			Climate, erosion, pollination	Indirect use
		Cultural services	Spiritual experiences, recreational values	
				Use and Non-use values

Figure 1. Ecosystems and biodiversity values

2.2. Monetary measures of value

The measurement of individual well-being in economics is based on a long-standing theory of consumer behaviour (Hicks, 1945). The basic idea is to obtain money metric measures of welfare. The standard approach is to rely on observed behaviour at the market and based on data on market transactions infer what the value is of a certain good. Economists refer to this as the consumer surplus. In general, we will refer to two monetary welfare measures: Willingness to pay (WTP) and Willingness to accept compensation (WTA). Let us define these two measures in the context of this paper. Think of a situation with two potential levels of biodiversity: poor and good. As discussed above there are plenty of reasons to believe that an individual is better off with a good level of biodiversity. We would therefore say that, all else equal, the utility of an individual is higher if the level of biodiversity is good. From this we can now define WTP: It is the maximum amount of money the individual can pay so that the utility with a good level of biodiversity is the same as the utility with a poor level of biodiversity. In other words, WTP measures the maximum amount of money the individual would be willing to give up obtaining the change, the improvement in biodiversity. Conversely, WTA is the minimum amount of money the individual would require so that the utility with a poor level of biodiversity is the same as the utility with a good level of biodiversity. WTP is more commonly used than WTA, but it depends on the property rights. In the case where an individual owns something that she/he asked to give away then WTA is the correct choice. WTP is however more common to use since we most often investigate individuals´ willingness to pay for improvements of public goods such as biodiversity or their willingness to maintain the actual level of the good.

These measures of welfare rest on a set of premises that can be questioned. For example, it is implicitly assumed that individuals have correct information when making decisions and that they can infer their utility from all alternatives that are present to them. An individual's willingness to pay indicates how increased biodiversity enhances personal well-being, but policy decisions often focus on the broader objective of social well-being. Social well-being is an aggregate of individual well-being. Another concern when aggregating WTP across individuals and using it in policy is that the monetary measures depend on the income of the individuals. This is especially problematic when conducting WTP or WTA in countries (or of individuals) with inequality in income between individuals. However, using distributional weights based on the income level when aggregating WTP or using distributional impacts when evaluating policies are two ways to deal with this.

3. Nature-based Solutions and Biodiversity

3.1. Why are not ecosystem services provided at a socially desirable level?

If we focus on biodiversity values, it is important to understand why ecosystem services will not be provided at an optimal level for society. As mentioned in the introduction, biodiversity is a public good, and therefore, consumers will not be charged for their use and will not have incentives to pay, and suppliers will not have incentives to supply the appropriate level of biodiversity for society. Much of the loss of biodiversity can also be attributed to human activities. According to the report from IPBES (2019), the five main drivers, connected to human activities, for biodiversity loss are i) Land, freshwater and sea use changes that seriously modify nature, ii) Resource exploitation, iii) Pollution, iv) Invasive species and diseases, and v) Climate change where the most severe biodiversity losses are caused by "Land, freshwater and sea use changes" through unsustainable production processes and practices across key sectors such as agriculture, forestry, fisheries and aquaculture, energy, and mining, as well as the broader impacts of urbanisation (WWF and Bain & Company, 2023). These activities often proceed without sufficient incentives for sustainable management, making the decline in biodiversity worse. Thus, to protect biodiversity, policies are needed. The scale of the policies could however differ since biodiversity losses can be local, regional, or even global. Many of the direct use values of biodiversity do come from well-functioning markets, such as the food market and the corresponding input markets. Here actors have an interest in protecting ecosystems and making sure that they provide the services necessary for the production and consumption of various goods and services. If property rights are well-defined or if regulations are in place that govern the use of these resources, ecosystem services that provide direct use values are likely to be provided. If the resource is shared on the other hand and lacks well-defined property rights the risk of overexploitation is immediate.

Amenity values are also an example where the services can be provided through the market, often through various nature-based solutions, national parks being the primary example. However, without clearly defined property rights or regulations, even these services would be underprovided.

For other services and the corresponding values, there are often no markets. Economists denote these as non-market values. This is particularly true for most of the Regulating and maintenance services and some Cultural services. Without appropriate regulations or voluntary efforts, these services will be underprovided. Take the example of pollination, which is essential for food production. Unless a policy is designed, there is no market for planting flowers for bees that boost pollination, which means that a lack of incentives for this service will lead to socially suboptimal behaviour. This even though it will provide enormous benefits to the population.

For non-use values, market solutions are even less likely to arise, and they are likely underprovided. The primary example of how non-use values could be provided is through donations to various e.g. environmental organizations that help to protect nature. Important to remember is that while citizens differ in their preferences for biodiversity, some have preferences for non-use values such as existence, altruistic, or bequest values of biodiversity. Not considering non-use values may thus result in decisions that would be suboptimal from an economic perspective and generate losses for society.

3.2. How do nature-based solutions contribute to biodiversity

Nature-based solutions manage, restore, and protect ecosystems, while at the same time benefiting people through ecosystem services. In Figure 2 we add NbS at the ecosystem level. However, the value of the NbS is through the ecosystem services it affects and the corresponding biodiversity values.

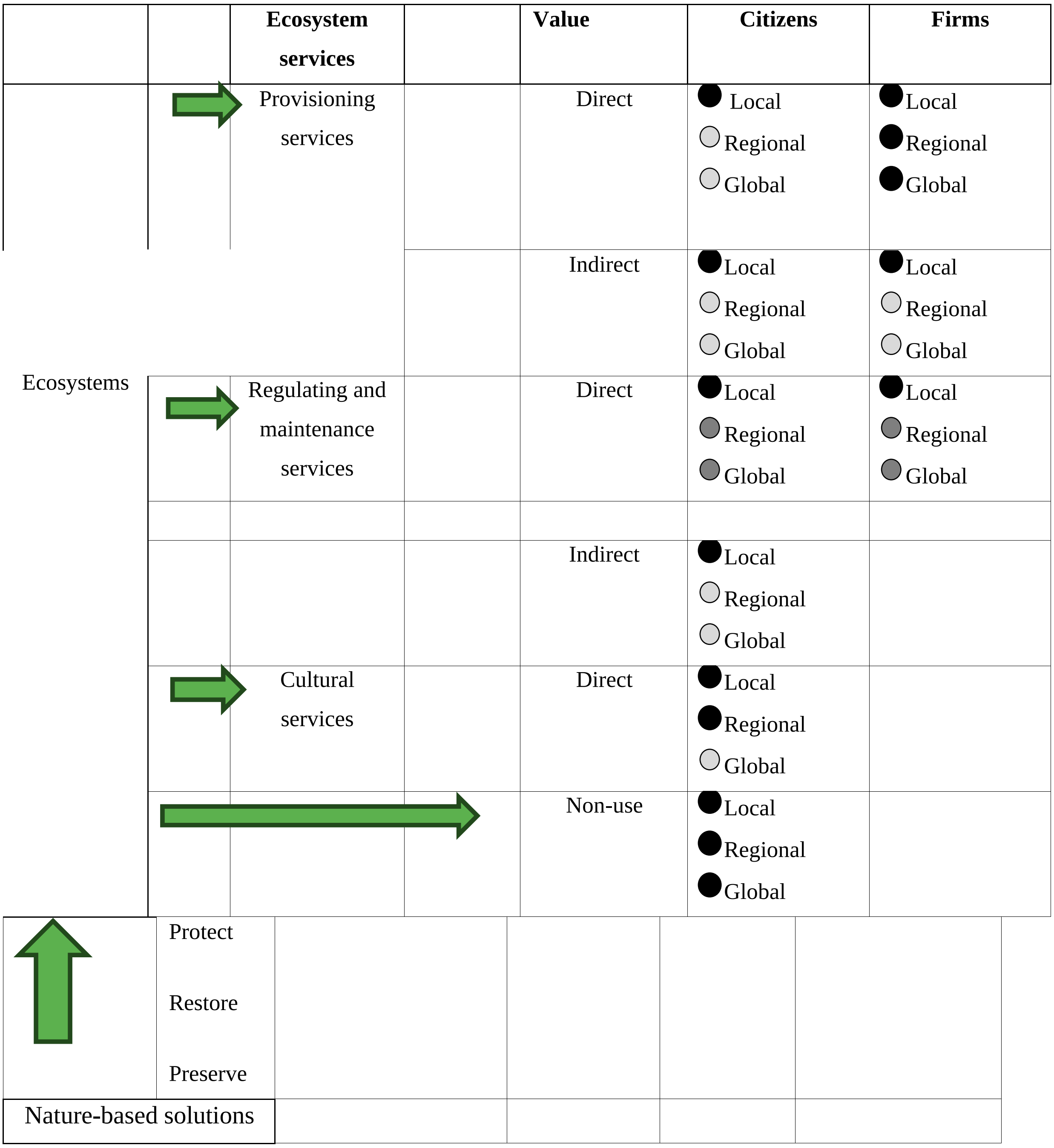

Figure 2. Ecosystems, NbS, values and users

If we consider the biodiversity values generated through NbS then it is natural to think of two users: citizens and firms. Citizens benefit directly from improved health and as buyers of goods that rely on ecosystems. Firms in turn use ecosystem services for their production and benefit from e.g. climate regulation (locally and globally).

We believe that one important aspect is where the user is located relative to the NbS. We distinguish between local, regional, or global. We use a traffic-light system to show how much users depend on the services: black means strong dependence, dark grey means dependence, and light grey means little reliance. There is often a difference in what services that, for example, local and global firms would derive benefits from, and the exact service depends on the type of ecosystem. Furthermore, firms would mostly rely on direct-use values from ecosystems. The provisioning services primarily benefit individuals who are close to the NbS, while in this global economy, the direct use of provisioning services could benefit firms that are located far from the NbS. The indirect use values of provisioning and regulation services are primarily of value for local citizens and firms. The global concern about NbS primarily relates to non-use values such as the existence value.

4. Methods for measuring values

4.1. Introduction

Most studies in economics study the value of biodiversity by valuing specific items of natural capital, for example, ecosystems (e.g. fisheries), specific species (e.g. endangered ones), and natural resources (e.g. groundwater) (Dasgupta, 2021). There are three prominent methods for valuing biodiversity and ecosystem services. Revealed Preference (RP) methods, Stated Preference (SP) methods, and the Production Function (PF) method. RP methods infer values from people's actual behaviour at existing markets, i.e., we indirectly reveal people´s preferences for a public good (that does not have a market) from people´s actual behaviour on a related market for a private good. This is possible when the level of the public good (e.g. water quality) affects the value of the private good (e.g. trips to the beach). With SP methods, we ask people directly in a survey or in an interview situation about their willingness to pay (WTP) for, for example, an improvement in the level of biodiversity by using constructed scenarios and in that way creating a market for the good in the survey. The PF method relies on estimating the relationship between production factors (inputs) and the output from the production. It is founded on the concept that the value of non-marketed environmental inputs can be assessed by their contribution to the value of the final product that is sold.

We will present all these methods and discuss critical aspects of them. However, a key issue of choosing a particular method is what values can be measured. This is partly dependent on the choices made by the analyst, but largely dependent on the actual method and the context. We will return to this important question after the presentation of the methods.

4.2. Revealed Preferences

How could revealed preference (RP) data be used for measuring the value of biodiversity? The use of RP is, by most economists, traditionally seen as the gold standard to study consumer demand. There are neither markets for biodiversity nor preferences observable directly. Individuals´ preferences are, however, revealed indirectly through actual choices and behaviour in existing markets using RP methods. Several distinct methods fall within the category of revealed preference approaches. Common to these methods is that they study the consumers' behaviour in the market for goods linked to non-market goods and offer environmental benefits to consumers, often referred to as the "weak complementarity" condition introduced by Mäler (1974). They also have in common that they can only measure use values. Two commonly used RP methods will be discussed here, the Travel cost-, and the Hedonic Price method.[3]

[3] A third approach is the defensive expenditure method, which quantifies the cost of replacing or restoring ecosystem services (Balmford et al., 2002). Defensive expenditures are thus actions taken by people to reduce their exposure to harm caused by pollution, diseases, and other environmental hazards. The defensive behaviour method simply assumes that a rational person will take defensive behaviours as long as the value of the damage avoided exceeds the cost of the defensive action (Dickie, 2003). For example, people might install special filters to get better water quality or special

4.2.1. Travel Cost

The travel cost method (TCM) measures willingness to pay for goods such as national parks and other recreational areas. The idea is that individuals enjoy visiting parks, consuming a set of goods including biodiversity, and that they spend money and time to travel to the site as well as money and time while at the site. These expenditures, including the cost of time, can be seen as the price they pay to enjoy visiting the park, and the sum of these expenditures can be used to infer the WTP for visiting the park. The amount a person is willing to pay for visiting the recreational must be at least the total travel cost. Otherwise, the person would not visit the place (Hotelling, 1949).

The method uses the fact that different individuals have different costs to travel to the same place and that each person has different costs to travel to different places. An individual's choices are typically constrained by their budget. Consequently, the decisions people make reflect both their preferences and budgetary limitations. Consider a recreational area and two groups of individuals with similar preferences for the area, one residing nearby and the other at a greater distance. We would, all else equal, expect the group of individuals living closer to the recreational area to visit the area more frequently since they face a lower cost of visiting the area. Using this variation in the cost makes it possible to estimate a demand function for visits. This serves as a simplified example of the intuition of the travel cost methodology.

A travel cost study collects data on travel costs and the number of visits to the recreational area. The target population is visitors to the area, and the focus is on the direct use value of the area, usually the recreational value. Given a specific set of assumptions, one would expect a negative demand relationship between cost and the number of visits, and this relationship is interpreted as the demand for the recreational area. From this demand we can calculate a welfare measure called the consumer surplus.[4] This measures the total value that individuals derive from visiting the site representing the welfare beyond the incurred costs.

There are different types of travel cost models, the earliest and simplest form of TCM is the zonal TCM where visitors are grouped into zones based on their distance from the site (e.g., by city or postal code) and it is assumed that everyone within a zone faces the same travel cost (Clawson and Knetsch, 1966). This makes it the least data-intensive approach. An Individual TCM is slightly more data-intensive and focuses on individual rather than aggregated data on travel costs (Brown et al., 1983)). The most data-intensive model (the Random Utility Model) examines individuals' choices among multiple recreational sites and can to some extent estimate the value of site-specific characteristics (Kling, 1988). It could, for example, be used to see how much more people are willing to pay to visit a recreational site with more biodiversity compared to one

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windows to decrease noise. The cost of the defensive expenditure (i.e. filter or window) is the value of better environmental quality. In the case of biodiversity, defensive expenditures can also for example be that states or communities can be willing to use expenditures to protect specific, red-listed species by saving genetic resources or protecting native species from threatening weeds (Sinden et. al, 2008). People can also be willing to buy goods that protect their gardens from invasive species etc.

[4] Consumer surplus is strictly not a measure of WTP or WTA. However, under fairly general assumptions WTP and WTA can be estimated from the consumer surplus (Randall and Stoll, 1980).

that is poor in this aspect. Examples of previous studies that have used TCM are Getzner (2010) who investigated preferences for a national park in Poland, and Ezebilo (2016) who studied recreational trips to nature areas, the economic value of recreation in nature, and factors influencing such trips in Sweden.

4.2.2. Hedonic pricing

Another RP approach is the hedonic pricing method (HPM), where differences in house characteristics explain variations in house prices. Environmental characteristics could be one of many characteristics that affect price, and therefore the method can be used to estimate the WTP for these different characteristics. Examples where the hedonic pricing method has been used are studies about air quality, view, proximity to parks, and neighbourhood safety on house prices (Chau and Chin, 2003). According to the method, bad environmental quality leads to lower house prices, while good quality means higher house prices. The price for the quality is the difference between house prices. Thus, these environmental attributes are not directly traded in markets, but they are aspects of a house´s location and therefore bundled with the market value of a house.

The hedonic theory of equilibrium in markets for differentiated products was developed by Rosen (1974). The value of a house depends on the bundle of attributes that characterize the house. The hedonic price function specifies how the market prices of the product vary as the attributes vary. The equilibrium house price results from the interaction of supply and demand in equilibrium. The hedonic price function p(z) is an equilibrium concept, and each point of the hedonic price function characterizes different equilibria based on the demand and supply of the characteristics of the vector z. Controlling for various attributes, the price difference between two otherwise identical houses, except for one having an additional bedroom, will represent the value of the extra bedroom. This logic also holds for non-market goods, such as air quality. All else equal, it is possible to retrieve the valuation of non-market characteristics such as clean air or biodiversity by studying how these attributes affect the house's value. The hedonic price method uses the complementarity relationship between a market good and a non-market good. If the quantity of the non-market good that is bundled with the market good increases, the demand for the market will increase. An increase in air quality can increase the market price for housing. Note, however, that the hedonic price function shows the overall price based on the combination of characteristics and this is not the marginal valuation for a certain characteristic. Taking the slope of the hedonic price function reflects the marginal valuation, i.e., the additional price consumers are willing to pay for one more unit of a specific characteristic. The literature has outlined a two-step procedure; step 1 is to estimate the hedonic price function. It is of course not obvious which functional form to use, but it has to be determined from what best fits the data (Rosen,1974; Palmquist, 2005) suggests that the choice can be based on what best fits the data. In the second step, the inverse demand function is estimated. To do this the marginal valuation (the slope and the partial derivative) of the hedonic price function is computed, evaluated at the sample values of the vector z, and the resulting variables are used as the dependent variables. The main independent variable is the quantity/quality of the environmental attribute together with the socio-economic characteristics of the households. Once again, the area below the estimated demand function has a meaningful interpretation in terms of individual welfare based on the quantity/quality of the environmental attribute. Examples of studies using the HP method to value biodiversity are Tyrväinen and Miettinen (2000) who investigated preferences for urban forests in Finland and Ratzke (2023) who investigated preferences for urban biodiversity in Hamburg, Germany.

4.3. Stated Preferences

Stated preference (SP) methods are primarily used to estimate values of goods that do not have a market, primarily public goods, but are also used to evaluate something that does not exist today in the market (for example, a new good or project) or a change in a quality of an existing good. SP methods started to be used more widely in the 1980s and 1990s and are today established, especially in environmental-, transport-, and health economics. The basic idea of SP methods is to, directly, *create* an artificial market for the public good in a survey or in an interview situation. Therefore, SP methods are also called *hypothetical methods* since no actual money transaction is done. In a survey (or in an interview), individuals are asked to state their preferences for the good in question by giving a monetary value: their willingness to pay (WTP) for the good or for the quality improvement of the good. Alternatively, individuals are asked to express their preferences by choosing an alternative among several alternatives. From these choices, one can estimate their WTP for the good in question. Respondents to SP studies are most often citizens, but firm managers, experts, etc. can be the target population: all depending on the context of the valuation study. Results from SP methods can be used to inform politicians, other decision makers, and people working in various governmental agencies and non-governmental organizations about individuals´ preferences for the public good in question.

There are two prominent methods using stated preference data. One is the contingent valuation (CV) method, and the other is the discrete choice experiment (CE) method. The choice between which to use depends on the objective of the study. Both methods measure individuals´ preferences (in most cases) for a public good by conducting surveys (postal surveys, web surveys, or interviews). In addition, sampling, forms for conducting the survey (postal, in person, or online), the inclusion of socio-economics questions in the survey, etc. are often similar for CV and CE surveys. The CV method gives a valuation for a bundle of attributes of the good, whereas the CE method facilitates the valuation of individual attributes of a good. The valuation in both kinds of studies is generally based on a change from a baseline, e.g., an improvement in biodiversity from the status quo to a proposed change relative to the baseline which often is the current situation of the good (biodiversity). Alternatively, it concerns avoiding deterioration of environmental quality from the current baseline. In general, we can say that the CE method is more demanding for a respondent to answer compared to the CV method, but it also gives more detailed information about respondents´ preferences for the good.

How a survey is designed has also similarities between CV and CE methods. An important part of a SP study is the constructed scenario. The scenario includes a description of the good and the characteristics of the good, the current situation of the good, as well as what the improvement will be, when and how it will be achieved. Moreover, respondents get information about how it will be financed: voluntary payments, coercive taxes, etc.) According to Johnston et al., (2017) and their guidelines for well-done SP studies, a payment vehicle should be realistic, credible, familiar, and binding for all respondents to ensure that payments are viewed as fixed and non-malleable. Non-binding payment vehicles, like donations, are not incentive compatible while mandatory payments are, and they can also prevent free riding.[5] In addition, respondents will also get information on whether the payment is a one-time payment or monthly/yearly payment, and if not a one-time payment, respondents should also know the length of the payment period. After the scenario, the sample is asked to state their WTP (CV) or make choices among the different alternatives (CE). To increase the validity, respondents are often reminded of substitute goods, and they are given a "budget reminder" i.e. they are reminded that if they will pay for this good, they will have less money left for other purposes.

4.3.1. Contingent Valuation

With the CV method, respondents are asked to state their maximum WTP for a certain scenario, for example, a change in the quality of the biodiversity. As we have discussed, WTP is a monetary measure of the welfare effect of the improvement in the good, biodiversity here.[5]

The WTP question itself can be asked in several ways. The most common alternatives are *open-ended*, *closed-ended,* and a *payment card*. The open-ended question openly asks the respondent to state his or her WTP. That can be experienced as difficult since we are not familiar with deciding a price, instead, we are used to saying yes or no to a given price. Moreover, the open-ended format is susceptible to strategic behaviour, where a respondent who does not want the good states a very low (even zero) WTP, while a respondent who wants the good states a very high WTP; both to affect the outcome of the process. (Carson and Groves, 2007). The closed-ended alternative means that each respondent is asked to accept or decline a given bid (amount of money); the bid is randomized among respondents from a s-called bid vector which often ranges from low, medium to high levels of the bid. With a closed-ended payment question, based on the raw data we only know if the WTP of an individual is higher or lower than the bid, and thus information is less extensive than in the open-ended format. The distribution of the WTP is, however, possible to infer using econometric models.

The closed-ended payment question thus resembles a market transaction (making it easier for a respondent compared to the open-ended format), but it also demands a larger sample size than open-ended since less information is obtained from each respondent. The closed-ended format is also less sensitive to the strategic behaviour of the respondents (Carson and Groves, 2007). Finally, the payment card means that a respondent is presented with several bids at the same time, and he/she is asked to choose the one that is closest to his/her true WTP. The payment card gives thus more alternatives to respondents compared to closed-ended and it also makes the choices of WTP easier compared to the open-ended format. Econometric models are then applied to estimate welfare measures such as mean or median WTP. In addition, it is common to investigate what are the most significant determinants of WTP by using attitudinal and socio-economic

[5] Incentive combability means that respondents have incentives to tell their true and fully preferences.

background questions included in the survey. It is for example possible that education level has a significant impact on WTP for increased biodiversity or that those who are more worried about biodiversity have a higher WTP for improvement in biodiversity than those who are less worried. Examples of studies that have investigated biodiversity using CV are Getztner et al., (2015) and Tonin (2018) who both studied WTP for the conservation of marine biodiversity in Croatia and Italy respectively. Moreover, Christie et al., (2006) studied WTP for biodiversity enhancements associated with agri-environmental and habitat re-creation policy.

4.3.2. Choice Experiment

The second SP method is the discrete choice experiment (CE) method. The background for the CE method comes from Lancaster (1966), who specified that individuals derive utility from the characteristics of the goods and not from the goods per se. In a CE survey, respondents are asked repeatedly to make choices between different alternatives described by attributes of the good (attributes capture the good characteristics). Examples of biodiversity-related attributes are among others e.g. increasing number of species, the variability of species, and a decrease in the number of red-listed animals or plants. In each choice set, respondents make trade-offs between attribute levels and differences in costs. Importantly, in a CE, we do not observe individuals´ WTP. What we observe is their choices. This is because respondents are asked to choose the alternative in each choice set that best corresponds with their preferences and not to directly state their WTP as done in an open-ended CV study. From their choices we can then, using appropriate econometric analysis, estimate the WTP for a bundle of the attributes and, more commonly, the marginal willingness to pay (MWTP), which measures the strength of individuals´ preferences for each of the attributes (several aspects of biodiversity here) and not only one measure for biodiversity as a bundle of goods. Thus, in this respect a CE survey gives more information than a CV survey.

A CE study usually includes 4-6 choice sets and individuals can only choose one alternative per choice set.[6] CE can be generic or alternative-specific. Generic designs do not use any labels for the alternatives. Instead, it focuses on the trade-offs between the attributes and results can be generalized. Moreover, attributes are always the same for each alternative and in each choice set but the attribute levels vary across the choice sets. Attributes characterize the public good, here biodiversity, and they should be expected to affect peoples' choices and be policy relevant. Thus, individuals´ choices will depend on how they make trade-offs between all the attribute levels. From respondents´ choices the analyst can then estimate an underlying utility function, and from this function estimate the WTP for different levels of the attributes (often referred to as MWTP i.e. the marginal WTP).

Respondents must understand the attributes. This can be particularly problematic for environmental attributes such as biodiversity. Boyd and Krupnick (2009) suggested that attributes should be thought of as endpoints that directly affect the utility of respondents. In addition to identifying utility endpoints, Schultz et al. (2012) recommended that attributes in SP studies should be measurable (endpoints are quantifiable),

[6] There are other approaches as well, where respondents rank or rate the alternatives, see e.g. Louverie (2001)

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interpretable (endpoints can be understood by respondents), applicable (attributes should be relevant for the good or project in question as well as that the endpoints must be linked to specific effects i.e., changes in ecosystem services over which respondents have preferences), and comprehensive (all relevant endpoints are described in the survey). Thus, values associated with e.g., forest biodiversity, may be described using attributes of species richness (Horne et al. 2005). One example of a CE study on biodiversity is the study by Boeri et al., (2020) where preferences for improving bird diversity on the U.K. coast were studied. The attributes to capture diversity of birds were i) number of bird species, ii) number of individual birds, iii) probability of seeing a rare or unusual bird species, and iv) probability of seeing large flocks of birds. Jobstvogt et al., (2014) studied preferences for additional deep-sea protected marine areas in Scotland where they especially investigated two aspects of marine biodiversity: the existence value of deep-sea species and the option-value of deep-sea organisms as a potential future medical resource.

The challenges for choice experiments are in many ways the same as for contingent valuation. Additional complexity comes from the number of choice sets and the number of attributes presented to the respondents. Too many choice sets as well as too many attributes in a choice set may lead to a severe decrease in the data quality due to the task complexity. In complex cases, respondents may answer carelessly or use some simplified lexicographic decision rule.

4.4. The Production Function Method

The environment is crucial in supporting the production of goods and services sold in markets. An economic production function describes the relationship between production factors (input) and output of the production. Notably, we have so far focused on how environmental quality affects the welfare of individuals and less on its effect on economic production. The production function (PF) method focuses on economic productivity and how it increases environmental quality and is based on production and cost data. The production function method is founded on the concept that the value of non-marketed environmental inputs can be assessed by their contribution to the value of the final product that is sold. That the environment is a non-marketed input does not hinder the marginal value of the environment. If there is a market price for the output it is relatively straightforward to estimate the marginal value of the non-marketed input by assessing its impact on the output's value (Freeman, 2003). To conduct a more thorough welfare assessment, one could also examine changes in the marginal value of marketed inputs within the production function. An improvement in environmental quality will affect the marginal cost of the output. If marginal cost decreases and increases consumer- and producer surplus this change can be used to infer the value of non-marketed environmental input. Hence, the mechanism goes through an improved environment that “lower costs and prices and increase the quantities of marketed goods, leading to increases in consumers’ and perhaps producers’ surpluses” (Freeman, 2003). To give some concrete examples, the PF methodology can be used to assess the value of pollinators on agricultural returns (Tibesigwa et al., 2019), the value of wetlands on fishery returns (Barbier 1994;2000), and more generally to value the maintenance of beneficial species for some marketable output (Barbier, 2007).

4.5. Critical Aspects of the Valuation Methods

4.5.1. What values are we measuring?

An important question is what values we can measure with the different methods. In the figure below we summarize what values can be measured with each of the mentioned methods.

Table 1. Overview of values and methods for measurement

Ecosystem services	Values	Example good	RP	SP	PF
Provisioning services	Direct use	Nature reserve, recreation	Travel cost	Yes	No
		Food production	No	Yes	Yes
	Indirect use	Health effects	Yes, hedonic	Yes	No
Regulating and maintenance services	Direct use	Health effects	Yes. Hedonic	Yes	No
	Indirect use	Human existence value	No	Yes	No
Cultural services					
	Non-use values	Existence value	No	Yes	No

Stated preference methods are the only methods that can measure non-use values. This is an important fact for goods such as biodiversity where the non-use values most likely are large (Wattage and Mardle, 2008; Marre et al., 2015). However, most SP studies focus on citizens and on non-market aspects; for example, the effects of provisioning services on agricultural productivity are often not included in SP studies. Moreover, the sample frame and sampling procedures of SP studies are crucial for understanding what values a study includes. Let us take two examples. If the sample only includes citizens from a specific country, which is often the case, then the values will only include values from those citizens. Several NbS can naturally have important impacts on citizens in other countries, and these would then not be included. The second example is when there are smaller groups within the target population that have substantial values of the NbS. With a standard random sampling procedure, these groups might be too small to be included in the study appropriately. This could for example be the local population close to the NbS, or small but important commercial actors. In such cases, specific groups of interest should be specifically targeted.

With RP and PF it is not as straightforward to put a value on new goods, or improvements from the current level of biodiversity, while this is possible with SP. Moreover, often we are interested in finding values of specific characteristics of a nature-based solution. This is not always feasible due to limitations in RP data quality, while with a CE (one of the SP methods) the analyst can decide what characteristics to value. Let us illustrate with the case of valuing a nature reserve. Using the travel cost method on this single nature reserve we can estimate the value visitors put on the nature reserve. However, we would not know what characteristics of the nature reserve that determine this value. To estimate this, we would need to have a situation with a choice between a set of nature reserves, and a variation of the characteristics of the nature

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reserves that allows us to identify the relevance of individual characteristics of the nature reserve. It is also important to be aware of whose values the methods cover. With hedonic pricing, it is the value of residents within the area that is studied, so it would not include the value of individuals that, say, live in another country. With the travel cost method, the values are those that visitors, or potential visitors, put on the reserve. The choice of what groups to sample is thus crucial here. Finally, with the production function, the choice of what sectors and what actors to include is crucial.

Although our focus here is on measuring values for individual NbS, it can be tempting to use these values to say something about the values of ecosystem services in general. This is in general not advisable. A majority of the studies we discuss are partial valuations of ecosystems and ecosystem services. Aggregating such values across say several NbS would not be appropriate. Let us illustrate, even if someone is willing to pay a certain amount (e.g., 1% of their income) to preserve a natural park, we cannot assume they would be willing to pay 10 times that amount to preserve ten parks. Aggregating the willingness to pay for 100 natural parks by a factor of 100 would of course be absurd.

4.5.2. Critical aspects of revealed preferences

Revealed preference methods rely on the existence of well-functioning markets for private goods that can be used to estimate non-market values. For non-market goods, such as biodiversity, it would be hard to use the method because of the lack of such markets. The use of non-experimental data also is embedded with econometric challenges (e.g. endogeneity, omitted variables, and other issues related to identification). We will continue discussing the critical aspects of different revealed preference methods separately.

Travel cost

Several critical issues require careful consideration for accurate application. First, if travel itself provides utility (e.g., scenic enjoyment or relaxation), the assumption that travel and time costs act as a proxy for the trip's "price" is weakened. In this case, travel costs would no longer reflect only the value of accessing the site, potentially inflating value estimates. Second, if the trip serves multiple purposes—such as combining a recreational visit with other activities (e.g., shopping, visiting family)—attributing all travel costs solely to recreation could misrepresent the true valuation of the site. Lastly, variation in trip length among visitors presents a challenge as travel costs for short and long trips cannot be simply aggregated. Addressing these issues is essential for accurately using TCM to estimate the economic value of environmental resources.

Hedonic Pricing

While valuable for non-market valuation, HPM faces several critical challenges. First, applying the method rests on several assumptions based on perfect competition. The method assumes that observed property prices reflect an equilibrium where property markets have fully adjusted to changes in either demand or supply. However, markets may not be in equilibrium due to time lags or information asymmetries, meaning observed prices could underestimate or overestimate the value of environmental features. The assumption that buyers and sellers have perfect information concerning the product could be troublesome especially when valuing environmental quality. Moreover, buyers and sellers are assumed to have the freedom to enter and exit the market but without market power to significantly affect the price of the property. Finally, all levels of the characteristics of the properties should be available, so that buyers can move to their preferred option. Second, **misspecification of the model** is a major issue that can lead to biased welfare estimates. If relevant variables are omitted, or if the functional form of the model does not accurately capture the relationship between property values and environmental attributes, the estimates will be inaccurate. For example, failing to include relevant neighbourhood characteristics or socioeconomic factors can distort the perceived value of environmental good, while choosing an inappropriate functional form (e.g., linear vs. non-linear) may fail to capture the true relationship. There are also well-known identification challenges associated with the application of the two-step procedure (Ekeland et al., 2002). Finally, **multicollinearity** is a common issue in HPM due to the strong correlations between explanatory variables, such as neighbourhood characteristics, school quality, and environmental attributes. High multicollinearity can make it difficult to determine the individual contribution of each variable to property prices, inflating standard errors and reducing the statistical reliability of the estimated coefficients. These limitations highlight the need for careful model specification, data collection, and statistical techniques to improve the reliability of HPM in valuing environmental goods. For example, ocean view and clean air are two attributes that are valued in the housing market. Houses further away from the ocean usually also have higher levels of air pollution. The distance from the ocean and the level of air pollution will therefore be correlated and could cause problems in identifying each of the variables' effect on house prices.

4.5.3. Critical aspects of stated preferences

The main critical issue in SP studies, both in CV and CE, is whether individuals would in reality act as they claim they would do when answering a survey and reacting to the hypothetical scenario. The fundamental assumption of SP methods is that stated behaviour mirrors real behaviour. However, substantial evidence suggests that people would not always truthfully reveal their WTP in hypothetical settings (List and Gallet, 2001; Murphy et al., 2005; Penn and Hu, 2018) leading to hypothetical bias. Hypothetical bias refers to the distortion that arises when respondents are asked hypothetical questions rather than being placed in a real situation when they need to pay. Studies testing the existence of possible hypothetical bias have compared stated WTP in a hypothetical setting with a real binding payment. Penn and Hu (2018) made a quite recent meta-analysis including 132 SP studies and found that the mean ratio between hypothetical WTP and real WTP was 2,29 (median 1.39) indicating over two times larger mean WTP when the WTP was hypothetical. The hypothetical bias was also found to be larger for public goods. When they excluded 5 % of the most extreme values the mean ratio decreased to 1.94. However, not every study finds hypothetical bias. For example, Johnston (2006) did not find any when they compared hypothetical answers of a CV study with real referendum results for identical programs of water supply in the U.S. Importantly, the respondents were not aware of the coming referendum at the time of the CV survey. The problem of hypothetical bias is well-known in the literature and today it is custom in a SP survey to include techniques to eliminate/mitigate the hypothetical bias. However, there is today not a general agreement on which of the techniques is the best one and it is also possible to combine several of them in the same study (Loomis, 2014). Several approaches to mitigate hypothetical bias have been explored: (i) cheap-talk scripts (informing respondents about the hypothetical bias to make respondents less prone to hypothetical bias), (ii) follow-up questions such as certainty responses (respondents rate the level of certainty about their response to the WTP question and only certain answers are included in the analyses), iii) consequential scripts (respondents know that their answers are consequential, i.e. their answers will possibly affect a policy outcome which makes the respondent more careful when answering the study), iv) time-to-think protocols (the idea is to give time to respondents to think about their answers), and v) taking an oath (respondents are asked to swear, or promise, to answer truthfully, mimicking the act of taking an oath in a courtroom. The idea behind taking an oath is to refer to an intrinsic motivation that will commit the respondents to answer truthfully. All of them, with one exception (the certainty follow-up question), are so-called “ex-ante“techniques meaning that the script or information to decrease or eliminate hypothetical bias is given to the respondents before the WTP question or choice sets in a survey. Penn and Hu (2018) analysed the impact of different methods and techniques for mitigating hypothetical bias. They found that choice experiments, cheap talk-, and consequential scripts, and certainty follow-up questions, all significantly reduced hypothetical bias. For example, follow-up questions reduced hypothetical bias by 73-100%, while ex-ante scripts had a smaller impact. In the best practice recommendations by Johnston et al., (2017), it is concluded that the most promising ex-ante approach is a consequential survey with a binding payment.

In examining the elicitation of preferences using SP methods, it is also essential to distinguish between goods with negligible non-use values and those with significant non-use values as is the case with biodiversity (Wattage and Mardle, 2008; Marre et al., 2015). There are notable challenges in measuring non-use values through hypothetical surveys. This does not imply that non-use values should not be measured, but rather that there are inherent difficulties in doing so. Non-use values are frequently driven by motivations such as "purchase of moral satisfaction" (Kahneman and Knetsch, 1992) and "warm glow" (Andreoni, 1989).

Another critical aspect of stated preference studies, in particular related to studies on ecosystems and biodiversity, is the so-called insensitivity to scope. Insensitivity to scope means that the respondents are unresponsive to the scope of the good that is studied. The debate around this issue is extensive. It largely originates from Kahneman and Knetsch (1992), who argue that stated WTP in SP studies are choices based on moral satisfaction and not economic choices. Because of this, respondents are likely to be insensitive to the extent of the good. This is illustrated with a case where they found that the WTP to prevent a drop in fish population in all lakes in Ontario, was only slightly higher than the WTP to prevent a drop of the fish population in only a small area of the province. There has been a comprehensive investigation and discussion around this issue ever since (see e.g. Carson, 1997; Diamond and Hausman, 1994), and many studies, including several meta-analyses (see e.g. Johnston et al., 2005; Richardsson and Loomis, 2009; Lindhjem 2007). The are very mixed results. Some studies find insensitivity to scope, some find positive scope effects, and some find even negative scope effects.

Several explanations for insensitivity to scope have been discussed in the literature. One is that warm-glow effects in the survey explain insensitivity to scope (Nunes and Schockaert, 2003). Here, in situations where we would expect sizeable warm-glow concerns in the survey, we would be more likely to observe insensitivity to scope. Another is that it is due to improper survey design and lack of information (Carson, 1997), or the sequencing of information (Bateman et al.,2004). Finally, Ojea and Loureiro (2011) find in a large-scale meta-analysis that how the change in the level of the good is critical. Studies where the change is measured in absolute terms (for example hectare) are more likely to pass a scope test than studies where the change is measured in relative terms.

4.5.4. Critical aspects of the production function method

To value the environment as an input one needs of course to have a deep knowledge about the relationship between various inputs and outputs in the environment. The complexity of ecosystems and lack of knowledge of the inherent complex interrelations is a challenge in using the production function method for valuing ecosystem services. Another related challenge is the problem of double counting which occurs if both the intermediate ecosystem functions and the final ecosystem services are estimated separately and aggregated in assessing the final value of an ecosystem service (Barbier, 2000; Bateman et al., 2014; Fisher and Turner, 2008).[7]

4.5.5. A special case: Benefit transfer

A different approach than the others we have covered is to use existing estimated values from primary studies in a specific context at a study site, to infer about the value of the good in another setting at a policy site. This is called benefit transfer where values are transferred from the study- to the policy site. In our specific case, it would mean that the analyst would use the estimated value (from any of the methods we have presented) for an ecosystem service from one location to infer the value of the same ecosystem service in another location (Barbier et al., 2009). Since valuation studies are expensive this is an interesting approach. There are two errors to consider in ecosystem benefit transfer: measurement error and generalization error (Johnston and Wainger, 2015). Measurement errors concern errors in the primary study, while generalization relates to the lack of similarity between the original site and the target site. The latter includes several factors, the error could result from environmental differences as well as differences in the populations between the study- and policy site.

The simplest transfer approach where unit values are simply transferred from one site to the other simply ignores these errors. However, by estimating a benefit function for the initial site, this function can be used for the target site. This approach allows for adjustments to account for differences between the study site and the policy site, ensuring that variations between the two are properly addressed. This approach is called a benefit function transfer (Johnston and Wainger, 2015). The benefit function could also be estimated on a set of studies (a meta-regression), allowing for more precise estimates, but also the identification of factors that might not be identifiable with only one original site/study (Johnston et al., 2005).

A benefit transfer approach relies on carefully conducted primary valuation studies and cannot replace these. As such it should be seen as a complementary approach to primary studies. One challenge for benefit transfer of NbS is that biodiversity projects are in many cases very local in nature and small in scale. The values are likely to be rather context specific, and it could be challenging to find appropriate comparison sites. It is also important to note that while transferring benefits from the study- to the policy site could be appropriate in some cases, we cannot repeat the exercise for multiple sites within the same population. This is the same problem as with aggregating values from individual studies.

[7] Double counting is a well-known term in economics that originally was used to refer to the erroneous practice of aggregating the value of a nation's goods and services. The problem is caused when both the intermediate- and the final good are aggregated and misses that the final good includes the value of the intermediate good.

5. What is particular about biodiversity?

In this section, we discuss a few aspects of biodiversity value that we believe are particularly important and challenging for the valuation of NbS.

5.1. Time

A key aspect of the value of biodiversity and ecosystems is the element of time. Ecosystems provide benefits over time, effects of restoration or damages of ecosystems can occur far in the future, etc. To compare streams of benefits and costs over time, a standard approach is to discount future effects to the present. This requires a so-called discount factor. The traditional Ramsey rule specifies that the discount rate is a function of the pure rate of time preference, the growth rate in income, and a measure of the marginal utility of money. The literature shows, however, considerable challenges in agreeing on one applicable discount rate. Sterner and Persson (2008) shows that increasing scarcity and limited substitutability between ecosystem services and standard goods implies an additional factor that needs to be considered when discounting, namely rising relative prices. This can be thought of as having good-specific discount rates (Hoel and Sterner, 2007; Traeger 2011), where the discount factor for each good depends on the growth rates and the elasticity of substitution between the two goods. Interestingly, the elasticity of substitution is inversely related to the income elasticity of the WTP for the environmental goods, under certain preferences (Ebert, 2003; Heckenhahn and Drupp, 2024). If the income elasticity is low, this corresponds to the case where market goods are substitutes for environmental goods, and if the income elasticity is high, this corresponds to the case where market goods are complements to environmental goods (Drupp et al, 2004). In a comprehensive study, Drupp et al. (2023) estimate an income elasticity of WTP of around 0.79, this implies an elasticity of substitution of 1,27, which is a relatively low degree of substitutability. However, the estimated income elasticity varies considerably between studies; see e.g. Hekcenhahn and Drupp, 2024, Jacobsen and Hanley, 2009). Irrespective of this, the choice of discount factor when evaluating any NbS is likely of great importance.

Another significant challenge is time-inconsistent preferences—where a decision maker's preferences shift over time, resulting in inconsistent choices. While it is rational to discount future benefits, a present bias, where immediate rewards are given too much weight over future gains, can distort the level of investment. Both present bias and failure to consider relative prices in discounting reduce environmental investment levels below the socially optimal amount.

5.2. Complexity and uninformed citizens

Biodiversity is complex. It is therefore not very realistic that actors such as citizens, consumers, or firms are fully informed when making decisions that can affect biodiversity. This raises the question of whether citizens' values or preferences are informative for policy development (Hanley and Perrings, 2019). One could take the view that because of the complexity of the problem, and because citizens do not have the appropriate information and knowledge to make informed decisions at the market or in surveys, we should not make policy decisions based on individual preferences. On the other hand, politicians cannot be assumed to have complete information either, and experts may differ from the general population not only in their expertise but also in other important aspects, such as income and preferences, which could make them less representative of the citizens they aim to serve (See e.g. Carlsson et al, 2011 and Eggert et al., 2018 for preference differences between citizens and environmental experts). However, let us assume that the policymaker does care about individual preferences and values. Then there are several aspects to consider if citizens are uninformed. 1. Decision utility versus experienced utility (Kahneman et al., 1997). Decision utility is what economists usually study when we observe choices made by individuals. It reflects the perceived satisfaction or benefit that decision-makers believe they derive from their choice. Note that all the methods we covered so far are based on decision utility. Experienced utility on the other hand refers to the post-choice satisfaction that people experience when actually utilizing the good (e.g. clean air). If we prioritize the utility of the experience and it diverges from decision utility, relying on decision utility as a measure of welfare becomes problematic. Notably, while the literature on valuing environmental goods and services primarily relies on decision utility, a smaller body of research highlights the potential of using the experienced utility for this purpose, as seen in studies by Ferreira and Moro (2010), Luechinger (2009), and Welsch (2002, 2006). This approach often involves using self-reported subjective well-being as a proxy for individual utility, allowing researchers to compute the marginal rate of substitution between income and non-marketed goods. From this, it is possible to infer the monetary value of non-marketed goods, offering a more experience-based measure of their contribution to welfare. A challenge with using subjective well-being responses for valuation is that they may be subject to biases common in survey methods, such as those related to question order and wording and the tendency of people to misstate their happiness (see, e.g., Bertrand and Mullainathan, 2001; Carlsson and Kataria, 2018). The understanding of incoherent/irrational/uninformed preferences has also led to a growing literature on paternalism within behavioural economics that argues that it gives room for policymakers to use their own judgment about what is best for an individual (Carlsson, 2010). 2. Focus on certain aspects. Because of the complexity, there is a risk that behaviour, and even policy, only focus on certain aspects of the problem. It could for example manifest itself in terms of disproportional focus on direct use values of ecosystems, or on certain types of species, such as iconic species. Citizens might have stronger preferences for such aspects, but problems arise if other aspects are not considered because of the complexity.

What does complexity imply for each of the valuation methods? The revealed preference method relies on consumers being informed when making their decisions in the market. Lack of information will distort the calculated benefits of these aspects in the overall valuation as consumers may not fully recognize the benefits of e.g. environmental quality or local biodiversity. An advantage of the stated preference method is that it allows for clear explanations to participants, helping them understand how specific environmental investments may impact them. This is of course not as simple as it sounds. Task complexity in SP studies can potentially affect both the extent of inconsistent choices, the decision rules adopted by the respondents, and the welfare estimates (see, e.g., DeShazo and Fermo, 2002; Swait and Adamowicz, 2001). There may even be scientific uncertainty about the physical effects of certain changes of a public good (such as biodiversity) as well as how these changes will affect human well-being. The effects of some changes may be difficult to translate in a survey into terms and language that can be readily understood by respondents. In addition, some changes are very complex and multidimensional and may provide only a limited picture of reality (OECD, 2006). In stated preferences, several ways to improve the communication of complex scenarios have been explored. For example, Tagliafierro et al. (2000) conducted a landscape analysis in a three-dimensional space to provide ecologically meaningful quantitative landscape indicators to respondents in a study on landscape valuation in Italy. Another interesting development is the use of virtual reality since this would provide respondents with much more freedom to explore different scenarios and to understand what would happen and how it would look (Carlsson, 2010). For example, Bateman et al. (2009) use a virtual reality world in which respondents can fly around and explore the area, and Fiore et al. (2009) use a virtual reality world where forest fires are simulated. However, it is far from clear that this would resolve all issues with complexity,

In summary, while it is hard to neglect the advantages of the stated preference methods to inform uninformed respondents, it does still come with its problems.

5.3. Uncertainty

The impacts of climate change, food insecurity, and disease outbreaks among other aspects, are consequences that can cause even massive losses of human lives. These are aspects that many people would think need special attention. From an economic point of view, the valuation of such horrific impacts can be assessed by something known as the value of statistical life (VSL); see e.g. Viscusi and Aldy (2003). This is not a measure of the value of life. Instead, it is a measure of the value of reductions in mortality risks, i.e. how much individuals are willing to pay for very small reductions in the probability of death. VSL can be estimated with hedonic wage methods (Viscusi and Aldy, 2003) and with stated preference methods (Krupnick, 2007).

The uncertainty and complexity in quantifying these risks present a significant challenge in assessing the value of human existence. One could argue for a precautionary approach for situations of potentially unlimited downside exposure (Weizman, 2009). However, what is also less studied and understood are the economic and financial risks associated with biodiversity loss. Understanding these risks is particularly important in a complex system, where there could be threshold effects and unexpected outcomes (Ranger et al., 2023).

An important aspect of ecosystems and biodiversity is the option value: the value we put on maintaining an option. Two aspects of ecosystems make option values important. The first is the obvious one: that there are benefits of ecosystems that are unknown to us today, or at least uncertain. This implies a value of protecting the ecosystem because it might have a value in the future, and we will learn more about this over time. The other is that the destruction or degradation of ecosystems implies irreversible or costly restoration decisions. Option value should thus be seen as an additional value of protecting and restoring ecosystems. The option value would depend on what we think the unknown/uncertain benefits are and what the costs of restoring ecosystems are (the degree of irreversibility). The complexity of the problem and the option values of biodiversity losses are clearly to be seen in the EU´s Biodiversity Strategy for 2030 (European Commission, 2020). The strategy's goal is to recover biodiversity and increase the share of legally protected land and sea areas in Europe, to build our societies' resilience for future threats such as climate change, food insecurity, and disease outbreaks among other aspects. In a future of rising sea levels and more extreme weather events, such investments could be very important.

5.4. Non-use values and whose values should we count?

If we were to rely exclusively on revealed preference methods to estimate the benefits of ecosystems, we might avoid the potential issue of hypothetical bias, which can lead to overestimating benefits. However, this approach would introduce a different problem: we would almost certainly underestimate the total benefits. This is because revealed preference methods are limited to capturing use values and cannot account for non-use values, such as the non-value of preserving biodiversity or the existence value of species. As a result, important dimensions to well-being might be overlooked, leading to inferior policy assessments.

Non-use values represent a sizeable share of the total value for biodiversity and ecosystem services (Wattage and Mardle, 2008; Marre et al., 2015). Wattage and Mardle (2008) found that 45 % of the total value for wetland conservation in Sri Lanka were non-use values (bequest and existence values). Similarly, Marre et al., (2015) found that the share of non-use values was 25-40 % for protecting the coral reef ecosystem. Hanli et al., (2023) did not investigate how large a share, of the total WTP was non-use values, but the relative importance of the non-use values for ecotourism resources in a national park. They found that preferences were highest for bequest value, followed by existence value, and altruistic value. Thus, people have intrinsic values concerning the existence of species, warm-glow, and other altruistic values (from supporting the preservation of species, etc). As we have discussed, if we would like to measure such values, stated preference methods are the only viable option. However, non-use values include a variety of values, ranging from valuing the existence of species to effects on moral utility in terms of utilities derived from the warm glow of contributing to the funding of the public good. It is far from clear that all these values should be considered when designing policies or evaluating projects. Scholars have argued that because these values are highly context-dependent and related to the social pressure to contribute they should not be considered (Diamond, 2006; Della Vigna et al., 2012). However, other authors such Kaplow and Shavell (2001) argue that benefits arising from the warm glow of giving should nevertheless be accounted for.

Another aspect of this that we have already touched upon is the population whose benefits we would care about. This would depend on the context, including what values the decision-maker cares about. Thus, depending on the topic and target group, the population might be ordinary citizens, experts of many kinds as well as politicians or other decision makers. However, the valuation methods that we have discussed can also to some extent be used to inform the decision-maker about who benefits. There is a sizeable literature on distance-decay (Hanley et al., 2003), in particular on use-values. The basic idea is that WTP declines with distance from the NbS, and by using distance as an explanatory variable one can identify the cutoff at which WTP is zero. This would then inform us about who is benefitting from the NbS, and who is not. However, many values, in particular non-use values, might not display distance decay. For example, the extinction of major species could have a global significance, and massive upscaling of an NbS in a country or a continent could also have global impacts that are not a function of the distance to the NbS

5.5. Implications for NbS provision and funding

We believe that there are some important implications for the provision and funding of NbS to be made from our discussion. The primary one is the importance of considering all the different values that an NbS provides. Non-use values represent a sizeable share of the values from NbS according to several case studies. There is a tendency, however, to focus on productive values and other direct-use values from ecosystems and NbS. While this could be a lower bound of the actual benefits, important values might be lost if non-use values are ignored. Furthermore, since NbS often provides a wide array of values, there is a risk that values that are more difficult in general to measure and monetize are left out. Furthermore, given the complexities of the ecosystem, the risks of catastrophic and unexpected outcomes with consequences for the whole economy are important.

The wide array of values and beneficiaries of NbS also means that there can be trade-offs among these that are important to consider. Moreover, in many cases, the NbS's effects are unclear. There are very few comprehensive impact evaluations of NbS. Instead, what is often valued is the state of the ecosystem and the ecosystem services that are connected to the NbS, or constructed scenarios where the impacts are expected to be there.

The complexity of biodiversity and ecosystems is important not only for assessing the values of NbS but also for the NbS itself when communicating about its role and what values it provides. This can be important both for policy support, but also for funding. If investors do not understand the role of NbS, and what values it provides, there is a risk that they will make other choices. NbS can often be a substitute to grey infrastructure, e.g. coastal wetlands can be an alternative to concrete sea defence walls. It's therefore important to investigate and communicate how NbS compares to "engineering solutions" and man-made structures. Vicarelli et al., (2024) examined 87 published scientific studies about 402 NbS sites. They compared the cost-effectiveness of the NbS solutions with engineering-based solutions and found that 65 % of these studies concluded that NbS are always more effective in attenuating hazards compared to engineering-based solutions and 26 % found that NbS are partially more effective.

Today, the public sector covers over two-thirds of the annual global biodiversity finance (OECD, 2020). However, if economic agents understand that biodiversity and ecosystem services have economic value, there is potential to attract the private sector. As private finance looks after economically viable business opportunities, they are increasingly identifying projects that protect and manage ecosystem services (The World Bank Group, 2020). Currently, the overall sustainable finance market is growing fast. However, biodiversity finance remains a small percentage of the total finance market (The World Bank Group, 2020). One apparent problem is that even if the investors do understand the role of NbS, and what values they provide, it is far from obvious that they would invest, and that socially optimal investments would be made. However, a transformative upscaling of NbS will also require innovative financing strategies and involving the private sector (Vicarelli et al., 2024).

Finally, we cannot stress enough the importance of time. Ecosystems, if managed properly, can provide benefits over a long period of time, and restoring damaged or destroyed systems can take a very long time. Not taking action comes with the risk of irreversible loss of species and ecosystems. This requires a decision-making approach that appropriately considers future effects, but it also requires a long-term perspective from policymakers and investors.

6. State of the Art of ES and NbS assessment tools

6.1. Overview

To explore the potential of assessment for deployment in financial decision-making and sustainable practices, our research aims to understand the state-of-the-art of those tools, mapping their awareness, knowledge, and usage across different stakeholders. Identifying different user profiles across the measuring, modelling and/or valuing of ES and NbS will reveal the existing tool network, i.e., who uses what under which thematic area. Thus, those links will uncover needs and opportunities for tool development according to market supply and potential demand.

In this chapter, we discuss a spectrum of tools currently in place to assess NbS and ES, examining their visibility (awareness), stakeholders' understanding of them (knowledge), and the extent of their application (usage). The outputs contribute to the broader objectives of the BIOFIN-EU project by linking tools to specific project tasks:

WP2 | Biodiversity Impacts & Supply of Ecosystem Services from NbS

- T2.1 Select tools to assess biodiversity and environment
- T2.2 Categorising NBS by organisational, spatial and thematic data
- T2.3 Identifying synergies, bottlenecks and trade-offs
- T2.4 A decision-tree to identify biodiversity impacts

WP3 | Economic Valuation of Ecosystem Services

- T3.1 NBS Governance Structures and ES Valuation
- T3.2 Valuation of ecosystem services and corporate finance decision-making

WP4 | Biodiversity-Linked Decision Support: From Data to Financing

- T4.1: Biodiversity Assessment, Monitoring and Data Collection

WP5 | Financial Instrument Design & Business Model Innovation

- T5.4 Analysis of adoption pathways and MCDA for financial institutions and markets

WP6 | Use-cases, Focus Groups and Policy Forum

- T6.1 Application of Key Nature-Related Classifications and Assessments

To achieve these outcomes, we compiled key data on the tools assessed, reviewing their potential for integration into decision-making processes across varied contexts. Our methodology involved collecting tools from diverse sources and conducting surveys in two phases to ensure stakeholder engagement in mapping assessment tools.

This chapter is structured into five sections. Section 1 presents general remarks including the problem statement and research objectives. Section 2 provides literature insights on previous reviews mapping and comparing NBS and ES assessment tools. Section 3 highlights the methodology, displaying the process of mapping the tools, including tools collection and primary data requirements, then listing the collected tools, and presenting the survey objectives and design. Section 4 displays the empirical analysis, including survey dissemination and data analysis, where the general results are displayed, as well as the awareness of the collected tools, and the tools' level of knowledge and usage. Section 5 concludes with brief remarks and future developments.

6.2. Literature insights

The term nature-based solution refers to the actions conducted to manage the ecosystems, which can handle societal challenges ensure human well-being, and benefit biodiversity (Cohen-Shacham et al., n.d.). This approach makes a frame to work with nature to provide solutions related to the social, economic, and environmental challenges (Seddon et al., 2020). As per the BIOFIN project, a working definition was addressed that aligns with the definition of the IUCN and gathers four key elements. NBS follows an area specific integrated approach with essential societal, economic, and ecological aspects. It has benefits for nature as sustaining and increasing ecosystem resilience and has human benefits in the social and economic aspects (Mark et al., 2024). Ecosystem services is another term that is interconnected with NBS and refers to the different benefits that are provided to people in several aspects, such as provisioning, regulation, cultural, and supporting services (Millennium Ecosystem Assessment, 2005), therefore, ensuring human health and well-being (Helm & Hepburn, 2014).

Despite the use of NbS in specific contexts, particularly in large-scale construction projects incorporating sustainable urban drainage systems (e.g., to manage drainage on-site through engineered solutions), substantial gaps persist in addressing worldwide needs (Jax et al., 2013). Applying tools for assessing ecosystem services is necessary for the decision-making process and to enhance the sustainable management of the resources. Indeed, that paradigm has been referred by different researchers who confirmed the role of tools in succeeding the implementation of the NbS (Giulia, 2024). Supporting tools allow to integrate the concept of monitoring and evaluation, measuring NbS impacts on nature and society more applicable and effective, ensuring sustainability and resilience (Chrysoulakis et al., 2021).

Limited assessments have been conducted to map tools targeting NbS and ES. Also, the number of tools assessed by most of those reviews is limited and aimed at comparing their functionality. As indicated by those reviews, despite the importance of the tools in enhancing the processes of conducting the NBS, there is still a lack of comprehensive mapping of tool availability and capability (Voskamp et al., 2021). Mapping and comparing the available assessment tools for NBS and ES will assist decision-making and help the practitioners with effective frameworks (Morri & Santolini, 2021), (Raymond et al., 2017). As highlighted, the growing demand for sustainable solutions requires the development of new integrated assessment tools (Drakou et al., 2015),(Barker et al., 2024). In some reviews, tools were catalogued focusing on how to promote their effective use (Czúcz et al., 2018). Further research focused on the comparative analysis of assessment tools, linking the theoretical knowledge of the tools with their practical application (Seddon et al., 2021). Even if the number of compared tools is different across the reviews, to find a more thorough listing there is a need to consult existing catalogues (Mino et al., 2021). The high number of assessment tools, with different structure and purpose, makes their understanding and classification challenging.

The scope of analysis differs across the studies, namely focusing on climate resilience (Mino et al., 2021), climate adaptation (Voskamp et al., 2021), and (from a distinct perspective) user interaction (Neugarten et al., 2018). The last one covers assessing tool purposes and outputs, along with practical considerations such as time, financial resources, and required expertise.

In an EU report (European Commission. Directorate General for Financial Stability, Financial Services and Capital Markets Union. et al., 2024) 15 NbS and ES assessment tools were discussed. Those tools are developed to help financial institutions evaluate their exposure to biodiversity-related risks. European research and innovation programs have been supporting the development of online catalogues and assessment tools for NBS, as there is a relevant knowledge gap related to the implementation, management, and monitoring of NBS to ensure sustainability and resilience (Mino et al., 2021).

There are more studies that compare only two or three tools, providing more details about their features and processes, and covering narrower sectors. InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) is the most mentioned tool according to our initial scan. The scope of analysis differs among those studies, from the comparison of tool performance on different provisioning and regulating services (water supply, carbon storage and nutrient retention) to tool development (considering other tools strengths and weaknesses). An example of the last case integrates the System of Environmental-Economic Accounting - Ecosystem Accounting (SEEA EA), with traditional methodologies as Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA), or Cost-Benefit Analysis (CBA) (Chairat & Gheewala, 2024). Table 2 highlights those reviews comparing the number of tools mentioned in each of them:

Table 2. Reviews that perform a comparative analysis of NbS and ES tools, with number of tools mentioned

Review title	Authors	Year	N.
Tools for Edible Cities: A Review of Tools for Planning and Assessing Edible Nature-Based Solutions	Mino et al.	2021	70
Nature-based solutions tools for planning urban climate adaptation: State of the art	Voskamp et al.	2021	44
Tools for measuring, modelling, and valuing ecosystem services	Neugarten et al.	2018	30
A comparative assessment of decision-support tools for ecosystem services quantification and valuation	Bagstad et al.	2013	17
Study for a Methodological Framework and Assessment of Potential Financial Risks Associated with Biodiversity Loss and Ecosystem Degradation: Final Report	EC et al.	2024	15
A comparison of ecosystem services mapping tools for their potential to support planning and decision-making on a local scale	Vorstius and Spray	2015	3
The Conceptual Quantitative Assessment Framework for Nature-Based Solutions (NbS)	Chairat & Gheewala	2024	3
Comparing Strengths and Weaknesses of Three Ecosystem Services Modelling Tools in a Diverse UK River Catchment’	Sharps et al	2017	2

6.3. Methodology

To achieve the research objectives, the methodology begins by identifying and collecting existing tools used to assess NbS and ES. This is followed by a survey targeting experts and specialists in NbS and ES assessment, aiming to gather their insights on the collected tools. The survey not only maps these tools but also identifies additional tools known to the respondents. Afterwards, the research narrows its focus to the most relevant tools, i.e., those with significant knowledge base and widespread usage. This step involves a second-phase survey designed to assess and validate the tools while linking them to the work packages of the BIOFIN-EU project. The sample of respondents will cover tool developers and experts, who participated in the initial survey.

Table 3. The research methodology, Planned / Achieved tasks

Task	Status	% of Completion
Collect tools used for ES and NbS assessments.	Done	100%
Literature review: To check the relevance (number of citations) of tools in scientific articles.	Done	100%
Clean data, e.g.: remove the duplicated tools.	Done	100%
Create an Excel database to insert the gathered data, benefiting from the existing databases, adapting existing typologies, labels, and filters used.	Ongoing	90%
Integrate the typologies included in the BIOFIN-EU Deliverable 2.1 with the NbS&ES tools database.	Done	100%
Prepare the first phase surveys: To map ES and NBS assessments tools (DESIGN).	Done	100%
Validate the first phase survey design and content (DESIGN VALIDATION).	Done	100%
Disseminate the first phase survey (DATA COLLECTION).	Done	100%
Analyse collected data (DATA ANALYSIS) - Primary analysis.	Done	100%
Include results in Deliverable 3.1.	Done	100%
Select tools from the collected list to validate their information, considering the reviews and first phase survey outputs.	Planned	5%
Fill Excel database with the selected NbS and ES tools information.	Ongoing	20%
Design the second phase survey with the information of the selected tools: To assess and validate tool info.	Ongoing	40%
Dissemination of the survey to assess and validate tool information.	Planned	0%
Comparative analysis of the NbS and ES tools.	Planned	0%

6.3.1. Tools collection

The tool collection process includes different steps, such as: reviews that reported specific tools or conducted comparative analysis of different tools; search engines (general and scientific), contributions from BIOFIN-EU consortium partners; and databases created by projects/entities. Additionally, a survey was conducted to map and collect further tools:

- Review:

Some reviews focused on specific tools or comparisons between different tools. However, comparative studies remain limited in terms of the number of studies and the tools covered.

- By search engine (general and scientific-based) considering a Population-Exposure-Outcome (PEO) framework to perform a thorough search, e.g., in Google, about “Ecosystem services tools” and “NBS tools”, along with alternative terms.
- Databases created by other projects / Entities, such as:

Ecosystem Knowledge Network: a platform dedicated to ensure the value of the natural environment for enhancing well-being and prosperity across the UK. This platform allows sharing knowledge, innovation, and ideas, in addition to display tools and insights needed to manage natural resources.

NatureServe: a Network of 60+ governmental and non-governmental programs located in the United States and Canada. NatureServe works on managing and analysing data, sharing it throughout its network, and further incorporating it into products and services through easy-to-use tools and infographics.

Nature4Climate (N4C): a consortium of organizations across environmental related sectors, which is focused on advancing nature-based solutions to promote sustainability, equity, and a nature-positive future.

The Green Gateway is a portal that helps in assessing and reporting on the green eligibility and green impact of projects. It offers essential guidelines and case studies on green investment criteria. The portal includes a set of tools that can assist in the allocation of green (sub)projects to European Investment Bank (EIB) intermediated finance products. The portal also offers support tools to financial institutions that provide green loans.

The European Climate Adaptation Platform (Climate-ADAPT) is a partnership between the European Commission and the European Environment Agency (EEA). Climate-ADAPT aims to support Europe in adapting to climate change helping users to access and share data and information, through tools that support adaptation planning.

The Ecosystem Services Valuation Database (ESVD) provides easily accessible information on the economic benefits of ecosystems and biodiversity, and the costs of their loss, to support decision making regarding nature conservation, ecosystem restoration and sustainable land management.

Earth Economics supports governments, businesses, and nonprofits in understanding the financial benefits of preserving natural resources, through offering services such as ecosystem service valuation, cost-benefit analysis, industry analysis, and investment strategies.

The Environmental Protection Agency (EPA) is a U.S. federal agency created in 1970 with the mission to protect human health and the environment in the United States. The agency conducts environmental research, provides education, and supports environmental justice initiatives, aiming to balance economic growth with sustainable environmental stewardship.

Oppla (NetworkNature**)** is a platform provided by NetworkNature to present the latest nature-based solutions research, news, and resources in addition to hosting related events.

- Contributions from consortium partners through active participation in various activities, providing guidance on existing tools and databases, and responding to the initial survey.

The number of collected tools at the end of this process was **275,** after cleaning the data (e.g., removing the duplicated tools).

6.3.2. Primary data requirements

To ensure the collection of relevant data on assessment tools in alignment with the research objectives, an Excel template was specifically designed based on a prior comparative analysis of existing tools. The template is organized into three sections as follows:

Primary details:

- **Toolkit information**, in case the tool is presented as a part of group of tools.
- **Tool information:**

This includes *Name, Acronym, Short Description, Long Description, Tool type, Primary Audience, Operating System, URL, Main topics, Sectors, Owner / Developer, Donor (in charge of funding), Interface, Year of Establishment.*

- **Tool information: (That will be used to compare with other tools):**

This part will be used to compare the tools, and it includes*: Cost (Free, not free), Open/ Closed source, Availability, Data input demand, Skill requirements, Scale of analysis, Quantitative / Qualitative, Monetary / Nonmonetary, Spatially explicit, User support, Level of development & documentation, Approach to uncertainty, Level of stakeholder engagement, Scenario comparison, Static (single time period) / dynamic (temporal variation)*

Typologies and dimensions related to NbS & ES, as addressed by BIOFIN project (Mark et al., 2024), were integrated in the tools DB to be linked with the tools:

Figure 3. Typologies and dimensions related to NbS and ES

- **Tool Workflow and Processing**

This section outlines the required inputs and expected outputs of the collected tools, as well as their processing methods, which vary depending on the tool's purpose and its intended users.

- **Indicators matrix**

This section explores the linkage between the indicators used for measurement and the tools themselves. The indicators will be derived from both the reviews and the tools. The development of this section will begin once the data collection for the tools is complete.

6.3.3. List of collected tools

A list of the collected tools was prepared, including the tool name, source, anonym, and website.

Due to the large number of tools collected, a screening process was conducted to objectively select the relevant tools:

- Check for accessible information, evaluating the potential tools by reviewing their websites.
- Tool validation by determining which potential tools meet further requirements, obtaining a first list of assessment tools.
- Selection of the most relevant tools (in terms of knowledge base and widespread usage), through a first phase survey (using the first list). The results of this survey will generate a final list of tools to be considered for the subsequent stages of the research.

The created definition was used to classify the potential tools into two main categories "Tools" / "Not tools", according to their compliance with the definition. As observed in the previous reviews there is no consensual definition of "assessment tool" used, which has led to confusion in identifying the tools. A "tool" is often defined as either a methodology, software, catalogue, repository, e-platform, guideline or handbook. Regardless of the tool's complexity, a "tool" is often defined as an ICT-based application or software designed to support decision-making, planning, the evaluation of environmental impacts (Costanza et al., 2014).

The definition of "tool" used herein is as follows:

An assessment tool for nature-positive decision-making *is considered any software, application, model, or web-based platform specifically designed to integrate environmental and/or biodiversity considerations into decision-making processes. These tools process data inputs to generate outputs such as reports, models, or metrics that help users understand the impacts of their decisions on nature. They may support various functions including risk assessment, impact evaluation, and scenario planning, and are used in fields such as project design, policy formulation, and investment analysis. Such tools often incorporate interactive features and can be developed using programming languages or standard software applications. Methodologies provided solely in static formats like PDFs or web documents are not classified as assessment tools.*

After checking each tool website, the potential tools were classified according to a predefined typology. The following table shows the result:

Table 4. N. Potential tool/Not tool for each classification

Typology	N. Tools / Not tool
Not tool - Database without user interaction	8
Not tool - Guideline / Methodology (PDF Format)	18
Not tool - Guideline / Methodology (Web-based)	22
Not tool - Model without user interaction	5
Not tool - Other reason to be mentioned	56
Not tool - Website without user interaction (Information Access)	18
Tool - Database with user interaction	18
Tool - Model with user interaction	60
Tool - Other type	1

Tool - Software	31
Tool - Website with user interaction	38
Total	**275**

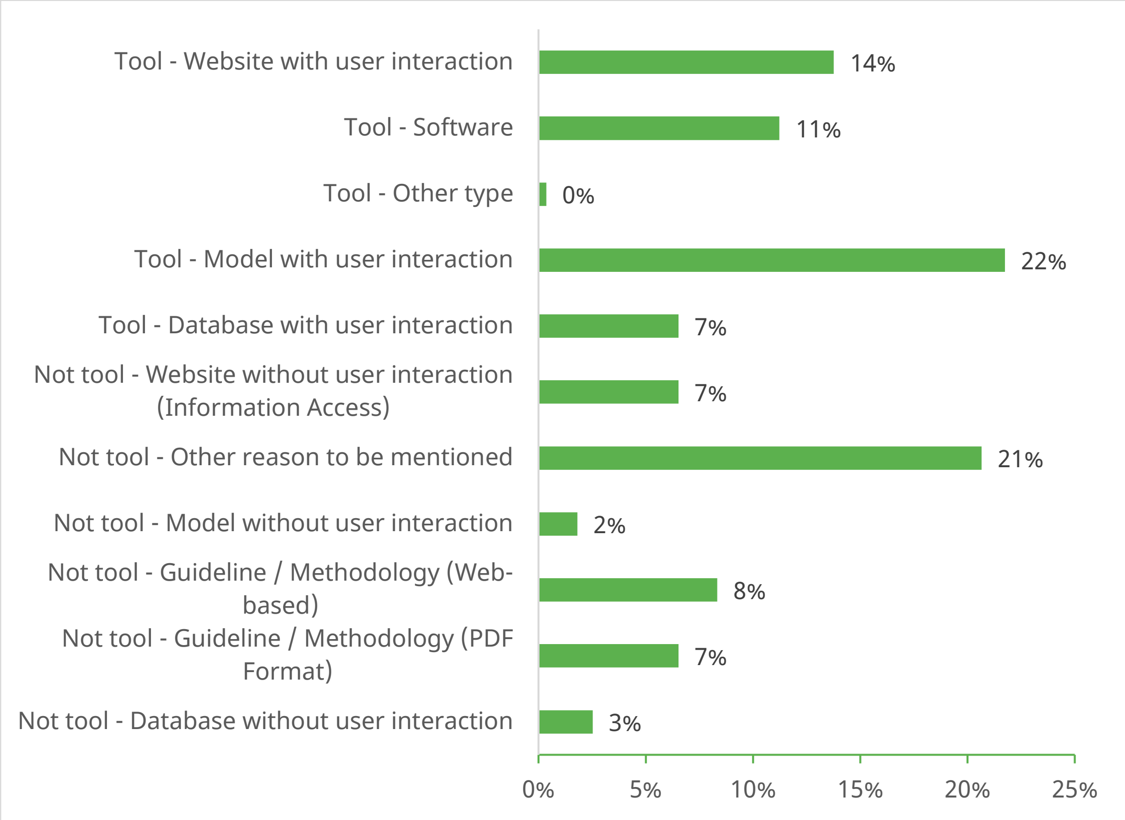

Figure 4. % of tools / Not tools for each classification

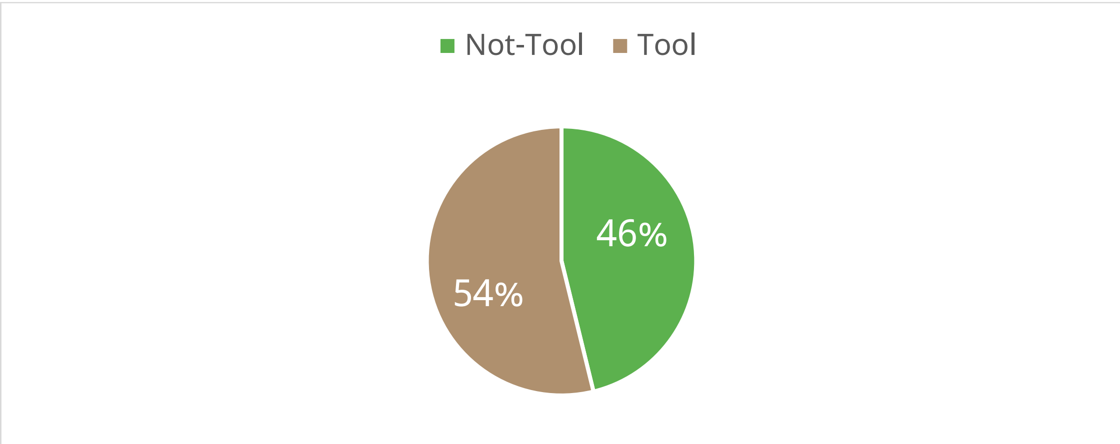

Figure 5. % of NBS and ES Tools / Not-Tools in the collected potential tools

As mentioned, the varying characteristics of the tools have led to some potential tools not fully aligning with the defined criteria ("tool definition"). Some are toolkits or projects funded by specific entities, such as:

Projects:

- The Global Forest Financing Facilitation Network

- Accounting for ecosystems and their services in the European Union
- Science for Evidence-based and Sustainable Decision about Natural Capital
- Integrated Science Assessments
- Bonn Challenge Commitments
- Climate Smart Planning Platform
- EcoMetrix
- Natural Assets Information System

Toolkits:

- Ecosystem Services Toolkit
- The Local Environment and Economic Development Toolkit
- Environmental Protection Agency Toolbox for Ecological Risk Assessors
- Caribbean Climate Change Tools
- Mapping Ocean Health Explorer
- Natural Capital Toolkit
- Natural Solutions Toolkit
- Free open-source solutions for forest and land monitoring
- Resource Watch
- Toolkit to Enhance Access to Adaptation Finance
- Ecosystem Valuation Toolkit
- Constant Flux Green Ampt (Infiltration Models)
- EPA ExpoBox (A Toolbox for Exposure Assessors)
- Green Infrastructure Wizard
- Green Infrastructure Modeling Toolkit
- Infiltration Models
- Sanitary Sewer Overflow Analysis and Planning Toolbox

Index (Indicator):

- Species Threat Abatement and Restoration
- Biodiversity Intactness Index
- Mean Species Abundance
- Potentially Disappeared
- Biodiversity Impact Metric

6.3.4. Survey on Mapping Assessment Tools for Nature-Positive Decision-Making:

6.3.4.1. Survey objective

The survey aims to map assessment tools for nature-positive decision-making. To do so, we survey the awareness of respondents against our list of assessment tools used for NBS and ES. The respondents are further asked to rate their knowledge and usage of each tool, with the opportunity to add new tools not previously listed.

6.3.4.2. Survey preparation

Aligning with the survey objective, a version of the survey was drafted using the KoBo toolbox for data collection. A workshop was prepared to present a draft version to the BIOFIN-EU consortium partners and get their suggestions. Also, the survey was further tested by the consortium partners through three questions to collect their feedback:

- How long did it take you to complete the survey?
- What suggestions do you have to improve this survey?
- To whom should we distribute the survey, and what are their contact details?

The insights and suggestions presented during the workshop and the responses received through the draft survey, were further matched against the feedback of a focus-group (5 respondents). The new version of the survey was issued and tested with the focus-group, before agreeing on the last version to be published.

6.3.4.3. Survey design

The survey consists of close-ended questions and a few open-ended questions to limit the responses range. It includes questions with multiple-selection and single-selection. As the survey was designed using the KoBo toolbox, the human mistakes in inserting the data were mitigated, reducing the need for extensive data cleaning. Moreover, some questions were mandatory to avoid missing the needed responses. From an “aesthetics” point of view, the project team ensured the display of the BIOFIN-EU project and the consortium entities logos in addition to the “Funded by the EU" banner with the full disclaimer: ***"Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.”***

The survey included the following sections:

Motivation section:

In this section, a motivation statement was included at the beginning of the survey to encourage participants to collaborate with the project team and show the importance of their contribution in achieving the project goals.

The motivation statement was:

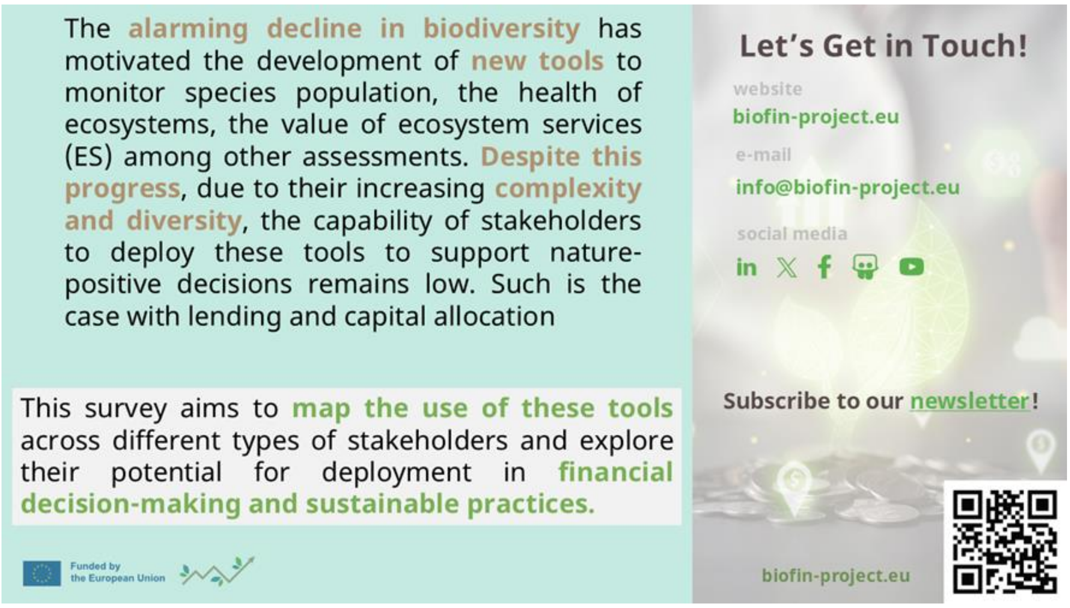

Figure 6. Motivation statement included in the survey first phase

The link to the project and invitation to subscribe to the newsletter were added under the motivation statement in the first page of the survey.

- **Introduction:**

In the introduction section, respondents will find a brief overview of the project's funding source and the survey's objective, which is to gather feedback on the tools used for NBS and ES, in alignment with the broader goals of the BIOFIN-EU project. Participation in the survey is voluntary, with the option to withdraw at any stage. The contact details of the researchers are provided to allow respondents to reach out with any concerns. The estimated time required to complete the survey is also stated. Additionally, the introduction confirms the anonymity of responses and includes information about privacy protection, data handling in compliance with GDPR, and the right to withhold personal information. It also outlines secure data storage procedures, specifying that all data will be stored on a server at Lusófona University for a limited time, accessible only to Lusófona University researchers involved in the BIOFIN project. The introduction further includes contact details for the Research Ethics Committee at Lusófona University, should respondents wish to consult an independent party. Respondents must read and acknowledge all information regarding the project, data protection, and privacy before proceeding, as participation is only possible with their consent.

- **Respondents' information:**

In this section, the respondents can voluntarily provide their name and email address. However, it is mandatory for the participant to choose their work country and add the name of their organization e.g. university / institute, research center, company, ...etc. Then, the respondent has to choose the type of organization from the following categories: Research and Academia, Government and Public Policy, Consulting Services, Civil society and NGO, Business and Industry, Standards Setting and Reporting, or other, in case the type is not mentioned in the provided list. The respondent provides also their role and department in the organization, e.g. Product Development, Sales and Business Development, Legal and Compliance, Project Management Office, ...etc. These questions are open-ended due to the variety of possible categories.

Additionally, the participants select their work sector from the following list, knowing that this question is multiple-selection, and the respondents have the option to add other options if not mentioned in the list:

- Agriculture and Farming
- Urban Planning and Development
- Healthcare and Public Health
- Water Management
- Forestry
- Fisheries and Aquatic Systems
- Climate Science and Meteorology
- Nature protection
- Infrastructure
- Retail
- Green Energy
- Traditional Energy
- Financing
- Other
- **Familiarity with the collected tools (Awareness):**

After addressing the definition of "NBS and ES assessment tool" in the beginning of the section, a list of tools was provided for the respondents to recognize them. They are invited to choose one or more of the mentioned tools that they are familiar with, or they have come across, even if only by name. Each tool is mentioned with its full name, acronym, and link to be accessible for the respondents to check, if needed. Additionally, respondents can add an unlimited number of tools that they think should be included in the list.

- **Knowledge of the collected tools:**

In this section, the respondents are asked to specify their level of knowledge regarding the tools that they have identified in the previous section from the list or the ones they may add to the list.

The section starts with an explanation of the tools' knowledge scale, which refers to the understanding and familiarity with a particular tool, including its features, functions, and applications. It involves understanding what the tool is intended to do and how it can be applied. This includes having general knowledge about its inputs, outputs, and processing methods. A six-point Likert scale is provided for each tool to rate the level of knowledge, as follows:

- **None** – I have only heard of this tool and know nothing about it.
- **Limited** – I know very little about its functions or uses.
- **Basic** – I am somewhat familiar with this tool but have limited understanding of its features and applications.
- **Moderate** – I have a general understanding of this tool and its primary functions, but not in-depth.
- **Considerable** – I have a good understanding of this tool, including its functions and applications, and can use it with some confidence.
- **Extensive** – I have a thorough understanding of this tool, including detailed features and advanced applications, and can use it proficiently.
- **Usage of the tool:**

The respondents are asked to define their level of usage for the tools that they have identified from the list and the ones they may have added to the list.

The section starts with the tool's usage scale definition, which refers to how frequently and in what capacity a particular tool is used. It refers to hands-on experience in academic or professional settings to achieve specific outcomes. For each tool, there is a six-point Likert scale to rate the level of usage, as follows:

- **Never –** I have never used this tool.
- **Rarely –** I have used this tool a few times.
- **Occasionally –** I use this tool occasionally, but not regularly.
- **Moderately –** I use this tool with moderate frequency, but not consistently.
- **Frequently –** I use this tool regularly and it is a common part of my work.
- **Extensively –** I use this tool very often and it is central to my work or projects.
- **Final section:**

The respondents can share their feedback related to the topic and the survey. Also, they give their consent to brief follow-up and further collaboration related to the project. This section concludes with a thank you message, the researcher's contact details, and an invitation to subscribe to the BIOFIN-EU newsletter.

6.4. Empirical analysis

6.4.1. Data collection

6.4.1.1. Research Sample

The target respondents of this survey are the experts and specialists in the fields related to NbS and ES, which encompass a broad range of fields such as environmental and economic science, engineering domains such as agriculture, civil, .etc. The research scope is global since most of the tools developed are intended for global use. As the target group size could not be defined, the sampling method was non-probability, using the purposive way to select the sample group, who are from a specific field of interest. Further, the snow-ball sampling was adopted as each respondent could send the survey to people that they know from their professional network. This approach led to a high number of survey recipients, as discussed previously.

6.4.1.2. Collecting Participant Contact Information

The participants were defined from the following:

- Consortium members and their contacts.
- Tool developers: The emails included in the collected tools websites, which are assigned to be contacted.
- Researchers from SCOPUS database:

SCOPUS database was used to search for the authors of the articles containing the following keywords (similar to those used considering a PEO framework during the review stage):

Environment / Nature-based AND solutions OR NBS / Ecosystem AND services / Climate AND change / Environmental / Watershed / Water AND management / Agriculture / Biodiversity / Ecological Wetlands / "Green infrastructure" / "Sustainable agriculture" / "Habitat fragmentation".

For each search result, the CSV file containing authors information (including their contact addresses) was exported. Since each CSV file is limited to a maximum of 20,000 rows, Python was used to compile all CSV files into a single Excel file. In the Excel file, the email addresses were extracted by removing all other content in each cell. Then, the duplicated emails were removed.

- Through social media and the BIOFIN-EU project platforms, Facebook, LinkedIn, X.

6.4.1.3. Survey Dissemination

In cooperation with the BIOFIN-EU project media specialists, an email -Appendix I- and the social media posts were prepared to be shared with the targeted respondents and through social media platforms.

The following links are to the posts on the BIOFIN-EU project social media platforms:

X/Twitter
LinkedIn
Facebook

The emails were sent using a local server email, which allows sending 2000 emails per day, then using the **Thunderbird application** to send the emails. One email was sent for each participant to ensure the email did not go to the spam folder of the receiver.

The final deadline for receiving the responses was on **20 Oct 2024**. While, on **14 Oct 2024, a** reminder -Appendix II- was sent to those who hadn't replied to the survey yet. The project team also reposted the posts on the BIOFIN-EU project social media platforms.

6.4.2. Data Analysis

The data cleaning was conducted on the XLSX file extracted from the KoBo toolbox, knowing that using KoBo with proper design, ensures less data cleaning requirements. The duplicated records were removed, which were 13. The final number of respondents was 737. The data analysis was conducted on an Excel file related to the respondents' information, the tools' awareness, the respondents' knowledge and their usage of tools. An in-depth analysis was conducted to link the knowledge and usage of the tools with the respondents' information.

6.4.2.1. General insights

Since the Scopus database provides access to a large number of researchers' emails, using it as a resource for gathering respondents resulted in approximately 88% of participants coming from academic and research organizations, such as universities and research centers. The remaining respondents represent a variety of other sectors. For instance, 4% of respondents work in government and public policy organizations, including ministries, the U.S. Environmental Protection Agency, and the G. B. Pant National Institute of Himalayan

Environment. Another 4% come from consulting services, including organizations like Trace & Save, the Association of Grapevine Growers of Palmela, Geotrilho Geosolutions, Etifor, and Stantec. Additionally, 3% of respondents represent civil society and NGOs, such as the Food and Agriculture Organization of the United Nations (FAO), Fisheries Conservation Foundation, and OceanCare. Other respondents are from business and industry, as well as standards-setting and reporting bodies. Respondents work in various departments related to the environment, biodiversity, climate, agriculture, forestry, fisheries, urban planning, water management, and more. Approximately 44% of respondents indicated that their work is focused on nature protection, while 33% reported working in agriculture and farming. The following figure illustrates the distribution of respondents by work sector:

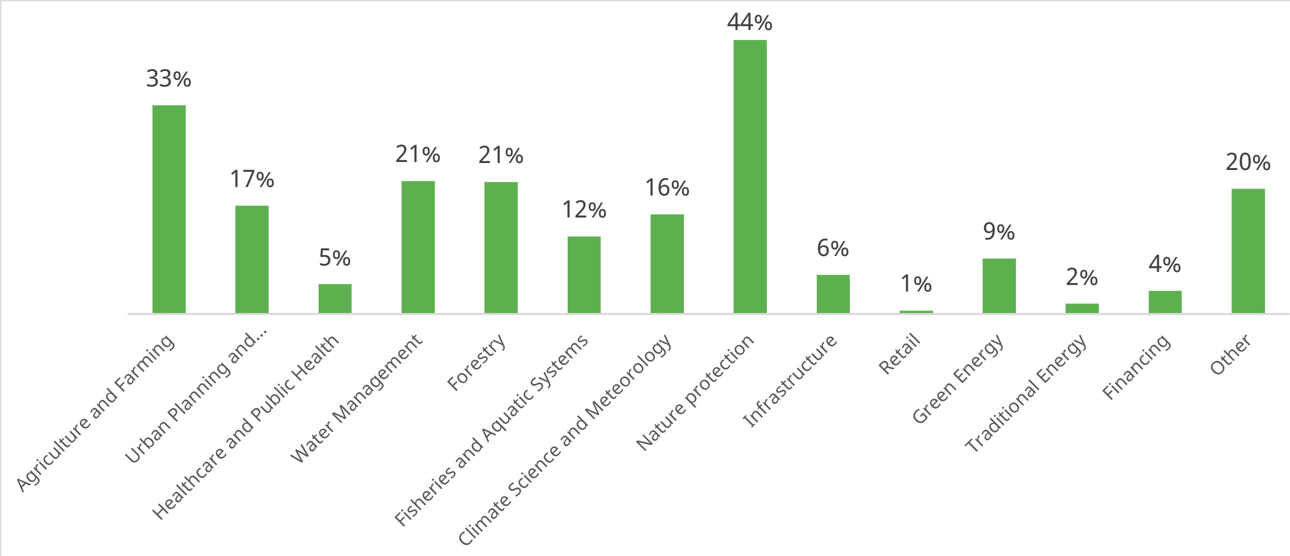

Figure 7. % Respondents according to their work sector

The respondents indicated their roles in their organizations, and 21% of them defined themselves as professors, 8% as PhD students or candidates, and 6% as post-doctorate students, while 38% of the respondents mentioned they are researchers / Senior researchers. Among respondents from organizations outside universities and research centers, 10% of the respondents were management staff, while only 2% were technical staff. The following chart shows those percentages in detail:

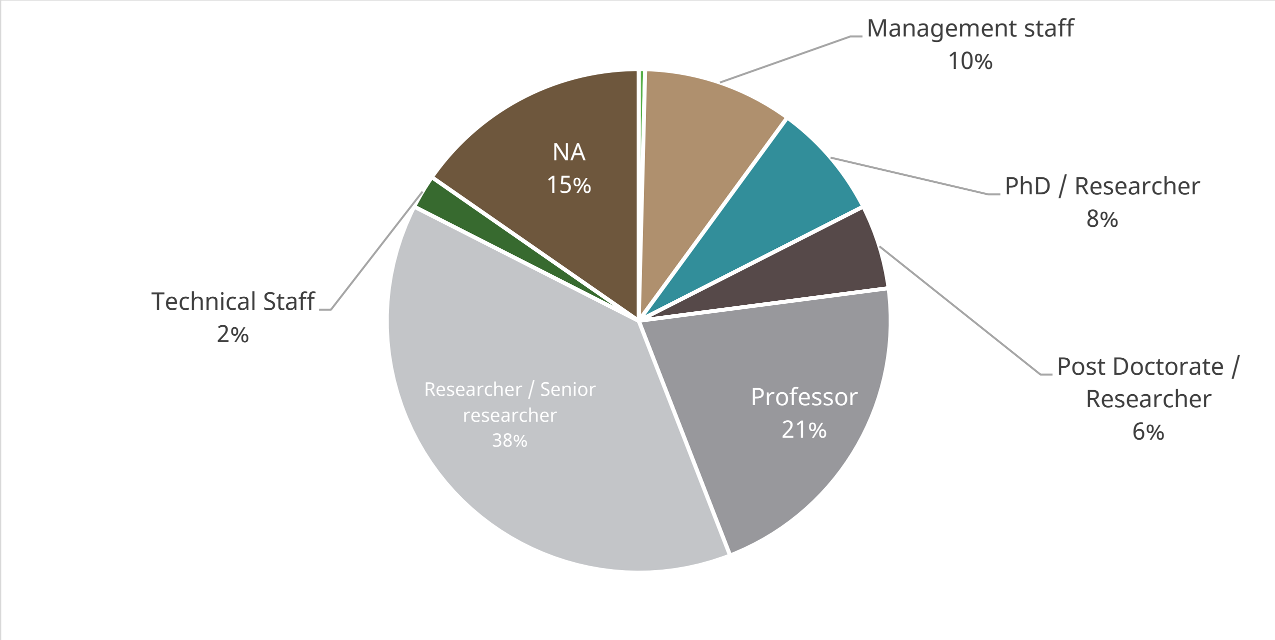

Figure 8. % Respondents according to the role in their organizations

There is a diversity of the respondents' country of work, as 89 countries were represented in the sample. In Italy, United Kingdom, and USA the percentage of respondents is 7% of the total, respectively, then Germany 6%, Portugal and Spain 5% each, and India, Canada and Ethiopia at 4% each. The respondents from the remaining countries contribute less than 3% each to the total.

The following map shows the percentage of respondents according to the population of each country (Source: https://worldpopulationreview.com/countries), with population measured per 100,000. Notably, Portugal has the highest percentage of respondents against their population, followed by Norway, Finland, Iceland, and Brunei Darussalam, while for the remaining countries, the percentage falls below 20%.

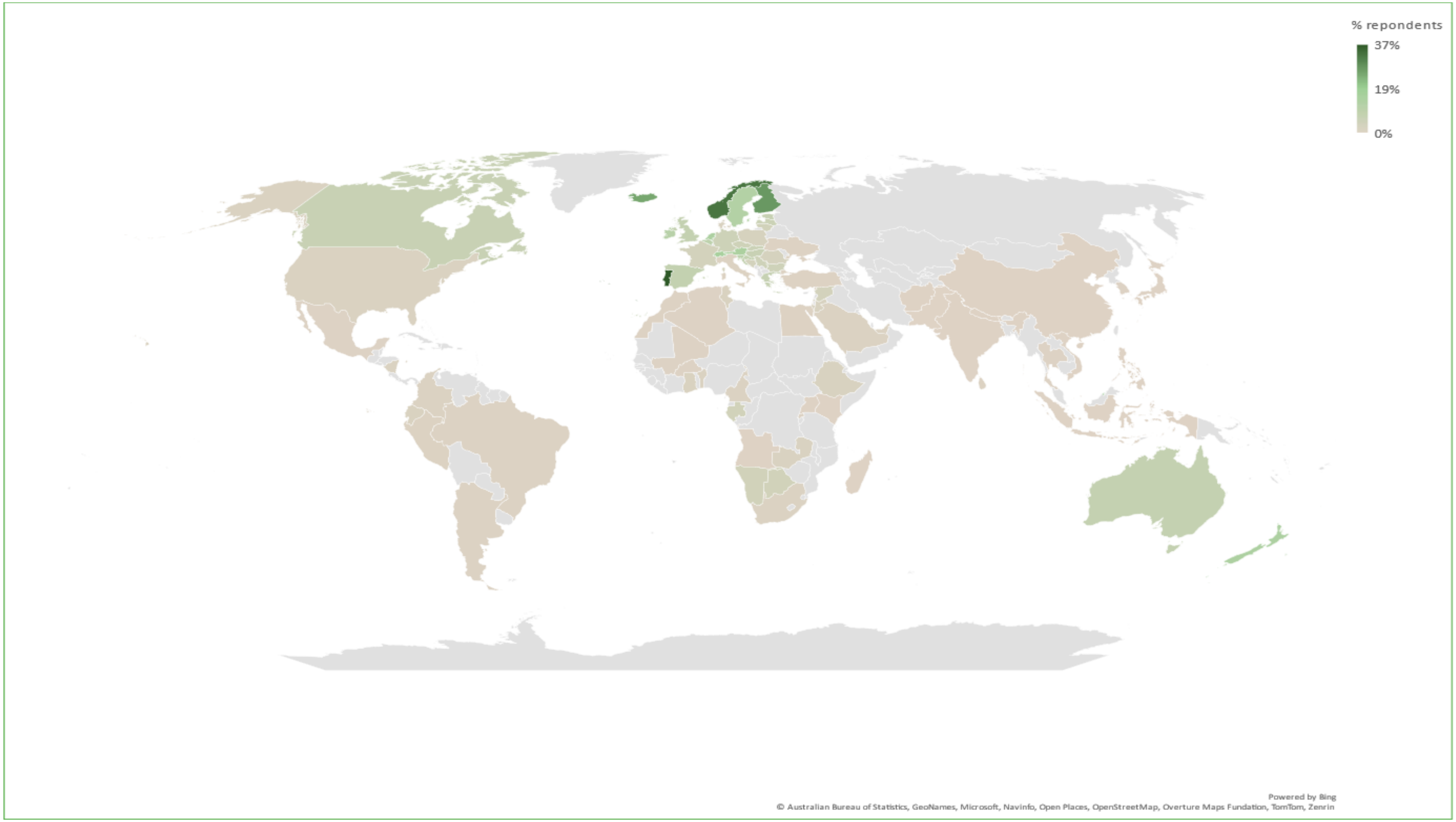

Figure 9. Map shows the distribution of the respondents according to their work count

From the represented regions' diversity point of view, as shown by the following chart, 56% of respondents are in Europe, while equal percentages (10%) of respondents work in Asia, Africa, and North America.

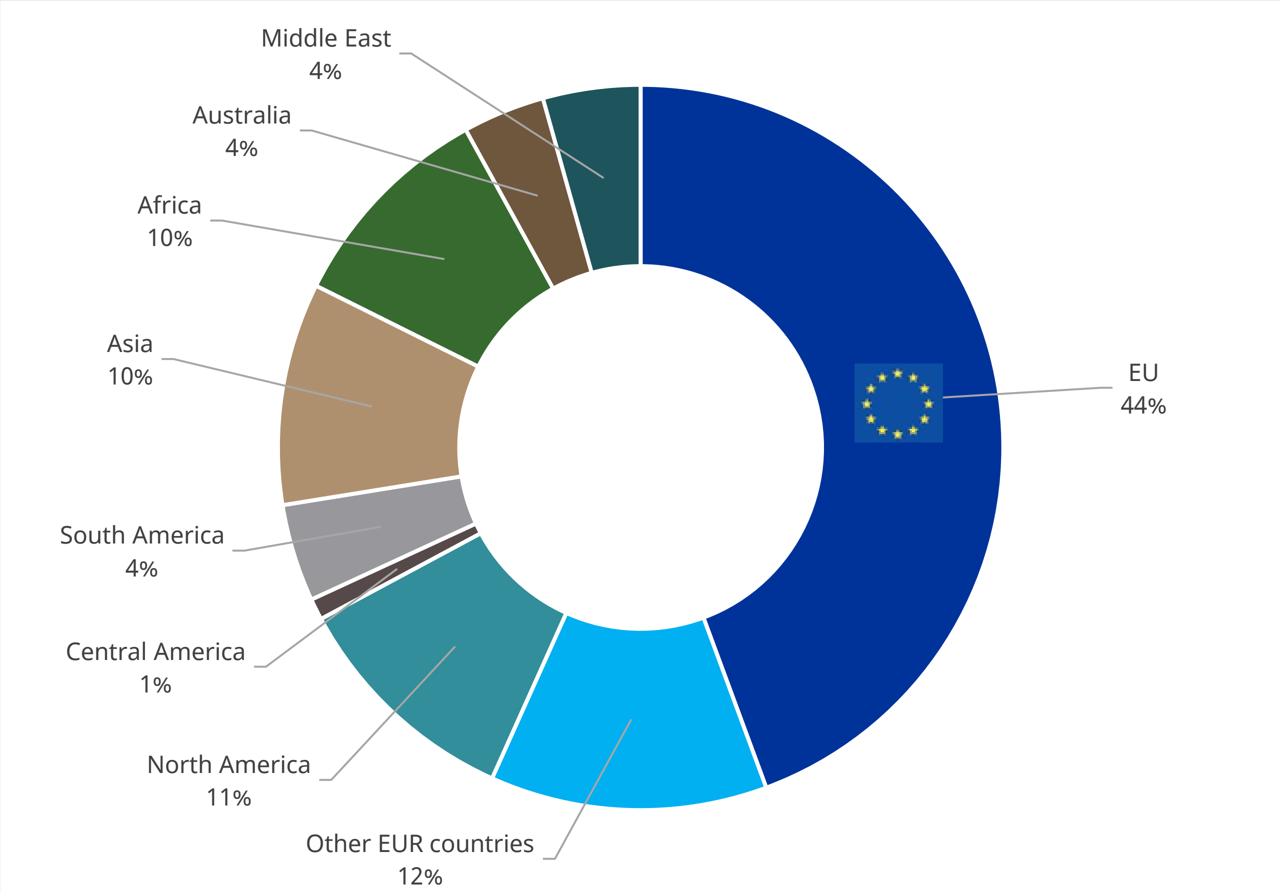

Figure 10. % Respondents according to their region of work

6.4.2.2. Tools' Awareness

The respondents checked the tools they were familiar with or came across even by name. The following chart displays for each tool, the percentage of respondents who are familiar with. Due to the large number of tools, only the ones that have awareness rates of 5% or higher are presented. As illustrated in the chart, IUCN tool is the tool that most respondents are aware of. InVest and FAOSTAT also have high awareness levels, with over 25% of respondents recognizing the tools. All other tools, starting from SWAT, indicate awareness percentages less than 18%.

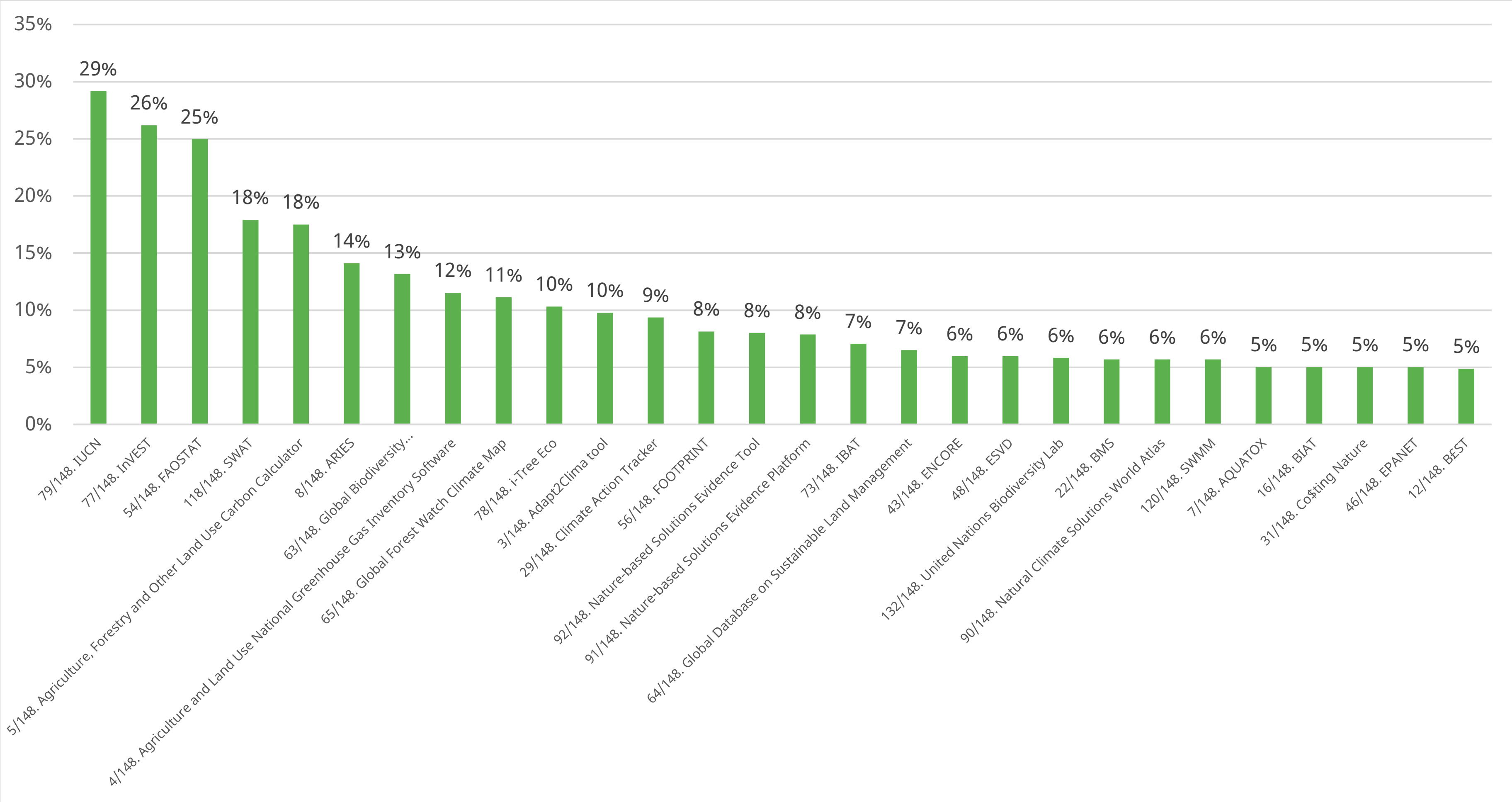

Figure 11. Percentage of respondents “aware of” the collected tools (included tools have awareness rates ⩾ 5%)

Out of 737 respondents, 99 contributed new tools to the list, resulting in the addition of 138 tools. The most mentioned tools were GBIF - Global Biodiversity Information Facility, ENVI-met and Arc-GIS, in addition to other tools as the following figure shows:

Table 5. Number of respondents who mentioned each of the new tools

New tools	N.
GBIF - Global Biodiversity Information Facility	5
ArcGis	4
ENVI-met	4
Biodiversity Net Gain Metric (UK gov)	3
Global Tree Knowledge Platform	2
MaxEnt	2
Nature Smart Cities Business Model	2
OpenLCA life cycle assessment tool	2
TAPE tool	2
Tree Globally Observed Environmental Ranges (TreeGOER)	2

Other tools mentioned by only one respondent are highlighted in **Appendix III.**

6.4.2.3. Tools' Level of Knowledge

The respondents have defined their level of knowledge, using the Likert scale, for each tool they are aware of. InVest has the highest number of respondents who indicated they have extensive knowledge of the tool. In contrast, FAOSTAT has the most respondents reporting they have a moderate and considerable knowledge. Although, the IUCN is the most recognized tool by the respondents, but a high percentage indicates a limited or basic knowledge of the tool. The following figure shows the percentage of respondents at each knowledge level, for each tool. **Note**: Only includes the tools recognized by 5% of the respondents or more.

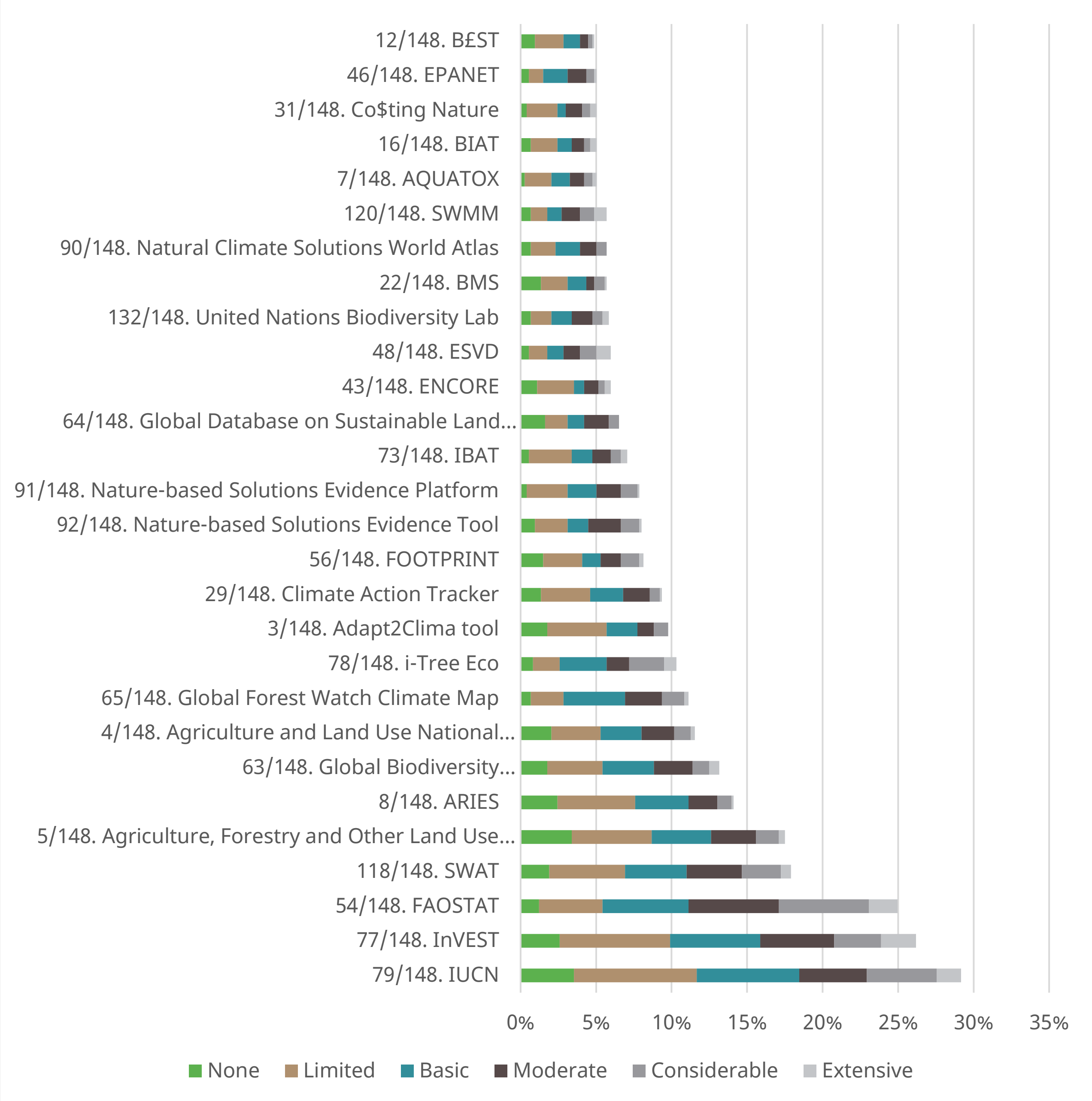

Figure 12. Respondents level of knowledge regarding each tool (included tools have awareness rates ⩾ 5%)

Analysed data considering all tools indicates that limited knowledge is reported for most of these tools, making it a central theme regarding the tools' knowledge. In contrast, fewer respondents have extensive knowledge, which appears to be the least common scale selected for the tools.

Considering the total number of respondents for each tool, it appears that 'Considerable knowledge' is the most frequently selected scale (on average 25%, in an intra tool analysis, each tool represents 100%), while 'Extensive knowledge' is the least selected (on average, 3%).

6.4.2.4. Tools' Level of Usage

Regarding the tools' usage, InVest has the highest number of respondents who reported extensive use, while FAOSTAT has the highest number of respondents with frequent, occasional, and moderately practical use. The figure below only includes the tools recognized by 5% of the respondents or more.

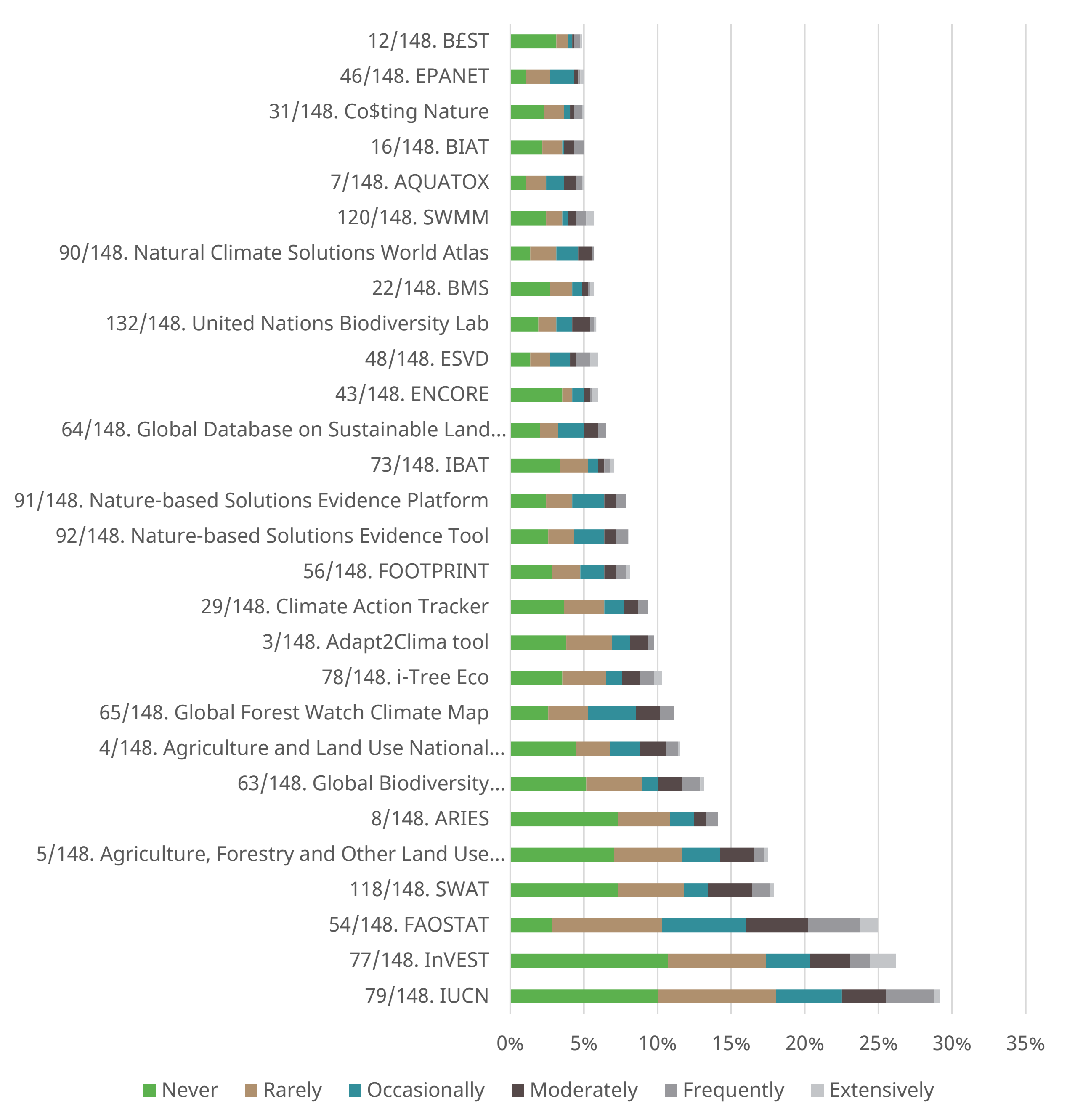

Figure 13. Respondents level of usage regarding each tool (included tools have awareness rates ⩾ 5%)

The data scanning of all tools indicates that poor usage is reported for most of these tools. While extensive usage has the lowest average percentage of respondents according to the total respondents.

Considering the total number of respondents for each tool, it appears that the scale of usage 'Never' is the most selected scale (on average 32%, in an intra tool analysis, each tool represents 100%), while 'Extensive usage' is the least selected (on average only 2%).

6.5. Key findings and planned activities

6.5.1. Key findings

The variety of assessment tools used for nature-based solutions and the ecosystem services, along with the different concepts related to the tool definition, makes it necessary to map these tools for more effective use. Thus, the research seeks to assess the tools and link them with the project work packages. In the first phase of the study, tools were collected from different resources, as the reviews, search engines, contributions from the BIOFIN consortium partners, in addition to the databases that present different types of tools. An Excel database was created to collect the tools' information in three sections: The primary details, tools workflow and processing, and the indicators matrix that links each tool with measurement indicators.

After compiling the full list of potential tools, a screening process was carried out to classify the tools into different types, excluding those deemed ‘non-tools’ based on predefined criteria (i.e., the "tool definition"). Initially, 275 tools were collected, but following the screening, 148 tools were retained. To involve stakeholders and gather practical insights regarding the tools, a two-phase survey was planned. The first phase presented the final list of tools to experts and specialists in fields relevant to the research topics. Respondents were asked to: identify the tools they were aware of; assess their level of knowledge on those tools; and indicate how frequently they used those tools. The survey was designed using the KoBo Toolbox for data collection, following an iterative process of testing/ incorporating feedback through workshops. The survey was distributed via email, using contact lists from the Scopus database, consortium partners contacts, and tool developers; and via BIOFIN social media platforms.

The number of respondents is 737. Most of the respondents are from academia and research field, but they work in different sectors, with high percentage of them working in nature protection, agriculture and farming sectors. 89 countries were represented by the respondents, most of them where from EU countries, as Italy. However, the percentage of respondents from UK and USA are also relevant.

IUCN, InVest and FAOSTAT were reported as being the tools most recognized by respondents (awareness). Regarding the level of knowledge, InVest has the highest number of respondents with an extensive knowledge, while FAOSTAT has the highest percentage of respondents with a moderate and considerable knowledge. Also, InVest has the highest percentage of respondents with an extensive usage, and FAOSTAT has the highest percentage with frequently, occasionally and moderately practical usage.

A total of 138 new tools were mentioned by 99 respondents. Global Biodiversity Information Facility (GBIF) is the most mentioned tool by the respondents.

6.5.2. Planned activities

aware of (according to their knowledge base and usage) and their specific information, such as their areas of specialization, the type of organizations they belong to, and the countries in which they work. This analysis will provide an overview of how tools are linked to each other and distributed across various sectors and regions, thereby supporting "tool development" decision making.

The survey conducted in this research represents the first phase of a study aimed at mapping the assessment tools used for NBS and ES. The second phase will focus on gathering further details about the most relevant tools (in terms of knowledge base and usage). Using the Excel database generated from this phase, primary information on the tools and the associated indicators matrix will be organized to assess and validate the tools. This research will provide a more comprehensive understanding of the most relevant tools, their effectiveness, and the possibilities for improvements shaping opportunities for tool development.

7. Overview of nature-based solutions impacts on ecosystem services

7.1. Overview

There is a growing set of evidence that NbS prove to be fundamental in the strategies for mitigation and adaptation to climate change, and conservation of biodiversity (CBD, 2022; Dodman et al., 2022; UNFCCC, 2022). NbS emerge as alternatives to the traditional engineering methods since these options incorporate methods that make use of natural processes and ecosystem services to tackle environmental challenges. With the increasing need for the global community to look for novel ways of trying to reduce negative anthropogenic and natural (e.g., climate change) impacts, while pursuing sustainable development, NbS have emerged as a promising approach. They represent a paradigm shift with the potential to redefine environmental management strategies.

NbS are an umbrella concept for a type of integrated landscape interventions that aim to achieve sustainable outcomes with co-benefits for both society and nature. The significance of NbS lies in the possibility of shielding ecosystem services that are under threat (Millennium Ecosystem Assessment, 2005). These services include a variety of benefits to society obtained from natural capital through ecosystem functions, such as clean air, water purification, carbon sequestration, and flood regulation (Cohen-Shacham et al., 2016; IUCN, 2020 a, b).

"Co-benefits" in this research were understood as the two categories (Miyatsuka & Zusman, n.d.). First, "development co-benefits" refers to the local benefits of climate change policies. Such as benefits that relate to improved air quality, to more sustainable technologies. Second, the "climate and weather co-impacts" refer to the multi-directional impacts of typical air pollution interventions on local, regional, and global climate systems. In the context of our research, however, the proposed meanings extend beyond climate change to incorporate all threats to the natural environment, including, but not limited to, climate change and biodiversity loss.

As an example, climate change linked to rising temperatures and weather extremes, has placed unprecedented strain on water resources globally, further exacerbated by human activities (Ochoa-Tocachi et al., 2019). The degradation and depletion of water resources are expected to have severe consequences for both human and environmental health (Oral et al., 2020; UNEP, 2019). Traditional infrastructure, such as dams and water treatment facilities, often fails to address these challenges, highlighting the need for more adaptable and sustainable solutions. The ongoing loss of wetland systems and riparian corridors significantly reduces groundwater recharge and exacerbates nutrient over flux, as vegetation and soil play a relevant role in water retention and contaminant uptake. These ecosystems act as natural sponges, absorbing rainfall and gradually releasing it into the groundwater, which helps reduce flooding, surface water drying, and improve water quality. Additionally, reforestation enhances soil stability, increases water infiltration rates, and improves the management of water resources. These nature-based interventions not only provide essential ecosystem services but also enhance social water security for communities, agriculture, and industry. By boosting ecosystem services and preserving biodiversity, they contribute for climate change mitigation and adaptation efforts (Spieles et al., 2022).

Further examples can be provided on the importance of implementing NbS in urban areas, where rapid population growth, infrastructure development, and economic activities exacerbate vulnerability to climate change. As a result, cities are increasingly turning to NbS to address challenges such as urban heat islands, flooding, and deterioration of air quality (Kabisch et al., 2017).

Despite the growing importance of NbS, the research landscape remains fragmented and multidisciplinary, which makes it challenging to establish a coherent framework that integrates the various aspects and quantifies their actual impacts.

The lack of consensus on terminology contributes to this fragmentation, even with the development of frameworks designed to clarify how to measure the multiple co-benefits of NbS, particularly in areas such as human health and climate change mitigation (Raymond et al., 2017; European Commission, 2021). However, it is also evident that standardised methods for quantifying the beneficial impact of NbS, not only at the environmental level, but also in the social and economic domains, have yet to be fully acknowledged.

The growing urgency to avert climate change and anthropogenic impacts, coupled with the recent commitments by international regulatory bodies, has intensified interest in the implementation of NbS. However, several gaps remain in the existing literature, particularly in quantifying the environmental, economic, and social impacts of these solutions, highlighting the need for a bibliometric analysis and systematic literature review. Our research addresses these issues, guided by the following research questions:

R1: What are the environmental, social, health, and financial impacts of NbS?

R2: Which methodologies are used to estimate the impacts of NbS?

R3: How is it possible to measure co-benefits related to ecosystem services with the support of NbS?

After this brief introduction, we will focus on the methodology employed, clarifying the various stages of research and the tools used. To conclude, we will highlight the preliminary results achieved.

After this brief introduction to the chapter, we will focus on the methodology employed, clarifying the various stages of research and the tools used. To conclude, we will highlight the preliminary results.

7.2. Methodology to map and explore the scientific landscape

To meet the goal of understanding actual gaps in the knowledge of NbS impacts on ES, we employed an integrated methodology, which involved the use of bibliometrics and a systematic literature review. This methodology provided a more complete analysis of the research progress, the evaluation of the environmental, social, health as well as economic impacts and an assessment of the evaluation methods used in these studies.

The present study followed the following steps, adapted from (Donthu et al., 2021)

- **Step 1** ✦ Define the aims and scope of the review study
- **Step 2** ✦ Collect the data for the review study
- **Step 3** ✦ Run the bibliometric analysis and report the findings
- **Step 4** ✦ Perform the systematic literature review to contextualize findings

7.2.1. Step 1: Define the aims and scope of the review study

The definition of the purpose and scope of the review analysis defines the size of the sample of documents to be taken into account and how to align research activities. In this case, the aim to understand and assess

NbS impacts on ES, and in which way it is possible to (e)valuate their impacts and to explore the topics over time, guided by the research questions defined in the previous section.

It is important to emphasise that during the process a Population-Exposure-Outcome (PEO) framework was used to brainstorm on the choice of keywords (i.e., including alternative concepts). This practise was necessary when it comes to unveiling the core features of research studies. It is also wise to acknowledge the identification of possible biases when keywords have been manipulated. This shortcoming is acknowledged, and it is believed that an exploratory analysis of this kind suffices and can provide meaningful pointers towards the guiding research questions.

In addition, the processes of bibliometric analysis and systematic literature review were well differentiated throughout the study. Since a bibliometric analysis is a mainly quantitative analysis, we aimed at the identification of trends and patterns in the scientific field (Passas, 2024; Wang & Su, 2020). In contrast, the systematic literature review was developed to understand the state-of-the-art and the main gaps of the topic (Carrera-Rivera et al., 2022).

The research was conducted using the main search string "Nature Based Solution*+ “impact* valuat*” + “servic*" (the asterisk in the search string was used as a wildcard to capture variations of that term, for instance “valuations”) in the Scopus database.

7.2.2. Step 2: Collect the data for review analysis

The scientific database used was Scopus, as it is the world's most comprehensive abstract and citation database for peer-reviewed academic literature (Cantú-Ortiz, 2017). This selection ensured the sample's robustness and representativeness of the current scientific landscape.

Filters were applied to include only English-language scientific articles published between 2016 and 2024, to cover a significant period and to include the most recent research. The selection of English-language documents sourced at scientific journals and books was made to ensure the consistency of the sample. A further screening over the title, abstracts, and keywords was performed to guarantee accuracy. The focus was on articles that addressed the use of NbS, their benefits in different areas (health, environmental and social), and methods for assessing their impact.

All articles that could not be traced back to impacts of NbS on ecosystem systems were excluded. Examples of included documents are those concerning case studies that were aimed at measuring the benefits of NbS on improving the thermal regime in cities avoiding heat island’s phenomena (e.g Biasin et al., 2023). Documents that provided examples of frameworks that could be used to quantify impacts were also included. The total number of documents was 163.

7.2.3. Step 3: Run the bibliometric analysis and report the findings

A bibliometric analysis provides researchers with a deeper comprehension of a field's dynamics, its key players, and the relationships between key concepts or themes. Bibliometric analysis uses two key techniques to explore scientific landscapes: 1. performance analysis; and 2. science mapping. These methods offer distinct yet complementary perspectives on the field.

Performance analysis (quantifying contributions) delves into the contributions of individual research entities, such as authors, institutions, countries, and journals, within a specific field (Cobo et al., 2011; Ramos-Rodríguez & Ruíz-Navarro, 2004). This descriptive approach forms the backbone of many bibliometric studies (Donthu et al., 2020). Performance analysis is routinely employed in literature reviews, even those not utilizing science mapping. It's akin to the background section in empirical research, painting a picture of the field's participants and their performance (e.g., publication outputs). However, performance analysis takes a more analytical approach than a simple profile.

Science mapping (unveiling relationships), on the other hand, focuses on the intricate relationships between research constituents (Baker et al., 2021; Cobo et al., 2011; Ramos-Rodríguez & Ruíz-Navarro, 2004). This analysis delves into the intellectual interactions and structural connections among research elements. Techniques like citation analysis, co-citation analysis, bibliographic coupling, co-word analysis, and co-authorship analysis are employed in science mapping. When combined with network analysis, these techniques become powerful tools for visualizing the field's bibliometric and intellectual structure (Baker et al., 2020; Tunger & Eulerich, 2018).

To run the bibliometric analysis, performance analysis and science mapping are conducted to map and highlight the impacts of NbS and visualize possible trends. The software used was R with Bibliometrix's package through its biblioshiny user interface (Aria & Cuccurullo, 2017) and VOS viewer (Van Eck & Waltman, 2007).

The bibliometric analysis was conducted using the following metrics: annual scientific production, most relevant words, and the most cited articles. By examining annual scientific production, the analysis provides insights into how the interest in NbS impacts has evolved. This temporal aspect provides insights into whether the interest in the topic is growing or declining.

Analysing the most relevant keywords found in the literature helps identify the predominant themes and areas of interest in impacts of NBS on ecosystem services. It also defines what are the emerging areas of interest. This, in turn, allows for a revelation of the themes and areas that dominate NbS impacts research in literature through an analysis of most relevant words. In addition, these allow the definition of emerging areas.

On the other hand, it is relevant to include highly cited articles that might provide a view of those studies making the most impact in this area. Highly cited works are usually seminally leading the ground of research, influencing policy decisions, or developing best practices within a scientific field.

7.2.4. Step 4: Literature Review

To get a more complete idea of the state of the art of knowledge regarding the issue of NbS impacts on ecosystem services and their quantification, it was decided to undertake a systematic literature review.

There are different varieties of literature reviews, and the type of review to be conducted depends on the objective of the review. The two most widely used types of literature reviews are the "traditional" or narrative review and the systematic review. Traditional reviews, or even conventional or non-systematic reviews, are generally faster and easier to conduct and are sometimes needed due to lack of time or data.

In the case of our study, a systematic literature review was chosen, thus defining clear research questions to be answered (Booth et al., 2016). We made this choice because the landscape of NbS design, evaluation, implementation, and monitoring in the literature is vast and we wanted to focus on the role that NbS have through their impact on ecosystem services.

The literature review coincides with a well-delineated approach to identify any gaps in current knowledge, summarize existing findings, and provide insights for future research directions. It also sizes the importance of a research problem and positions the new work within the broader academic landscape (Booth et al., 2016; Snyder, 2019).

A systematic review is critical in reducing the biases one may make in one's research and can guide the theoretical and practical development of the object of study (Kitchenham, n.d.; Tranfield et al., 2003).

Subsequently, we ordered all documents by their yearly average citations, and, through a predetermined cutoff, 30 documents were selected and assessed to provide a clearer distinction among the articles. To differentiate them and gain an understanding of the indicators and methodologies employed in this field, the articles were categorized specifically based on the methodologies applied.

7.3. Preliminary results and planned activities

Our preliminary findings shed light on the growing interest in NbS impacts research, highlighting key trends and laying the groundwork for further exploration.

The bibliometric analysis provided quantitative insights into the research landscape on NbS and their impacts on ES. Key findings include trends in research outputs, where since 2016, publications related to NbS have risen, peaking in 2021. A significant decline followed in 2022 and 2024. This decline may reflect shifts in priorities following the adoption of international definitions, such as the United Nations Environment Assembly resolutions in March 2022, which may have redirected research efforts (e.g., United Nations Environment Assembly, 2022). The bibliometric analysis highlighted "climate change" as the central theme. Other frequent keywords included "biodiversity", "urban development", and "public health", showcasing the multidisciplinary focus of research (Aronson et al., 2016). In terms of geographic trends, the USA, Italy, the UK, Germany, and China emerged as leaders in academic output and coverage of NbS impact research, especially in urban and aquatic ecosystems. This aligns with findings by Seddon et al. (2020), who identified similar patterns. Influential contributors such as Anderson V., Golich W.A., and Kumar P. have significantly shaped the field, covering diverse topics like climate change adaptation, sustainable urban planning, and ecosystem restoration.

The literature review offered a qualitative synthesis of how NbS enhance ecosystem services, addressing various domains. The documents reviewed highlight cases where NbS improve regulating services (e.g., flood mitigation, air quality), provisioning services (e.g., clean water, food), and cultural services (e.g., mental well-being). For example, wetlands reducing urban flood risks, and green roofs mitigating heat islands (Kabisch et al., 2017; Cohen-Shacham et al., 2019). Further examples of case studies include the Spercheios River Basin in Greece, where NbS reduced flood areas and enhanced groundwater recharge (Papadaskalopoulou et al., 2023). Key challenges include benefit valuation, governance issues, spatial constraints, and insufficient integration into municipal planning frameworks. Public awareness also hinders broader adoption (Frantzeskaki et al., 2019). As main knowledge gaps, standardized assessment methods for NbS impacts remain underdeveloped, limiting cross-comparability. Even frameworks rooted in the field of Ecological Economics, often overlook the Non-Use benefits of the natural environment and NbS. This omission neglects key aspects such as species preservation, and unique environmental features beyond ecosystem services. Incorporating Non-Use benefits, which primarily constitute non-market public goods, complicates the development of business models and funding mechanisms for NbS but is essential for comprehensive valuation. Furthermore, research is disproportionately concentrated in developed economies, leaving significant gaps in applications for the developing economies (Seddon et al., 2020).

To build on the preliminary findings and complete the full review, the next steps will focus on deepening the analysis and making the insights more actionable. One of the first steps will be focused on mapping research trends by assessing keyword clusters to identify emerging themes, such as the role of NbS in addressing climate resilience, urban health, and biodiversity loss. This will help reveal how research priorities have evolved over time. Next, we will incorporate diverse examples of NbS applications, from flood control in urban areas to biodiversity conservation in rural settings, highlighting successes and challenges in different contexts. Exploring the social dimensions of NbS, particularly their impact on public health and community engagement, appears to be a promising area for further investigation.

8. Concluding remarks

In conclusion, this report highlights the importance of Nature-based solutions (NbS) in preserving biodiversity and providing valuable ecosystem services. By leveraging the natural capabilities of ecosystems, NbS offers a potentially sustainable and cost-effective approach to address environmental challenges. One significant barrier to recognizing nature-based solutions (NbS) as a key tool for addressing biodiversity loss is the limited evidence regarding their effectiveness and knowledge of its economic value (Bockarjova et al., 2022). The complexity, various sources of values, and scale across space and time of NbS means many challenges. Numerous methods are available to assess the non-market values of nature-based solutions (NbS). We provide a comprehensive overview of these methods and critically examine the challenges associated with applying them to estimate the benefits of NbS. The various methods discussed for valuing biodiversity, including Revealed Preferences, Stated Preferences, and the Production Function method, provide a comprehensive framework for understanding the multifaceted benefits of NbS.

Many ecosystem services NbS provides have non-market values not captured by traditional market-based valuation methods. This includes cultural, spiritual, and existence values. Although direct use values often are of primary concern, there is a clear risk of disregarding non-use values. Interestingly, there is very little focus in the valuation literature on the broader picture. Although risks might be small, there is still a non-negligible risk of catastrophic outcomes for various ecosystems and for humans. The focus on individual studies of individual NbS or ecosystem services, means a risk of ignoring such outcomes. Moreover, there is a need for comprehensive frameworks that integrate various valuation methods to capture the full range of benefits provided by NbS. When comparing biodiversity loss to other major global challenges, such as climate change, the scientific community has established clearer links between emissions levels, global warming, and their impacts on human welfare, often measured by Gross Domestic Product (GDP). This clarity enables the assessment of welfare effects across various business scenarios, differing in their mitigation ambitions, over time. In contrast, a similarly rigorous framework for biodiversity is yet to be developed. This poses a significant challenge, as biodiversity loss cannot be addressed through a single, dominant mechanism like reducing global CO_2 emissions. Moreover, research on biodiversity often lacks a strong focus on effectively integrating the economic valuation of nature-based solutions (NbS) into policymaking and investment decisions. Such integration is essential to fully realize and protect the wide-ranging benefits that NbS offers. At the same time, NbS is no silver bullet, and in particular, the effects of NbS can critically depend on what other policies are in place.

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Appendix I - Email used to disseminate the survey (1st phase)

BIOFIN-EU

Flip the script:
Unlock finance
to protect & restore biodiversity

Greetings!

We are conducting a survey as part of the BIOFIN-EU **project,** an initiative dedicated to unlocking financial solutions for the protection and restoration of biodiversity.

We would like to invite you to participate in this **survey**, as we believe your expertise in **nature-based solutions (NBS)** and **ecosystem services (ES)** assessment tools would greatly contribute to our research.

The survey aims to explore your familiarity with and active use of the tools we have collected (*you may add your own*). Your input will help us understand how knowledge and usage of these tools are distributed across different sectors.

The survey will take approximately **15 minutes** to complete, and we would greatly appreciate your participation.

You can access and complete the survey using the following link: **https://ee-eu.kobotoolbox.org/x/rRSJ4LeY**

Please note that the survey will remain open until **October 22**.

We would also appreciate it if you could kindly share this survey with colleagues or other professionals who may be interested, to help us reach a broader audience of relevant experts.

Should you have any questions, please feel free to reach out to us. If you prefer not to receive future emails, simply let us know.

Thank you in advance for your valuable time and contribution.

With kind regards,

Mr. Hummam Shaheen *Email:* *Hummam.shaheen@ulusofona.pt*
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Appendix II - Email reminder used for the survey (1st phase)

Flip the script:
Unlock finance
to protect & restore biodiversity

Greetings again!

We would like to remind you about the opportunity to participate in our ongoing survey, that is being conducted as part of the **BIOFIN-EU project,** an initiative dedicated to unlocking financial solutions for the protection and restoration of biodiversity.

We would like to invite you again to participate in this **survey**, as we believe your expertise in **nature-based solutions (NBS)** and **ecosystem services (ES)** assessment tools would greatly contribute to our research.

The survey aims to explore your familiarity with and active use of the tools we have collected (*you may add your own*). Your input will help us understand how knowledge and usage of these tools are distributed across different sectors.

If you haven't had the chance to complete the survey yet, it will take approximately **15 minutes** to complete, and we would greatly appreciate your participation.

You can access and complete the survey using the following **link**: **https://ee-eu.kobotoolbox.org/x/rRSJ4LeY**

To ensure your participation, the survey opening deadline has been extended until **October 18**.

We would also appreciate it if you could kindly share this survey with colleagues or other professionals who may be interested, to help us reach a broader audience of relevant experts.

Should you have any questions, please feel free to reach out to us. If you prefer not to receive future emails, simply let us know.

Thank you in advance for your valuable time and contribution.

With kind regards,

Mr. Hummam Shaheen *Email: Hummam.shaheen@ulusofona.pt*
Dr. Francisco Silva Pinto *Email: francisco.pinto@ulusofona.pt*
Lusófona University
RCM2+ ***Research Centre for Asset Management and Systems Engineering***

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Appendix III

New tools that were mentioned by only one respondent (in alphabetical order):

New tools (A… H)	New tools (H… Z)
Adaptation pathways	HATCH
Adaptation, Biodiversity and Carbon Mapping Tool (ABC-Map)	Healthy Farm Index
Agricultural Policy/Environmental eXtender (APEX)	HEC GEO-HMS
Agroforestry Species Switchboard	HEC-HMS
AMDTreat acid mine drainage treatment cost assessment tool	HEC-RAS
BA-BK-FW model	Map biomas
Barcode of Life Datasystem (BOLD)	Climate positive design
benMAP-CE (US Environmental Protection Agency)	freshwaterecology
BioBaM-GHG	maes-explorer
Biofarming	IDEA4
Biogases and biofertiliser	INATURALIST
Bioinspire-Explore	InVEST
BiOMIg Search	IPCC software
Blue Economy Valuation Toolkit	IQAir Global AQI Map
CAP2'ER	IUCN Red List of Ecosystems
Carbon Pricing Incidence Calculator	JULES the Joint UK Land Environment Simulator
CLIMADA	Labos1point5
Climate explorer	LaRiMiT - Landslide Risk Mitigation Toolbox
Climate literature hub	Life Cycle Assessment (LCA)
Climate Policy Radar	LISFLOOD,3 DIFFERENT RAINFALL RUNOF models
Climate Resilient City Toolbox	Maptionnaire
Climatescan	MonitorEO (Monitoring Essential Biodiversity Variables through Earth Observation)
ClimateSERV	Naturally Resilient Communities
COBRA (U.S. Environmental Protection Agency)	Nature Metrics
Community Capitals Framework	NATURE tool 2.0
DayCent model	Nature-Based Solutions Climate Risk Assessment
Design Builder	NBN Atlas
DICE	NBSAP Forum Resources
DSSAT, Python, ArcGIS	NDC Expert Tool (NEXT)
EASETECH	OpenBioMaps
Ecodesign PILOT	Oppla
Ecoinvent Database	PHREEQC3 aqueous speciation modeling tool
ECOMETABOLOMICS	Python software
Economic Input-Output Life Cycle Assessment tool from Carnegie Mellon University	Qualitative Research
ECOPATH	RAPFISH
ECOSIM	Rapid Assessment of Wetland Ecosystem Services
EDEN (Ecological Discrete Event Networks)	Rayman
EFDC+	RBCA Risk Based Corrective Action
En-ROADS Climate Interactive	ROMS

New tools (A… H)	New tools (H… Z)
ENVIMAT	SAP
EPA CO2 equivalencies calculator	Scan Ecosystem Services
EPIC	Scientific Animations Without Borders
EX-ACT	SCIMAP Diffuse Pollution and Flood Water Source Mapping
Explore (Health, Wellbeing, Nature and Sustainability (HWNS))	Sefaira
Fair Supply's Supply Chain assessment platform - Biodiversity module (also their Emissions and Modern Slavery modules)	SimpleBox
FAO Family Farming Knowledge Platform	SimpleBox4Nano
FAO- GWIES Early warning system	SimpleTreat
FAO-RICCAR Portal	simulsoil
FAO-WaPOR Portal	Society for Ecological Restoration Resources Database
Farmland Ecosystem Assessment Support Tool (FEAST)	SPSS
FishPath Tool	STEER Diagnostic Water Governance Tool
ForSys	TEIEF
FREEWAT	TESSA
Gabi	The Economics of Ecosystems and Biodiversity (TEEB)
Global Biodiversity Standard	The Global Biodiversity Standard
Global Ecosystem Typology	The Resources for Tree Planting Platform
Global-detector	TICI
GlobalUsefulNativeTrees	Umberto
GLOBIO	Urban nature atlas
GlobUNT	Urban Nature Explorer
Grasshopper (Ladybug, Dragonfly etc)	Urban Nature Navigator
GrassPlot Diversity Explorer	VerifAId Transparency
GwPRS - Green Wall Perceived Restorativeness Scale	Wayfinder
half-earth project	WiM-Med