Communication

Maximizing Benefits to Nature and Society in Techno-Ecological Innovation for Water

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Abstract: Nature-based solutions (NbS) build upon the proven contribution of well-managed and diverse ecosystems to enhance resilience of human societies. They include alternatives to techno-industrial solutions that aim to enhance social-ecological integration by providing simultaneous benefits to nature (such as biodiversity protection and green/blue space) and society (such as ecosystem services and climate resiliency). Yet, many NbS exhibit aspects of a technological or engineered ecosystem integrated into nature; this techno-ecological coupling has not been widely considered. In this work, our aim is to investigate this coupling through a high-level and cross-disciplinary analysis of NbS for water security (quantity, quality, and/or water-related risk) across the spectrums of naturalness, biota scale, and benefits to nature and society. Within the limitations of our conceptual analysis, we highlight the clear gap between "nature" and "nature-based" for most NbS. We present a preliminary framework for advancing innovation efforts in NbS towards maximizing benefits to both nature and society, and offer examples in biophysical innovation and innovation to maximize techno-ecological synergies (TES).

Keywords: water security; nature-based solutions; technology and nature; ecological engineering; innovation systems; ecological civilization

1. Introduction

Globally, biodiversity, natural areas, and water security are in dramatic decline due to an unprecedented combination of climate, consumption, and pollution crises. Despite increased recognition of humanity's dependence on the ecosystem services (ES) that the natural world provides, status-quo trajectories suggest the overshoot of several planetary boundaries [1]. Nature-based solutions (NbS) are "living solutions inspired by, continuously supported by and using nature, which are designed to address various societal challenges in a resource-efficient and adaptable manner and to provide simultaneous economic, social, and environmental benefits" [2]. While no panacea, NbS aim to reconcile economic development and ecosystem stewardship, with the potential to reduce consumption of natural capital by substituting accrued 'natural interest' from enhancement of ES [3,4]. NbS for water security (acceptable quantity, quality, and/or water-related risk) are highly relevant for both society and nature: 4 billion people face severe water scarcity [5], 1.32 trillion USD is needed annually for water infrastructure just to maintain business-as-usual [6], and changes in environmental flows and water quality are dramatically impacting terrestrial and aquatic biodiversity [7].

As an emerging concept, the terminology and ideology of NbS, and how they differ from existing approaches, are still under debate [8–14], although there are general criteria [15], including: (i) simultaneous benefits for society and nature; and (ii) its use

as a transdisciplinary umbrella that encompasses existing concepts such as 'ecological engineering' and 'blue-green infrastructure' in engineering, 'natural capital' and 'ecosystem services' in economics, 'ecosystem-based principles' and 'ecological intensification' in agriculture, 'landscape functions' and 'rewilding' in environmental planning, and the family of other nature-based approaches, such as 'ecohydrology', 'ecosystem-based adaptation', 'ecosystem-based mitigation', 'eco-disaster risk reduction', and 'natural climate solutions' [11]. The NbS concept has had significant academic discourse on implementation, barriers, policy, and innovation, often with an emphasis on the urban or rewilding context [3,4,9,11,13,16–18]. On the other hand, science, technology, and innovation 'with and for nature' still remains a minor topic in the NbS literature, despite the acknowledgement of their importance in sustainability transitions [16,19–21]. Recently, a nature-based innovation system (NBIS) was described [16], and differentiated from technological innovation systems (TIS) for several key reasons: (i) NbS can be a product *or* process phenomenon; (ii) NbS generate dispersed, multifunctional, and mainly public values that are difficult to capture by sectoral organizations and markets; and (iii) NbS involve non-human species and ecosystems that may not be easy or desirable to control.

In this work, our aim is to build on the NBIS concept through a high-level and cross-disciplinary analysis of NbS for one sector, water (quantity, quality, and/or water-related risk). To this effort, our analysis examines naturalness, biota scale, and techno-ecological innovation as part of the broader NBIS. We begin development of operational frameworks for innovation efforts in NbS for water to support maximizing long-term benefits for both nature and society.

2. Methodology

For this analysis, we chose twenty-seven NbS from diverse fields to bridge disciplinary boundaries, including: restoration ecology, blue-green infrastructure, ecological engineering, and environmental engineering. The NbS were selected to highlight the breadth of techno-ecological innovation across time (from present, to near-term future), and place (from local/niche to globally widespread). NbS included are those that both directly sustain existing or create new ecosystems in nature (e.g., forests, wetlands, coastlines, greenspaces) and address water security challenges for society, specifically: improving quality, improving quantity, and/or reducing water-related risk. Thus, indirect supports of nature (e.g., wastewater resource recovery that could displace land use by bioenergy crops [22,23]) were excluded. To limit scope, we focus our discussion on product-like NbS (e.g., restoration, blue-green infrastructure, ecological engineering), and exclude process-like NbS (e.g., conservation, demand management, governance and finance innovation), recognizing that these are complementary, often with greater imperative, to sustainability transitions [24–27]. We include NbS involving ecosystems across biota scales, from microbiota (e.g., bacteria, archaea, fungi, phytoplankton, zooplankton, protozoa, etc.), to macrobiota (e.g., plants, insects, bivalves, fish, mammals, etc.). We include large and small-scale NbS across spatial landscapes—not just in the urban context (although we include urban greenspaces a part of nature for the purposes of this analysis). We acknowledge that most NbS discussed here are ecosystems designed for the benefit of humans; purported benefits to nature are often those that are also valued by humans (e.g., biodiversity protection, climate change mitigation, aesthetics) [28]. We draw inspiration from both NBIS [16] and techno-ecological synergy (TES) [29] frameworks in our comparitively simplified methodology and discussion on innovation in NbS for water.

3. Results and Discussion

3.1. Analysis of Naturalness in NbS for Water

NbS occur with varying degrees of 'naturalness' (closeness to an uninfluenced reference ecosystem), from minimal human influence, to modified environments, to human-built grey landscapes [4,10,11,30–34]. Defining naturalness for NbS is challenging; it invokes a classic dichotomy between nature and technology [35–38], and the 'uninfluenced' reference

state is itself the subject of debate [39]. Martin et al. (2016) argue that technology is best reserved for the "emergency room" and "techno-fix" options should not be the default approach to protecting nature [37]. Schaubroek (2018) rightly suggests a threshold value of naturalness to qualify as an NbS [10], although no such quantitative threshold value has been developed. Thus, for simplified classification purposes here, we use a gradient of naturalness between 'low', 'medium', and 'high'; qualitative approximations to nature somewhat paralleling Eggermont et al.'s (2015) three types of NbS relating to level of human intervention [40]. While this classification might be considered subjective and oversimplified [31], it is a useful starting point when comparing and contrasting NbS from seemingly disparate fields. For example, the difference in naturalness between wetland restoration and hypolimnetic oxygenation might be apparent, but significant evaluation would be warranted if comparing and ranking naturalness between, hypothetically speaking, green roofs and floating treatment wetlands. Of course, naturalness will clearly depend on *how* a specific NbS is implemented, e.g., a wastewater-fed wetland that results in anoxic conditions and low biodiversity would certainly be less natural than one that promotes the health of native plants and fish [18]. Certainly, a more quantitative assessment of naturalness is needed to evaluate contributions of techno-ecological innovation to NbS; i.e., contextual evaluation of process impacts on ES and biodiversity such as that seen in TES frameworks [22,29,41,42]. Table 1 summarizes direct benefits to society and nature for the selected NbS for water in order of decreasing naturalness. We iterate that Table 1 is not exhaustive; the NbS selected highlight the diversity across the analyzed spectrums—all variations of wetland restoration, bioretention, and living infrastructure would number hundreds. We select only several articles per NbS to highlight the breadth of transdisciplinary research.

As seen in Table 1, we find that, other than afforestation and restoration, few of the NbS analyzed approximate a natural ecosystem, with most having significant technological/designed attributes. This is not *necessarily* problematic, all NbS we analyzed are more natural than conventional techno-industrial solutions for water. However, it does highlight the clear gap between "nature" and "nature-based", indicating a major priority for ecological design in NbS for water. It also suggests a need for (i) accepted definitions of NbS including threshold values of naturalness and benefits to nature [10], and (ii) a better understanding of the role of technology in a NBIS, as has been sought for sustainability more broadly [19,20,101]. Within the NbS that fall under the 'engineering' categories, a spectrum of naturalness also exists, ranging from the more natural ecological engineering approaches (e.g., wetland restoration [102,103]), to hybrid blue-green infrastructure (e.g., green roofs and constructed wetlands [104]), to the less natural eco-industrial environmental engineering (e.g., bioremediation, some forms of wastewater resource recovery [105,106]). From a transdisciplinary perspective, we note that this naturalness offers somewhat of a disciplinary correlation. 'Technology' has been defined as the "subset of knowledge that includes the full range of devices, methods, processes, and practices that can be used to fulfill certain human purposes *in a specifiable and reproducible way*" [19,107]. While not discretely defined, ecological engineering often encourages self-design which is not necessarily specifiable and reproducible, and thus can be considered less technological [10,102,103,108]. Blue-green infrastructure and environmental engineering, on the other hand, certainly have more technological characteristics, often *aiming* to be specifiable and reproducible, and thus "validated" by researchers and industry.

Table 1. NbS for water, benefits to society, nature and co-benefits. In order of decreasing naturalness from green to grey.

Nature-Based Solution for Water	Direct Benefits to Society (Water-Related)	Direct Benefits to Nature	Co-Benefits	Ref.
Natural wetland restoration: restoring a degraded wetland/floodplain/riparian buffer zone to a pre-degraded or functional condition	Reduces risk (flood & drought mitigation), improves quantity (storage, aquifer recharge), improves quality (nutrient, pollution assimilation)	Restores natural wetland ecosystem, augments environmental flows, moderates eutrophication	Biodiversity, aesthetics, cultural ES (recreation, traditional), food, nutrient/climate regulation (carbon sink)	[25,32,43]
Coastal mangrove/saltmarsh/kelp/coral restoration: restoring a degraded coastal ecosystem to a pre-degraded or functional condition	Reduces risk (flood & storm surge control), improves quality (carbon and nutrient assimilation)	Restores natural coastal ecosystem, moderates marine eutrophication	Biodiversity, food, moderation of sea-level rise, soil protection, climate regulation (carbon sink)	[25,44,45]
Afforestation for erosion control: promoting vegetation in riparian or sloped zones to prevent erosion	Reduces risk (flood control), improves quality (sediment control)	Creates or restores a new forest ecosystem, buffers environmental flows	Biodiversity, aesthetics, food (tree crops), timber, soil protection, climate regulation (carbon sink)	[46–48]
Afforestation to stimulate precipitation: planting trees to induce evapotranspiration, cloud formation, and precipitation	Improves quantity (increasing precipitation and aquifer recharge)	Creates a new forest ecosystem, augments environmental flows	Biodiversity, food (tree crops), timber, climate regulation (carbon sink)	[49,50]
Woody debris in waterways: leaving or supplying woody debris in rivers and lakes as habitat and carbon source	Improves quality (physiochemical/biological filtration), reduces risk (buffers flooding)	Creates aquatic ecosystem, provides habitat and nutrient subsidies for microbiota with resultant trophic cascades	Food (fish)	[51,52]
Surface infiltration and retention: small constructed wetlands (e.g., bioretention, swales) to capture runoff and hydrologically connect water systems	Reduces risk (flood control), improves quantity (storage, aquifer recharge, hydraulic connectivity), improves quality (nutrient, pollution assimilation)	Connects small wetland ecosystems, provides habitat and nutrients to microbiota, buffers environmental flows	Aesthetics (greenspace), nutrient regulation, soil protection	[53–55]
Denitrification walls: buffer regions/strips with favorable conditions for denitrifying microbiota	Improves quality (nutrient assimilation)	Creates a small wetland/soil ecosystem, provides habitat and nutrients for denitrifying microbiota, moderates eutrophication	Nutrient regulation, protecting aquatic life (preventing hypoxic zones and harmful algal blooms)	[56–59]
Large-scale storage retention: large constructed wetlands (e.g., regional wetland, parkland) to capture and store precipitation and runoff	Reduces risk (flood control), improves quantity (storage, aquifer recharge, hydraulic connectivity), improves quality (nutrient, pollution assimilation)	Restores or creates a wetland ecosystem, provides land and aquatic habitat, buffers environmental flows	Biodiversity, aesthetics, cultural ES (recreation, traditional), food, nutrient regulation, blue/green connectivity	[53,60]
Nature-based coastal defenses: shoreline macrobiota (e.g., oyster reefs, shoreline plants) or sand to prevent damage/erosion	Reduces risk (flood & storm surge control), improves quality (carbon, nutrient, pollution assimilation)	Provides and protects habitat for coastal marine ecosystems	Food (fish), biodiversity, protecting navigable waterways	[61–65]
Bioaugmentation/biomanipula introducing or augmenting biota in water bodies to improve water quality (e.g., to control cyanobacterial blooms)	Improves quality (biological algae control, algal toxin prevention, nutrient assimilation)	Augments aquatic ecosystem, reduces ecotoxicity	Nutrient regulation, protecting aquatic life (preventing hypoxic zones and harmful algal blooms)	[30,66–68]
Aquifer bioremediation: addition of microbiota and/or carbon for remediation of contaminated aquifers	Improves quality (biological redox and/or assimilation of pollutants)	Augments subsurface ecosystem, reduces ecotoxicity	Soil and agriculture protection (e.g., removal of uranium, arsenic)	[69,70]
Vegetation for shading water: Planting trees adjacent to water bodies to prevent evaporation	Improves quantity (if transpiration rate is lower than evaporation rate), improves quality (reduces temperature)	Augments habitat for biota and supports water for vegetation	Biodiversity, aesthetics, soil protection, climate regulation	[71–73]

Table 1. *Cont.*

Nature-Based Solution for Water	Direct Benefits to Society (Water-Related)	Direct Benefits to Nature	Co-Benefits	Ref.
Green roofs: construction of building roofs that retain storm/rainwater and support biota	Reduces risk (flood control), improves quantity (seasonal storage), improves quality (carbon, nutrient, pollution assimilation)	Creates small urban ecosystem, habitat and nutrients for microbiota and plants, habitat for birds	Food, biodiversity, aesthetics, urban cooling, nutrient regulation, blue/green space connectivity	[32,74]
Wastewater ponds/lakes: constructed wetlands that collect and retain industrial, agricultural, or municipal wastewater	Improves quantity (seasonal storage, aquifer recharge, water reuse), improves quality (carbon, nutrient, pollution assimilation)	Creates aquatic ecosystem, habitat and nutrients for microbiota and plants, buffers environmental flows	Biodiversity, aesthetics, food (fish), nutrient regulation, climate regulation (carbon sink)	[53,75,76]
Marine bioremediation: introducing or augmenting microbiota to remediate marine pollution (e.g., oil spills, microplastics)	Improves quality (biological assimilation of pollutants)	Augments marine ecosystem, reduces ecotoxicity	Protection of marine life	[75,77–79]
Sub-surface ecological sanitation: addition of micro or macrobiota to latrine or septic systems	Improves quality (nutrient, pollution assimilation), improves quantity (water reuse potential in low-income regions)	Creates aquatic ecosystem, habitat and nutrients for biota (e.g., microbes, worms, plants)	Public health and ecosystem protection in low-income regions	[32,80]
Floating treatment wetlands: floating mat (natural or artificial) of macrophytes or other plants for remediation of runoff/wastewater	Improving quality (nutrient assimilation)	Augments aquatic ecosystem by providing consumers of excess nutrients, habitat for macrobiota	Food (fish), biodiversity, nutrient regulation	[81,82]
Water-related agroecology: water security within an agroecology setting (e.g., flooded rice paddies, amendments for water retention, wetlaculture)	Reduces risk (flood and erosion control), improves quantity (water retention in soil), improves quality (carbon and nutrient assimilation)	Creates aquatic ecosystem, provides habitat for various biota, buffers environmental flows	Soil protection, biodiversity, aesthetics, climate regulation (carbon sink)	[25,83–86]
METlands: producing electricity and nutrient recovery from dissolved organics in wetlands	Improves quality (carbon and nutrient assimilation), improves quantity (water reuse potential)	Creates or augments wetland ecosystem, provides habitat for microbiota, plants	Nutrient regulation, climate regulation (prevention of methane release in wetlands)	[87,88]
Living infrastructure: infrastructure integrated into nature; e.g., subsurface detention with revegetation, ecological engineering in infiltration basins	Improves quantity (storage), improves quality (carbon and nutrient assimilation)	Creates or augments wetland, aquatic, or forest ecosystem, provides habitat to biota	Nutrient regulation, aesthetics	[89–91]
Integrated mariculture for water: water treatment using fish, shellfish, or seaweeds	Improving quality (carbon and nutrient assimilation)	Creates or augments freshwater or marine ecosystem, provides nutrients for plants, trophic cascades for macrobiota	Food	[87,88]
Hypolimnetic oxygenation: Pumping oxygen into hypolimnetic region to mitigate eutrophication	Improves quality (promotes nutrient sequestration)	Augments freshwater ecosystem, provides oxygen for aerobic biota	Food (fish), nutrient regulation, biodiversity, protecting aquatic life (preventing hypoxic zones and harmful algal blooms)	[92]
Artificial reefs: addition of non-natural materials to promote reef growth or fish habitat	Reduces risk (storm surge control), improves quality (carbon and nutrient assimilation)	Creates small aquatic ecosystem, provides habitat to biota, enables trophic cascades	Food (fish), biodiversity, protecting navigable waterways	[93,94]
Building-wetland integration: urban vegetation for water treatment and reuse	Improves quantity (water reuse), improves quality (carbon and nutrient assimilation)	Creates urban aqueous ecosystem, provides habitat and nutrients to microbiota and vegetation	Aesthetics, nutrient regulation, energy conservation	[95,96]
Porous pavement: non-impervious surfaces to facilitate urban infiltration	Reduces risk (urban runoff control), improves quality (urban nutrient assimilation); improves quantity (groundwater recharge)	Augments water and nutrient supply to subsurface microbiota and plant roots	Nutrient regulation, soil protection	[97]
Water-related bioengineering: biosystems engineering to augment grey infrastructure (e.g., fungi biofilms in constructed wetlands)	Improves quality (carbon and nutrient assimilation)	Creates self-regenerating micro-ecosystem, habitat and carbon source for microbiota	Nutrient regulation, energy/materials conservation	[98]
Wastewater dark food chain: multitrophic wastewater treatment to produce food (e.g., biogas as an aquafeed in wetlands)	Improves quality (wastewater treatment and nutrient recovery), improves quantity (water reuse)	Creates small-scale ecosystem, provides habitat and nutrients for biota, trophic cascades	Food (fish, prawn), nutrient regulation	[99,100]

3.2. Analysis of Biota Scale in NbS for Water

As within nature, we find that NbS involve a wide range of biota scale (Table 2), ranging from microbiota (e.g., denitrification walls, reductive dechlorination in bioremediation, algae ponds), to macrobiota (e.g., plants in bioretention, oysters in living reefs, fish in wetland restoration). However, we find no clear trend between range of biota scale and naturalness. In most cases, a greater range of biota scale typically has a higher degree of naturalness, e.g., highly diverse and interacting micro and macro ecological networks are found in highly natural NbS such as wetland restoration. But this is not always the case—bioremediation, biomanipulation, and sub-surface infiltration can involve engineering habitat specific to microbiota while maintaining a relatively high degree of naturalness. We do observe some relationship between biota scale and implementation timescale. Many of the NbS that span the biota spectrum tend to be longer-term interventions on the order of years to decades (e.g., restoration, afforestation), partly because these typically involve ecosystems with slower-growth species (e.g., trees). However, some NbS spanning the biota spectrum mature far more quickly (<5 years), often those that have economic outputs or are hazard-reducing (e.g., agroecology, living infrastructure, riparian planting). Likewise, NbS utilizing microbiota are often far more rapid interventions on the order of weeks to months (e.g., subsurface ecological sanitation, denitrification walls) due to their inherently shorter lifecycles. Again, this is not always the case—e.g., aquifer bioremediation can take years to be successful. We also note discontinuities across many fields involving ecosystem engineering at different biota scales. Ecological engineering, ecohydrology, and blue/green infrastructure tend to focus on diversity and abundance of macrobiota, perhaps due to higher visibility and ease of monitoring; e.g., freshwater invertebrates are often prioritized over the underlying microbial ecology. On the other hand, environmental engineering is often associated with controlled microbiomes [109,110], rarely scaling up to higher trophic biosystems. This is despite a clear interdependence between biota scales, and calls for a more unified ecology [111,112].

Table 2. NbS for water, biota scale, technological, and regions. In order of decreasing naturalness from green to grey.

Nature-Based Solution for Water	Biota Scale	Technological Aspects	Applicable Regions	Ref.
Natural wetland restoration	Macro, co-occurring microbiota	None	Global	[25,32,43]
Coastal mangrove/saltmarsh/kelp/coral restoration	Macro, co-occurring microbiota	None	Coastal	[25,44,45]
Afforestation for erosion control	Macro, co-occurring microbiota	Large scale landscape alteration can be required: e.g., berms, terraces, ditches	Global	[46–48]
Afforestation to stimulate precipitation	Macro, co-occurring microbiota	Large-scale landscape alteration can be required: e.g., irrigation, reservoirs, etc.	Global—arid regions	[49,50]
Woody debris in waterways	Micro to macro	Roads/paths for supplying biomass	Global	[51,52]
Surface infiltration and retention	Macro, co-occurring microbiota	Small-scale landscape/hydrology alteration: e.g., diversions, reservoirs, etc.	Global—urban regions	[53–55]
Denitrification walls	Micro, co-occurring macrobiota	Microbiome control, small-scale landscape/hydrology alteration	Global—agriculture regions	[56–59]
Large-scale storage retention	Macro, co-occurring microbiota	Large-scale landscape/hydrology alteration: e.g., diversions, reservoirs, etc.	Global	[53,60]
Nature-based coastal defenses	Macro, co-occurring microbiota	Large scale landscape alteration can be required: e.g., dredging, sandbanks, etc.	Coastal	[61–65]
Bioaugmentation/biomanipulat	Micro to macro	Biome control: e.g., alteration of macro and micro communities	Global	[30,66–68]
Aquifer bioremediation	Micro	Microbiome control with introduced or enriched species	Global	[69,70]
Vegetation for shading water	Macro	Alteration of flows, horticultural maintenance	Global—arid regions	[71–73]
Green roofs	Macro, co-occurring microbiota	Structural and hydrological engineering, design, horticultural maintenance	Global—urban regions	[32,74]
Wastewater ponds/lakes	Micro to macro	Engineered infrastructure: reservoirs, diversions, dredging, aeration	Global	[53,75,76]
Marine bioremediation	Micro	Pumps, tanks; introduced or selected/enriched species	Oceans	[75,77–79]
Sub-surface ecological sanitation	Micro to macro	Sanitary engineering and logistics required for collection and treatment	Global—low-income regions	[32,80]
Floating treatment wetlands	Micro to macro	Structural engineering, transportation, maintenance	Global	[81,82]
Water-related agroecology	Micro to macro	Agriculture management and infrastructure: ditches, piping, machinery, etc.	Global	[25,83–86]
METlands	Micro, co-occurring macrobiota	Bioelectrochemical engineering: wires; altered flows; controlled biomes	Global	[87,88]
Living infrastructure	Macro, co-occurring microbiota	Engineered infrastructure: tanks, pipes, electrical, etc.	Global—urban regions	[89–91]
Integrated mariculture for water quality	Macro, co-occurring microbiota	Engineered infrastructure: pens, pumps; introduced species	Oceans	[87,88]
Hypolimnetic oxygenation	Micro to macro	Engineered infrastructure: tanks, pumps, electrical power; altered flows	Global	[92]
Artificial reefs	Macro, co-occurring microbiota	Engineered materials: e.g., plastic, concrete, dredging, monitoring	Coastal	[93,94]
Building-wetland integration	Micro to macro	Distribution system, tanks, pumps, monitoring, maintenance	Global—urban regions	[95,96]
Porous pavement	Micro, co-occurring macrobiota	Engineered surfaces and materials, excavation, maintenance	Global—urban regions	[97]
Water-related bioengineering	Micro	Introduced or selected/enriched species; monitoring and maintenance	Global	[98]
Wastewater dark food chain	Micro to macro	Wastewater collection; fermentation tanks, pipes, monitoring, maintenance	Global	[99,100]

3.3. Analysis of Benefits to Nature and Society through Techno-Ecological Synergies throughout the Development and Diffusion of NbS

Technological innovation has been defined as the "process by which technology is conceived, developed, codified, and deployed", as one part of a broader innovation system [19,101,107]; i.e., innovation does not occur in a vacuum. Here, we consider technological innovation that enables connections between technological and ecological systems. We recognize considerable work has developed this concept in the TES approach [29], although, for the purposes of our simplified analysis, we distinguish two types of innovation processes: (i) innovation to biophysically integrate natural and ecological systems, and (ii) innovation to maximize ES synergies. These clearly have significant overlap, and both can be thought to operationally advance "availability of technologies supporting NbS development" [16].

3.3.1. Biophysical Innovation

Biophysical innovation is specific to mechanisms that couple the metabolic and information flows between ecological and technological systems. Self-design is a primary example of biophysically linking technological and ecological systems, in which an ecological system adapts to the environmental constraints of the technological system it finds itself in, with minimal human interference [102]. Constructed wetlands that are built to evolve and adapt to fluctuations in runoff quantity and quality are an example of this. Innovation processes that encourage self-design thus lead to higher naturalness (green vertical arrow in Figure 1A). Another biophysical innovation approach, albeit far less natural, is ecological forcing by a technological system. Ecological enrichment is an example of this approach, e.g., forcing a desired microbiome community structure through human activity (e.g., aquifer bioremediation, hypolimnetic oxygenation). This has the opposite effect of self-design, constraining evolution and adaptation of the ecological system, resulting in decreased naturalness (grey arrow in Figure 1) and obligate reliance on human intervention. Less natural solutions, such as ecological forcing, are often justified with techno-economic efficacy rationale. This is despite the fact that many highly natural NbS are lower cost than industrial counterparts over long time horizons [24,32]. New York City's provisioning of drinking water is an oft-cited example, where conservation of watershed lands was far lower cost than installing improved technology. Reliability concerns are another common driver of ecological forcing and/or lower naturalness, e.g., mangrove restoration has shown mixed success in different locations [44], and some NbS for stormwater management have shown up to 6 orders of magnitude of variation in the efficacy of reducing coliforms [113]. NbS that do not reliably achieve societal objectives incentivize actors to revert to readily available industrial technology or stimulate demand for less-natural industrial innovation. Root causes of unreliability include "pervasive knowledge gaps" [24], and variation in local social-ecological systems that suggest challenges for the scalability of "proven" NbS [32,114]. Driving adoption of more natural NbS (horizontal green arrow in Figure 1A) relies on advancing reliability in place and time; e.g., UN Water indicates a need to "test NbS in different hydrological, environmental, socio-economic and management conditions" [32]. Innovation processes that increase naturalness and reliability prior to widespread adoption are thus critical to maximizing long-term benefits.

Yet, this does present a paradox-how can biophysical innovation both increase naturalness (i.e., less controlled and specifiable), and also increase efficacy and reliability (typically more controlled and specifiable)? Technological innovation systems have historically trajected towards advancing *efficiency* metrics (output divided by input energy/resources), usually accompanied by decreased naturalness. For example, wastewater-fed wetlands were mostly displaced by technologically "efficient" activated sludge tanks—less natural, but more reliable effluent water quality. Moving in the opposite direction presents significant challenges—naturalness is not typically seen as something that can be *increased* by human activity; rather, it needs be included in ecological design objectives. A major challenge to this is that more natural NbS are more complex systems—decomposing the larger system does not necessarily elucidate its understanding [115]. One plausible workaround to increasing naturalness in NbS is to supplement specific objectives with broader ones, promoting environment-guided function [115]. A rainforest is certainly not a technology, yet *effectively and reliably* produces food, water, oxygen, and biodiversity. Techno-ecological innovation could better invoke nature by including broad non-specifiable objectives [116] along with one or several specifiable objectives. Agroforestry is a food-system example of this biophysical innovation, coupling unspecifiable biodiversity in tree canopies (facilitating naturalness) with crop production (e.g., coffee) in the understory with high efficacy and reliability, and still maintaining some degree of naturalness. For water, Shijun (1985) describes a millennia-old innovation for utilizing wastewater and forest debris in an aquaculture-sericulture pond-forest biosystem [108,117]. The complete system mimics nature and produces non-specific trophic interactions, water treatment, oxygen, and biodiversity, while concurrently achieving several specifiable objectives (fish, silk) within a (relatively) natural biosystem. Technological *efficiency* is low as it is certainly more

efficient to keep silkworms in a single-trophic captivity system; this is because natural systems do not necessarily organize themselves according to *efficiency* [118]. On the other hand, *efficacy* and *reliability* are high; the system continuously produces fish and silk with few non-renewable inputs and maintains itself due to engineered resiliency. Todd et al. (2003) give contemporary examples of utilizing multitrophic engineered ecologies for both broad (biodiversity, carbon fixation, aesthetics) and specific (wastewater treatment, food) objectives [119]. Biophysical innovation for broad and/or multiple objectives also allows for a more adaptive NbS that works with the complexity of nature, and is less likely to experience "catastrophic failure" [120].

3.3.2. Innovation to Maximize ES Synergies

Maximizing ES synergies between technological and ecological systems is the core concept of the TES framework [29], and innovation in NbS can aspire to maximize this synergy. As one (highly simplified) example in the water sector, innovation in technological systems for green roofs can augment synergistic ES in ecological systems. For example, well designed green roof systems will improve water storage, habitat, and nutrient cycling that support the ecological system—plants, microbes, soil animals, urban fauna. By augmenting the ecological system, reciprocal synergistic ES result, e.g., increased transpiration of urban runoff, biotransformation of xenobiotics, strong root systems to prevent soil loss, etc. Design for co-benefits may also result in a solution with increased ES synergies for both nature and society. For example, a single objective of flood control might utilize dams or levees, but adding an additional design objective to also reduce nutrient loading might lead to distributed denitrifying bioswales with greater naturalness and less technological aspects (Table 2) and cascading co-benefits (i.e., aesthetics, interconnected greenspaces). On the other hand, introducing multifunctionality has the potential to increase complexity, introduce unintended consequences such as positive feedback loops, or deliver sub-optimal benefits [121], e.g., both a poorly functioning wetland and a poorly functioning wastewater treatment system can result from inadequate ecological design [119].

Figure 1B shows high-level categorizations of benefits to nature and society, again acknowledging limitations of the qualitative and subjective conceptualization of "benefits" and "naturalness". Quantitative valuation of ES to society is an ongoing (and contentious) discussion with major consequences for NbS development and diffusion [11]. Likewise, quantitative evaluation of benefits to nature (e.g., restoration, enhancement) requires a broader suite of metrics under current development, such as trophic relationships, gene flows, meta-community interactions [122], and net-positive outcomes [123]. Despite examples that offer tangible benefits to human society and suggest at least some benefit to nature (at least compared to techno-industrial solutions), there has been no longitudinal analysis of quantifying benefits to nature from these types of initiatives, perhaps due to the same incongruencies that challenge ES valuation.
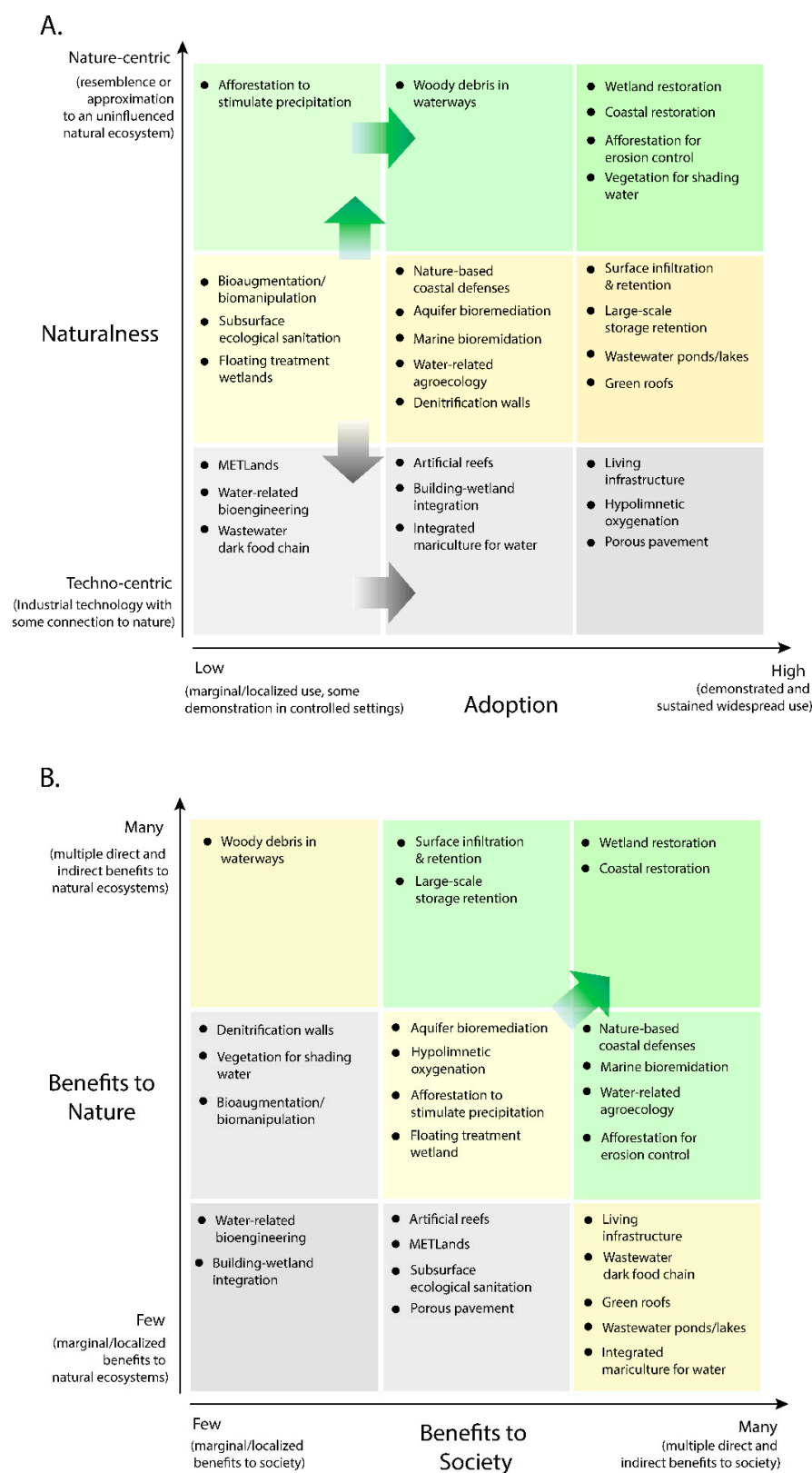
Figure 1. The development and diffusion of NbS for water. (**A**) Innovation can increase or decrease naturalness and drive adoption. (**B**) Innovation can advance ES synergies and maximize benefits to both nature and society.

4. Conclusions

From this work, several key findings emerge:

1. NbS for water exist across a wide spectrum of naturalness and biome scale, all generally showing some technological characteristics. While not inherently problematic, we further highlight the significant gap between "nature" and "nature-based", demonstrating the major challenge for both ecological design and innovation systems in NbS that needs to be addressed for comparative analysis and future policy. We find evidence of innovation mechanisms in NbS with potential to increase naturalness. These include, amongst others, biophysical innovation and innovation to maximize ES synergies, and specific examples include design for broad objectives to supplement specific ones, and design for co-objectives.

2. While increasing naturalness in innovation stages prior to widespread adoption has potential to maximize longer-term benefits to nature and society, this coupling of technological and ecological systems does not come without the possibility of unintended consequences, such as positive feedback loops creating uncontrollable novel ecosystems. "The road to extinction is paved with good intentions" resonates. To mitigate this risk, robust evaluation methodologies for these coupled systems are urgently needed.

3. We find examples of innovations, such as the forest-pond biosystem described, that have been ongoing for millennia and purposefully provide benefits to both society and nature. Many Indigenous societies, and even some Western ideals such as permaculture, have a belief system that supports natural systems while achieving societal objectives. Indeed, the Brundtland Report remarked over thirty years ago that the only people with a proven record to achieve sustainability within their ecological limits are Indigenous societies. Despite historical and ongoing environmental and economic injustices, many of these knowledge systems continue and are as relevant today as ever. Innovation policies should acknowledge, learn from, and respectfully invoke at large-scale these "ecological civilization" philosophies before planetary boundaries are further compromised.

Author Contributions: Conceptualization, K.L.D.; Software, E.B., I.D., K.L.D.; Resources, E.B., I.D., S.S., K.L.D.; Writing—Original Draft Preparation, K.L.D.; Writing—Review and Editing, E.B., I.D., S.S., K.L.D.; Visualization, E.B., I.D., K.L.D.; Funding Acquisition, K.L.D. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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