Nature-Based Solutions 3 (2023) 100047

Contents lists available at ScienceDirect

Nature-Based Solutions

journal homepage: www.elsevier.com/locate/nbsj

How would nature design and implement nature-based solutions?

Alessandro Bianciardi[a,*], Niccolo' Becattini[b], Gaetano Cascini[b]

[a] *Planet s.a.s, Italy*
[b] *Politecnico di Milano, Department of Mechanical Engineering, Milan, Italy*

ARTICLE INFO

Keywords:
Biomimicry
Biologically-inspired design
Nature-based solutions
Green-grey infrastructure

ABSTRACT

Nature-based Solutions (NbS) are gaining momentum as potential solutions to restore, preserve and enhance ecosystem services for societal challenges, in general. In particular they improve ecological, social and economic urban resilience. As nature provides structure and carries out functions in NbS, from a designer's perspective, it is beneficial to explore and understand the strategies and mechanisms that living systems deploy to carry out those functions (ecosystem services) we are looking for. To date, exploration of the biological and ecological domains has mainly been instrumental in answering the question: *how does nature provide ecosystem services?* This type of broad inquiry, however, may not allow the identification of best practices to set up successful NbS projects. What if the question was: *how would nature design and implement NbS?* This inquiry falls within the domain of biomimicry. This work mainly aims at introducing the benefits that biomimicry or a biologically-inspired design (BID) approach could bring to address technological barriers and knowledge gaps currently hampering NbS diffusion. The work starts by clarifying if and how bio-inspiration is embedded within the main definitions of NbS (which also lead to determining the official definition of NbS by the European Commission). Furthermore, initial elements are provided to apply a bio-inspired approach to NbS. The approach is demonstrated on three levels:

i) Formulation of broad principles/guidelines for NbS (based on *Life Principles*);
ii) Generation of bio-inspired ideas (for green-grey, blue-green infrastructure) and identification of existing bio-inspired solutions which could improve various phases of the NbS project cycle (through multiple inquiries in *Asknature.org*); and
iii) Indication of on-going biomimetic research and development, which could assist in innovating NbS.

As the scientific literature seems rather dry on this specific topic, this work, far from being exhaustive, aims to contribute to kick-starting the missing dialogue surrounding NbS and bio-inspiration; a dialogue among the scientific community, as well as among all the actors involved in the NbS project cycle.

Introduction

Could a bio-inspired solution be more sustainable than a nature-supported solution in delivering the same functions to address societal challenges? Could there be benefits in terms of effectiveness and sustainability in developing solutions, which both utilise living systems and emulate the strategies of such systems? This work contributes to the conversation around these broad questions, considering that the scientific literature seems not to be addressing them in a consistent way or with a coherent approach.

Nature-based Solutions (NbS) are gaining momentum as measures to protect, restore, conserve and sustainably manage ecosystems, so as to enhance their capacity to provide provisioning, regulating, cultural and supporting services (Millennium Ecosystem Assessment [[1]am] 2005) to address societal challenges, in general, and to improve ecological, social and economic urban resilience, in particular. NbS have, therefore, the potential to contribute to the 2030 Agenda for Sustainable Development targets and to help achieving some of the UN Sustainable

* Corresponding author.
E-mail address: alexbiancia@hotmail.com (A. Bianciardi).

https://doi.org/10.1016/j.nbsj.2022.100047
Received 28 February 2022; Received in revised form 25 November 2022; Accepted 18 December 2022
Available online 19 December 2022

Development Goals (SDGs), such as those concerned with Climate Action, Sustainable Cities and Communities, Clean Water and Sanitation and Life on Land [2]. Furthermore, there are a number of European policies to which NbS are expected to contribute and these include: the Biodiversity Strategy for 2030, the Forest Strategy, the Common Agricultural Policy, the Strategy on Adaptation to Climate Change, and the Urban Agenda for the EU [3].

Emerging in the early 2000s [4,5], the concept of NbS possibly evolved because it represents not one, but clusters of solutions and tools, many of which already existed before the term NbS was even coined [6]. Despite the various definitions of NbS and the categorisation of NbS activities proposed and reviewed in the scientific literature [7,8,4,9,10], three definitions are mostly quoted [5]. One definition was formulated by the International Union for Conservation of Nature (IUCN) and two were attributed to the European Commission (EC) in two different contexts:

- **IUCN definition**: [NbS] "*actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits*" (E. [11]). According to IUCN, NbS can be considered as an umbrella concept for ecosystem-related approaches which address societal challenges. These approaches can be placed into five main categories: ecosystem restoration approaches, issue-specific ecosystem-related approaches, infrastructure-related approaches (i.e. green infrastructure), ecosystem-based management approaches, and ecosystem protection approaches. In most cases, these approaches are complementary and sometimes overlapping. The essence of this definition was recently revised and adopted by the UNEA in this formulation: [NbS] "*actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits*" [12]
- **EC definition n.1**: [NbS] "*aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions which are inspired by, supported by or copied from nature. Some involve using and enhancing existing natural solutions to challenges, while others are exploring more novel solutions, for example mimicking how non-human organisms and communities cope with environmental extremes. Nature-based solutions use the features and complex system processes of nature, such as its ability to store carbon and regulate water flow, in order to achieve desired outcomes, such as reduced disaster risk, improved human well-being and socially inclusive green growth. These nature-based solutions are ideally energy and resource-efficient, and resilient to change, but to be successful they must be adapted to local conditions*." [13]
- **EC definition n.2**: [NbS] "*Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions. Nature-based solutions must benefit biodiversity and support the delivery of a range of ecosystem services.*" [14]

The definitions of IUCN emphasise the preservation of ecosystems which provide services to society, while the EC definitions seem more focused on using nature and natural features (there is no specific reference to ecosystems, as in the IUCN definition) to respond to societal challenges, especially in urban environments. An analysis of the different terms is provided in Nesshöver et al. [9].

All of the definitions, however, agree that NbS are based on the utilisation of living systems combined with various degrees of (bio)diversity and interrelatedness. Furthermore, NbS should possess characteristics such as: aligning with natural ecosystem processes and supporting their adaptability, providing multiple benefits to biodiversity, people and the environment, setting up locally appropriate actions, addressing societal challenges and enhancing human well-being [5].

The flourishing of various definitions of NbS may be considered an attempt to determine more operative ones, which could be instrumental in allocating international and local funding for NbS projects, as well as to set up tools to measure their lifecycles and impacts. While the first NbS definition (by IUCN) is rather general, the EU one already contains more details which allow a better framing of NbS actions, in terms of scope and applicability, however, this does not narrow it down to the level of categories of solutions, so as to leave it open to a case-by-case assessment for the allocation of funding and the future development of innovative NbS.

According to these definitions, in NbS, living systems deliver functions (or ecosystem services) which address societal challenges. Therefore, from a design perspective, it is beneficial to explore and understand the strategies and mechanisms that living systems deploy to carry out those functions we are looking for when designing and implementing NbS.

To date, the exploration of biological and ecological domains has mainly been instrumental in answering the question: *how does nature provide ecosystem services?* The knowledge acquired allow us to generate design concepts which utilise natural features (up to entire ecosystems), representing the 'core technology' within NbS projects.

This type of broad inquiry, however, may not allow the identification of best practices to set up successful NbS projects which could be *inspired by* the functioning of biological systems, rather than being exclusively based on the exploitation of these systems.

What if we would ask ourselves: *how would nature design and implement NbS?*

In this perspective, we would let nature have a seat at the design table, informing stakeholders' decisions in all the phases and components of the NbS project cycle. Nature could provide us with insights, not only into how to provide an ecosystem service, but also on how to set up effective networks of relationships, exchange information, energy and material, and how to create industrial symbiosis or optimally integrate grey and green infrastructure (all of the necessary ingredients to make a NbS project successful).

Therefore, answering this question may not only contribute to improving the performance of living systems within NbS projects, but also generate *bio-inspired ideas*, for innovative and more effective NbS which *emulate* nature rather than just utilise it.

This work aims to:

1 Clarify if and how bio-inspiration is embedded within the main definitions of NbS; as a consequence, clarify if bio-inspired solutions can belong to the category of NbS;
2 Introducing the benefits that a bio-inspired approach could bring to address technological barriers and knowledge gaps currently hampering NbS diffusion. As the depth of scientific literature linking NbS and biomimicry/ bio-inspired design is largely a function of the specific exclusion of these latter concepts from the EC definition of NBS, this work would like to contribute to kick-starting the conversation around the potential for bio-inspired design to support NbS actions; particularly where hybrid blue-green grey/integrated NbS and engineered systems are the desired output.

Before proceeding with the formulation of the research questions, an introduction to the domain of bio-inspiration is provided, so as to frame the relevant concepts that are utilised in this work.

Bio-inspiration: terminology, concepts and methodology

As the outside (natural) world is the only 'learning space' for humans, it cannot be excluded that many of the technological solutions conceived by human kind may have been triggered by a conscious or unconscious reference to biological phenomena [15,16] and, therefore, could be branded as *bio-inspired*.

Nowadays, the process of bio-inspiration is studied as a conscious and structured approach to solve problems that uses biological phenomena as analogies. Evidence of a growing interest in bio-inspiration is given by a six-fold increase in published scientific papers on bio-inspired topics in the last two decades [17]. This is due to advanced tools for exploring and understanding living systems, as well as the development of the technology and materials to reproduce nature's solutions [18].

For the last four billion years, living systems evolved to thrive on a planet with finite resources, leveraging cyclical processes, utilising locally available renewable resources and creating conditions conducive to life [19]. Ecosystems can be considered to be examples of applied circular economies with inclusive, cooperating communities and a complex problem-solving capacity. Indeed, stimulating the creative process in design could represent another ecosystem service, not yet recognised but fundamental to contributing to sustainable development. Nature has had to solve similar challenges to those which human society is currently facing. Therefore, looking at natural strategies and mechanisms deployed by living systems could provide ideas for innovations.

The development of approaches to bio-inspiration has seen the flourishing of different terms and concepts such as *Biomimicry, Biomimetics, Bionics* and *Biologically-Inspired Design*. These terms are sometimes used synonymously, sometimes decoupled and sometimes applied for different purposes.

A distinction and relation among the terms adopted in this work, based on various sources [20,21,22,23,24] and adjusted by the author, is presented in the graph in Fig. 1. The graph considers *Bio-inspiration* as an overarching term, where a biological phenomenon is utilised consciously or unconsciously, as an analogy, to stimulate the creative process and solve any sort of problem (technical, organisational, social, economic). Bio-inspiration encompasses biomimicry, biomimetics and bionic.

While *Biomimicry* is defined by Janine Benyus as being the conscious process of emulating nature in terms of form, processes and ecosystem [19], *Biomimetics* and *Bionics* do not have a specific definition. However, as biomimicry, they are processes aiming at emulating biological processes and systems to design tangible and non-tangible solutions (e.g. robotic systems, materials, structures, algorithms) [25,26]. The three terms do not refer to any specific method or tool, nor any specific problem or domain. On the contrary, *Biologically-Inspired Design* (BID) identifies a group of methods and tools (belonging to the broader category of Design-by-Analogy approaches [27]) whose aim is to assist the bio-inspired ideation process by helping the search into biology literature, retrieving meaningful information and presenting biological phenomena by abstract models. BID methods and tools can be utilised within the approaches of biomimicry, biomimetics and bionics. A further parallel distinction could be made between *imitating* nature and being *inspired* by it, where the former refers to the translation and exact applicability of a biological phenomenon to a technological solution (e.g. artificial photosynthesis inspired by plants) and the latter to a more metaphorical utilisation of the same phenomenon (e.g. PV panels inspired by the photosynthesis of plants).

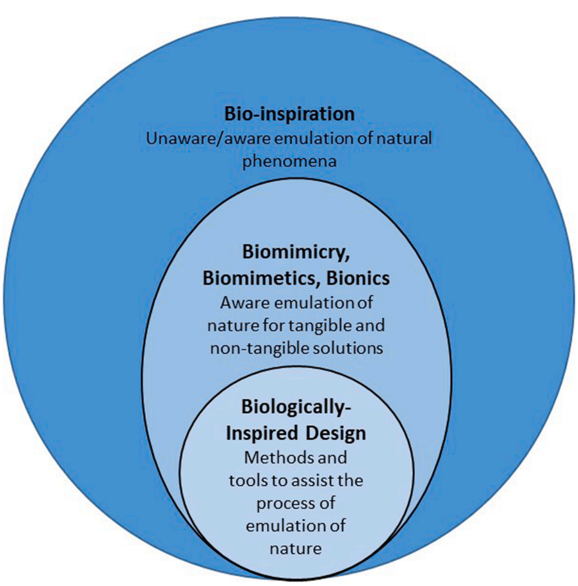

Fig. 1. A proposal for an understanding and connection among processes, methods and tools using biological systems as analogy.

Because of this transfer of analogies from the domain of biology to other domains, BID approaches are intrinsically multi-transdisciplinary, requiring the involvement of experts in biology, as well as experts in the field of the original problem to be solved. In this work, only the term biomimicry will be utilised later on and BIDs will refer to methods and tools that practice biomimicry.

BID methods have been developed by different research groups and organisations [20,28,29] and they follow two main broad approaches: *solution-driven* or *problem-driven* approaches. An approach is solution-driven when biological knowledge stimulates the solution of a specific technical problem. Problem-driven approaches start with a challenge to be solved and then research biological knowledge for solutions. The problem-driven process foresees several steps [30], as described in Table 1. The solution-driven process refers to similar steps but with biological strategy identification as its first step.

A first attempt to provide standards for the terminology, concepts and methodology for the development of bio-inspired products came from the International Organization for Standardization (ISO) with BS ISO 18458:2015 [22]. In essence, it is a re-formulation of the stages identified in Table 1.

Questions and methodology

As this work aims at presenting a perspective where NbS can be

Table 1
Steps of the problem-driven approach. Adapted from [30].

Problem-driven approach steps	Description
1 *Problem definition/ analysis*	Selection of a problem to solve and perform further definitions of it through functional decomposition. The identification of the function(s) characterising the problem is the keyword to the inquiry in the biology domain.
1 *Reframe the problem*	Redefining the problem using broadly applicable biological terms. Asking the question: "How do living systems perform this function?"
1 *Biological solution search*	Selection of biological model(s) of interest. Find solutions that are relevant to the biological problem utilising various techniques (i.e. consulting biologists, text-mining and database approaches [31]). Biological solutions could be broad natural principles, as well as specific strategies and mechanisms deployed by champion organisms.
1 *Definition of the biological solution*	The process of refining the biological knowledge to some working principles, strategies or representative models that explain the biological solution and how the problem is solved in nature. May include references to functions, structures, behaviours or principles that are related to the solution.
1 *Principle extraction*	After a solution is understood, relevant principles are extracted into a 'solution-neutral' form, so references to the biology domain should be removed/replaced, to make it usable by designers.
1 *Principle application/ Idea generation*	Design concepts can be generated. This activity will culminate in the embodiment of a bio-inspired solution of a technological product or system.

supported by biomimicry, the analysis has been split into two parts. The first one aims at answering the following question:

- *Is biomimicry included in the definitions of NbS? And, as a consequence, can a bio-inspired solution fall within the category of NbS actions?*

While a NbS could be recognised, even the process of generating it is not known; a bio-inspired solution may not be recognisable unless a structured process of bio-inspiration is determined. Therefore, to answer the question, the definitions quoted (see Section 1) have been assessed. As there appear to be two different EC definitions for NbS, a preliminary inquiry had to be carried out to answer *which is the most appropriate EC definition of NbS*. In particular, how have these definitions been quoted in peer-reviewed literature, what is the source of the quotations utilised and how has biomimicry been considered. The research question has also been addressed directly to relevant EC staff, to complement and clarify what emerges from the literature.

The second part of the analysis aims at answering the following explorative question:

- *How can BID approaches/Biomimicry be beneficial to NbS?*

To answer the question, five main steps have been followed, with different methodologies:

1 Analysis of NbS project cycle. This includes the phases of implementation, recurring features, guiding principles, technical barriers and knowledge gaps. This step was carried out by screening and assessing peer-reviewed literature and technical reports from NbS projects.
2 Identification of bio-inspired broad principles/guidelines for NbS. The *Life Principles* [32] is a BID tool, developed by Biomimicry3.8, which proposes overarching natural principles to guide and/or evaluate the design process, and has been utilised to abstract principles for framing and improving the NbS project cycle. For each life principle, one or more NbS guiding principles have been identified.
3 Identification of biological strategies for NbS. *Asknature*, an online database of biological strategies and bio-inspired innovations, has been utilised to identify a preliminary list of biological strategies, which could generate ideas for improved and innovative NbS.
4 Identification of existing bio-inspired solutions for NbS. Asknature has also been utilised to identify already existing bio-inspired solutions, which could be integrated in NbS projects to improve their efficiency and effectiveness.
5 Biomimetic research for future applicability to NbS. Preliminary indication, through peer-reviewed literature, of the current research and development of biomimetic technologies and processes, which could be introduced in NbS projects and contribute to their improvement.

Is biomimicry included in the definitions of NbS?

The ambiguity in the definition of NbS attributed to the European Commission (see Section 1) is reflected in scientific publications. Through a preliminary keyword search on Google Scholar[1], it emerged that papers sometimes quote the IUCN definition, sometimes the EC definition n.1 or n.2, and even, on a few occasions, all three definitions are found together (Fig. 2).

According to Cohen-Shacham et al. [33], while acknowledging the utility and need for the creation and interventions that are inspired by nature in specific contexts, the IUCN definition (see Section 1) excludes them from being considered as NbS, because they are not connected to natural ecosystems.

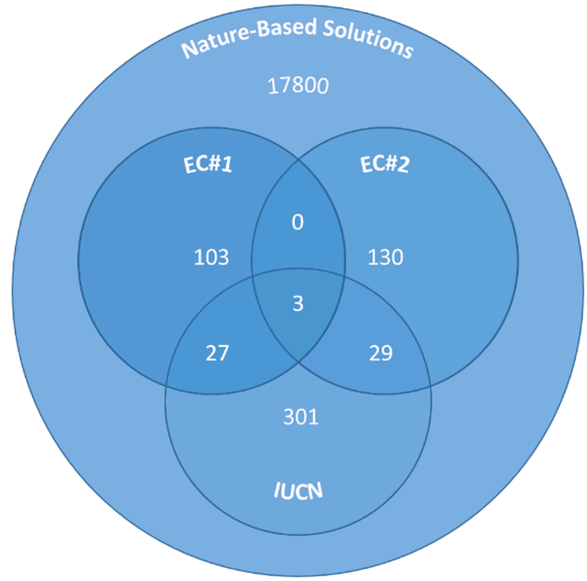

Fig. 2. Among all publication quoting 'Nature-based solutions' (bigger circle), indicated are publications quoting IUCN definition of NbS, EC definitions 1 and 2 of NbS; alone (smaller circles) and together (intersection of circles). Search on Google Scholar (23/02/2022).

Recent literature (among the references cited elsewhere in this work: [34,35,9,10,36,37]) still refers to the EC Definition n.1 of NbS as "*actions inspired by, supported by, or copied from nature*". This clear distinction among three types of actions seems to also embed solutions derived from BID approaches.

However, the referenced study should not be considered as being the official EU definition. In fact, studies commissioned by the EC (or other EU institutions) for third parties normally contain disclaimers which releases the EC from responsibilities on the content and use of the studies. Similarly, the often referenced study [13] contains such a disclaimer (as a '*legal notice*' on page 3 of the study): *"Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use which might be made of the following information. The views expressed in this publication are the sole responsibility of the authors and do not necessarily reflect the views of the European Commission."*

The study was, indeed, conducted by a group of experts from public and private organisations with stakes in the business of NbS and biomimicry.

EC Definition n.2, being published on the EC website, has been reviewed and approved by the internal decision-making process of the EC:

"*Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions.*"

Different from EC definition n.1, the wording "*copied from nature*" has been removed and a comma has been replaced by the Boolean operator AND (see the underlining in the above definition). This definition appears to not consider bio-inspired solutions that do not embed living systems to function.

Therefore, a green building façade utilising plants to passively regulate indoor temperature and absorb CO_2 can be considered to be a NbS. On the contrary, a building façade engineered to emulate natural forms and processes to carry out the same functions cannot be considered a NbS.

[1] The search has been carried out looking for 'Nature-based Solutions' AND (Boolean combination of short excerpt of the definitions), with no time limitations.

To further confirm this, the author wrote directly (in December 2021) to relevant staff at the EC responsible for commissioning NbS studies [13,8]. The reply confirmed that EC definition n.2 can, indeed, be considered the official EC one and that bio-inspired solutions, such as the abovementioned bio-inspired building façade, is not considered NbS.

How can BID approaches/biomimicry be beneficial to NbS?

As mentioned in Section 1, searches of the scientific literature addressing NbS and the terms related to the process of bio-inspiration indicate limited overlap between these two domains. In particular, Fig. 3 shows the results from a search on Google Scholar (full text search) of publications quoting “nature based solutions” in combination with other bio-terms, such as "biomimicry", "biomimetics", "bio-inspiration" and "bioinspired" (these last two terms have been merged into one category).

The paper search on Google Scholar returned approximately 23,700 results for the keyword «Nature Based Solution», with approximately 5000 papers appearing in 2022. The same search on Scopus returned 1993 results, with 540 papers published in 2022. The overall ratio of the publishing progression suggests that the two results are potentially well aligned, despite the Scopus publication record being one order of magnitude smaller. The characterisation of the thematic areas that collect most of the papers on NbS has been carried out by means of the analytical tools proposed by Scopus, e.g. the collection of keywords characterising the publications. Approximately two thirds of the total number of papers (64%) covers the topics of Climate Change, Green Infrastructure, Water Management and Ecosystem Services. More specifically, the topic of Climate Change is relevant to 40% of the papers mentioning NbS. The topics of Green Infrastructure, Water Management and Ecosystem Services also cover almost half of the publications dealing with NbS (44%). This highlights the fact that there is a large area of publication that addresses Climate Change via one of the three possible solution strategies mentioned. Moreover, the results also show that, within the remaining 36% of publications, more than one third (13% of the NbS-related papers) also aim to connect NbS with the urban dimension (e.g. urban planning, urban management, urban restoration, etc.). The remaining papers (less than 25%) present a less marked thematic characterisation.

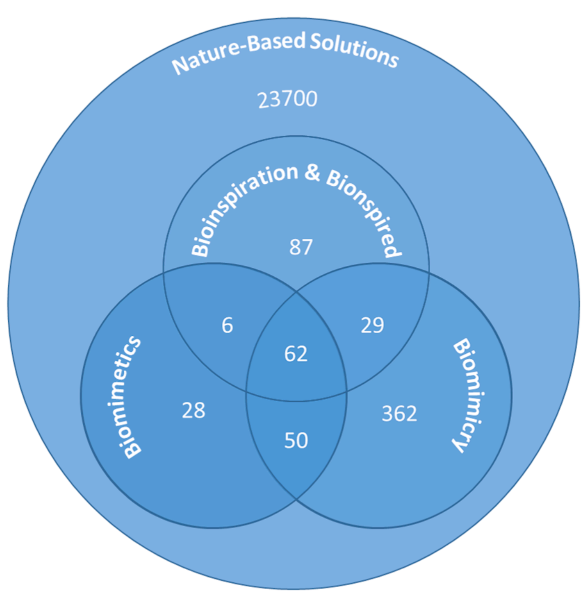

Fig. 3. Among all the publications quoting “Nature-based solutions” (bigger circle), indicated are publications quoting frequent bio-terms; alone (smaller circles) and together (intersection of circles). Search in Google Scholar (03/08/2022).

Regarding the presence of bio-terms, the paper search on Google Scholar returned 503 results for published papers on biomimicry, 146 for biomimetics and 184 for the merged category ‘bio-inspiration/bio-inspired’. In the case of the smaller intersection of Fig. 3 (i.e. six entries), all manuscripts were checked by the authors; bigger clusters were analysed by randomly selecting 30% of the retrieved documents. It appears that the keywords are quoted together but they are operatively decoupled, either publications on NbS quoting bio-terms, as complementary approaches to sustainable development/innovation, or vice-versa.

A further search was carried out for: "nature-based solutions" AND "biophilic". This provided 534 entries. This result highlights how NbS seem more connected with the concept of biophilia rather than biomimicry. Biophilia is largely defined as *the need of humans to connect with nature* [38], and NbS can satisfy such a need as a co-benefit. This analysis shows that terms related to bio-inspiration (bio-terms) are not normally associated with NbS practice, neither as typology of NbS nor as a tool to assist NbS practice. They are, rather, considered complementary approaches to NbS.

Analysis of NbS project cycle - barriers, gaps and guiding principles

Before presenting the BID and its potential contribution to NbS, it is necessary to frame NbS in terms of the type of solutions, project cycles and other relevant features which are useful for contributing to answering the research questions.

According to Eggermont et al. [7], NbS can be characterised into three types: (i) NbS that address a better use of natural or protected ecosystems, (ii) NbS for sustainability and multi-functionality of managed ecosystems, and (iii) NbS for the design and management of new ecosystems (closer to the EU definition of NbS). Combinations of different types are also possible [36].

The project cycle of NbS has been divided into different phases by different authors. Three main stages of development of NbS projects have been identified: planning, execution, and delivery (as well as sub-stages) [39,40]. It should be noted that the coherence of this progression of stages with the largely utilised PDCA (plan–do–check–act) method, used an iterative design and management method to control and continuously improve processes and products [41].

The additional features common to NbS have also been highlighted [39,40] (see Table 2).

These characteristics clearly highlight how the successful delivery of NbS is affected by the intrinsic complexity of these multi-dimensional factors and by the uncertainty associated with the functioning of natural systems, which does not occur in traditional engineered (grey) solutions. Because of the tested designs and based on the processes which are fully controllable by humans, the latter can guarantee performances which are compliant with the regulations’ requirements (e.g. quality and quantity of water managed), whereas the former may not.

Technical barriers and knowledge gaps affecting the uptake and effective implementation of NbS have been identified by several authors [42,43,35,10,36,37,44,40,45,46]. In general, these emerge throughout the whole NbS project cycle when trying to:

- design, implement and maintain efficient and effective NbS;
- monitor the effectiveness of NbS;
- quantify the benefits and co-benefits provided by NbS;
- identify and involve the right stakeholders in the NbS project cycle.

In order to address the complexity of NbS and the identified barriers and gaps, general guiding principles and criteria have been identified by several authors. IUCN identified eight core principles and related criteria (‘Resolution 69 on Defining Nature-Based Solutions [[47] 2016-Res-069] - World Conservation Congress Honolulu’ 2016) to build a common understanding of NbS and enable their implementation and upscaling. Additional guiding principles (or criteria) for various phases of the NbS project cycle have been identified by other authors: some

Table 2
NbS project cycle and features. Adapted from [39,40].

Main phases	Sub-stages	NbS features
Planning	• Problem definition • Stakeholders' selection • Scoping analysis • Alternative scenarios • Preliminary assessment	*Dynamic solutions*: NbS project design has to take into account uncertainty derived from possible evolution of ecosystem functions over time; *Multiple stakeholders*: NbS project success depends on multi-stakeholders' consultations and involvement in various phases of the project; *Multiple designs*: optimisation has to be sought among several scenarios of solutions; *Multiple scales (spatial/temporal)*: different solutions apply to different spatial scales and become fully effective at different time scales. *Multiple benefits*: NbS is likely to create additional benefits not directly linked to the problem at hand; *Multiple risks:* risks of generating negative impacts at different scales of intervention or unsuccessful implementation during project life-cycle; *Adaptive management*: the dynamic nature of NbS may require adjustments over time; *Monitoring and feedbacks* are necessary to guarantee a certain control over the dynamics of projects and apply adaptive management.
Execution	• Detailed design • Business case/financing • Implementation	
Delivery	• Monitoring • Evaluate/Adapt (back to execution or planning)	

more relate to the planning phase [34] and others to the implementation/delivery phase [40] (see Table 3).

Identification of bio-inspired broad principles/guidelines for NbS

Biomimicry can enrich the conversation around the aspects highlighted in Section 4.1, such as the operative principles to design, implement and evaluate NbS projects and develop frameworks of NbS principles, which could guide decision-makers, planners and implementers of NbS. Ultimately, the guiding principles listed in Table 3 are similar to the overarching principles governing the development and growth of organisms and ecosystems.

For example, the *Life Principles* (LPs) framework, a biomimicry tool developed by Biomimicry3.8 [32], could serve as a basis upon which to build a customised framework of guiding principles throughout the whole NbS project cycle.

The LPs are a selection of consistently repeated principles which are identifiable in organisms and ecosystems. They have been identified by teams of biologists from different specialisations and structured in a usable framework to assist the BID process. They can inform the design from an early stage, so as to guide the generation of design concepts, embedding such principles and/or utilising them to evaluate existing solutions. The LPs could, therefore, represent a framework to introduce sustainability principles within NbS. The LPs framework is composed of one overarching principle and six main principles, with their own sub-principles (20 in total).

Usually, the evaluation of NbS and related indicators, aims at measuring efficiency and effectiveness: quantifying the performance of NbS in providing environmental, social and economic benefits to society, as well as benefits to biodiversity and the cost of it [8,39].

Setting up a framework of principles based on, and expanding from, the LPs could help in assessing the compliance of NbS, vis-à-vis the operating principles of living systems, ultimately, to measure the NbS project cycle alignment with sustainability principles embedded in nature.

Table 3
Principles and criteria for effective NbS: IUCNx-IUCNCrx (from 'Resolution 69 on Defining Nature-Based Solutions [[47]2016-Res-069] World Conservation Congress Honolulu' 2016), CAx from Albert et al. [34] and TNx from Somarakis, Chrysoulakis, and Stagakis [40]

IUCN NbS principles/criteria	Other guiding principles
1 NbS embraces nature conservation norms and principles; (IUCN1) 2 NbS can be implemented alone or in an integrated manner with other solutions to societal challenges (e.g. technological and engineering solutions); (IUCN2) 3 NbS are determined by site-specific natural and cultural contexts that include traditional, local and scientific knowledge; (IUCN3) 4 NbS produce societal benefits in a fair and equitable way in a manner that promotes transparency and broad participation; (IUCN4) 5 NbS maintain biological and cultural diversity and the ability of ecosystems to evolve over time; (IUCN5) 6 NbS are applied at a landscape scale; (IUCN6) 7 NbS recognise and address the trade-offs between the production of a few immediate economic benefits for development, and future options for the production of the full range of ecosystem services; (IUCN7) 8 NbS are an integral part of the overall design of policies, and measures or actions, to address a specific challenge. (IUCN8) NbS Criteria (reflecting the principles above) 1 NbS effectively address societal challenges; (IUCNCr1) 2 Design of NbS is informed by scale; (IUCNCr2) 3 NbS result in a net gain to biodiversity and ecosystem integrity; (IUCNCr3) 4 NbS are economically viable; (IUCNCr4) 5 NbS are based on inclusive, transparent and empowering governance processes; (IUCNCr5) 6 NbS equitably balance trade-offs between achieving their primary goal(s) and the continued provision of multiple benefits; (IUCNCr6) 7 NbS are managed adaptively, based on evidence; (IUCNCr7) 8 NbS are sustainable and mainstreamed within an appropriate jurisdictional context. (IUCNCr8)	1 Place-specificity i.e. adapted to context; (CA1) 2 Evidence based; (CA2) 3 Integration i.e. consider related approaches, temporal, spatial and sectoral scales for planning; (CA3) 4 Equity i.e. recognise rights, values and interests of different actors and builds on inclusive participation, equal distribution of costs and benefits; (CA4) 5 Trans-disciplinarity i.e. cooperation from different disciplines of academic and non-academic actors; (CA5) 6 Use recycled materials; (TN1) 7 Use renewable energy and targeted energy savings; (TN2) 8 Minimise irrigation or re-used water; (TN3) 9 Avoid materials with potential heavy environmental footprint; (TN4) 10 Target simple systems; (TN5) 11 Do not use invasive species - favour local native ones; (TN6) 12 Use local materials; (TN7) 13 Combine NbS with solar panels; (TN8) 14 Make sure irrigation is available at installation; (TN9) 15 Install fire breaks where needed; (TN10) 16 Install safety railings and fall prevention device for installation and maintenance. (TN11)

Starting from the LPs and NbS principles/criteria already identified (Table 3), a set of NbS guiding principles is distilled and proposed for future reference, when planning and implementing NbS (Table 5). The process of abstraction from the LPs (the first column of Table 5) to the extracted principles (second column) has been carried out by considering keywords (verbs and nouns) present in the LP definitions, as well as synonyms, which evoke a connection with:

- Actions considered best practice within the NbS project cycle (e.g. adaptive management, hybrid solutions, etc.);
- Actions considered suitable to embed sustainability in design (e.g., regenerative design, biomimicry, using green chemistry, etc.);

Table 4
Principle/Guideline for NbS extracted from the Life Principles - Column 1: quoted LPs (main and sub-principles) with short definitions; reference, if suitable, to NbS criteria, as coded in Table 3; reference, if suitable, to NbS features as per Table 2. Column 2: extracted principles. Column 3: reference, if suitable, to technical barriers and knowledge gaps for efficient/effective NbS, mentioned in the literature, which the extracted principles could help address.

Life Principles	Extracted principles/guidelines	Linked to identified technical barriers and knowledge gaps to achieve efficient-effective NbS
1 **Life creates conditions conducive to life** (IUCNCr3)	**NbS shall create conditions conducive to life**	
1.Evolve To Survive		
1.a Replicate strategies that work Repeat successful approaches. (IUCN1) (IUCN4) (IUCN5) NbSfeatures: Multiple designs	• *Consult case studies of NbS databases* and other ante-NbS definition case studies related to ecological engineering, river restoration, green-blue infrastructure, etc. with longer life-span and results to be assessed • *Apply Biomimicry* to take inspiration from successfully adapted biological strategies	• Poor availability of consistent datasets to evaluate NBS impacts [40] • Uncertainty about temporal evolution and long-term effects of NBS [40]
1.b Integrate the unexpected Incorporate mistakes in ways that can lead to new forms and functions. NbSfeatures: Dynamic solutions, Adaptive management	• *Convert/build on the existing* to carry out new and possibly more sustainable functions.	• Combination of NbS (small and large) with grey infrastructure [10] • Framework for optimal combination of NbS [10]
1.c Reshuffle information Exchange and alter information to create new options. (IUCN2) NbSfeatures: Dynamic solutions, Multiple designs	• *Integrate mutually benefitting solutions* (e.g. green-grey infrastructures) • *Design hybrid solutions* combining existing technologies/processes to create new/improved functionalities	• Combination of NbS (small and large) with grey infrastructure [10] • Framework for optimal combination of NbS [10]
2. Adapt To Changing Conditions		
2.a Incorporate diversity Include multiple forms, processes, or systems to meet a functional need. (IUCN2) (IUCN5) (IUCNCr3) (CA3) NbSfeatures: Multiple designs, decentralisation and/or functional redundancy	• *Increase diversity* of organisms and technologies utilised in NbS so as to guarantee operability through functional redundancy, also in case of changing conditions (seasonal weather patterns, floods, fires) • *Use multiple diverse solutions* to carry out similar function • *Carry out multi-disciplinary design* process to address multiple factors of the challenge • *Set up multi-stakeholder platforms* of dialogue to participate throughout NbS project's life-cycle	• Silos mentality [10] [35, 37] • Lack of deep understanding among multidisciplinary key actors [40]
2.b Maintain integrity through self-renewal Persist by constantly adding energy and matter to heal and improve the system. (IUCN5) (IUCNCr7) NbSfeatures: Dynamic solutions, Adaptive management	• *Utilise regenerative design*: technologies and processes that restore, renew, and revitalise their own sources of energy and matter [67] • *Utilise Adaptive Management* to adapt to changing conditions during NbS project cycle • *Set up financially sustainable business models* to build, operate and maintain NbS	• Lack of available financial resources and adequate incentive [37]
2.c Embody resilience through variation, redundancy, and decentralisation Maintain function following disturbance by incorporating a variety of duplicate forms, processes, or systems that are not located exclusively together. (IUCN5) NbSfeatures: Multiple design, multiple scales	• *Promote distributed/decentralised solutions* • *Introduce functional redundancy* in design process, management and technical solutions • *Increase redundancy of technological systems through NbS*. NbS designed to augment and/or replace specific functions of engineered solutions	• Framework for optimal combination of NbS [10] • Design specifications for combination of NbS (small and large) with grey infrastructure [10] • Impacts of scale of NbS [10]
3. Be Locally Attuned And Responsive (CA1)		
3.a Leverage cyclic processes Take advantage of phenomena that repeat themselves. (TN3) (TN8) NbSfeatures: Dynamic solutions	• *Exploit cyclical natural processes* to power technologies and operate the solutions (gather rainwater, exploit the sun, wind, tides, regular floods and other seasonal changes of weather patterns) • *Adapt to and exploit seasonal changes* of local environment/landscape	• Existing uncertainties associated with changing climatic conditions [44]
3.b Use readily available materials and energy Build with abundant, accessible materials while harnessing freely available energy. (TN2) (TN6) (TN7) (TN8) (TN9)	• *Use locally available plants, materials and renewable energy* (sun, gravity, wind, water flow, tides, waves, etc.) • *Involve local to Km-zero value chain*	
3.c Use feedback loops Engage in cyclic information flows to modify a reaction appropriately. (IUCN3) (CA4) NbSfeatures: Dynamic solutions, multiple stakeholders, monitoring and feedback	• *Set up monitoring systems* and monitor development of the solution throughout the life-cycle and adopt standard monitoring protocols to enable meta-analysis of NBS actions • *Set up multi-stakeholder platforms* (public/private) for consultation • *Set up multi-level communication plan* to inform decision making process and stakeholders • *Design local context-adapted solutions* based on local feedbacks - no blueprint approach	• Lack of ready to use and easy to install technical products [40] • Lack of design standards and guidelines for maintenance and monitoring [37] • Accuracy and quality of the monitoring approaches [40] • Absent in-depth stakeholder mapping and outreach [40] • Lack of public awareness and support [37] • Risk aversion and resistance to change [37]
3.d Cultivate cooperative relationships Find value through win-win interactions. (IUCN2) (IUCN3) (IUCN4) (IUCN5) (IUCNCr5) (CA4) (CA5) NbSfeatures: Multiple stakeholders	• *Apply principles of Ecology/Permaculture*: utilise plants and introduce organisms which synergise exchanging nutrients, water, energy and information for their mutual benefit so to create and sustain an ecosystem; • *Set up local entities for operation and maintenance* of the solution • *Apply multi-disciplinary design process* throughout the NbS project cycle • *Apply co-creation/co-design process* involving public/private stakeholders in designing the solutions • *Involve relevant stakeholders in managing/operating the solution*	• Lack of deep understanding among multidisciplinary key actors [40] • Lack of interdisciplinary skilled personnel [40] • Property ownership complexities [37] • Lack of available financial resources and adequate incentive [37] • Lack of supportive policy and legal frameworks [37] • Lack of political commitment [37]

(continued on next page)

Table 4 (*continued*)

	• *Foster Open Innovation* set ups to find innovative solutions	• Lack of sense of urgency among policymakers [37]
4. Integrate Development With Growth		
4.a Self-organise Create conditions to allow components to interact in concert to move toward an enriched system. NbSfeatures: Dynamic solutions, Multiple scales	• *Set up design and management guidelines* with sets of principles/ rules to be followed by different actors • *Set up directories of relevant entities* specialised in various aspects of NbS project cycle • *Design self-organising NbS*: utilise systems of organisms that can self-organise themselves (ecosystems at different scale) • *Utilise Adaptive Management*	• Lack of sufficient guidance-protocols and technical support in terms of instructions for implementation and maintenance [40] • Lack of appropriate training of planners, developers, and construction professionals [37, 40] • Absence of a widely established holistic framework for the assessment of NbS impacts [40] • Lack of evidence regarding the quantitative benefits of NbS [40]
4.b Build from the bottom up Assemble components one unit at a time. (CA4) NbSfeatures: Multiple stakeholders	• *Build from the bottom up*: design and implement large scale NbS building in self-organising/self-sustaining phases/subsets. • *Set up bottom-up decision making processes* and consultations	• Lack of supportive policy and legal frameworks [37] • Lack of political commitment [37] • Absent in-depth stakeholder mapping and outreach [40]
4.c Combine modular and nested components Fit multiple units within each other progressively from simple to complex. NbSfeatures: Multiple scale	• *Utilise modular elements* when possible, to increase adaptability, redundancy and overall resilience of the system	
5. Be Resource Efficient (Material And Energy)		
5.a Use low energy processes Minimise energy consumption by reducing requisite temperatures, pressures, and/or time for reactions. (TN2)	• *Apply passive solutions* using available free energy (sun, gravity, wind, waves, etc.) • *Exploit locally available sources of wasted energy* (heat, hydrodynamic power, pressure) and wasted materials • *Use low-energy input materials*: favour materials which are locally abundantly available, renewable and efficiently extracted elements	
5.b Use multi-functional design Meet multiple needs with one elegant solution. NbSfeatures: Multiple benefits	• *Design to address multiple challenges* • *Integrate (and assess) multiple functionalities* when designing and operating the solution. Extra functionalities planned or unexpected, that do not fulfil the challenges the NbS is requested to deliver but that could increase the efficiency of the solution.	• Address multiple challenges [40] • Framework for multi-functional design [10]
5.c Recycle all materials Keep all materials in a closed loop. (TN1) (TN3)	• *Use recyclable/re-usable/biodegradable materials* • *Exploit material circularity*	• Use of environmental friendly materials [40]
5.d Fit form to function Select for shape or pattern based on need. NbSfeatures: Multiple scales	• *Do not overdesign* so as to **optimise** use of resources and reduce waste • *Design and implement NBS actions to address core challenges*	
6. Use Life-Friendly Chemistry		
6.a Break down products into benign constituents Use chemistry in which decomposition results in no harmful by-products. (TN4)	• *Use biodegradable materials* during set up and lifetime of the solution	• Use of environmental friendly materials [40]
6.b Build selectively with a small subset of elements Assemble relatively few elements in elegant ways.	• *Apply green chemistry principles for* materials development and production	• Use of environmentally friendly materials [40]
6.c Do chemistry in water Use water as a solvent.	• *Apply green chemistry principles for* materials development and production	• Use of environmentally friendly materials [40]

- Actions aimed at increasing efficiency and effectiveness in product development (e.g. introducing redundancy, applying passive solutions, using modular elements, etc.).

These actions can address specific barriers and gaps (as highlighted in the third column of Table 4). This process of abstraction is affected by subjectivity because the broad definitions of the LPs widen the range of ideas for extracted principles. This was a preliminary attempt at abstraction, which could be repeated and further developed.

Even if many of these extracted principles are known to product developers and NbS practitioners, they are organised into a framework connected to natural principles. The principles are recognised as contributing to making living systems sustainable.

Identification of biological strategies for NbS

While LPs, as a tool utilising overarching principles recurring throughout nature, can support the definition of guidelines to design and implement NbS projects, as well as evaluate them, other BID methods and tools, exploring specific biological strategies of living systems, can help generating innovative ideas to:

- Increase efficiency and effectiveness of phases and components of NbS project cycle;
- Design new and/or improved NbS.

If NbS mainly aim at leveraging ecosystem services for the benefit of society, ecosystems also provide services to other species thriving in those ecosystems. Therefore, learning how ecosystems provide services to other species could generate ideas for new and more effective NbS.

To demonstrate the applicability of BID to NbS, the problem-driven approach described in Table 1 is followed. In essence, the process starts with the definition of the problem and a clear identification of the function solving it. Then, the re-framing of the problem in biological terms allows exploration in the biological domain, to identify relevant biological solutions to carry out the desired function. Finally, such solutions are translated into design principles and are usable in the innovative idea generation process.

To demonstrate the applicability of such a process, some functions have been selected related to the ecosystem services to be performed by NbS (see the first column of Table 5).

These were introduced in the Asknature search engine, the most successful openly accessible biological repository for BID activity. In

Table 5
Bio-inspired ideas for NbS (column 4) extracted from biological strategies (column 3), mainly provided by querying Asknature with typical NbS functions (column 1). For some organisms (column 2) the link to the related entry in Asknature is provided.

Function to be performed by NbS	Organism carrying out the function	Biological Strategy	Generated Ideas for NbS or supporting actions to enable NbS
Regulate/Respond to floods Exploit floods	Beavers Fire ants Irish Moss	Beaver dams change stream flows and create a patchwork of habitat diversity. Interlocking matrix of mixed material slows water and traps particulates by spanning perpendicular to the water's flow. [68] Fire ants self-assemble into waterproof rafts to survive floods connecting with mandible–tarsus and tarsus–tarsus attachments [69] Irish moss responds to the speed of flowing water by changing its configuration. In calm water it stands upright. Mild currents push the algae into a cone-shaped position, which still allows for photosynthesis but minimises drag [70]	Design beaver dams analogue to regulate river water/ sediment flow or design urban bioswales [71] [68] Design modular connectable floating devices/structures to adjust to floods/tides Design structures that reconfigure themselves to respond to changing water drag
Reduce soil erosion	Mangrove forest Mangrove forest Prairie ecosystem Forest canopies	Roots of red mangrove forests protect coastal shorelines by absorbing energy from waves. Dead roots of Mangrove trees are empty and get filled with soil, avoiding coastal erosion. [72] Diversity and life-span of plants help prairie ecosystems use water and nutrients efficiently. Canopies of old growth forests intercept, store, and slow water [73]. The multi-layered architecture of an old growth canopy intercepts, stores and breaks up water droplets, slowing the rate at which water hits the ground and increasing the potential for evaporation.	Design network of pillars as breakwaters, coastal structures to absorb wave energy and empty structures to allow soil deposition Increase biodiversity in NbS to increase resilience of the system (via functional redundancy) and improve water and nutrient management Set up patterns of vegetation to increase dampening effects on rainfall. Design modular distributed structures to intercept rainfall and reduce its kinetic energy
Capture CO2	Cacti and other plants Diatoms	Cacti sequester atmospheric carbon dioxide by converting it to oxalate and combining it with soil-derived calcium ions which ultimately lead to the formation of solid calcium carbonate (Calcium Oxalate Path). Diatoms assimilate inorganic carbon via carbon concentration mechanisms such as carbonic anhydrase. [74]	Utilise plants that store carbon through the Calcium Oxalate Pathway (CAP) [75] or engineer a biomimetic CAP Use carbonic anhydrase (CA) as a carbon sequestering agent or engineer a biomimetic CA [74]
Manage water/fluids (collect, store, distribute, regulate)	Arid ecosystem plants Leaves Tree evaporation	Plants in arid ecosystems self-organise to minimise water loss and aid plant and seed survival. Vein systems in leaves allow for optimal flow and resilience to damage due to a dense network of nested, interconnected loops. [76] Vascular systems of plants transport fluids and solutes by creating pressure via evapotranspiration and capillarity.	Emulating plant diversity and distribution to create efficient natural water storage systems Design of optimal water networks [76] Design more efficient pumping systems [49] and filtering systems [77]
Set up/ maintain communities/ biodiversity	Forest canopies Nurse shrubs Wetlands	Forest canopies create microclimates where tens of thousands of other plant species grow. Pioneering nurse shrubs in Mediterranean montane forests promote ecosystem regeneration by increasing shade above ground and potassium below ground. Wetlands create diversity by having micro-topographic relief that creates microhabitats for plants and animals. Furthermore, wetlands are ecotones (transition zones) between terrestrial and aquatic environments.	Emulate diversity, distribution and relationships of organisms in order to design self-sustaining and resilient ecosystems in different environmental contexts.

Asknature, biological solutions are organised according to the taxonomy of biological functions (called *Biomimicry Taxonomy*). This taxonomy categorises the different ways, or 'biological strategies', in which living systems fulfil their functional needs.

Some of the entries suggested by the database are described in Table 5 (column 3), complemented by other biological strategies which the author identified from previous research, but which are not included in Asknature. From the strategies, the author generated some design principles and ideas for applicability in NbS/ green-grey infrastructure (column 4). Some of these ideas are already objects of research and applications (see references provided).

For a more thorough exploration in Asknature, the broad function "provide ecosystem services" is indeed available among the functions of the biomimicry taxonomy. This function has 130 entries divided into sub-functions (e.g. Control Erosion and Sediment, Generate Soil/Renew Fertility, Regulate Climate, Maintain Biodiversity, Regulate Hydrological Flows) linked to biological strategies, which could be imitated or just provide inspiration to design innovative ideas for NbS and supporting actions to enable NbS, as well as filling gaps in knowledge about ecosystem functions and their services, removing some of the technical barriers to the uptake of NbS. For example, bio-inspired solutions could partially or completely replace conventional grey infrastructure and support the development of more effective Hybrid Green-Grey infrastructure.

Identification of existing bio-inspired solutions for NbS

To provide evidence of the potential synergy between NbS and bio-inspired solutions, Table 6 has been compiled, listing some existing bio-inspired solutions, which could be integrated in NbS projects. The majority have been extracted from Asknature which, aside from biological solutions, also includes a substantial archive of bio-inspired solutions at different stages of development (from research and development (R&D) to commercialisation). Likewise, biological and bio-inspired solutions can be identified by querying Asknature, using functions as keywords. Additional bio-inspired solutions known to the author, but not listed in Asknature, have also been added. The list is far from being exhaustive, as it aims to demonstrate the existence of already developed bio-inspired solutions which are potentially applicable to NbS projects.

Biomimetic research for future applicability to NbS

Aside from the usefulness of utilising BID methods to innovate the

Table 6
Sample of the solutions suggested by Asknature, organised according to the challenges NbS typically address (column 1). The commercial name of the solution is provided (with links to official websites) (column 2) with a short description (column 3), whether the solution is only inspired by nature or also supported by nature (to be in line with the EU definition of NbS) and if the solution could potentially enhance local biodiversity (column 2). The progress in market penetration of each of the solutions is not known.

NbS Challenge	Bio-inspired solution (commercial name)	Brief description of the solution
Coastal erosion	Econcrete Inspired and supported by nature Asknature entry Potential for enhancing local biodiversity	The chemical composition of the concrete, combined with moulds with specific macro and micro designs of the surface, promote the growth of marine organisms like oysters, corals, or barnacles, which act as biological glue, enhancing the strength and durability of structures, and adding to their stability and longevity.
	CCell Inspired and supported by nature Potential for enhancing local biodiversity	CCell uses wave-generated electricity to grow coral reefs on artificial steel frames. The reefs can be used to protect coastal communities from erosion and revive an important marine ecosystem. The wave energy collected is processed through a smart power management (SPM) system. The electric current from the SPM causes natural minerals found in seawater to accumulate around the steel frames, forming limestone (calcium carbonate) at around 2.5 cm per year. To create a fully functioning coral reef ecosystem, coral gametes are collected, grown using coral gardening techniques and then transplanted onto the calcified frame.
Coral ecosystem degradation	Intellireefs Inspired and supported by nature Potential for enhancing local biodiversity	IntelliReefs are bio-inspired marine structures made with Oceanite. Engineered reef structures that mimic established coral to build an oceanic infrastructure that improves resistance to climate stressors and diseases. Exposed aggregates on IntelliReefs include small pockets where biodiverse coral larvae can attach, be protected and grow.
Land degradation	Waterboxx, Cocoon, Inspired by nature Asknature entry Potential for enhancing local biodiversity	Water efficient tree growers. Waterboxx and Cocoon are containers made from plastic or recycled material. The container has holes in the top and bottom for new seedlings, which creates a shelter to help it survive through the initial part of their growing cycle. They are filled with water just once, and thereafter capture additional water through the collection of rainwater and condensation.
	Mangrove Technology Platform Inspired and supported by nature Potential for enhancing local biodiversity	The Mangrove Technology Platform is a system of cooperating technologies inspired by the Mangrove Ecosystem, aiming at regenerating land in arid areas with an abundance of saline water (seawater / brackish water). It combines a solar-driven modular desalination system (to produce fresh water and salt), water-efficient organic incubators/tree growers (to facilitate plant uptake and soil nutrient distribution) and the Internet of Thing system (to monitor and control the overall system).
Water scarcity	Warka Tower (and other fog catchers) Inspired by nature Asknature entry	A Warka Tower is a passive structure which harvests water from the atmosphere (rain, fog, dew) functioning only by gravity, condensation and evaporation. It has been inspired by the darkling beetles which can sip water from the air by using their own body surfaces to condense it. Micro-sized hydrophobic grooves and hydrophilic bumps on a beetle's elytra accumulate water droplets (e.g. morning dew), then direct the water towards its awaiting mouth.
Wastewater treatment	Biolytix - BioPod Inspired and supported by nature Asknature entry	A Biopod is a self-contained system that removes contaminants from wastewater and replaces septic tanks. It emulates the soil ecosystem, which supports plant growth through interactions of millions of organisms that work together to decompose organic matter and aerate the soil. In a Biopod, solid waste is first converted to liquid/humid material by tiger worms. Then, wastewater is cleansed by microorganisms as it trickles through a filter system.
	Bio-Domes Inspired and supported by nature Asknature entry	Bio-Domes sit at the bottom of wastewater treatment lagoons and consist of concentrically nested domes that are infused with air from underneath. These domes are coated with naturally occurring biofilms and provide an additional surface for biofilms to grow. This helps to more effectively reduce contaminants in the water such as ammonia and nitrogen, similar to the process that occurs in wetlands.
	Eco-machine Inspired and supported by nature Asknature entry	Eco-machines use sunlight, biodiversity and natural processes to create clean water with the by-products of natural gases and biological material. They also use naturally occurring organisms to break down waste and organic materials, which are then used by other organisms in the machine. This can jumpstart the ecology of a water body, digest sediments and reduce nutrient levels, bringing the water body back into ecological health. They can also serve as a habitat for wildlife and as a recreational amenity within a community.
	BioHaven Inspired and supported by nature Asknature entry	The BioHaven concentrates wetland plants and microbes on a fibrous matrix made of recycled material. The high surface area in the matrix promotes a large amount of growth of biofilms that filter contaminants such as phosphorus, copper, zinc, nitrogen, and ammonia out of the water. Additionally, the matrix acts as a filter for larger particles and an optimal location for plant roots and shoots to grow.
Pest control	Nemastim Inspired and supported by nature Asknature entry	Nemastim, exploiting the efficiency of nematodes in protecting crops by eating harmful organisms and recycling nutrients into the soil, uses pheromones to stimulate beneficial nematode activity as a natural pesticide (protecting from fungi and microbes) to help improve crop production.

design and implementation of NbS, this increasing research and development activity in biomimetics may lead to the creation and production of new technology, processes and materials which could help remove technical barriers and support various phases of the NbS project cycle. A non-exhaustive list of biomimetic research and development paths, whose results could have future applicability in NbS projects, include:

- Multi-functional and composite materials with higher mechanical properties inspired by tissues, cuticles, leaves of various organisms, which have lower cost and reduce environmental impact [48]. These could be utilised to design more sustainable, innovative and efficient NbS, particularly hybrid green-grey infrastructure.
- Water management practices and processes for water treatment, air moisture harvesting, desalination, filtering systems and other separation technologies inspired by separation mechanisms of various organisms [49,50,51,52,53,54]. These could be instrumental in better-integrating grey and green infrastructure, as well as improving the design of bioswales, green roofs, flood management strategies and infrastructure.
- Sensoring are IoT systems inspired by genetic algorithms and swarm intelligence [55,56,57]. These could assist in monitoring and evaluating NbS projects (qualitative/quantitative determination of co-benefits).
- Urban planning/design inspired by natural strategies of efficient exchange of materials and energy, by organic structures and

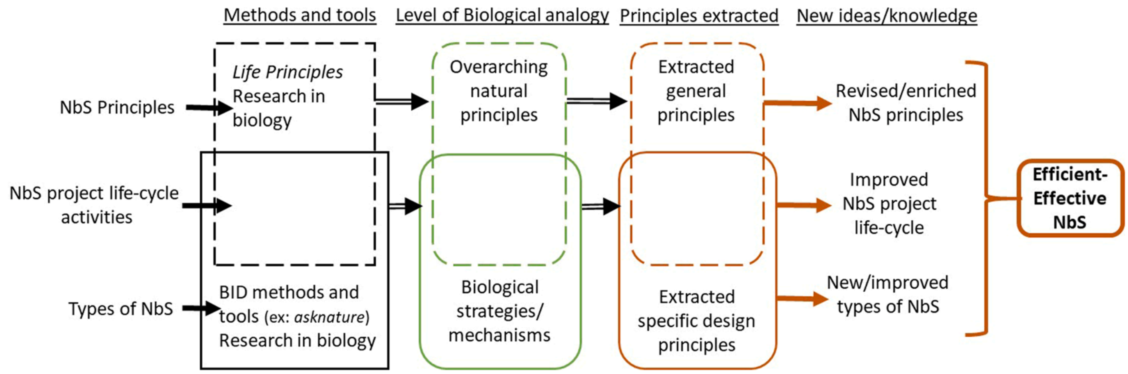

Fig. 4. Opportunities for generating more efficient and effective NbS, utilising a bio-inspired approach. Vertically: Three levels of intervention: NbS principles, project cycle and typology. Horizontally: the BID process' macro-steps.

materials [58,59,60]. These could support the design for arborisation, green facades and sustainable buildings, design for biophilia, e-mobility and green corridors.

- Collaborative communities, cooperation/coopetition models inspired by mutualistic networks, ecotones (i.e. transitional areas of vegetation between different plant communities) and natural self-organisation processes [61,62]. These could assist in setting up multi-stakeholders' platform models of communication and cooperation (public/private stakeholders), open innovation platforms (i.e. living laboratories) and design transitions between urban green infrastructure and the built environment.
- Business models, organisational/management structures inspired by natural principles (i.e. the Life Principles) [63,64,65,66]. These could assist in developing financially viable and sustainable NbS projects, as well as effective adaptive management strategies.

Discussion and emerging framework

This work aimed at answering the reflective and the explorative questions formulated in Section 2.

- *Is biomimicry included in the definitions of NbS?*

It is confirmed that biomimicry is not included in the most referred to definitions of NbS (Section 3). Furthermore, it has been clarified that the official EC definition of NbS is EC Definition n.2 (Sections 1 and 3). This result can be relevant to various entities, when allocating and applying for national, international and EU funding for NbS projects.

- *How can BID approaches/Biomimicry be beneficial to NbS?*

It has been demonstrated that biomimicry and BID approaches can be instrumental in planning and delivering more effective and efficient NbS, by identifying principles/guidelines (Section 4.2), improving the NbS project cycle (Section 4.3) and innovating NbS (Sections 4.4, 4.5).

Considering what has been analysed and identified throughout this work, we propose a preliminary framework to highlight and organise the opportunities that a bio-inspired approach could generate when utilised for NbS, as well as a general step-wise process to follow (see Fig. 4).

The LPs, complemented by other targeted research in biology, could assist in finding overarching natural principles from which general ones could be abstracted to revise/enrich NbS guiding principles (dashed boxes, upper-horizontal path in Fig. 4). Other BID methods and tools, again complemented by targeted research in biology, could assist in identifying relevant biological strategies and mechanisms whose abstraction into specific design principles could generate ideas for improving/innovating types of NbS (continuous line boxes, lower-horizontal path in Fig. 4).

Integration of the two aforementioned paths could help in finding solutions to improve different aspects of the whole NbS project cycle (the central-horizontal path in Fig. 4).

Conclusions

This work has the objective and the expectation of kick-starting a still-missing dialogue around NbS and bio-inspiration: a dialogue among the scientific community, as well as among all the actors involved in the NbS project cycle.

The initial elements are provided to frame this connection between NbS and bio-inspiration and to start reflecting on the benefits that a bio-inspired approach could bring to the whole NbS project cycle.

We propose the Life Principles as a possible framework from which to extract broad principles to guide the NbS project cycle and, possibly, embed the principles of sustainability. Furthermore, through Asknature, we identified bio-inspired ideas as well as already existing bio-inspired solutions to be integrated in NbS projects. It should be noted that the principles and guidelines for NbS, extracted from the Life Principles, have been formulated by building on the authors' experience, but without a rigorous validation and no verification of their exhaustiveness. However, they still keep their main role in this work, i.e. demonstrating the role that Bio-Inspiration can have in the ideation of NbS. Similar considerations could be made with reference to the exemplary bio-inspired ideas for NbS, formulated from the biological strategies retrieved from AskNature.

Ultimately, the paper highlights some of the on-going biomimetic research which could be relevant to the future applicability to NbS projects.

The principles upon which BID approaches are based are fundamentally the same as those that underpin NbS: knowledge of biology, ecology and ecosystem sciences. While NbS action mainly focuses on regaining ecosystem integrity and utilising ecosystems to provide services for the benefits of people, BID approaches exploit the knowledge of natural systems to create technological solutions.

If, through NbS, we co-operate with nature in the physical environment, with BID we co-design with nature. Combining the two approaches could benefit both: it can boost NbS development as well as bio-inspired design utilisation and it can assist in defining suitable standards for concepts and methodologies for both practices, as well as defining criteria and metrics to measure the sustainability of their outcomes. This could also be valuable in the granting of EU and public funds for NbS projects more effectively.

Combining NbS with BID could, ultimately, further assist our society to develop "with" and "like" nature.

NBS impacts and implications

- *Environmental concerns*: the paper proposes bio-inspired principles to guide NbS project cycle and identifies bio-inspired solutions to support NbS. Being inspired by nature, both principles and solutions can improve the effectiveness of NbS as well as their impact on the environment.
- *Economic concerns*: Applying biomimicry to NbS project cycle would allow increasing its effectiveness and efficiency by reducing water-energy consumption, as well as innovating NbS so to generate more opportunities for marketable solutions and to apply NbS to a broader range of contexts.
- *Social concerns*: Applying biomimicry to NbS project cycle can increase job opportunities for designers/planners, as well as the social awareness of the importance of nature as source

Declaration of Competing Interests

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

No data was used for the research described in the article.

References

[1] Millennium Ecosystem Assessment (Program), Ecosystems and Human Well-Being: Synthesis, Island Press, Washington, DC, 2005.
[2] United Nations. 2022. 'United Nations - The Sustainable Develoment Goals'. https://sdgs.un.org/goals. 2022.
[3] European Environmental Agency, Nature-Based Solutions in Europe: Policy, Knowledge and Practice for Climate Change Adaptation and Disaster Risk Re, EEA, 2021.
[4] Hai-Ying Liu, Jay Marion, Xianwen Chen, The role of nature-based solutions for improving environmental quality, health and well-being, Sustainability 13 (19) (2021) 10950, https://doi.org/10.3390/su131910950.
[5] The German Environment Agency, 'Nature-Based Solutions and Global Climate Protection—Assessment of Their Global Mitigation Potential and Recommendations for International Climate Policy—Policy Paper', 2022.
[6] Nathalie Seddon, Alison Smith, Pete Smith, Isabel Key, Alexandre Chausson, Cécile Girardin, Jo House, Shilpi Srivastava, Beth Turner, Getting the message right on nature-based solutions to climate change, Glob. Change Biol. 27 (8) (2021) 1518–1546, https://doi.org/10.1111/gcb.15513.
[7] Hilde Eggermont, Estelle Balian, José Manuel N. Azevedo, Victor Beumer, Tomas Brodin, Joachim Claudet, Bruno Fady, Martin Grube, Hans Keune, Penelope Lamarque, Katrin Reuter, Matt Smith, Chantal van Ham, Wolfgang W. Weisser, Xavier Le Roux, 'Nature-based solutions: new influence for environmental management and research in Europe, GAIA 24 (4) (2015) 243–248.
[8] Evaluating the Impact of Nature-Based Solutions: a Handbook for Practitioners, Publications Office, LU, 2021. https://data.europa.eu/doi/10.2777/244577.
[9] Carsten Nesshöver, Timo Assmuth, Katherine N. Irvine, Graciela M. Rusch, Kerry A. Waylen, Ben Delbaere, Dagmar Haase, et al., The science, policy and practice of nature-based solutions: an interdisciplinary perspective, Sci. Total Environ. 579 (February) (2017) 1215–1227, https://doi.org/10.1016/j.scitotenv.2016.11.106.
[10] Laddaporn Ruangpan, Zoran Vojinovic, Silvana Di Sabatino, Laura Sandra Leo, Vittoria Capobianco, Amy M.P. Oen, Michael E. McClain, Elena Lopez-Gunn, 'Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area, Nat. Hazards Earth Syst. Sci. 20 (1) (2020) 243–270, https://doi.org/10.5194/nhess-20-243-2020.
[11] Cohen-Shacham, E., G. Walters, C. Janzen, and S. Maginnis, eds. 2016. Nature-based solutions to address global societal challenges. IUCN International Union for Conservation of Nature. 10.2305/IUCN.CH.2016.13.en.
[12] United Nations, Environment Assembly of the, United Nations Environment, and Programme. n.d. 'Draft Resolution on Nature-Based Solutions for Supporting Sustainable Development'. UNEP. https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/38282/L.9%20-%20DRAFT%20RESOLUTION%20-%20NATURE-BASED%20SOLUTIONS%20FOR%20SUPPORTING%20SUSTAINABLE%20DEVELOPMENT%20-%20English.pdf?sequence=1.
[13] European Commission. 2015. 'Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities—final report of the horizon 2020 expert group on nature-based solutions and re-naturing cities'. European Commission - Directorate-General for Research and Innovation.
[14] ———. n.d. 'Nature-Based Solutions - European Commission Definition'. Accessed 21 December 2021. https://ec.europa.eu/info/research-and-innovation/research-area/environment/nature-based-solutions_en.
[15] Pizzocaro, Silvia. 2015. In Evoluzione - Per Una Storia Quasi Naturale Degli Artefatti. Edizioni Unicopli.
[16] Julian F.V Vincent, Olga A Bogatyreva, Nikolaj R Bogatyrev, Adrian Bowyer, Anja-Karina Pahl, Biomimetics: its practice and theory, J. R. Soc. Interface 3 (9) (2006) 471–482, https://doi.org/10.1098/rsif.2006.0127.
[17] Lenau, Torben A., Anna-Luise Metze, and Thomas Hesselberg. 2018. 'Paradigms for biologically inspired design'. In Bioinspiration, Biomimetics, and Bioreplication VIII, edited by Akhlesh Lakhtakia, 1. Denver, United States: SPIE. 10.1117/12.2296560.
[18] Bharat. Bhushan, Biomimetics: lessons from nature—an overview, Philos. Trans. R. Soc. A 367 (2009.1893) 1445–1486, https://doi.org/10.1098/rsta.2009.0011.
[19] Janine M. Benyus, Biomimicry - Innovation Inspired by Nature, Harper Perennial, 1998.
[20] P E Fayemi, K Wanieck, C Zollfrank, N Maranzana, A Aoussat, Biomimetics: process, tools and practice, Bioinspiration Biomim. 12 (1) (2017), 011002, https://doi.org/10.1088/1748-3190/12/1/011002.
[21] Helfman Cohen Yael, Yoram Reich, Biomimetic Design Method for Innovation and Sustainability, Springer International Publishing, Cham, 2016, https://doi.org/10.1007/978-3-319-33997-9.
[22] ISO, ISO 18458:2015(E)2015—Biomimetics—Terminology, Concepts and Methodology, ISO, 2015.
[23] L.H. Shu, K. Ueda, I. Chiu, H. Cheong, Biologically inspired design, CIRP Ann. 60 (2) (2011) 673–693, https://doi.org/10.1016/j.cirp.2011.06.001.
[24] Runhua Tan, Wei Liu, Guozhong Cao, Yuan Shi, Creative design inspired by biological knowledge: technologies and methods, Front. Mech. Eng. 14 (1) (2019) 1–14, https://doi.org/10.1007/s11465-018-0511-0.
[25] Arnim Gleich, Christian Pade, Ulrich Petschow, Eugen Pissarskoi, Potentials and Trends in Biomimetics, Springer Berlin Heidelberg, Berlin, Heidelberg, 2010, https://doi.org/10.1007/978-3-642-05246-0.
[26] Olga Speck, David Speck, Rafael Horn, Johannes Gantner, Klaus Peter Sedlbauer, Biomimetic bio-inspired biomorph sustainable? An attempt to classify and clarify biology-derived technical developments, Bioinspiration Biomim. 12 (1) (2017), 011004, https://doi.org/10.1088/1748-3190/12/1/011004.
[27] Diana P. Moreno, Maria C. Yang, Alberto A. Hernández, Julie S. Linsey, Kristin L. Wood, A step beyond to overcome design fixation: a design-by-analogy approach, in: John S. Gero, Sean Hanna (Eds.), Design Computing and Cognition '14, Springer International Publishing, Cham, 2015, pp. 607–624, https://doi.org/10.1007/978-3-319-14956-1_34, edited by.
[28] Katherine Fu, Diana Moreno, Maria Yang, Kristin L. Wood, Bio-inspired design: an overview investigating open questions from the broader field of design-by-analogy, J. Mech. Des. 136 (11) (2014), 111102, https://doi.org/10.1115/1.4028289.
[29] Kristina Wanieck, Pierre-Emmanuel Fayemi, Nicolas Maranzana, Cordt Zollfrank, Shoshanah Jacobs, Biomimetics and its tools, Bioinspired Biomim. Nanobiomater. 6 (2) (2017) 53–66, https://doi.org/10.1680/jbibn.16.00010.
[30] Michael Helms, Swaroop S. Vattam, Ashok K. Goel, Biologically inspired design: process and products, Des. Stud. 30 (5) (2009) 606–622, https://doi.org/10.1016/j.destud.2009.04.003.
[31] Alessandro Baldussu, Gaetano Cascini, About integration opportunities between TRIZ and biomimetics for inventive design, Procedia Eng. 131 (2015) 3–13, https://doi.org/10.1016/j.proeng.2015.12.342.
[32] Dayna Baumeister, Biomimicry Resource Handbook: A Seed Bank of Knowledge and Best Practices, 2011.
[33] Emmanuelle Cohen-Shacham, Angela Andrade, James Dalton, Nigel Dudley, Mike Jones, Chetan Kumar, Stewart Maginnis, et al., Core principles for successfully implementing and upscaling nature-based solutions, Environ. Sci. Policy 98 (August) (2019) 20–29, https://doi.org/10.1016/j.envsci.2019.04.014.
[34] Christian Albert, Mario Brillinger, Paulina Guerrero, Sarah Gottwald, Jennifer Henze, Stefan Schmidt, Edward Ott, Barbara Schröter, Planning nature-based solutions: principles, steps, and insights, Ambio 50 (8) (2021) 1446–1461, https://doi.org/10.1007/s13280-020-01365-1.
[35] Nadja Kabisch, Niki Frantzeskaki, Stephan Pauleit, Sandra Naumann, McKenna Davis, Martina Artmann, Dagmar Haase, et al., 'Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action, Ecol. Soc. 21 (2) (2016) art39, https://doi.org/10.5751/ES-08373-210239.
[36] Han Sarabi, Vries Romme, Wendling, Key enablers of and barriers to the uptake and implementation of nature-based solutions in urban settings: a review, Resources 8 (3) (2019) 121, https://doi.org/10.3390/resources8030121.
[37] Shahryar Sarabi, Han Qi, A. Georges, L. Romme, Bauke de Vries, Rianne Valkenburg, Elke den Ouden, Uptake and implementation of nature-based solutions: an analysis of barriers using interpretive structural modeling, J. Environ. Manag. 270 (September) (2020), 110749, https://doi.org/10.1016/j.jenvman.2020.110749.
[38] Edward Osborne Wilson, Biophilia, Harvard University Press, Cambridge, Mass., 1984.
[39] Raymond, Christopher M. 2017. 'A Framework for Assessing and Implementing the Co-Benefits of Nature-Based Solutions in Urban Areas', 10.
[40] Somarakis, Giorgos, Nektarios Chrysoulakis, and Stavros Stagakis. 2019. 'Nature-based solutions handbook'. ThinkNature project.
[41] Marta. Jagusiak-Kocik, PDCA cycle as a part of continuous improvement in the production company—a case study, Prod. Eng. Arch. 14 (14) (2017) 19–22, https://doi.org/10.30657/pea.2017.14.05.

[42] Judy Bush, Andréanne Doyon, Building urban resilience with nature-based solutions: how can urban planning contribute? Cities 95 (December) (2019), 102483 https://doi.org/10.1016/j.cities.2019.102483.

[43] Hade Dorst, Alexander van der Jagt, Helen Toxopeus, Laura Tozer, Rob Raven, Hens Runhaar, What's behind the barriers? Uncovering structural conditions working against urban nature-based solutions, Landsc. Urb. Plan. 220 (April) (2022), 104335, https://doi.org/10.1016/j.landurbplan.2021.104335.

[44] Nathalie Seddon, Alexandre Chausson, Pam Berry, Cécile A.J. Girardin, Alison Smith, Beth Turner, Understanding the value and limits of nature-based solutions to climate change and other global challenges, Philos. Trans. R. Soc. B 375 (1794) (2020), 20190120, https://doi.org/10.1098/rstb.2019.0120.

[45] C. Wamsler, J. Alkan-Olsson, H. Björn, H. Falck, H. Hanson, T. Oskarsson, E. Simonsson, F. Zelmerlow, Beyond participation: when citizen engagement leads to undesirable outcomes for nature-based solutions and climate change adaptation, Clim. Change 158 (2) (2020) 235–254, https://doi.org/10.1007/s10584-019-02557-9.

[46] C. Wamsler, B. Wickenberg, H. Hanson, J. Alkan Olsson, S. Stålhammar, H. Björn, H. Falck, et al., Environmental and climate policy integration: targeted strategies for overcoming barriers to nature-based solutions and climate change adaptation, J. Clean. Prod. 247 (February) (2020), 119154, https://doi.org/10.1016/j.jclepro.2019.119154.

[47] 'Resolution 69 on Defining Nature-Based Solutions (WCC-2016-Res-069). World Conservation Congress Honolulu'. 2016. IUCN (International Union for the Conservation of Nature). https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2016_RES_069_EN.pdf.

[48] Michael Nosonovsky, Pradeep K. Rohatgi, Biomimetics in materials science, in: Springer Series in Materials Science, 152, Springer New York, New York, NY, 2012, https://doi.org/10.1007/978-1-4614-0926-7.

[49] D Bach, F Schmich, T Masselter, T Speck, A review of selected pumping systems in nature and engineering—potential biomimetic concepts for improving displacement pumps and pulsation damping, Bioinspiration Biomim. 10 (5) (2015), 051001, https://doi.org/10.1088/1748-3190/10/5/051001.

[50] Lidia. Badarnah, Water management lessons from nature for applications to buildings, Procedia Eng. 145 (2016) 1432–1439, https://doi.org/10.1016/j.proeng.2016.04.180.

[51] Alessandro Bianciardi, Gaetano Cascini, A bio-inspired approach for boosting innovation in the separation technology sector, in: Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, November, 09544062211052128, 2021, https://doi.org/10.1177/09544062211052128.

[52] Alessandro Bianciardi, Caterina Credi, Marinella Levi, Francesco Rosa, Alessandro Zecca, Biomimicry thinking: methodological improvements and practical implementation, Bioinspired Biomim. Nanobiomater. 6 (2) (2017) 87–101, https://doi.org/10.1680/jbibn.16.00007.

[53] Philip S. Brown, Bharat Bhushan, Bioinspired materials for water supply and management: water collection, water purification and separation of water from oil, Philos. Trans. R. Soc. A 374 (2073) (2016), 20160135, https://doi.org/10.1098/rsta.2016.0135.

[54] Alfredo Gonzalez-Perez, Kenneth Persson, Bioinspired materials for water purification, Materials 9 (6) (2016) 447, https://doi.org/10.3390/ma9060447.

[55] Lepora, Nathan F., Anna Mura, Holger G. Krapp, Paul F. M. J. Verschure, and Tony J. Prescott, eds. 2013. Biomimetic and biohybrid systems: second international conference, living machines 2013, London, UK, July 29 – August 2, 2013. Proceedings. Vol. 8064. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg. 10.1007/978-3-642-39802-5.

[56] Stroble, J.K., R.B. Stone, and S.E. Watkins. 2009. 'An overview of biomimetic sensor technology'. Edited by Torben Lenau. Sensor Review 29 (2): 112–19. 10.1108/02602280910936219.

[57] Weifeng Sun, Min Tang, Lijun Zhang, Zhiqiang Huo, Lei Shu, A survey of using swarm intelligence algorithms in IoT, Sensors 20 (5) (2020) 1420, https://doi.org/10.3390/s20051420.

[58] Andrea Quintero, Marichell Zarzavilla, Nathalia Tejedor-Flores, Dafni Mora, Miguel Chen Austin, Sustainability assessment of the anthropogenic system in panama city: application of biomimetic strategies towards regenerative cities, Biomimetics 6 (4) (2021) 64, https://doi.org/10.3390/biomimetics6040064.

[59] Yuta Uchiyama, Eduardo Blanco, Ryo Kohsaka, Application of biomimetics to architectural and urban design: a review across scales, Sustainability 12 (23) (2020) 9813, https://doi.org/10.3390/su12239813.

[60] Maibritt Pedersen Zari, Katharina Hecht, Biomimicry for regenerative built environments: mapping design strategies for producing ecosystem services, Biomimetics 5 (18) (2020), https://doi.org/10.3390/biomimetics5020018.

[61] Luis M. Camarinha-Matos, Hamideh Afsarmanesh, Roots of collaboration: nature-inspired solutions for collaborative networks, IEEE Access 6 (2018) 30829–30843, https://doi.org/10.1109/ACCESS.2018.2845119.

[62] Sumin Lee, Joon Sang Baek, 'Nature-inspired design for self-organized social systems: a tool for collaborative communities, in: Proceedings of the Design Society: International Conference on Engineering Design 1, 2019, pp. 189–198, https://doi.org/10.1017/dsi.2019.22.

[63] Hutchins, Giles. 2012. The nature of business - redesigning for resilience. Green books.

[64] Edita Olaizola, Rafael Morales-Sánchez, Marcos Eguiguren Huerta, Biomimetic organisations: a management model that learns from nature, Sustainability 12 (6) (2020) 2329, https://doi.org/10.3390/su12062329.

[65] Biomimetic leadership for 21st century companies, Biomimetics 6 (3) (2021) 47, https://doi.org/10.3390/biomimetics6030047.

[66] Unai Tamayo, Gustavo Vargas, Biomimetic economy: human ecological-economic systems emulating natural ecological systems, Soc. Responsib. J. 15 (6) (2019) 772–785, https://doi.org/10.1108/SRJ-09-2018-0241.

[67] Raymond J. Cole, Peter Busby, Robin Guenther, Leah Briney, Aiste Blaviesciunaite, Tatiana Alencar, A regenerative design framework: setting new aspirations and initiating new discussions, Build. Res. Inf. 40 (1) (2012) 95–111, https://doi.org/10.1080/09613218.2011.616098.

[68] Biomimicry Oregon. 2013. 'Nature's Strategies for Managing Stormwater in the Willamette Valley'.

[69] N.J. Mlot, C.A. Tovey, D.L. Hu, Fire ants self-assemble into waterproof rafts to survive floods, Proc. Natl. Acad. Sci. 108 (19) (2011) 7669–7673, https://doi.org/10.1073/pnas.1016658108.

[70] Adam. Summers, Keep me hanging on : surviving in the intertidal zone tests the rubbery limits of algae, Nat. Hist. 115 (6) (2006) 26–27.

[71] J.M. Wheaton, S.N. Bennett, N. Bouwes, J.D. Maestas, S.M. Shahverdian, Low-Tech Process-Based Restoration of Riverscapes: Design Manual. Version 1.0, Utah State University Restoration Consortium, Logan, UT, 2019.

[72] B.A. Middleton, K.L. McKee, Degradation of mangrove tissues and implications for peat formation in Belizean island forests: mangrove decomposition in Belize, J. Ecol. 89 (5) (2001) 818–828, https://doi.org/10.1046/j.0022-0477.2001.00602.x.

[73] Guijing Li, Long Wan, Ming Cui, Bin Wu, Jinxing Zhou, Influence of canopy interception and rainfall kinetic energy on soil erosion under forests, Forests 10 (6) (2019) 509, https://doi.org/10.3390/f10060509.

[74] Himadri Bose, Tulasi Satyanarayana, Microbial carbonic anhydrases in biomimetic carbon sequestration for mitigating global warming: prospects and perspectives, Front. Microbiol. 8 (August) (2017) 1615, https://doi.org/10.3389/fmicb.2017.01615.

[75] Shameer Syed, Viswanath Buddolla, Bin Lian, Oxalate carbonate pathway—conversion and fixation of soil carbon—a potential scenario for sustainability, Front. Plant Sci. 11 (December) (2020), 591297, https://doi.org/10.3389/fpls.2020.591297.

[76] Eleni Katifori, Gergely J. Szöllősi, Marcelo O. Magnasco, Damage and fluctuations induce loops in optimal transport networks, Phys. Rev. Lett. 104 (4) (2010), 048704, https://doi.org/10.1103/PhysRevLett.104.048704.

[77] Hongya Geng, Qiang Xu, Mingmao Wu, Hongyun Ma, Panpan Zhang, Tiantian Gao, Liangti Qu, Tianbao Ma, Chun Li, Plant leaves inspired sunlight-driven purifier for high-efficiency clean water production', Nat. Commun. 10 (1) (2019) 1512, https://doi.org/10.1038/s41467-019-09535-w.