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Research article

Unlocking the potential of ponds and pondscapes as nature-based solutions for climate resilience and beyond: Hundred evidences

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ABSTRACT

Unlocking the full potential of ponds (small water bodies) and pondscapes (network of ponds) as Nature-based Solutions (NbS) is critical pursuit for enhancing ecosystems and societal resilience to climate change and other societal challenges. Despite scattered initiatives for pond/pondscape creation, restoration and management—each considered here a distinct NbS—there is a significant knowledge gap in utilising ponds/pondscapes as effective NbS. We aimed to assess these NbS in terms of their objectives, outcomes, effectiveness, multifunctionality, delivery of potentially conflicting effects, and the implementation process while considering their Nature's Contributions to People (NCPs, i.e., benefits to society). We compiled data on 183 NbS actions implemented across 93 ponds/pondscapes from 24 countries, predominantly from Europe, via a questionnaire distributed to experienced stakeholders implementing NbS in ponds/pondscapes. One single pond/pondscape may imply more than one NbS action. Two-thirds were in rural areas, and one-third in urban settings. Our analysis revealed that *Creation of habitat for biodiversity* was a primary delivery objective (targeted NCP) in the implementation of most NbS in ponds/pondscapes, often also combined with other NCPs such as *Learning and inspiration*, *Regulation of water quantity*, and *Physical and psychological experiences*, showcasing their intended multifunctionality. Implemented NbS primarily focused on climate change adaptation (especially *Regulation of hazards and extreme events*, and *water quantity*) rather than mitigation, with less emphasis on measures like direct greenhouse gas emissions reduction or enhancing carbon sinks. The costs associated with pond's NbS varied significantly depending on factors such as project scope, objectives, location, socio-economic-cultural system, and specific implementation requirements. The creation of ponds/pondscapes often entailed the highest financial investment, much more than their restoration or their management. In conclusion, our study underscores the multifunctionality of ponds/pondscapes and provides insights about their significant potential as cost-effective NbS for enhancing ecosystem and societal resilience to climate change and biodiversity. It underscores the importance of further research to fully understand and measure the diverse range of NbS they offer, particularly in the context of climate change mitigation. Standardised measurements of the NCP provided by these NbS in ponds/pondscapes are essential for validating managers' claims and exploring their role in addressing climate change.

1. Introduction

Nature-based Solutions (NbS) are defined by the International Union for the Conservation of Nature (IUCN, 2020) as: "Actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges, such as climate change, effectively and

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adaptively, simultaneously providing human well-being and biodiversity benefits". In recent years NbS have been increasingly promoted internationally, for example, by the European Union (Ryfisch et al., 2023), Latin America and the Caribbean (Watkins et al., 2019), China (Li et al., 2021), or the United States of America (Sklar et al., 2005) because of their multifunctional characteristics, as a way of tackling numerous societal challenges at the same time. To date most focus has been on NbS in urban areas (Sarabi et al., 2019) and in relation to green infrastructure (Pauleit et al., 2017; Wild et al., 2017). Much less attention has been paid to blue infrastructure, especially in rural areas (Raška et al., 2022).

Ponds and their interconnected networks, when congregated together in a landscape and collectively referred to as pondscapes, are increasingly recognised as ideal environments for successfully implementing NbS (Cuenca-Cambronero et al., 2023). Henceforth, whether discussing NbS implemented in an isolated pond or in a cluster of ponds, we will refer to it as a pond/pondscape NbS. A NbS action within a pond/pondscape encompasses any deliberate activity or intervention related with the creation, restoration, and management of a pond/-pondscape, that addresses both societal and environmental challenges. We thus consider actions undertaken within a pond/pondscape as distinct NbS. Consequently, a single pond undergoing creation and subsequent management would constitute two separate NbS. Pond/-pondscape creation involves creating one or several ponds in a site where there was formerly no waterbody (e.g., Hankin et al., 2021; Zamora-Marín et al., 2021). Pond/pondscape restoration encompasses various measures aimed at rehabilitating or recovering ponds that have been polluted, structurally and functionally altered or lost. This can include activities such as excavating a pond in a location where there used to be one (Alderton et al., 2017), rejuvenating a pond that has been filled in with landfills, or implementing significant transformations to restore the functionality of an existing pond (e.g., Indermuehle and Oertli, 2006). These transformations may involve adjusting the depth, morphometry, slopes, and shoreline design, as well as reintroducing or enhancing the flora and fauna within the pond. Pond/pondscape management can be implemented at local scales, focusing on individual ponds and their immediate vicinity (small-scale), or at regional scales, encompassing the entire pondscape (large-scale), or a combination of both. They can be divided in three distinct types of actions: a) pond infrastructure measures targeting the immediate surroundings of ponds, b) pond management measures implemented within the ponds themselves, and c) land-use actions necessary to facilitate the proper functioning of the entire pondscape. Examples of such actions include the removal of vegetation or tree shade, introduction or removal of specific species, water management practices, among others (e.g., Sayer et al., 2012; Short et al., 2019). It also involves the implementation of protective measures, such as designating protected areas such as nature reserves, regional or national parks (e.g., Fahy et al., 2023).

Nature's Contributions to People (NCP) (Díaz et al., 2018; IPBES, 2019) encompass a wide range of benefits and services that the natural world provides to humans, from food and clean water to cultural and spiritual enrichment. Ponds/pondscapes, when used as NbS (Table 1), have the potential to tackle multiple societal challenges, including regulatory, material and non-material NCPs (Cuenca-Cambronero et al., 2023; Oertli et al., 2023). The multifunctionality of ponds/pondscapes as NbS renders them invaluable assets for promoting sustainable development and addressing various interconnected environmental and societal concerns (Hambäck et al., 2023), including the pursuit of Sustainable Development Goals (SDG).

Despite the increasing interest in adopting NbS initiatives in ponds/pondscapes, there is limited information concerning their societal and ecological benefits including their potential role in climate change mitigation and adaptation. Furthermore, the existing information is scattered and primarily found in the form of grey literature or expert knowledge. One significant knowledge gap revolves around the basic characteristics of ponds/pondscapes where NbS have been implemented. These include factors such as land use in the surrounding areas,

Table 1
Description of the Nature Contributions to People (NCP), with examples from ponds/pondscapes (IPBES, 2019; Díaz et al., 2018).

Nature Contributions to people (NCP)	Examples from ponds/pondscapes
REGULATING NCP	
Creation of habitat for biodiversity	Growing sites for plants; nesting, feeding, and mating sites for animals; resting and overwintering areas for migratory mammals, birds, and butterflies; nurseries for juvenile stages of fish, etc.
Pollination	Provision of habitats and food resources for pollinating insects.
Regulation of the climate	Positive or negative effects on emissions of greenhouse gases (e.g., biological carbon storage and sequestration; methane emissions from wetlands); and direct and indirect processes involving biogenic volatile organic compounds (BVOC), and regulation of aerosols and aerosol precursors by phytoplankton and terrestrial plants.
Regulation of water quantity	Regulation of the quantity, location, and timing of the flow of surface and groundwater; regulation of flow to water dependent natural habitats; and modification of groundwater levels
Regulation of water quality	Filtration of particles, pathogens, excess nutrients, and other chemicals.
Regulation of hazards and extreme events	Mitigation of the impacts of floods, storms, heat waves, fires, seawater intrusion, tidal waves, etc.
MATERIAL NCP	
Food and feed	Production of food from wild, managed, or domesticated organisms, such as fish, crayfish, beef, game, dairy products, edible crops, wild plants; and production of feed (forage and fodder) for domesticated animals (e.g., livestock, work and support animals, pets) or for aquaculture, from the same sources.
NON MATERIAL NCP	
Physical and psychological experiences	Opportunities for physically and psychologically beneficial activities, healing, relaxation, recreation, leisure, tourism, and aesthetic enjoyment based on the close contact with nature (e.g., hiking, recreational hunting and fishing, birdwatching, snorkelling, diving, gardening).
Learning and inspiration	Opportunities for the development of the capabilities that allow humans to prosper through education, acquisition of knowledge and development of skills for well-being, information, and inspiration for art and technological design (e.g., biomimicry).
Supporting identities	Provisioning of opportunities for people to develop a sense of place, belonging, rootedness or connectedness, associated with different entities of the living world (e. g. cultural, sacred and heritage landscapes, sounds, scents and sights associated with childhood experiences, iconic aquatic animals or flowers); basis for narratives, rituals and celebrations; and source of satisfaction derived from knowing that a particular pond/pondscape exists.
Maintenance of options	Benefits (including those of future generations) associated with the continued existence of a wide variety of species, populations, and genotypes, including their contributions to the resilience and resistance of pond/pondscape properties in the face of environmental change and variability; or future benefits (or threats) derived from keeping options open for yet unknown discoveries and unanticipated uses of particular ponds/pondscapes.

the size and number of ponds, the overall pondscape area, the extent of protection provided to these areas, and the ponds/pondscapes geographical distribution across countries. Comprehending these characteristics is vital for understanding the context in which NbS have been implemented and their potential scalability. Moreover, there is a lack of detailed information concerning the extent of societal and environmental benefits (NCP) provided by specific types of NbS implemented in ponds/pondscapes (Thorne et al., 2018), as well as the motivations and expectations of stakeholders in adopting these actions. When deciding what pondscape NbS actions to implement, it is also important to consider costs i.e., how much time, money, other resources are required to implement the NbS action. The scale and types of costs will depend on the pond NbS action and the local context. By filling these gaps, stakeholders can gain a deeper understanding of the capabilities and potential benefits associated with NbS implemented in ponds/pondscapes. This will enable them to make informed decisions regarding the implementation of NbS and promote the wider adoption and implementation of ponds/pondscapes as effective NbS to maximise the positive impacts on both the environment and society (i.e., NCP).

The objective of the study was to evaluate an extensive set of case studies where NbS (i.e., creation, restoration and management actions) were implemented in ponds (local NbS) and pondscapes (landscape NbS) to promote biodiversity and other NCP, predominantly in Europe, but also in other world's regions. We analysed the characteristics, objectives, and perceived outcomes of NbS in pondscapes, with a particular emphasis on the types of actions implemented and their effectiveness in providing various NCPs. First, we provide a comprehensive overview of the implementation of pond/pondscape NbS by: (1) exploring the objectives behind the implementation of NbS in ponds/pondscapes, (2) assessing the intended outcomes and benefits they deliver (targeted NCPs within each NbS) and the perceived effectiveness of NbS in achieving these outcomes, (3) examining the multifunctionality of NbS in ponds/pondscapes, showcasing their ability to enhance biodiversity while delivering multiple environmental, social, and economic benefits simultaneously, and (4) evaluating the delivery of potentially conflicting NCPs of implementing an NbS with a specific objective (targeted NCP within each NbS) on delivery of other NCPs. Second, we describe the implementation process of the pond/pondscape NbS by (1) identifying key stakeholders involved in this process, (2) investigating the timeline of implementation, and (3) assessing the associated costs of implementing NbS in ponds/pondscapes. Based on the results we discuss the potential of ponds/pondscapes as NbS to address environmental and societal challenges, particularly in the context of climate change, showcasing their effectiveness in promoting several NCP.

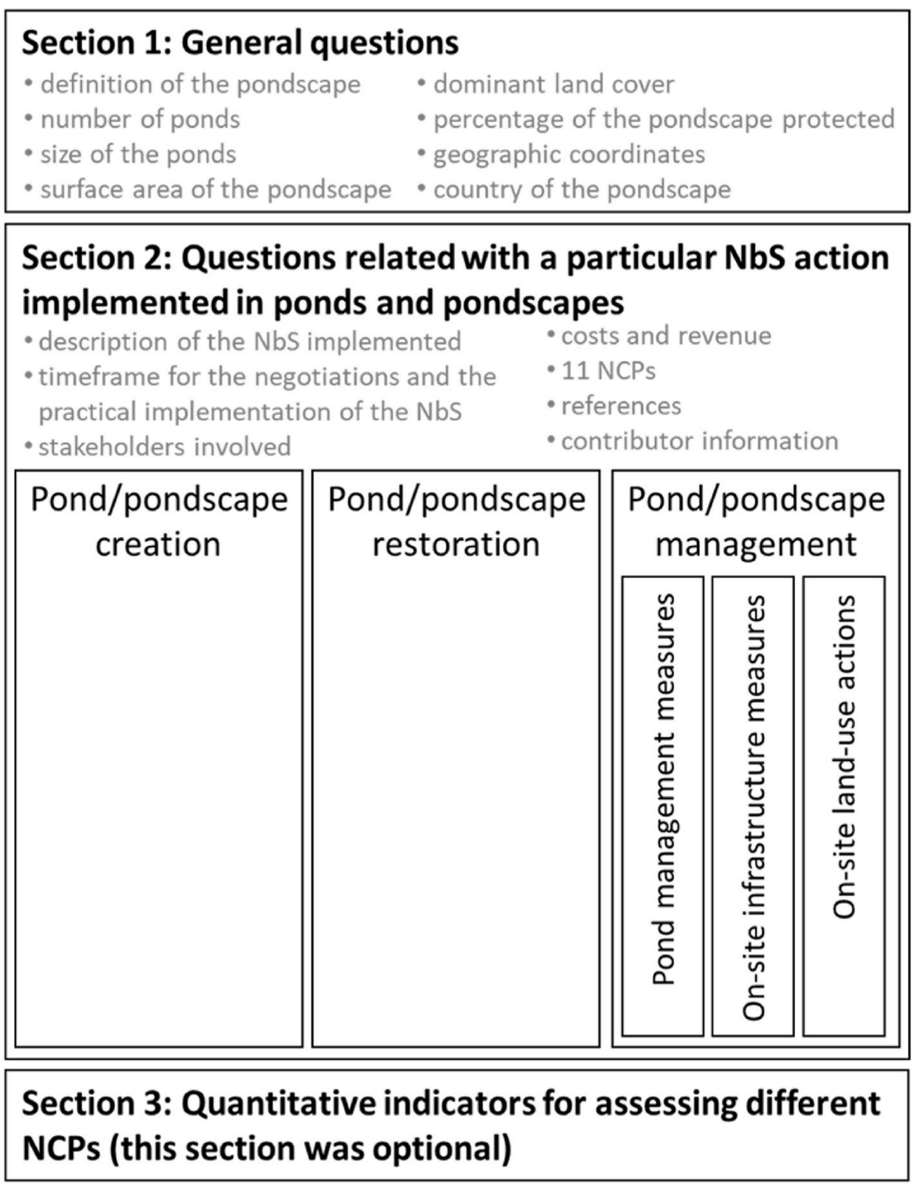

Fig. 1. Structure of the questionnaire..

2. Methods

2.1. Data collection

The information on NbS implemented in ponds/pondscapes and their associated societal and environmental benefits (NCP) was obtained through an online questionnaire (Supplementary Material 5), which was shared with different stakeholders who were actively involved in or had experience with the implementation, restoration or management of ponds/pondscapes. These included scientists, local authorities, and representatives of the private sector, such as NGOs and SMEs members. The questionnaire was sent out using the platform Survey Monkey and was distributed through professional contacts associated with the members of the European Project PONDERFUL (https://ponderful.eu/), International Scientific Societies and projects websites, newsletters, social media, and email lists, as well as utilising snowballing (when respondents suggested other potential respondents or resent the questionnaire to others). Additionally, we gathered information for the questionnaire from 31 case studies that involved NbS implemented in ponds/pondscapes from research papers, and web pages containing information on the actions, such as https://oppla.eu, https://renature-project.eu, https://climate-adapt.eea.europa.eu, https://una.city.

The respondents were asked to provide an example of an NbS action implemented in the pond/pondscape they were familiar with, an example that they considered as particularly significant and with a potential transferability to other regions in Europe and elsewhere, and were asked also to indicate the different NCP that the ponds/pondscapes NbS delivered (Table 1).

The questionnaire was organised in three sections (Fig. 1). Section 1 General questions focused on describing the selected example of NbS: name of the pondscape, the number of ponds, the size of the ponds, the surface area of the pondscape, the dominant land cover according to CORINE land cover (CLC) nomenclature from the European Environment Agency, the percentage of the pondscape protected (e.g., nature reserve), the geographic coordinates and the country where the pondscape was located.

Section 2 NbS implemented focused on the description of the NbS implemented, the timeframe for the negotiations and the practical implementation of the NbS, the stakeholders involved, their total costs and revenues of the NbS, the different NCP that the pond/s NbS delivered and the references (if relevant). Specifically, the respondent was asked to choose among 11 NCP options: *Creation of habitat for biodiversity*, *Pollination, Regulation of the climate, Regulation of water quantity, Regulation of water quality, Regulation of hazards and extreme events, Food and feed, Physical and psychological experiences, Learning and inspiration,* Supporting *identities, Maintenance of options* (Table 1). For each NCP, we inquired about the degree to which an NCP was the delivery objective when implementing the NbS (targeted NCP within each NbS), the perceived effectiveness of an NbS at delivering each NCP, the degree of confidence of the respondent in the effectiveness of the NbS at delivering each NCP, the delivery of potentially conflicting NCPs of implementing a NbS on the delivery of other NCP, and the degree of confidence in judging that through the Likert scale. In some cases, it became evident that while a particular NCP was not the primary target, the implemented NbS still demonstrated significant effectiveness in delivering this NCP, sometimes even surpassing the intended target. As a result, these NbS were considered in the analysis. We did not specifically mandate NbS to be multifunctional or to provide benefits to both human well-being and biodiversity. Section 2 was repeated five times with slight modifications adapted to each NbS type: 1. Pond/pondscape creation, 2. Pond/pondscape restoration, and 3. Pond/pondscape management (including: 3.1. those on-site infrastructure measures (acting on areas immediately surrounding a pond/s), 3.2. pond management measures (actions within pond/s) and 3.3. on-site land-use actions that are needed to ensure the appropriate functioning of the pondscape). If the respondent had experience with implementing multiple ponds or pondscapes NbS with different purposes, they were encouraged to provide separate information for each NbS (i.e., respond to the questionnaire separately for each NbS).

Section 3 was optional and requested quantitative indicators for assessing different NCP.

All questions included both closed-ended options with predefined response choices (yes/no or Likert scale) and possibility to provide open-ended response. This approach allowed respondents to provide detailed and unrestricted responses in their own words.

2.2. Data cleaning and validation

The questionnaire respondents were requested to provide references to support their responses. A 79% of the responses related to the creation of ponds/pondscapes included a reference in the form of a scientific article, report or webpage, while 76% of the responses regarding management and 63% of the responses regarding restoration included a reference. Therefore, in most cases, the study not only captured the participants' perceptions and opinions but also allowed for a more comprehensive analysis by incorporating scientific evidence. This approach strengthens the credibility and reliability of the findings, as it combines subjective perspectives with objective information from established sources.

We ensured quality control for all responses in the questionnaire. In cases where the information provided was unclear (such as variations in pondscape names, lack of explanation for implemented NbS or targeted NCP, etc.), we proactively reached out to the respondents to seek clarification (approximately 30 study cases). If the clarification obtained remained inconclusive, the respective record was excluded from the analysis (a total of 11 study cases).

2.3. Data coding and transformation

We used coding schemes to transform qualitative responses into quantitative data. For Likert scale responses, we assigned numerical values accordingly: 4 for "Extremely effective or confident", 3 for "Very effective or confident", 2 for "Somewhat effective or confident", 1 for "Not so effective or confident", 0 for "Not at all effective or confident", and NA for "Unknown." For binary responses, we assigned 1 for "yes" and 0 for "no". In parameters such as pond and pondscape size (area) and pond numbers, we calculated the median value of the interval to facilitate frequency calculations and visualization of the results.

2.4. Data analysis

We calculated basic statistics (e.g., percentages, medians, ranges, etc.) at the level of NbS ($n = 183$) to summarize the data and used visualizations like histograms and bar charts to identify patterns in the data.

To determine whether there were statistically significant differences in the targeted NCPs within each NbS, the effectiveness of each NbS in delivering these NCP, and in the confidence by the respondents in their responses in achieving these objectives, a post-hoc multiple comparison test was conducted using the Honestly Significant Difference (HSD) method. The significance level (α) was set at 0.05 for all statistical analyses.

We performed a principal component analysis (PCA) to discern dominant trends among NbS implementations in ponds/pondscapes in relation to their targeted NCP (i.e., the 11 NCP defined in Table 1). Additionally, we aimed to test whether these predominant trends remained consistent across the three broad categories of NbS (creation, restoration and management) by plotting the uncertainty associated with these three categories of NbS (i.e., ellipse 95% confidence regions were constructed based on the multivariate t-distribution). The data were centred but not scaled as they all shared the same scale from the outset.

To ensure comparability and meet the assumptions of parametric tests, data were normalized when necessary. Data were analysed, and all plots were generated using R v. 4.3.1 (R Development Core Team, 2023).

3. Results

3.1. NbS implemented in ponds/pondscapes

3.1.1. Types of implemented NbS

We gathered data on 183 NbS actions implemented across 93 ponds/pondscapes from 24 countries, mainly from Europe (Fig. 2), but also from other countries (Argentina, China, Palestine, Russia, Turkey, United States and Uruguay). The majority of the actions (particularly restoration and creation) were implemented over the past 20–25 years. Several actions have sometime been implemented in one pond/pondscape, resulting in the recording of multiple NbS actions for a specific pond/pondscape in the database.

Pond/pondscape creation was the most frequent (n = 80) NbS action implemented, followed by management (n = 62) and restoration (n = 41) (Table 2). Within restoration, “restoring a pond in a site where formerly a pond was existing” was the main NbS implemented (16 cases), before “significant alterations to an existing pond (e.g., pond morphometry)” (10 cases). Within management, “access restrictions” dominated (17 cases), together with “management of riparian vegetation and wetland plants” (12 cases) and “placing the pondscape (or a part of it) under protective status” (12 cases). Other frequent management actions included “development of trails or wildlife observatories” (11 cases) and “enhancing the connectivity between ponds or pondscapes” (10 cases).

The land cover (i.e., the land cover that appeared most frequently) across the pondscapes was dominated by rural areas such as farm and pastureland, forest, shrubland, grassland and wetlands (75%), with relatively few pondscapes in urban environments (17%) (Fig. SM1). Most pondscapes comprised between 5 and 25 ponds, exhibiting heterogeneity within the pondscape in terms of pond sizes (e.g., small ponds <100 m^2, to large ponds >5000 m^2), and generally encompassed very large pondscape surface areas (>10 km^2) (Fig. SM2).

3.1.2. Targeted NCPs within each NbS and NCP delivery effectiveness

The primary focus of NbS implementation was on delivering the NCP *Creation of habitat for biodiversity* – 91% (Fig. 3A). Other highly targeted NCPs were *Learning and inspiration* – 52%, *Physical and psychological experiences* – 51%, *Regulation of water quantity* – 49%, and *Regulation of water quality* – 39% (Fig. 3A). However, NCPs such as *Regulation of the climate* and *Pollination* were rarely targeted (10% and 2%, respectively).

Very few NbS (9%) did not primarily target *Creation of habitat for biodiversity;* in these cases, the NCPs were *Food and feed* and *Regulation of water quantity,* and in only one instance each, *Regulation of hazards and extreme events* and *Learning and inspiration or* Supporting *identities.*

Respondents provided insights into the effectiveness of the NbS implemented in ponds/pondscapes targeting various NCP. Overall, the NbS actions were considered effective in delivering most targeted NCPs (i.e., *Creation of habitat for biodiversity*, *Learning and inspiration*, *Regulation of hazards and extreme events*, *Regulation of water quantity*, and *Physical and psychological experiences*) (Fig. 3C). The NbS were perceived as less effective in providing the NCPs of *Pollination* and *Regulation of the climate* (p-value <0.05). The confidence of respondents in the effectiveness of the NbS in delivering the targeted NCP reflects a similar pattern (Fig. 3D).

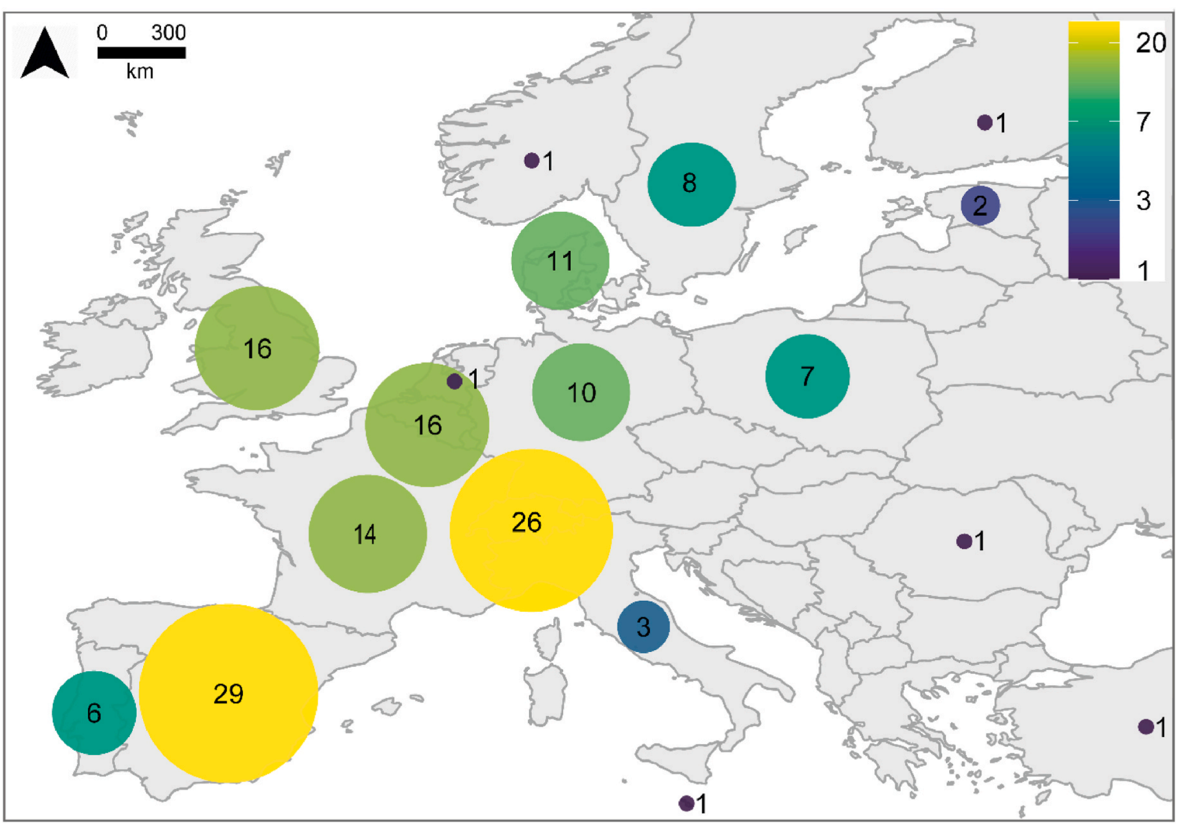

Fig. 2. Number of NbS actions implemented in ponds/pondscapes of Europe, considered in this study. In the database there are also other countries represented (Argentina n = 4, China n = 1, Palestine n = 2, Russia n = 1, Turkey n = 1, United States n = 4, and Uruguay n = 17). The range of colours and sizes of the circles are related to the number of NbS implemented in each country (blue/small: 1 case to yellow/large: up to 29 cases). Note that a particular pond/pondscape could involve implementation of more than one type of NbS, and thus was recorded multiple times in the database.(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
List and number of the 183 Nature based Solutions (NbS) compiled in the database. Some case studies implemented multiple NbS simultaneously within each category. *Within each category (NbS pond/pondscape creation, restoration and management), the respondents were able to select more than one subcategory. Therefore, the sum of subcategories within each category may exceed the count of the category itself.

NbS	Number
1. Pond/pondscape creation Creating one or several ponds in a site where there was formerly no waterbody.	**80**
2. Pond/pondscape restoration Any kind of measure to restore ponds that are damaged or lost:	**41***
Creating or restoring a pond in a site where formerly a pond was existing, e.g., excavating a pond that had been filled in.	16
Significant alterations to an existing pond, e.g., depth, morphometry, slopes, shoreline design, flora or fauna.	10
Both restoration actions.	4
No specification.	11
3. Pond/pondscape management Three subcategory of actions:	**62**
3.1. Pond management measures Actions within pond/s:	**16***
Removing invasive alien plant and animal species.	4
Removing all fish.	1
Reintroducing or protecting threatened plant and animal species.	3
Pond water management, e.g., manage input, output (e.g., sluice repair or adjustments, lining), drying rate.	3
Routine management actions in relation with the pond design and depth (e.g., slight re-profiling of banks, removal of sediments, creation, or removal of an island, scraping edges to maintain populations of pioneer species).	1
Mowing and removal of submerged, floating, or emergent plants.	2
Regular monitoring of physical, chemical, or biological indicators.	7
Planting or introducing structured vegetation into ponds (e.g., planted coir rolls).	2
Shade management (e.g., a few trees or large % of cover).	2
Part-desilt.	1
Other.	1
3.2 Pond infrastructure measures Actions on areas immediately surrounding a pond/s:	**27***
Access restrictions, e.g., fencing to prevent access by livestock, dogs, or visitors - or removing fencing to allow livestock access.	17
Development of trails or wildlife observatories.	11
Management of riparian vegetation and wetland plants.	12
Removal of invasive alien plant species.	6
Implementation (or enlarging) of a buffer area immediately surrounding the pond.	8
Creation of terrestrial habitats in the vicinity of the pond (e.g., for reptiles or amphibians).	8
Removal of hard infrastructure (e.g., concrete edge).	0
Other.	10
3.3 Land-use actions that are needed to ensure the appropriate functioning of a pondscape. They can be local (pond scale, e.g., small-scale) or regional (pondscape, e.g., large-scale), or both:	**19***
Placing the pondscape (or a part of the pondscape) under protective status (e.g., protected areas regulations).	12
Changing land use in the pondscape and in the area surrounding the pondscape (e.g., convert arable land or intensive livestock grazing area to extensive grassland; decrease impervious surfaces e.g., asphalt in neighbouring areas).	7
Enhancing the connectivity between ponds or pondscapes. This involves the creation of terrestrial or aquatic corridors, removing obstacles, or active transport of propagules.	10
Other.	4

3.1.3. Multifunctionality of the implemented NbS

The implemented NbS demonstrated high multifunctionality, with an average delivery of 4 targeted NCP per NbS (Fig. 4A). The most frequent combination of 4 NCPs included *Creation of habitat for biodiversity*, *Learning and inspiration*, *Regulation of water quantity*, and *Physical and psychological experiences* (13%). Mono-functionality was nevertheless also present in a limited number of cases (8%). When the NbS targeted the delivery of only one NCP, *Creation of habitat for biodiversity* was most common (Fig. 4B).

The dominant trends among NbS implementations within ponds/pondscapes, concerning the delivery of their targeted NCP, highlight that besides focusing on *Creation of habitat for biodiversity*, the implemented NbS concurrently pursued the delivery of three primary objectives (Fig. 5). These objectives align with the NCP groups described by IPBES (Díaz et al., 2018): (1) non-material or cultural NCPs (*Physical and psychological experiences*, Supporting *identities* and *Learning and inspiration*), (2) regulating NCPs (*Regulation of hazards and extreme events*, *Regulation of water quality*, *Regulation of water quantity* and *Regulation of the climate*), and (3) material NCPs (*Food and feed* provision). Usually if the NCP targeted in the implementation of an NbS was regulation, it concurrently addressed other regulating NCPs. The concurrent pursuit of the NCPs *Maintenance of options* and *Water regulation* was infrequent in the majority of implemented NbS (PCA1 – 29% explained variance, Fig. 5). The same was valid for the NCP *Food and feed*, and *Creation of habitat for biodiversity* and non-material NCP in most NbS, albeit with weak explanatory capacity (PCA2 – 18% explained variance, Fig. 5). This second PCA further underscores the association between *Creation of habitat for biodiversity* and non-material NCPs in the implementation of NbS, and between *Food and feed* and regulating NCPs. *Regulation of the climate* and *Pollination* made a relatively minor contribution to the overall data gathered in comparison to other NCP. The analysis showed that these predominant trends remained consistent across creation, restoration and management NbS actions (illustrated by ellipses in Fig. 5). However, *Food and feed* was more closely associated with creation and management actions than restoration actions; and there were no direct associations between regulatory NCPs and certain non-material or cultural NCP (i.e., *Physical and psychological experiences* and *Learning and inspiration*) with management actions.

3.1.4. Conflicting NCP

In 21% of the 183 implemented NbS actions, respondents acknowledged conflicting effects on the delivery of other NCPs, implying that the implementation of the action with the aim of delivering a specific NCP had negative effects on other NCP. The NbS actions targeting *Food and feed,* showed the highest conflicting effects on delivery of other NCPs, including *Creation of habitat for biodiversity*, *Regulation of water quality*, *Regulation of the climate*, *Pollination*, and *Regulation of water quantity* (Fig. 6). The delivery of all other NCP showed low conflicting effects with the delivery of other NCP and, when present, they predominantly influenced the *Creation of habitat for biodiversity*. In accordance, the NCP most negatively affected was *Creation of habitat for biodiversity*, but also *Regulation of water quality*, *Regulation of water quantity*, and *Food and feed*. In contrast, non-material or cultural NCPs such as *Physical and psychological experiences*, Supporting *identities* and *Learning and inspiration* were perceived as less affected by the implementation of NbS action with other objectives.

3.1.5. NbS that focus on adaptation and mitigation to climate change

The implementation of NbS frequently aimed to deliver NCPs related to climate change adaptation. For example, NCPs like *Regulation of hazards and extreme events* or *Regulation of water quantity* were frequently targeted (32% and 49%, respectively). Moreover, NbS often prioritized delivering other NCPs such as *Creation of habitat for biodiversity*, promoting *Learning and inspiration*, and fostering *Physical and psychological experiences* (91%, 52%, and 51%, respectively), which indirectly support climate change adaptation. However, the delivery of the NCP *Regulation of the climate* was rarely targeted (10%), and in most cases (71%), it was not the primary focus.

3.2. Implementation process of the NbS

3.2.1. Stakeholders involved in the implementation of NbS

The public (excluding policymakers) and private sectors were the stakeholders with the highest involvement in all NbS (creation, restoration, and management, with both formal and informal roles; 46%), followed by scientists (23%) and civil society (19%), while the policymakers were least involved (11%) (Fig. SM3). Most stakeholders had formal involvement in the NbS implemented (73%), but civil society and

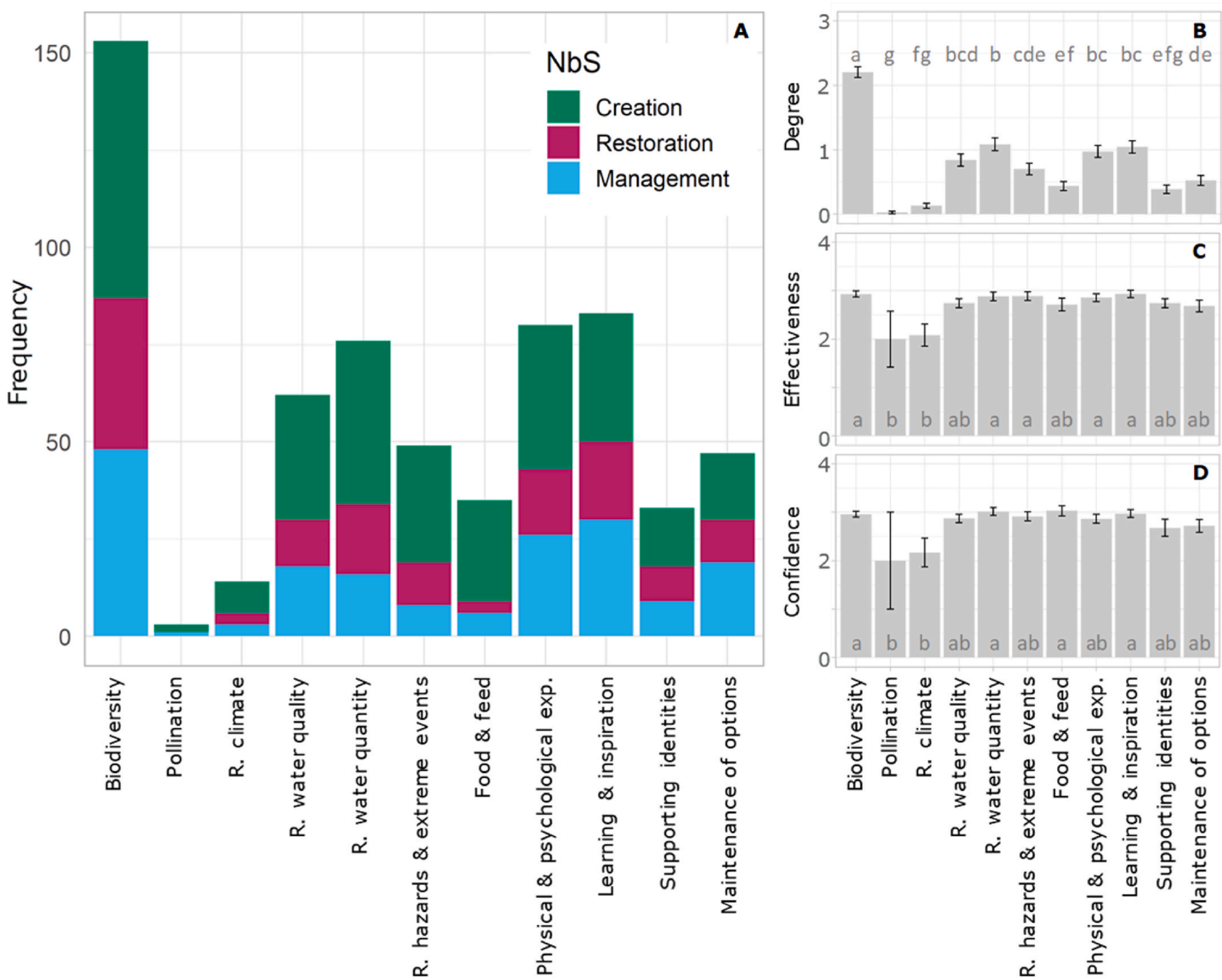

Fig. 3. (A) Frequency of each of the 11 Nature Contributions to People (NCP) selected as objective for each of the 183 NbS (creation, restoration, and management) (1: yes, 0: no). (B) Degree to which the delivery of an NCP was the objective when implementing the NbS in a particular pond/pondscape (3: high degree, 0: it was not an objective). (C) Effectiveness of a pond/pondscape at delivering each NCP (4: Extremely effective, 3: Very effective, 2: Somewhat effective, 1: Not so effective, 0: Not at all effective). (D) The respondents' confidence regarding the answer on effectiveness (4: Extremely confident, 3: Very confident, 2: Somewhat confident, 1: Not so confident, 0: Not at all confident). Biodiversity: *Creation of habitat for biodiversity*; R. climate: *Regulation of the climate*; R. water quality: *Regulation of water quality*; R. water quantity: *Regulation of water quantity*; R. hazards & extreme events: *Regulation of hazards and extreme events*; Food & feed: *Food and feed*; Physical & psychological exp.: *Physical and psychological experiences*; Learning & inspiration: *Learning and inspiration*. Letters (a, b, c, d) assigned to different groups indicate statistically significant differences between group means (*p-value* = 0.05) for a post-hoc Multiple Comparison Test Using HSD (Honestly Significant Difference) Method..

scientists were also selected by the respondents as having an informal role (20%).

3.2.2. Timeframe for the negotiation for the implementation of the NbS

The median timeframe for the negotiation (e.g., political negotiations, site permissions, etc.) for the implementation of the NbS, from the idea to the establishment, was 9 months, but showing a large range (1–156 months, Fig. SM4). The median implementation time for the NbS in practice was 2 months, also evidencing a large range (1–240 months), with the specific subcategory pondscape scale land use actions within management actions requiring longer times (median: 36 months; range: 24–63 months) (Fig. SM4).

3.2.3. Costs of NbS implementation

The specific costs associated with each NbS were very variable and depended on the project scope, objectives, geographic location, socio-economic-cultural system, and the specific activities and resources required for implementation. Among the NbS, the creation of ponds/pondscapes usually required the highest financial investment, with a median cost of 175,750 Euros - 310 Euros/ha (range: 600-13M Euros – 0.1–2.2M Euros/ha, Fig. 7). Within this category of pond creation, 17% exceeded 1M Euros (7%>1M Euros/ha), specifically focused on creating pondscapes (>1 pond), 71% of the cases included landscape management measures, such as road path adjustment, topography updates, site decontamination, and groundwater circulation improvements. The majority (60%) of these actions with cost information were implemented in urban settings, predominantly in Switzerland, Denmark, Netherlands, Norway, and Spain. One exceptional case had costs exceeding 10M Euros, which involved the creation of a single large pond for water retention in Switzerland; these costs included the expensive land acquisition near an urban area. Restoration actions had a median cost of 15,000 Euros - 55 Euros/ha (range: 600-1.6M Euros - 0.1–1M Euros/ha). Among the restoration actions with cost information, 11% exceeded 1M Euro (8%>1M Euros/ha), with 66% of these actions

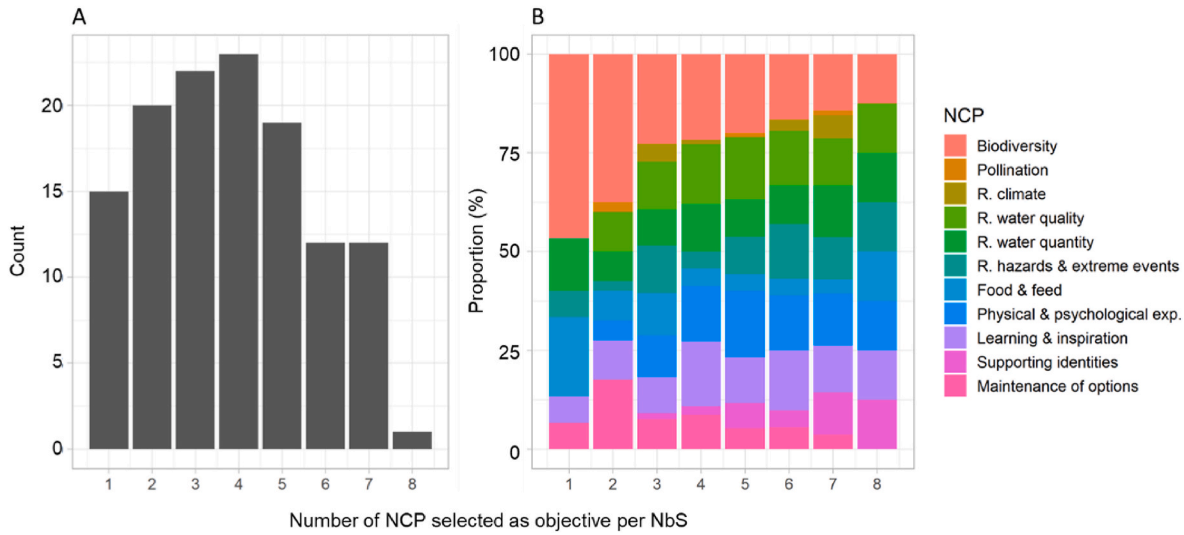

Fig. 4. Total count (A) and proportion (B) of Nature Contributions to People (NCP) selected as objective for each NbS action implemented in ponds/pondscapes. For example, 15 NbS only targeted the delivery of one NCP when implementing the creation, restoration or management actions. Among these, 47% targeted the delivery of only *Creation of habitat for biodiversity*, 20% *Food and feed*, 13% *Regulation of water quality* and 7% *Regulation of hazards and extreme events*, *Learning or inspiration* and *Maintenance of options*. For abbreviations see Fig. 3..

implemented in urban environments and focused on modifications of a single pond (e.g., depth and perimeter of the ponds, removal of the hillock) in Spain, Romania and Poland. Management actions with cost information had the lowest median cost of 5677 Euros - 22 Euros/ha (range: 500-4M Euros - 0.03–23m Euros/ha). Among the management actions, 8% exceeded 1M Euro (none>1M Euros/ha), which included whole pondscapes (>1 pond) from the United States and Spain. The costs were mainly attributed to de-urbanisation efforts and preservation of natural drainage corridors (including streams, ponds, and wetlands).

4. Discussion

4.1. The NbS based on ponds/pondscapes

The database includes 183 NbS, particularly creation, restoration and management actions implemented in ponds/pondscapes from Europe, but also from other countries (Argentina, China, Palestine, Russia, Turkey, United Kingdom, United States and Uruguay). In general most NbS initiatives tend to focus on urban areas (Sarabi et al., 2019) and green infrastructure (Pauleit et al., 2017; Wild et al., 2017), however, this database reveals that a large proportion (two-thirds) of the actions in ponds/pondscapes were implemented in rural areas. While, due to the nature of respondents' selection process, our results cannot be seen as representative for all NbS worldwide, it highlights the importance of pond/pondscape NbS in rural areas. Rural areas can benefit greatly from NbS, as they often face unique challenges related to land use and climate change, especially in the agricultural sector and in relation to water management (Keesstra et al., 2018). Furthermore, the NbS implemented in rural areas are often tightly linked to urban areas, as many deliver NCP promoting the well-being of citizens (e.g., flood risk reduction in downstream cities, leisure, relaxation). Specifically, our results showed that approximately 45% of the NbS focused on creating new ponds/pondscapes, while ponds/pondscapes management and restoration actions accounted for approximately 35% and 20%, respectively.

The implemented NbS prioritized the delivery of the NCP *Creation of habitat for biodiversity*, accounting for ca. 90%. This aligns with the definition of NbS: implementation of actions to address societal challenges while simultaneously providing benefits for human well-being and biodiversity (IUCN, 2020), including the achievement of Sustainable Development Goals (SDGs). Thus, the *Creation of habitat for biodiversity* should be an integral element of any NbS. Particularly, creating, restoring and managing ponds/pondscapes, should aim at supporting and promoting the richness and diversity of aquatic—but also terrestrial— species and ecosystem functions (Cuenca-Cambronero et al., 2023; Oertli et al., 2023).

Besides focusing on *Creation of habitat for biodiversity*, the implemented NbS also targeted the delivery of other NCP. In most cases, the delivery of multiple NCP was pursued simultaneously to achieve three main objectives: non-material or cultural NCPs (*Physical and psychological experiences*, Supporting *identities* and *Learning and inspiration*), regulating NCPs (*Regulation of hazards and extreme events*, *Regulation of water quality*, *Regulation of water quantity* and *Regulation of the climate*), and material NCP (*Food and feed* provision). These objectives align with the three groups of NCP described by IPBES (Díaz et al., 2018).

The delivery of non-material NCPs, which encompasses recreational, aesthetic, and spiritual values associated with nature, was identified as the second most important target when implementing a NbS. These NCPs contribute to people's well-being and quality of life by providing opportunities to actively engage with and enjoy nature including fishing, boating, wildlife watching, picnicking, contemplation, connection to nature or healing. They also play a direct role in our adaptation to climate change (i.e., warming), offering aquatic areas where freshness can be perceived (e.g., during walking or resting) or directly experienced (e.g., swimming), as it was evidenced for example in Bois de Jussy (Switzerland). By preserving and restoring natural habitats, actions that provide non-material NCPs also have a positive impact on biodiversity conservation, as healthy ponds provide essential habitats for a wide range of species, promoting biodiversity and supporting ecological balance (Naeem et al., 2016). Indeed, our results also show that respondents closely associated these non-material NCPs with biodiversity, for example by mentioning nature watching trails or observatories that allow people to engage with and appreciate the surrounding biodiversity,

Additionally, ensuring effective solutions for water regulation was also frequently targeted. Examples provided of such solutions included the regulation of water flow, the mitigation of flood risks, and the improvement of water quality, and in many cases, they were also linked with non-material NCPs. The creation of ponds in agricultural landscapes can act as natural retention basins, buffering the flow of water and preventing its rapid discharge into rivers or other water bodies thereby reducing flood risk (Hefting et al., 2013; Kędziora et al., 2011;

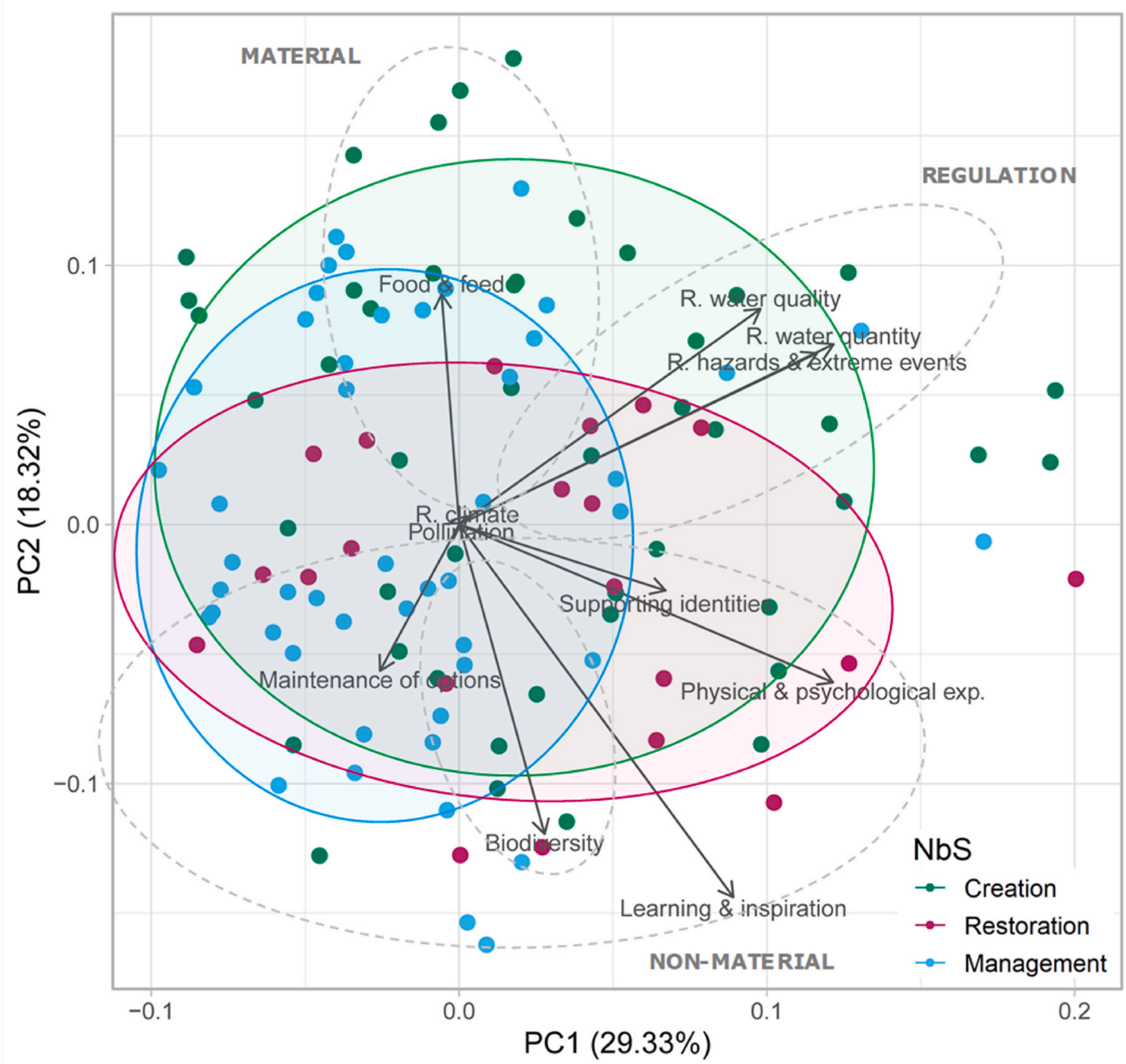

Fig. 5. Principal Component Analysis (PCA) results for the NCP selected as objective in each category of NbS (creation, restoration, management). Each of the 183 NbS is represented by a coloured marker, green representing creation, red restoration and blue management. The explained variance ratio indicates the proportion of total variance explained by each principal component. In this analysis, PC1 explains 29.33% of the variance, while PC2 explains 18.32% of the variance. The coloured ellipses represent the 95% confidence regions for a multivariate t-distribution for each category of NbS. Grey dashed lines are used as visual aids to represent the three broad groups described by IPBES (Díaz et al., 2018), namely material, non-material, regulation, in addition to biodiversity. For abbreviations see Fig. 3.(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Short et al., 2019). Well-planned NbS actions aiming at water regulation can effectively complement traditional approaches, providing natural pathways for climate change adaptation and delivering significant economic benefits (Hankin et al., 2021).

The database also includes several examples of NbS that predominantly prioritise the delivery of the NCP *Food and feed*, with a particular focus on water storage for livestock, particularly in cases from Uruguay and France. Indeed, the majority of these cases (80%) also show a high perceived effectiveness in providing relevant water regulation NCPs. On the contrary, the delivery of the NCP *Food and feed* was typically not pursued concurrently with *Creation of habitat for biodiversity* and other non-material NCP. This highlights the potential trade-offs and challenges associated with prioritising the delivery of specific NCP aspects over others when implementing NbS in ponds. While addressing the immediate needs of resources like water and food for livestock is undoubtedly important, adopt a more holistic and integrated approach is crucial. This approach should incorporate the delivery of multiple NCP objectives, preferably at the pondscape scale (Hambäck et al., 2023). A notable example of such integration can be found in the Dombes region (France) where pondscapes were created by private landowners for hunting and fish farming, concurrently promoting biodiversity.

Pollination was not often targeted as an NCP in the implementation of NbS in ponds/pondscapes. Despite a growing acknowledgment of the crucial role pollinators play in ecosystem functioning and food production (Ollerton, 2017), *Pollination* was not seen in the results of the questionnaire as an important NbS objective. However, in the cases where *Pollination* was targeted as an objective, it demonstrated effectiveness in farmland pondscapes from Norfolk-United Kingdom and Trönningeån-Sweeden targeting biodiversity conservation and nutrient retention. Recent studies show that NbS implemented in ponds/pondscapes can notably enhance flower resources for pollinating insects through the establishment of diverse micro-habitats within and around ponds (Walton et al., 2021).

Overall, the implemented NbS in ponds/pondscapes demonstrated high multifunctionality by promoting several NCP, as reported by respondents. On average, each NbS action contributed to the promotion of

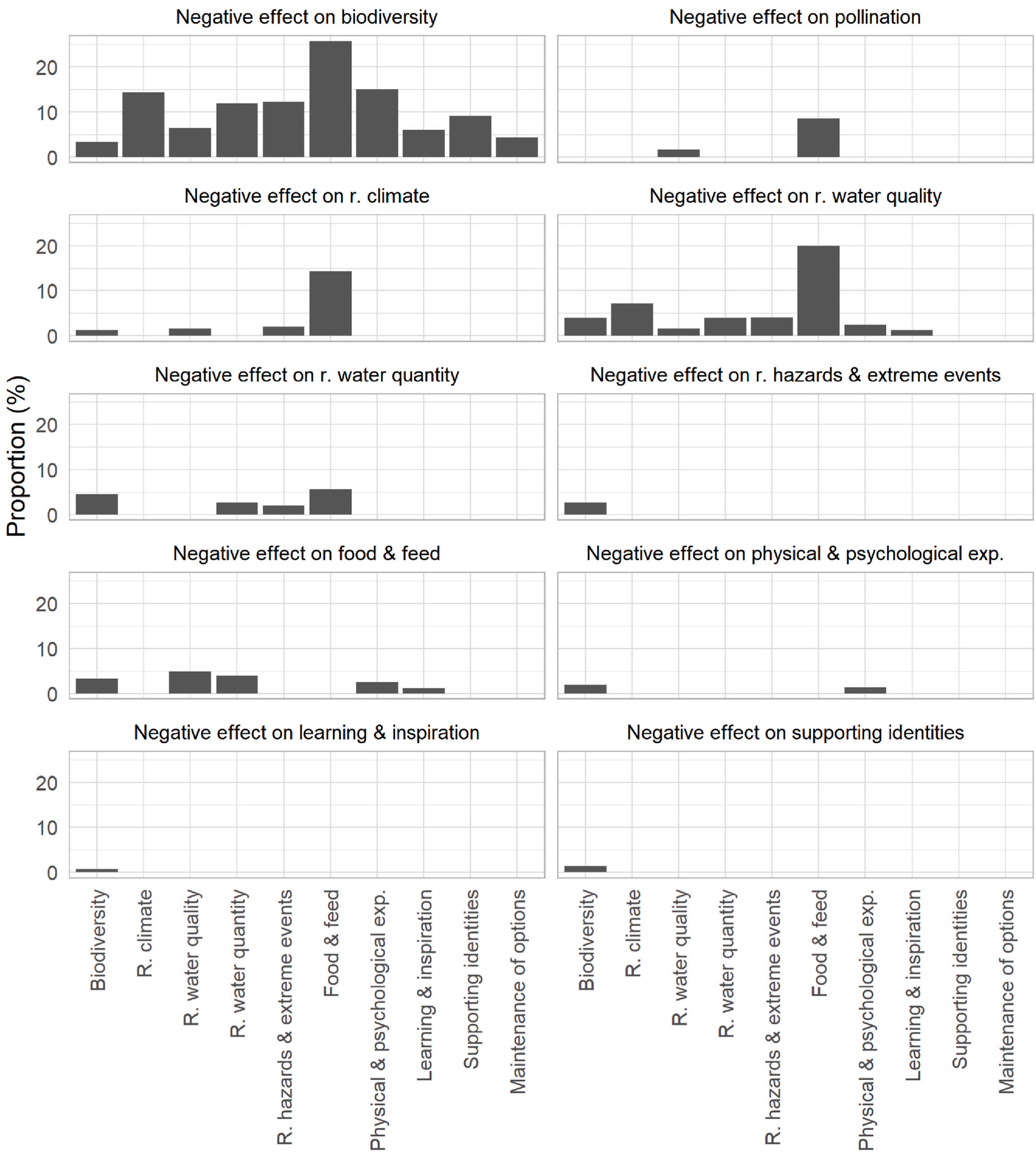

Fig. 6. Conflicting NCPs: negative effect (in percentage) with the objective of delivering a particular NCP (x axis) on other NCP (filled colours). The percentage was calculated as the number of times the delivery of an NCP (NCP1) had a negative effect on the delivery of another NCP (NCP2) divided by the total number of times the delivery of NCP1 was selected as objective. We only show the NCP that were selected as objective >10 times. For abbreviations see Fig. 3..

four NCP. These effective multifunctional NbS implementations highlight the potential for addressing multiple environmental and societal challenges simultaneously. Only a small percentage (8%) of the selected NbS focused only on the delivery of one NCP. According to the definition of NbS provided by the IUCN (2020), these cases would be at the threshold of being considered a real NbS. Nevertheless, the coupling of several mono-functional ponds (each with a different objective) in a pondscape, may turn a pond into a relevant part of an NbS (Hambäck et al., 2023).

The respondents considered NbS as highly effective in delivering the targeted NCP. This high confidence in the design, implementation, and the observed/expected outcomes of the actions, was evident in the

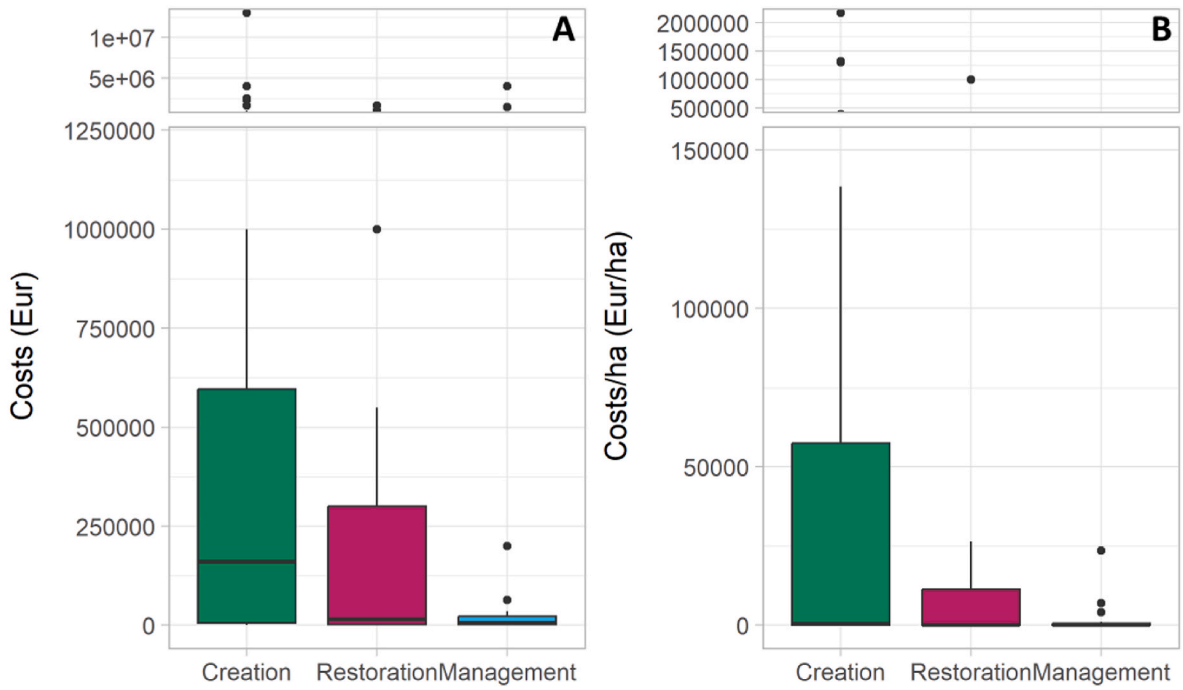

Fig. 7. Boxplot illustrating the costs (A) and costs/ha (B) (in Euros) for the implementation of each NbS category (creation, restoration and management). The boxplot displays the median (line within the box), interquartile range (box), and range of the data (whiskers). Outliers are represented as individual points beyond the whiskers.

answers and supported by the references provided. The high degree of effectiveness reported aligns with the purpose of the questionnaire, which specifically requested respondents to provide examples of an NbS implemented in their respective areas, with a focus on their potential applicability and interest for other regions in i.e., Europe. Therefore, most of the examples provided can be considered as a compilation of successful practices. In contrast, approximately 20% of the respondents acknowledged the possibility of conflicting effects arising from the implementation of NbS on the delivery of a non-targeted NCP. Among these cases, the NbS aimed at providing *Food and feed* exhibited most conflicting effects on the delivery of other NCP, such as on *Regulation of water quality* (for downstream areas) and *Creation of habitat for biodiversity*, but less frequently on *Regulation of the climate*, *Pollination*, or *Regulation of water quantity*. Most of these observations came from the creation of pondscapes primarily designed for agricultural functions (e.g., watering cattle in Uruguay). Stakeholders involved in these pondscapes—located entirely within privately owned lands—favour economic over environmental benefits, and thus other potential benefits, like preventing potential water eutrophication, are not actively pursued. Additionally, within the 20% of NbS with conflicting effects, the *Creation of habitat for biodiversity* was perceived as the NCP most negatively affected. *Regulation of water quality* and *Regulation of water quantity*, and *Food and feed*, were also among the negatively impacted NCPs as observed by Erisman et al. (2016). While NbS aim at holistic and integrated approaches, it is crucial to carefully balance the trade-offs and ensure that the *Creation of habitat for biodiversity* remains a fundamental consideration.

4.2. Ponds/pondscapes NbS for adaptation to climate change

The implemented NbS exhibited a significant emphasis on the delivery of NCP related to climate change adaptation policies rather than NCP focused on directly regulating the climate by reducing greenhouse gas emissions or enhancing carbon sinks. In this sense, the delivery of NCP such as the *Regulation of hazards and extreme events* and *Regulation of water quantity* received frequent attention. Furthermore, the delivery of other NCPs, including *Creation of habitat for biodiversity*, *Physical and psychological experiences* and *Learning and inspiration*, indirectly contribute to climate change adaptation and were also frequently targeted to help maintaining suitable microclimates, buffer temperature fluctuations, provide habitat for diverse species that contribute to ecosystem resilience and simultaneously provide recreational opportunities, cultural values, educational benefits, and contribute to the overall well-being of local communities affected by climate change. Contrary, there was a relatively minor focus on climate change mitigation (*Regulation of the climate* NCP - 10%). This contrasts from policy approaches, where adaptation is often less developed (Lesnikowski et al., 2015, 2017), despite the United Nations Framework Convention on Climate Change, aiming to prioritise adaptation equally with mitigation (Lesnikowski et al., 2017), indicates a positive shift towards considering adaptation with the increased utilisation of NbS.

The low focus of the ponds/pondscapes NbS on the NCP *Regulation of the climate* is also linked to the lack of scientific knowledge in this field. The importance of the ponds for the carbon cycle has been only recently recognised for and is still under investigation (e.g., in the EU H2020 program PONDERFUL). On one hand, ponds are sequestering a large amount of carbon (Downing et al., 2008; Taylor et al., 2019), on the other hand they also producing CO_2, CH_4 and NO_2 (Holgerson and Raymond, 2016). The balance between sequestration and production is still unclear, as also the factors that influence this balance in one direction or the other. This highlights the importance of encouraging research in this field and to promote the flow of information among interested actors, including stakeholders, the public and policy makers.

4.3. Implementation process of the NbS actions on ponds/pondscapes

A range of stakeholders was formally involved in the implementation of NbS; however, an informal involvement of civil society and scientists is worth mentioning. These actors often work as intermediaries between local communities and other stakeholders (Kiss et al., 2022), advocating for the adoption of NbS, raising awareness, and mobilising support, while the later conducting research, assessing the effectiveness of NbS, and providing expert knowledge. Ryfisch et al. (2023) emphasised that for many pondscapes the involvement of civil society is crucial in advancing NbS through advocacy, policy changes, and direct implementation.

The implementation sequence of NbS in pondscapes can vary based on the project-specific goals, context, associated complexities, and available resources. For instance, among the NbS included in our database, the oldest ones were related to pondscape scale land use actions. An example of such an action took place in Vanhankaupunginlahti, Old Town Bay, Finland already in 1959. Furthermore, our results showed that the implementation of pondscape scale land use actions tend to require more time compared to other pond/pondscape NbS (36 months for pondscape-scale action compared to 2 months for all other actions). This indicates that the planning, coordination, and execution of these land use actions in pondscapes can be complex and time-consuming due to factors such as stakeholder involvement, permitting processes, and resource mobilisation.

There was a wide range of NbS costs, which depended on project-specific factors such as size, complexity, and geographical and political requirements. A comprehensive understanding of these factors and conducting thorough cost assessments are essential for promoting the effective implementation of NbS initiatives, particularly now as we strive to find effective solutions for addressing aquatic biodiversity loss (Lago et al., 2019) and climate resilience (Van Zanten et al., 2023). Increased understanding on the financial accountability of NbS actions is needed to leverage public and private sources of financing. This is ultimately a necessary condition to pave the way for increased NbS uptake and implementation (McDonald et al., 2023).

The main trends and the median unit costs for pond creation (310 Euros/ha), restoration (55 Euros/ha) and management (22 Euros/ha) underline that actions implemented in ponds/pondscapes might have significant potential as cost-effective NbS, especially considering the multiple benefits delivered. In addition, emerging evidence suggests that ponds/pondscapes are likely to have positive benefit to cost ratios, making them attractive investment opportunities along socially desirable options to address environmental concerns (Trémolet et al., 2019). All these aspects contribute to their reputation as unexpensive management solutions if compared with grey infrastructure alternative management approaches (Bassi et al., 2021).

5. Conclusion

Our analysis of approximately a hundred case studies evidenced the high potential of utilising ponds/pondscapes NbS to address environmental and societal challenges, including the achievement of Sustainable Development Goals (SDGs). Our analysis of ponds/pondscapes creation, restoration and management actions showed i) the significance of these NbS in rural contexts, effectively addressing unique challenges related to land use and climate change, particularly in agriculture and water management sectors; ii) the wide range of NbS objectives, and thus the delivery of the targeted NCP, with the *Creation of habitat for biodiversity* being the predominant, coinciding with the holistic approach to NbS use; iii) the high NbS effectiveness in promoting NCP; iv) the high multifunctionality of these NbS for their simultaneous promotion of biodiversity, provision of cultural values, regulation and purification of water, and enhancement of *Food and feed* provision through water storage for livestock; v) the trade-offs in prioritising certain NCPs, such as *Food and feed* provision, which may conflict with other NCPs, particularly the *Creation of habitat for biodiversity*; vi) the focus on climate change adaptation, particularly through the *Regulation of hazards and extreme events* and *water quantity*; vii) the limited explicit focus on climate change mitigation, indicating the need for further exploration of NbS's role in climate regulation; and vii) the emergence of pond/pondscape NbS as promising cost-effective strategies, underscoring their potential as impactful investments in enhancing climate resilience with multiple benefits.

CRediT authorship contribution statement

Mireia Bartrons: Conceptualization, Formal analysis, Investigation, Writing – original draft. **Carolina Trochine:** Investigation, Validation, Writing – review & editing. **Malgorzata Blicharska:** Writing – review & editing, Conceptualization. **Beat Oertli:** Conceptualization, Writing – review & editing. **Manuel Lago:** Conceptualization, Writing – review & editing. **Sandra Brucet:** Conceptualization, Writing – review & editing.

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.

Data availability

The data is available through Zenodo: zenodo.org/records/10419359

Database of best practice for pondscape NbS for CC adaptation and mitigation (Original data) (Zenodo)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.120992.

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