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Using ecosystem services to measure the degree to which a solution is nature-based

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ABSTRACT

There has been a recent surge of interest in Nature-based Solutions, a concept encompassing a broad suite of ideas that have arisen from the intersection of ecology, engineering, sociology and economics. Solutions founded in nature are promised to resolve many issues resulting from global change, including reducing flood risk and air pollution, building social cohesion and enhancing resilience. However, what a Nature-based Solution means in practice remains unstructured and vaguely defined. Specifically, what is meant by Nature-based is not well defined and there has been little effort to rigorously understand how a solution is created. In response, we propose an integrated conceptual framework, extending the service-benefit relationship to include solutions, while acknowledging that multiple types of service exist (ecosystem services, technological services and labour). We present a method to measure the degree to which a solution is Nature-based: calculate the relative contribution of ecosystem services, compared with technological services and labour. The method and framework are applied to projects dealing with problems related to water pollution, demonstrating their applicability. The framework can be a useful tool to guide environmental managers in identifying both the scale and context at which, and the problems to which, Nature-based Solutions are applicable.

1. Introduction

Nature-based Solutions (NbS[1]) are emerging as an influential idea. NbS promote nature as a means of providing solutions to societal challenges, while contributing to the sustainable management of the natural environment (Eggermont et al., 2015; Keestra et al., 2018). European policy makers have funded €240 million worth of research, innovation & action on NbS (CBD, 2018), in the hope of using the ecosystem services concept to align biodiversity conservation, mitigation and adaptation to climate change and job creation (Maes and Jacobs, 2015). The International Union for the Conservation of Nature (IUCN) has positioned itself as a leader in NbS setting out the principles that should guide the development of the concept (Cohen-Shacham et al., 2016, 2019). Interest from private industry is building: the giant oil company Shell invested $200 million in NbS (Shell, 2019), Amazon's Right Now Climate Fund of $100 million focuses on conserving and restoring forests, wetlands and peatlands for carbon storage (Amazon, 2021), while Apple's Carbon Solutions Fund targets savannahs in Kenya and mangroves in Columbia for protection and restoration (Apple, 2020). Indeed, the NbS concept has already diversified, with nature-based infrastructure (US Army Corps of Engineers, 2013), nature-based enterprises (Kooijman et al., 2021), and nature-based innovation (van der Jagt et al., 2020) appearing in the literature.

NbS explicitly incorporate ecological and social concern, including social equity, governance, and biodiversity conservation (Eggermont et al., 2015; Cohen-Shacham et al., 2016). The strength of the NbS concept is this integrative, people and nature approach to problem solving, preventing it from becoming a justification for the conventional model of natural resource exploitation (Nesshöver et al., 2017). A current limitation is identifying when, and measuring to what degree, a solution is Nature-based. The IUCN, in acknowledgement of the difficulty in identifying NbS, developed a global standard that established best practice norms, management guidelines and governance structures (IUCN, 2020). Eight criteria have been established to be self-assessed using a traffic light system (strong, adequate, weak, insufficient), where a project scoring an 'insufficient' rating on any criterion fails to meet the standard of a NbS. The IUCN criteria are useful for understanding what type of project would qualify as a NbS and will be useful

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[1] Please refer to the glossary for a note on the useage of this abbreviation throughout.

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in planning and designing: NbS must be socially inclusive, economically viable and benefit biodiversity. However, the IUCN leave two central aspects of NbS undefined: what is meant by 'Nature-based', with ongoing debate as to what this means (Nesshöver et al., 2017, see Table S1 for varied definitions of NbS), and what is meant by 'Solution', with no method that can be applied on a project by project basis to identify when a solution is achieved. At an aspirational level, NbS seek to create novel ecotechnologies and management practices organised in business models that sustainably capture and deliver value, offering a path to sustainable socio-economic development (Maes and Jacobs, 2015). The urgent need for sustainable development requires the development, testing and subsequent scaling of NbS that successfully address interrelated climate, biodiversity, and development targets. The research community will play a central role in developing and testing NbS, and thus need a framework to measure the degree to which a solution is nature-based. The scaling of solutions that are not in fact nature-based, or indeed the reverse, the scaling of nature-based projects that are not solutions, would represent a failure of the research community to meet the urgent challenge of sustainable development (Seddon et al., 2020).

Our objective is to resolve two issues: how to measure 'Nature-based' and how to agree a 'Solution' has been achieved. The degree to which a solution is Nature-based can be measured by the contribution of ecosystem services (here, we choose to use ecosystem services to describe 'those aspects of nature that contribute benefit to society' but the method to identify and measure NbS is agnostic to how nature's benefit is conceptualised: e.g. the more relational Nature's Contributions to People (Díaz et al., 2015). Solutions are created when a project creates enough benefit to resolve an identified problem. By connecting solutions and ecosystem services through the benefit-production chain we link the concept of solution with a metric to measure Nature-based, allowing solutions to be measured in terms of how Nature-based they are. A NbS can be identified when ecosystem services, the benefits supplied by nature, contribute the majority of service input. Finally, we demonstrate the utility of this framework using a case study and identify an NbS to water pollution. We conclude that the proposed framework improves our understanding of the relationship between ecosystem services, benefits and solutions.

2. A Framework to Identify Nature-based Solutions

To identify an NbS, we must define 1) what we mean by Nature-based and 2) what we mean by solution?

2.1. Defining and measuring Nature-based

Attempting to define the term Nature-based leads to a discussion on what is natural versus anthropogenic, a discussion which has a rich history, and is especially important in the context of NbS where the question is central to the aim of the discipline. Indeed, an early paper on NbS describes a typology of Type 1, Type 2 and Type 3, where NbS are categorised according to how much engineering of ecosystems is involved (Eggermont et al., 2015), suggesting some NbS are more natural than others. The typology is useful to identify the scale and context of a NbS, essential for properly understanding what is involved in a given project. This framework does not advance our understanding of what we mean by Nature-based, it rather provides broad categories to fit NbS into, describing them phenomenologically. What is needed is a universal understanding of what we mean when we say 'Nature-based'.

2.1.1. Nature vs Nature-based vs Anthropogenic

Nature, and that which is 'natural', is typically dichotomously juxtaposed to modern society, and that which is anthropogenic. Importantly however, 'nature' need not be defined in order to understand 'Nature-based', particularly given the context of delivering solutions. Defining 'nature' or what is and what is not 'natural' is not the goal of this paper. Rather, we seek to understand 'Nature-based', and it is essential to note that NbS are inherently anthropocentric; we are solving problems for society. Even in the case where biodiversity loss is the challenge to solve, it is society who has decided it is a problem in the first place. NbS are also utilitarian: we are interested in the use value of nature and are asking questions about how useful nature would be in solving various societal challenges. The anthropocentric utilitarian context of solving problems using nature provides some guidance as to how we might universally define Nature-based.

Ecosystem services are quantitative measures of the benefit that nature provides to society. It is the benefit described and measured by ecosystem services that will deliver a solution. Pollinating insects provide benefit by increasing fruit production, vegetation along hillsides provides benefit by reducing soil loss and river pollution, upstream wetlands produce benefit by regulating peak water flows; these benefits can be used to provide solutions. A pollination gap was a problem for Blueberry (*Vaccinium corymbosum* L.) farmers in the North Eastern Atlantic US. Blaauw and Isaacs (2014) established wildflower strips beside Blueberry crops, attracting native pollinators and boosting pollination to the wildflower strip, increasing fruit production with economic returns over a 5-year period. Pollutant runoff and soil loss were problems in the arable regions of the Midwest United States, and Schulte et al. (2017) created vegetation strips across the sloping arable fields, mitigating the runoff of pollutants to nearby water systems, trapping soil, and creating co-benefits in terms of aesthetic appreciation and biodiversity conservation. Flood risk was a major problem for a catchment in the southern Cotswolds, UK, and Short et al. (2019) demonstrated how, by using natural flood retention measures, the flood risk was significantly reduced, with the co-benefit of ensuring the aesthetic appeal of the Cotswolds remained intact. In each of these cases a solution was created using the benefits provided by nature. Thus, when we consider what Nature-based means in the context of a solution, 'that which delivers ecosystem services' is an appropriate and productive definition. When we want to assess whether a solution is Nature-based, we should start by measuring how much ecosystem services contribute to the solution.

Ecosystem services are not the only source of benefit that can contribute to a solution. Here we use a broad conception of service types based on three different types of capital: Natural, Technological and Human. The biotic and abiotic components of ecosystems, and their interactions, are the stocks of natural capital from which flow ecosystem services (see glossary). Human skill, knowledge and health are human capital, with human work and labour being the associated service, while produced goods, like machinery, are technological capital, which can provide services (Fig. 1). Humans, however, use 'outcomes' that are derived from and depend on the services that flow from the three types of capital. An 'outcome' here is similar to how a 'good' is considered in economics, yet an outcome is much broader than commodities that can be traded on a market. Outcomes include all the material and non-material outputs from services (see glossary) that result in a benefit. Benefit is used as a general term to denote the many ways that human wellbeing is enhanced through services (see glossary). For example, nutrient cycling (an ecosystem function from natural capital) is necessary for pollutant removal (ecosystem service), but good water quality status (the outcome) requires other capital inputs, including wastewater treatment infrastructure and human labour. Similarly, primary production (an ecosystem function) is necessary for there to be a wheat crop (an ecosystem service) but the outcome, which may be flour, requires many other inputs (cultivation, harvesting, transport, preparation) before it can be consumed. Examining the contribution of ecosystem services to an outcome allows assessment of how nature-based the outcome is.

To demonstrate the different ways that natural, technological and human capital deliver their respective services, we can consider pollination-dependent crops. Alfalfa (*Medicago sativa* L.) is the most valuable crop that requires bee pollination in the US (USDA, 2017). The

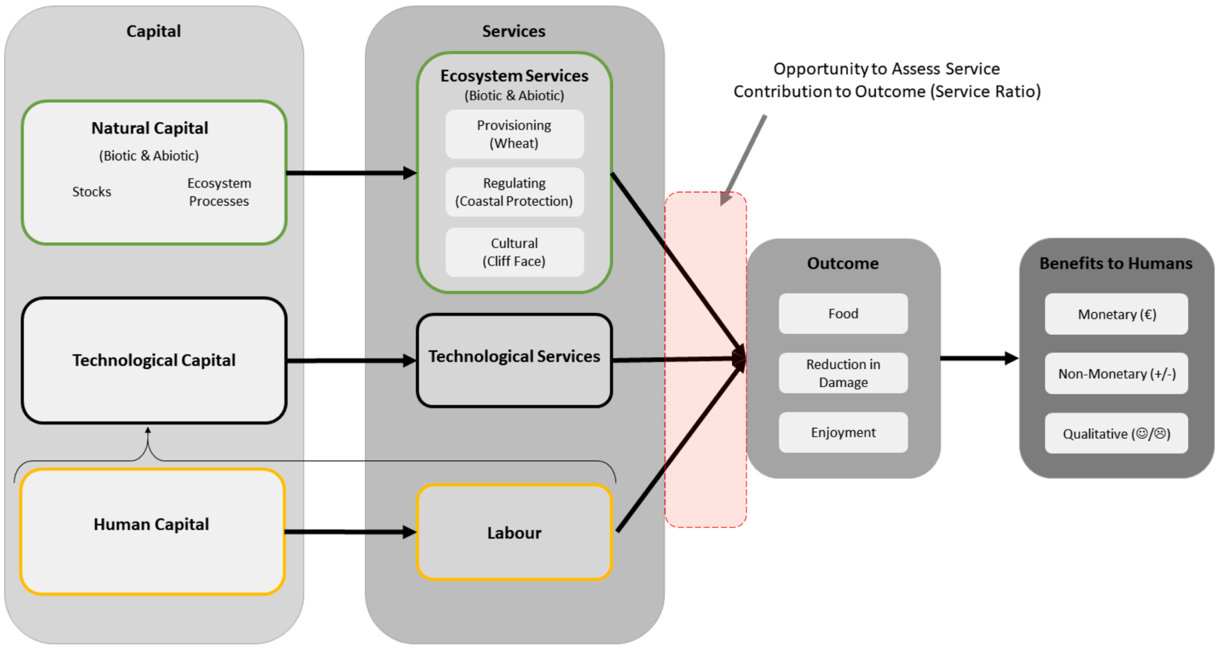

Fig. 1. Schematic illustrating the benefit-production chain, demonstrating how capital types and their respective flow of services are linked to outcomes and benefits they generate for people. Outcomes are derived from and depend on services which lead directly to benefits to people. Benefit can be expressed monetarily (€), quantitatively non-monetarily (+/-) and/or qualitatively (☺/☹). Adapted from Mace et al. (2012).

honeybee (*Apis mellifera*) is a poor pollinator of alfalfa, to the extent that solitary bee species such as the alkali bee (*Nomia melanderi* Cokerell) have been managed to efficiently pollinate alfalfa (Cane, 2002). As a result of management for pollination, a meta population of the alkali bee in Washington State numbered in the millions (Cane, 2008), and is an example of using an element of the ecosystem (in this case, the pollination service provided by the bees) to boost pollination-mediated crop production. Transgenic technology, breeding programmes and foliar application of plant hormones are examples of a technological approach that have removed the reliance of fruit crop production on pollinators (Knapp et al., 2017). Aubergine (*Solanum melongena* L.) has been genetically engineered to produce seedless fruit, increasing consumer convenience and fruit quantity without negatively affecting quality (Varoquaux et al., 2000; Knapp et al., 2017). The date palm (*Phoenix dactylifera* L.) is naturally wind pollinated but hand pollination has traditionally been employed to boost fruit production, relying on a high input of human labour (Mostaan et al., 2010). Human operated mechanical pollinators have been developed (Mostaan et al., 2010), yet human labour, the service that is derived from human capital, is still essential to date production.

The outcome in each of the crop systems is the same: marketable fruit or seeds. We can consider the different strategies employed in securing the outcome to be multiple ways of solving the same problem: ensuring the production of a marketable crop. Each strategy depends to a differing degree on ecosystem services, technological services and labour. In alfalfa, the pollination service is provided only using the ecosystem service of wild bee pollination, so an NbS has been achieved. Date palm pollination is provided by a mixture of labour and technological services, yet labour is still the majority service input, meaning that a Labour-based Solution has been implemented, while technological services have eliminated the need for pollination in aubergine, creating a Technological-based Solution. Acknowledging the three service types and calculating the relative contribution of each service type to achieving the beneficial outcome can be used to define the type of solution achieved.

2.1.2. Distinguishing Proximate vs Ultimate Service Delivery

It will be possible to parse the relative contribution of services when the services are provided independently of each other. Take for example flood risk at a catchment scale: it would be possible to estimate the reduced flood risk due to ecosystem services (the contribution of various upstream ecosystems to reducing peak flows) and technological services (the contribution of engineered structures to reduce peak flows) independently and so assess the service contribution ratio. However, in most situations the services will not be independent, but rather, the occurrence of one or more service(s) will cause another to exist (Fig. 2). For example, take the causative case that occurs in the more engineered solutions such as constructed wetlands. The ecosystem service of pollution removal would not exist if it were not for the knowledge (human capital) and construction of the wetland (technological service and labour). It is impossible to assess the relative contribution of the different services to the creation of a solution in the causative case unless we take a proximate versus ultimate view of service delivery. The ultimate origin of the pollutant removal ecosystem service in a constructed wetland involved knowledge, engineering and labour, but the proximate cause of the pollutant removal, the desired outcome, is the ecosystem service.

It is useful to draw an analogy between the stages of project development, and ultimate versus proximate service delivery: ultimate services are delivered during the building stage of a project, where initial capital costs are required, while proximate services are delivered in the subsequent operational stage, where operational costs are needed to ensure that the project is maintained. The project does not exist without the building stage, but it is the operational stage of the project that is functional and provides benefit. For example, bioswales are systems which allow infiltration of runoff water, typically used in urban settings. The building stage involves digging out a trench, carefully selecting gravel of suitable grain size to allow maximal infiltration and planting suitable species; a mixture of labour, knowledge and technological services from machinery. However, the operational phase of the bioswale involves the abiotic ecosystem service of infiltration and the biotic ecosystem services of transpiration. These ecosystem services have been enhanced using knowledge, labour and technological services in the building stage and so the bioswale is not strictly natural, in the sense that there has been no human involvement, yet the benefit is still delivered by ecosystem services and so can be considered to be Nature-based. The

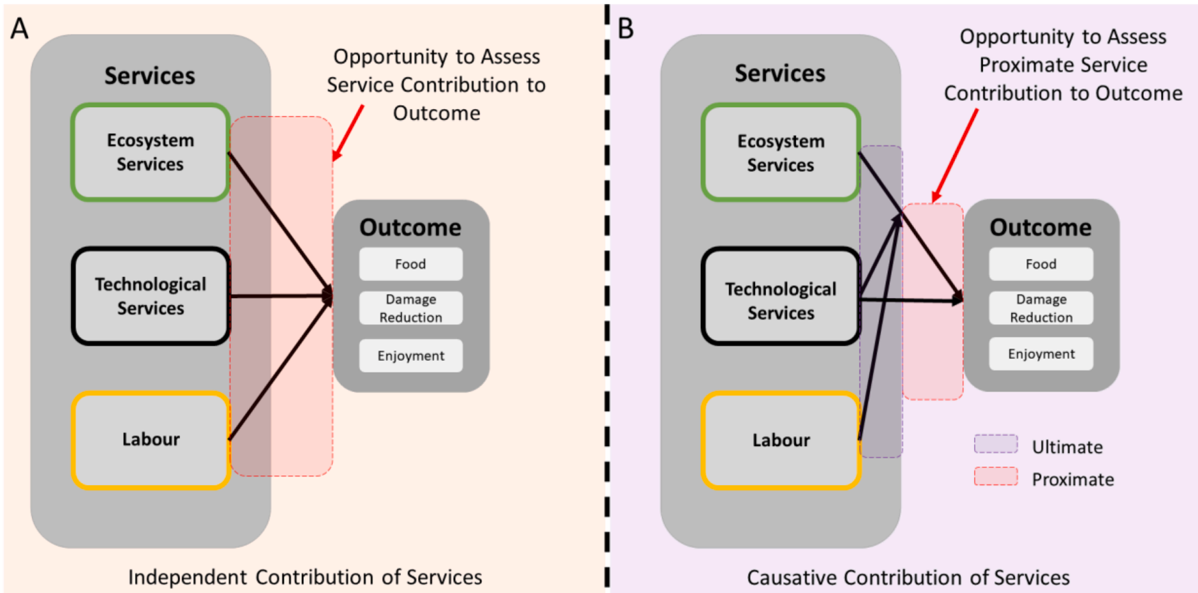

Fig. 2. Where services are provided independently of each other, it is possible to assess the relative contribution of each service type to an outcome of interest (A). Where services have a causative relationship, the provision of one type of service allows a second to exist, the services must be divided into ultimate and proximate services relative to how they produce the outcome (B). In the causative case, it is only in assessing the relative contribution of proximate services that it is possible to assess how Nature-based the outcome is.

relative contribution of proximate services, in this case ecosystem services, can be used to assess the degree to which the bioswale is Nature-based.

To explore how technological services often play both an ultimate and proximate role, let us consider two cases: a constructed wetland and a conventional wastewater treatment plant. In a constructed wetland, we are creating the conditions by which an ecosystem service can carry out pollutant removal. The same situation occurs in the much more technological wastewater treatment plant, where conditions have been refined to an extreme to make the ecosystem service maximally efficient. The proximate cause of pollutant removal in both the constructed wetland and wastewater treatment plant is an ecosystem service, so should a wastewater treatment be considered an NbS? In the constructed wetland, technological services (energy required to dig the ponds and erect the walls) were used in the construction phase of the wetland, but once operational, the technological service can be considered ultimate; the walls and ponds allow for an ecosystem to develop. The ecosystem service delivery, however, is proximate: the activities carried out on an ongoing basis by the functioning of the ecosystem directly transform waste products. This proximate service delivery is what we should be concerned about when assessing whether the solution is nature-based. In the wastewater treatment plant, technological services are required to build the plant, and once the plant is built, these services become ultimate to the aim of the plant - they allow for the operations of the plant. However, there are many active technological services in a wastewater treatment plant: aeration, chemical amendment, filtering, heating etc, that are part of the everyday operation of the plant. These technological services should be included in the assessment of service ratios; they are proximate, directly contributing to the ongoing pollution removal. A guide to deciding whether a service is ultimate or proximate is whether the service is used once at the onset of the project (ultimate) or whether the service is provided continuously or at regular intervals during the operational stage (proximate). The use of chemical amendments, aeration, heating and filtering in wastewater treatment plants either actively contribute to pollution removal or create ideal conditions for the ecosystem service of pollution removal. To assess how much these proximate technological services contribute to the wastewater treatment plant, one would only have to cease their operation and see how much the efficiency of the plant decreases.

Shutting off the operations of wastewater treatment plant is unnecessary if we want to quantitatively measure how Nature-based the plant is. Rather a comparison is needed, one where there are no proximate technological services assisting the ecosystem service. Constructed wetlands are a valid comparison (See section 3.1). In projects where multiple proximate services exist, it is essential to make a comparison to a singular proximate service project to measure the degree to which the multi-service project is Nature-based, providing a relatively cheap, in terms of time and effort, quantification of the term 'Nature-based'.

2.2. *Defining Solution*

2.2.1. *Scale, context and type of problem determine whether a solution can be achieved.*

A difficulty with the NbS concept is the ambiguous difference between the everyday usage of the term solution and how solution is used within the NbS literature. In a recent review, Keeler et al. (2019) consider street trees, city parks, gardens, bioswales, wetlands and green roofs to be NbS. However, the problems they are solving are not specified, rather the ecosystem services each potential NbS deliver are detailed (Keeler et al., 2019). Is it inappropriate to name something am NbS when what is meant in practice is that ecosystem services will be provided? Street trees, commonly cited NbS (reviewed in Keeler et al., 2019), have been shown to improve urban air quality, sequester carbon, improve stormwater management, boost urban water supply, improve mental health and mitigate the urban heat island effect (Keeler et al., 2019). So, what is the evidence that these ecosystem services from street trees deliver a solution?

One promising way street trees could be an NbS is in mitigating the urban heat island effect. A meta-analysis indicated that green space tends to be 0.94 °C cooler during the day and having trees in parks increases this effect (Bowler et al., 2010). In Bangalore, India, researchers found that afternoon ambient air temperatures were 5.6 °C lower on roads lined with trees than those measured in comparable streets without trees (Vailshery et al., 2013). More recently, in a temperate city, streets with tree canopy cover greater than 40% have been shown to be 1.5 °C cooler, with context and scale dependent effects (Ziter et al., 2019). Indeed, at a city scale, modelling indicates that widespread deployment of urban vegetation can reduce the heat profile of cites (Coutts and Harris, 2013; Santamouris, 2014), yet the effect of street trees mitigating the urban heat island at a city level has still to be adequately explored.

Recent research on the impact of nature on mental wellbeing indicates potentially strong wellbeing improvements. Having ten or more trees on a city block improves health perception in ways comparable to an annual income increase of $10,000, or being seven years younger, having controlled for socio-economic and demographic factors (Kardan et al., 2015). At the metropolitan scale, whether cites with more trees have happier residents is still an open question.

Trees can also be effective at removing particulate matter pollution at a local scale. Thirty meters downwind of a tree, 16% of pollutants can be removed (McDonald et al., 2016). However, when planted too densely, trees in the street canyon have been shown to increase ambient pollutant concentrations by trapping particulate matter (Janhäll, 2015). At a city level, the effectiveness of trees removing air pollutants at the city airshed remains low (0.001% to 0.4% depending on the pollutant, Nowak et al., 2006), demonstrating that the scale of a problem can determine whether an NbS can be achieved.

It is unlikely that the remainder of the ecosystem services provided by street tress will deliver NbS. While street trees do sequester carbon (643 million tonnes of carbon are stored in street trees in the US, Nowak et al., 2013), they are by no means an offset to a city's carbon emissions (Chen, 2015). Further, the emissions from the maintenance of street trees, such as limb pruning, have been shown to potentially mitigate any carbon storage gains (Nowak et al., 2002). Street tree performance to mitigate storm water flooding demonstrated a negligible impact, contributing 1.1% to city scale mitigation (Zölch et al., 2017). Empirical work indicates that street trees are only effective at reducing runoff volumes for low-intensity storms (Kuehler et al., 2017), with acknowledgement that nature-based flood mitigation will be a small component to city level flood mitigation (Hardy et al., 2015). Street trees may also negatively impact a city's water supply, especially in warmer regions where trees must be irrigated (Vico et al., 2014). More broadly, urban nature can be a serious source of water expenditure, with urban lawns in Los Angeles contributing up to 70% of the city's evapotranspiration, a significant water loss for the city (Litvak et al., 2017). Simply put, the type of problem determines whether street trees can deliver an NbS.

Obviously, street trees do have value. Planting schemes in Lisbon, New York and Indianapolis have an average 5.5:1 return on investment (Soares et al., 2011; Peper et al., 2007, 2008). However, positive cost-benefit ratios do not make solutions, rather they are good investment opportunities. The evidence indicates that both the spatial and temporal scale of a problem, the context in which the problem occurs, and the type of problem itself, are all decisive factors in determining whether a NbS can be achieved. Simply referring to street trees as NbS without reference to the scale, context and type of problem is inappropriate, as shown in Table 1.

2.2.2. *Defining solution as an agreed change in benefit.*

Considering the difficulty in understanding when a solution is achieved, we find it useful to provide a definition of a solution and specifically relate this definition to the benefit-production chain (Fig. 2). The three service types contribute to outcomes which are valuable to society, the outcomes create benefit and so we define solutions in terms of benefit.

To be able to recognise a solution, it is necessary to conceptualise a problem. In the context of NbS, a problem can be usefully defined as a lack of benefit. The problem of climate change can be viewed as a lack of benefit from climate regulation services, the problem of flooding can be viewed as a lack of benefit from flood regulation services while the problem of a pollination gap in fruit crops can be viewed as a lack of benefit from pollination services. Viewing problems as a lack of benefit allows a solution to be defined in terms of benefit. By setting an agreed threshold of positive benefit change a solution can be achieved, connecting the benefit-production chain to solutions (Fig. 3A and B).

A well-defined problem is essential to creating a solution, quantified using a measurable benefit metric, which is bounded temporally and spatially. For example, river water quality can be assessed by level of pollutants in the water at a particular place and time, and can be recognised as a problem if it is below a clearly defined threshold, such as those set by the EU's Water Framework Directive (European Commission, 2000) (baseline in Fig. 3A). Re-measuring the focal metric after a project has been implemented will allow quantification of whether a solution is achieved (Project 1, 2 and 3 in Fig. 3A). Once a wastewater treatment project is operational, water quality can be re-measured, thus, the change in water quality pre and post project can be defined as the benefit delivered by the project. Where the magnitude of the benefit change is enough to meet the agreed threshold, a solution has been achieved (Project 2 and 3 in Fig. 3A).

By examining the ratio of service inputs to an outcome, the type of outcome can be identified. Where ecosystem services contribute the largest service input, a Nature-based outcome is achieved. Solutions have been defined here in terms of a lack of benefit to link solutions to the benefit-production chain. A NbS can be identified when ecosystem services have contributed the largest service input to an outcome that

Table 1
Potential for street trees to be a Nature-based Solution to each urban pressure that cities face at two spatial scales. The potential was deemed low, moderate or high when the evidence indicated that street trees could contribute marginal, moderate or substantial impact. Grid colours correspond to the level of uncertainty: low (green), moderate (orange), and high (red). Adapted from Baró and Gómez-Baggethun (2017). Evidence based on reviewed studies in Keeler et al. (2019) and Baró and Gómez-Baggethun (2017).

Potential for Street Trees to be a Nature-based Solution

Scale	Air Quality Regulation	Carbon Sequestration	Storm water management	Water supply	Mental Health	Temperature regulation
Local (Site)	Low to Moderate	Low	Low - Moderate	Low	Moderate - High	Moderate - High
Regional (Metropolitan)	Low	Low	Low	Low	Unknown	Unknown

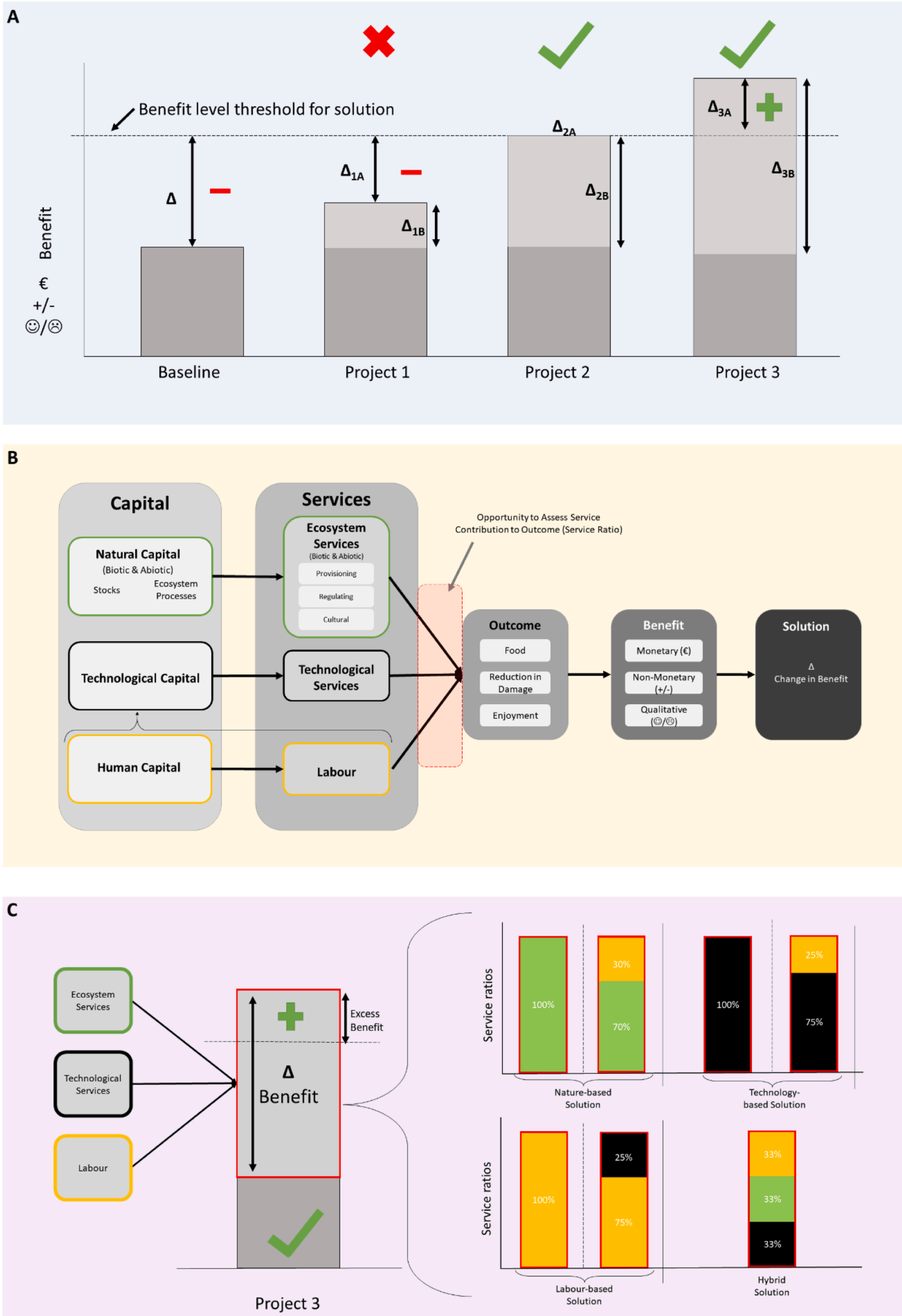

Fig. 3. A) Schematic Illustrating when a Solution is Achieved. The problem is well defined, with the metric of interest chosen (€,+/-,☺/☹), a *Baseline* scenario assessed, a threshold benefit level is set. The difference between the *Baseline* and threshold is negative (-) indicating a problem is occurring, with the magnitude of the problem being the size of the difference (Δ). *Project 1* increases the benefit delivered (Δ $_{1B}$) but *Project 1* is not a solution as the difference between *Project 1* benefit level and the threshold (Δ $_{1A}$) is negative (-). *Project 2* produced benefit (Δ $_{2B}$) large enough to meet the threshold, so the difference between the threshold and benefit supplied (Δ $_{2A}$) is zero, meaning a solution has been reached, while *Project 3* produced benefit (Δ $_{3B}$) large enough to exceed the threshold, meaning the difference between the threshold and benefit supplied is positive(+), so a solution with extra capacity (Δ $_{3A}$) has been achieved. Benefit can be expressed monetarily (€), quantitatively non-monetarily (+/-) and/or qualitative (☺/☹). B) Schematic Illustrating the Benefit-Production Chain. Capital types and their respective flow of services are linked to outcomes and benefits they generate for people, which in turn can be used to create solutions. Adapted from Mace et al. (2012). C) Service Ratio Inputs Determine Type of Solution. With three service types, four categorical solution types are possible: Nature-based, Technological-based, Labour-based and Hybrid.

has created enough benefit to solve a well-defined problem (Fig. 3 C). Adopting this framework allows the implementation of the NbS concept, as it can be used to both identify NbS and measure the degree to which a solution is Nature-based on a project by project basis.

3. Demonstrating the Method to Identify Nature-based Solutions

To identify a solution as Nature-based, two criteria must be reached: 1) a solution to a well-defined problem is achieved; and 2) ecosystem services make the largest contribution to the solution. To demonstrate the applicability of this framework, we assess four projects tackling the problem of wastewater pollution to determine whether a problem has been solved and the type of solution achieved.

3.1. A Case Study of Wastewater Projects

The Ringsend Wastewater Treatment Plant (WWTP) in Dublin, Ireland, will have the capacity to treat 2.4 million person equivalents (pe) of wastewater on 10 ha of land, once upgraded, making it one of the most efficient treatment plants in the world (Irish Water, 2018). The plant generally meets the water quality standards set by the Irish Environmental Protection Agency, and will reliably meet these standards once the upgrades are complete, and so can be considered a solution to the problem of wastewater pollution (Table 2). The plant relies on highly intensified ecosystem functions and services to break down the polluted water and so makes a useful study for whether this highly intensified system can be considered an NbS. Considering ultimate and proximate services, it is clear that a lot of knowledge, labour and technological services went into the construction of Ringsend WWTP. To assess how Nature-based the project is, we need to assess proximate services. The intensified nature of the ecosystem service of pollution removal is due to the proximate technological services of aeration, chemical amendment, filtering, heating etc. To measure the contribution of these proximate services to the pollution removal we must compare Ringsend WWTP to a constructed wetland (CW) where there are no proximate technological services. The Glaslough CW in Monaghan, Ireland, has the capacity to treat 1750 pe on 6.7 ha (Kayranli et al., 2010). Taking 260 pe per ha to be the expected treatment capacity of the hypothetical Ringsend CW, the 10-ha space could treat 2600 pe when ecosystem services are employed alone. The gap between the hypothetical CW capacity and the actual capacity of Ringsend WWTP (2399400 pe) is a rough estimate of the contribution of the proximate technological services to Ringsend WWTP. The technological services contribute 99.9% of the benefit to this solution and so we can conclude that the Ringsend WWTP is a technology-based solution (Table 2).

The Glaslough CW treats wastewater to a standard that has no detectable impact on the receiving river (Kayranli et al., 2010), and so can be regarded as a solution to wastewater pollution. The CW has no mechanical operating parts and was designed to solely use ecosystem services to treat the wastewater. Proximate ecosystem services make the sole contribution to the solution and so the Glaslough CW can be considered an NbS (Table 2).

In the UK, the ability of an intensified CW to treat wastewater was tested, implementing artificial aeration (Butterworth et al., 2013). While the removal efficiency increased with the aeration, there was no measurement of the impact of the constructed wetland on the receiving stream and so it could not be determined whether a solution had been achieved. Due to the experimental nature of the CW the contribution of the proximate technological service, the aeration, to the removal of pollutants could be calculated. However, ecosystem services still had the highest contribution to the removal of pollutants and so this project can be classified as Nature-based, but it not clear whether a solution was achieved (Table 2). A hybrid storm water runoff treatment system was designed and tested in Łódź, Poland (Jurczak et al., 2018). The system contained an engineered and ecological section, allowing for assessing the contribution of each service type. While ecosystem services contributed the most benefits in this project and so the project is Nature-based, the receiving river's water quality did not meet water quality standards downstream of the hybrid system. Failure to meet the water quality standards means this project cannot be referred to as a solution. Even though the hybrid system delivers benefits by decreasing the amount of pollution entering the receiving river, it did not do so the extent that the receiving river's water quality was unaffected. In this case, the project should be viewed as a nature-based project that delivers benefits, but benefits are not delivered to the extent that it can be referred to as a solution (Table 2).

3.2. Evidentiary Standards

We have used a stringent measure here to assess whether a solution has been achieved. The aerated constructed wetland likely treated wastewater to a level with no measurable impact on the receiving water quality, yet without confirming evidence we have chosen not to apply the solution label. Similarly, the solution threshold for the hybrid runoff system, not impacting the receiving stream's water quality, is likely an unattainable standard for such a system. A more agreeable standard could be negotiated from the outset of the project, like the development of key performance indicators. We chose not to classify these projects as solutions to demonstrate that a project can be Nature-based without having to be a solution and vice versa, highlighting the necessary and sufficient conditions for a NbS. Under the framework outlined in this paper, to be labelled an NbS a solution to a well-defined problem must be achieved and ecosystem services must contribute the largest proximate service provision.

4. Discussion

With a framework to identify NbS, research can begin to explore how

Table 2
Identifying Nature-based Solutions by examining the ratio of service inputs and assessing whether a solution was achieved. The sum of service contributions ranges from −100 (all contributions are disservices) to +100 (all contributions are services), with a sum contribution above 0 indicating that benefit is being created. See Manuscript Data for calculation of service contributions.

Problem	Management Action	Location	Solved (Y/N)	Ecosystem Service	Technological Service	Labour	Intervention Assessment	Source
Pollution due to wastewater	Wastewater Treatment Plant	Ringsend, Dublin. 53.338943, −6.196545	Y	0.001	99.9	0	Technological Solution	Irish Water (2018)
Pollution due to wastewater	Constructed Wetland	Glaslough, Ireland 54.318336, −6.893872	Y	100	0	0	Nature-based Solution	Kayranli et al. (2010)
Pollution due to wastewater	Aerated Constructed Wetland	UK. Unspecified Coordinates	?	30	19	0	Nature-based Intervention	Butterworth et al. (2013)
Pollution due to urban runoff	Hybrid Constructed Wetland	Łódź, Poland. 51.821194, 19.486722	N	57	26	0	Nature-based Intervention	Jurczak et al. (2018)

scale and context impact the ability to solve problems through NbS. It is important to be able to understand how useful NbS will be as an eco-technology to addressing global challenges. For example, recent research has indicated that if global tree restoration reached the tree carrying capacity of the Earth, two thirds of the carbon that has been emitted (205 gigatonnes of carbon) would be sequestered, meaning that, in theory, a global tree restoration project could deliver an NbS to climate change (Bastin et al., 2019). In practice, afforestation will be one of a portfolio of actions to address climate change. Due to land use and socio-economic constraints, afforestation could realistically result in global annual sequestration rates of one gigatonne of carbon, a significant yet small proportion of the greater than 50 gigatonnes of annual emissions (National Academies of Sciences Engineering & Medicine, 2019). While we certainly encourage the exploration of the potential of NbS, it is also essential to explore their development in a realistic context and in comparison to other problem solving methods. Being able to identify, and measure the contribution of ecosystem services to, NbS is the first step in this process.

4.1. Benefits of the framework

The framework seeks to define Nature-based quantitatively and determine whether a solution has been achieved. As such, it presents the necessary and sufficient conditions by which a project can be considered to be an NbS. These conditions are compatible with many of the varied definitions of NbS (Table S1), but the framework attempts to provide some fundamental unity to the concept. The IUCN has outlined criteria to verify an NbS, discussed in the introduction. The IUCN could adopt the necessary and sufficient conditions proposed in this paper without compromising on any of the other criteria they consider essential in an NbS. Thus, the primary benefit of the framework is its potential to be widely used and adopted.

The explicit acknowledgement of different service types (ecosystem services, technological services, and labour) allows for the quantitative measurement of the degree to which a solution is Nature-based, Technology-based or Labour-based. Further capital types and the services delivered therefrom can be easily incorporated, thus a second benefit of the framework is the generality it enables in describing solutions.

4.2. Insights provided by the framework

Given a framework to describe differed types of solutions, we can now compare the characteristics of different solution types. NbS, particularly those without any ultimate technological services or labour involved, are self-sustainable: the ecosystem services are being delivered without any human intervention. Wild bees pollinating crops will continue to pollinate crops, all else being equal, for the foreseeable future. This solution to crop pollination is potentially infinitely sustainable given wild bee habitat is not destroyed. For example, consider the case where the ground nesting alkali bee (*Nomia melanderi*) has been managed to efficiently pollinate alfalfa in Washington State (Cane, 2002). Aggregations of the bee have been managed – the soil containing the nests is excavated, transported and buried in fields where pollination is most needed – ultimate labour services leveraging the proximate service of pollination to create an NbS. Without continued management of aggregations by alfalfa farmers the NbS wouldn't be sustainable, and the management provides additional benefit by ensuring the crop is adequately pollinated. Moving up the scale of increasing human involvement, we can also consider the honey bee (*Apis mellifera*) and its use as a pollinator. Intense management of hives allows honey bee keepers to migrate around the US following the flowering of major crops (Scientific American, 2013). The multi-billion dollar industry supported by the intense management of hives highlights that increasing the amount of human involvement, labour and technological services, can substantially increase efficiency; a honey bee hive could pollinate four crops on the annual migration whereas the equivalent number of alkali bees will pollinate one crop, benefit per bee quadrupling with increased human involvement. The pollination provided by the honey bee is not self-sustainable, without human involvement there would be no migration of hives.

The pattern being outlined is an apparent inverse relationship between sustainability and efficiency of benefit. We broadly define sustainability as the degree to which the solution is self-sustainable, with sustainability being inverse to the amount of human intervention (technological capital, technological services, knowledge and labour) needed to continue to solve the problem. We choose to define efficiency of benefit on a benefit per unit area basis (or some such equivalent metric: volume, individual etc.), where human intervention tends to increase the benefit per unit area. A constructed wetland is much more self-sustainable than a wastewater treatment plant, but the treatment plant produces much more benefit per unit area. In general, NbS will be more self-sustainable, resulting in lower operating costs, while Technology-based Solutions will produce more benefit per unit area but will have high operating costs due to the proximate technological services and labour (Fig. 4). The context of a given problem will determine whether the characteristics of the different solution types are suitable to creating a solution. Where low operating costs and sustainability are preferred, and the cost of land is not prohibitive, NbS are desirable. Where maximising the benefit per unit area is needed to solve a problem, more technological solutions will be required.

At either end of the inverse relationship between sustainability and efficiency of benefit there is, in theory, an asymptote (Fig. 4). An NbS with no human involvement, and so self-sustainable, can be considered effectively infinitely sustainable. Pollination of crops by wild bees, transformation of waste products by wetlands and stabilisation of soil by vegetation will continue indefinitely, all else being equal. In reality, all else is not equal, the world is not at equilibrium as disturbances alter ecosystem functioning and service provision, yet for this thought experiment we can consider NbS without human involvement to be infinitely self-sustainable. Similarly, it appears that it is possible for the benefit per unit area relationship to be asymptotic, a technological solution can solve a problem once and for all and not be parochial to a given area. For example, the Aubergine has been genetically engineered to produce fruit without the need for pollination (Knapp et al., 2017). In this case the problem of pollinating Aubergine has been eliminated.

Ecosystem services are co-opted ecosystem functions that happen to be beneficial, they are not designed to solve problems but can be managed to do so. In comparison, knowledge explains a phenomenon at a fundamental level and solutions using knowledge produce benefit more efficiently, and in the limit, can solve the problem once and for all. The reach of a technological solution can be infinite, while NbS are parochial, their reach is limited to the area in which they occur.

4.3. Difficulties in using the framework to identify Nature-based Solutions

Deciding what services count as proximate can be difficult and is all important to classifying solutions. A suggested rule is to count any labour or technological services which recur frequently through the operational phase of a project as proximate services. For example, we could consider farming to be a solution to food insecurity. Provisioning ecosystem services are central to even intensive farming, yet the ongoing use of herbicides, pesticides, fertiliser and machinery, all which can be considered proximate technological services, would mean intensive farming would not be a NbS but instead a technology-based solution.

Measuring the relative magnitude of proximate services is a second methodological difficulty. Experimental systems, such as the comparison of aerated and non-aerated constructed wetlands by Butterworth et al. (2013) (Section 3.1), permit accurate partitioning of the service contributions. A project attempting to solve a problem is unlikely to include an experimental aspect to allow such partitioning, that is the realm of science, not practice. Including sensors which measure the contribution from each service type could be feasible, as Jurczak et al.

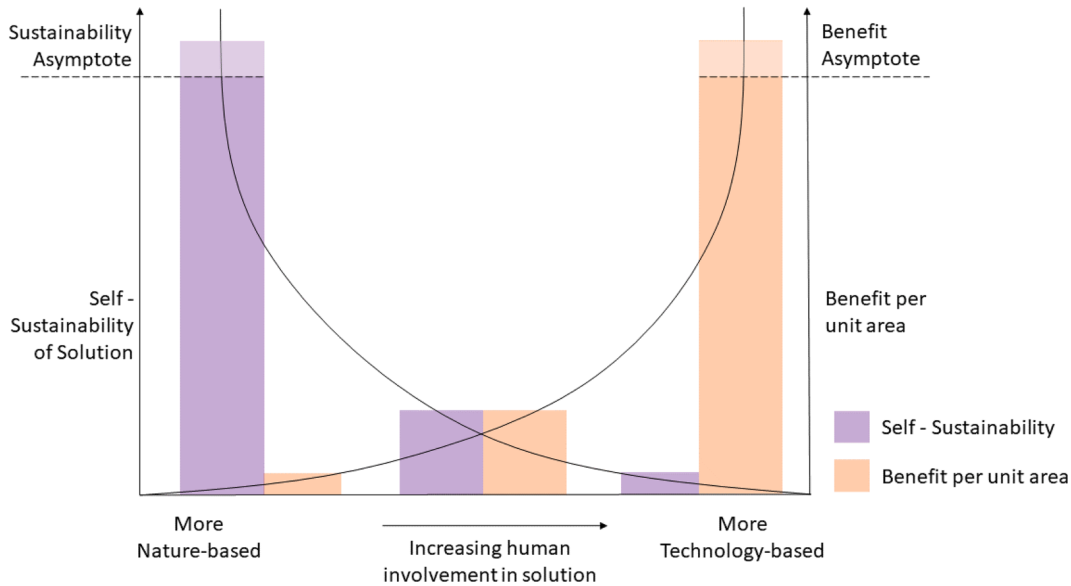

Fig. 4. Inverse relationship between self-sustainability and benefit production efficiency (measured as benefit per unit area) as human involvement in solution increases. NbS will tend to be more sustainable, while technology-based solutions will create more benefit due to the application of fundamental knowledge. In the limit, NbS can be infinitely sustainable, ecosystem services will continue to solve problems without any management (sustainability asymptote). Similarly, Technology-based solutions may solve a problem in an absolute sense, eliminating a specific problem (benefit asymptote). See text for examples.

(2018) demonstrate by measuring pollutant removal at each stage of the hybrid retention pond. The most likely way that NbS will be identified is by comparison with a hypothetical alternative. For example, the efficiency of Ringsend WWTP was compared to the hypothetical efficiency of a constructed wetland that could fit in the same sized land parcel (see section 3.1). Care must be taken when comparing to a hypothetical alternative to ensure that the comparisons are valid. The hypothetical alternative must be calculated from a solution where there was a single service input (only ecosystem services contributed to the efficiency of the constructed wetland) and must be scaled appropriately (scaling up the hypothetical wetland to the size the Ringsend land parcel) to make a valid comparison.

It would be possible to manipulate the definition of solution put forward in this paper by setting a low benefit threshold for a solution to be achieved. To ensure the setting of a meaningful threshold, thresholds can be based on regulations. For example, in Europe thresholds for water quality would be set according to the European Water Framework Directive. In the absence of regulations, prior engagement with stakeholders is essential to setting meaningful thresholds. The IUCN's fifth criteria, that NbS must be based on inclusive, transparent and empowering governance processes, will encourage stakeholders who have an interest in the project succeeding to set a threshold deserving of the name solution. For Blueberry farmers of the Midwest US mentioned in section 2.1.1, a likely threshold that would be of interest would be an economic return on the costs of setting up a wildflower strip.

Finally, the magnitude of benefit produced by a project may vary through time. Where a project initially creates an NbS but subsequently the benefit produced falls below the solution threshold, it can no longer be considered a solution. Where a project is meeting a regulatory threshold, such as water quality standards, legal repercussions are likely with fines for failure to meet standards being issued by environmental protection agencies. Where a project is to the benefit of local stakeholders, continuing to refer to the project as a solution after it has failed to reach the stakeholder set threshold may erode trust in NbS more generally. In both situations it would be erroneous to continue to refer to the project as a solution. In general, solutions sit downstream of the outcome and benefits that services produce. Only through monitoring the benefit and assessing the proximate service contributions can a NbS be confirmed. As such, not all constructed wetlands are NbS, rather they become NbS when they solve a well-defined problem and ecosystem services contribute the majority of proximate service input. A constructed wetland that created an NbS can also lose its status as an NbS if it fails to continue to solve the problem. To avoid such circumstances, it is advisable to design capacity into the project to exceed the benefit threshold to ensure that the project will continue to meet regulatory standards or stakeholder set thresholds given variability in benefit production over time.

5. Conclusion

Nature-based Solutions are an influential topic of research, drawing a diversity of researchers to study how nature can be used to solve problems. A major limitation of this contested concept is that there has been little development of what NbS mean in practice. We have presented a framework linking ecosystem services and solutions, defining what Nature-based means in practice, which allows the identification of NbS on a project by project basis. By connecting the concept of a solution to the benefit-production chain, it is possible to link solutions to the three capital types and the services they provide. The framework illustrates that solutions sit downstream of the outcomes and benefits that services produce, demonstrating the novel conceptual space that NbS inhabit. By examining the ratio of proximate service inputs to a solution, the type of solution can be identified quantitatively. This framework can thus serve a useful tool to identify NbS and improve our understanding of the linkages between ecosystem services and solutions. The application of the framework using a case study problem area demonstrated the useful discernibility of the framework, being able to quantitatively describe the degree to which a solution is Nature-based. Previous literature struggled to define what Nature-based means in the context of creating solutions in a structured and objective fashion, and the proposed framework overcomes that barrier, resulting in the first universally generalisable method to measure and identify NbS on a project by project basis.

The aspiration of NbS is to bring about an innovation in technology to address environmental problems. This ecotechnology would attempt to use the benefits we derive from ecosystems as the vehicle to solve problems. By combining such NbS with business models that appropriately capture and deliver value, ecotechnology could result in sustainable business models (Bocken et al., 2014) with a strong stewardship role (e.g. embracing conservation norms), ultimately contributing to a more environmentally sustainable socio-economic system. The proposed framework is a valuable tool that provides a structured approach to identify, and measure the degree to which, solutions are Nature-based, while additionally improving our understanding of the relationship between ecosystem services, benefits and solutions.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Glossary:

Benefit: In this context, used as a general term to denote the many ways that human wellbeing is enhanced through services.

Outcome: All use and non-use value, material and non-material outputs from services that people value through experience, use or consumption, whether that value is expressed in economic, social or personal terms. (Defined here following 'Good' in Mace et al., 2012)

Ecosystem Service: the benefits flowing from natural capital stocks consumed or used by humans to sustain or advance wellbeing. Ecosystem services can be provided by ecosystem processes, ecosystem structures or both. Abiotic and biotic services are included and considered to be subdivisions of the broad ecosystem service concept (see Haines-Young and Potschin, 2018).

Ecosystem Management: A management style using renewable and manageable natural capital stocks and the flow of ecosystem services to manage problems.

Natural Capital: The abiotic and biotic elements of nature, including all natural resources (such as soil, water, vegetation, species) and physical, biological, and chemical processes (Mace et al., 2015).

Nature-based Solution: A solution to a well-defined problem where ecosystems services comprise the largest service input. Note: in this paper we use the abbreviation 'NbS' as both singular (Nature-based Solution) and plural (Nature-based Solutions) interchangeably.

Service: The activity, function or flow of a capital that provides benefits to humans.