Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in
Environmental Sustainability

Challenges to realizing the potential of nature-based solutions

Donald R Nelson[a,b], Brian P Bledsoe[b,c], Susana Ferreira[b,d] and Nathan P Nibbelink[b,e]

Globally, rising seas, coastal erosion, extended dry periods, and flooding contribute to decreased water security and increased disaster incidence. Nature-Based Solutions (NBS) are increasingly advanced as innovative responses to promote adaptation and build resilience, and they are arguably more sustainable than traditional gray infrastructure. There is a growing body of information regarding the material, social, and technological advances that constitute NBS and the ways in which nature can complement traditional built infrastructure. However, critical gaps remain. Promoting a coupled systems approach, we explore fundamental challenges, including issues of participation and equity, economic valuation, scalar mismatches, the integration of natural and built infrastructure, and governance. NBS do not entail quick solutions, and to reach their full potential NBS require a fundamental rethinking of society's relationship with nature.

Addresses
[a] Department of Anthropology, 250 Baldwin Hall, University of Georgia, Athens, GA 30602, United States

[b] Institute for Resilient Infrastructure Systems, Driftmier Engineering Center, University of Georgia, 597 DW Brooks Drive, Athens, GA 30602, United States
[c] College of Engineering, Driftmier Engineering Center, University of Georgia, 597 DW Brooks Drive, Athens, GA 30602, United States
[d] Department of Agricultural and Applied Economics, 314D Conner Hall, University of Georgia, Athens, GA 30602, United States
[e] Warnell School of Forestry and Natural Resources, 180 E Green St., University of Georgia, Athens, GA 30602, United States

Corresponding author: Nelson, Donald R (dnelson@uga.edu)

Current Opinion in Environmental Sustainability 2020, **45**:49–55

This review comes from a themed issue on **Open issue**

Edited by **Eduardo Brondizio**, **Opha Pauline Dube** and **William Solecki**

Received: 07 February 2020; Accepted: 03 September 2020

https://doi.org/10.1016/j.cosust.2020.09.001

Introduction

Nature-based solutions (NBS) are an emerging worldwide practice that uses natural features and processes to increase resilience to climatological and environmental stress and change, while providing environmental, economic, and social benefits. NBS encompass conservation and rehabilitation of natural ecosystems, and the enhancement or creation of natural processes in modified or artificial ecosystems [1••]. Solutions span a range of scales, from small local features to entire landscapes [2], and work with conventional infrastructure to meet a range of objectives [1••], such as reducing flood damages and securing safe and ample water supplies. Examples of NBS include construction of dunes, marshes, islands, and reefs that protect coastal communities against storms, and forest management to reduce riverine flooding and purify water for downstream communities [2,3••]. The rapid expansion of NBS implementation in diverse geographical and cultural contexts [1••,2,4] has the potential to catalyze an extensive reframing and integration of ecosystem services and infrastructure resilience concepts. However, the introduction of natural dynamics into our conceptualization of infrastructure requires profound changes in the way we conceive, design, and implement projects to be effective at meaningful scales. This manuscript identifies challenges and emerging responses to advance the science and practice of NBS. Drawing on a systems-based approach, there is a focus on rethinking hydrological infrastructure to account for the particular demands and risks of water management in the 21st Century.

The historical and conceptual foundations of NBS have been shaped by a diverse collection of intersecting ideas, resulting in a broad range of contemporary definitions, applications, and objectives. For centuries, traditional knowledge governed land stewardship for delivery of ecosystem services and resilience through intentional management of fire, grazing, and fisheries. As an outgrowth of the nascent science of restoration ecology and practice of ecosystem restoration [5,6], in the early to mid-20th century, the field of ecological engineering was concurrently developed with ecosystem ecologists H.T. Odum in the USA and Ma Shijun in China. Ecosystem restoration and ecological engineering, so-called 'acid tests' of ecological theory, intersected the field of environmental economics and its emphasis on valuation of ecosystem services [4,7]. The contemporary recognition of natural systems and processes as societal infrastructure, and NBS as a viable means of counteracting the compounding threats of climate change and urbanization, is rooted in a transdisciplinary confluence of concepts. This confluence continues to yield a rich set of frontiers for developing the science and practice of NBS, which include Engineering With Nature, Ecosystem-based Adaptation, Ecosystem-based Disaster Risk Reduction, Green/Blue Infrastructure, and Natural Capital, among others [8,9].

NBS as complex systems

NBS confront challenges similar to other paradigm shifts including: limited awareness; knowledge gaps surrounding applications and their effectiveness; insufficient understanding of costs and benefits; diverse stakeholder values and perceptions; and limited policy and economic instruments (and/or the will to apply them) [3••,10–13]. Key elements of NBS, which present even knottier challenges, are the high levels of complexity and uncertainty, the need to work with imperfect information, and the need to move forward despite a paucity of evidence and standards [14]. Although pursuit of NBS is rapidly growing, these elements pose real risks that may limit broader adoption and successful implementation. Related challenges in Ecosystem-based Adaptation (EbA) and climate change, often characterized as wicked socio-environmental problems, are well documented [15,16]. They emerge from the complexity and dynamic essence of social-ecological systems (SES), largely due to uncertainties in the behavior of natural systems, the number of stakeholders, large spatial scales, and long temporal scales. Common within proposed solutions are calls for a more comprehensive framework [17,18••,19], an ecosystem approach [20], a dynamic framework [21], and the use of sustainability science [22].

The dynamic essence of *nature* implies a necessary shift in the way we think about infrastructure solutions [11••]. A systems-based framework incorporates the relationships and feedbacks within coupled social, ecological, and infrastructure components and scales and undergirds sustainable and resilient NBS by giving weight to the socio-political and biophysical elements of risk [22]. Figure 1 is a heuristic to elucidate the complex set of relationships between the technical and social domains and components of NBS with socio-hydrological outcomes. Projects that do not consider systemic relationships with social and ecological components, nor account for dynamic, emergent complexities, potentially undermine the ability to meet desired outcomes or create unanticipated results [23,24]. Integrated natural/gray (e.g. built from concrete, asphalt, steel, etc.) infrastructure is central to the ability to alter hydrological risks and mitigate vulnerability outcomes. But, through political processes, decision-makers enact decisions that (tacitly) prioritize risks and vulnerabilities for particular places and populations, and every response has the potential to introduce new fragilities into the system [25]. In order to sustainably mitigate hydrological risks and alter vulnerability outcomes, project designs must focus on the relationships between system domains, which include *Socio-hydrological risk and benefits*, *Socio-political context* and *Infrastructures within landscapes*. To account for dynamics, a systems-based framing anticipates change as an inherent element — whether initiated by social or biophysical factors [26]. This requires the fostering of intentional double, or triple-loop collaborative learning with multiple stakeholders [27], to continually evaluate and refine goals, objectives, and processes [28,29].

NBS challenges

Five categories of NBS challenges and corresponding emergent responses are described in Table 1. The categories are derived from a list of the challenges and responses from all the literature reviewed for this manuscript, which were then assessed and organized into coherent themes. The examples provided for each category are not exhaustive, but rather, highlight key challenges and innovative responses. These categories are mapped onto the system domains and relationships in the diagram (Figure 1) to illuminate their interrelated nature. The *Socio-political context* – which encompasses the challenge categories of (1) Participation and equity, (2) Governance, and (3) Valuation – influences decisions, actions and behaviors that alter physical infrastructures. It further bears on the ways in which patterns of risk, vulnerability, and benefits are valued, interpreted, and assessed. The *Infrastructures within landscapes* domain, confronts the challenges associated with (4) Infrastructure integration. The ways, in which these are overcome directly influence material changes in patterns of risk. They also reflect back on the *Socio-political context* as landscape changes alter future options for adaptation scenarios and decisions. The *Socio-hydrological risk and benefits* domain includes the challenges of (1) Participation and equity and (3) Valuation. The ways in which outcomes and patterns of risks, vulnerabilities, and benefits are considered, assessed, and realized, depict a direct reflection of the level and types of participation and valuation approaches. The (5) Scale and feedback challenges are embedded in the mediating relationships between the other domains and challenges, controlling the iterative and dynamic expressions of a system.

Participation and equity

The broad push for robust participation within academic NBS literature acknowledges the temporal dynamism, variations in risk perceptions, socially structured vulnerabilities, and the disciplinary diversity fundamental to sustainability. These characteristics necessitate innovative forms of participation that are responsive to system dynamics [11••] and work to build social resilience, complementing the resilience of natural and gray infrastructure [30]. Because NBS are suitable for a range of applications, offering a myriad of potential benefits, agreement on priority problems must happen before collaboratively

Table 1

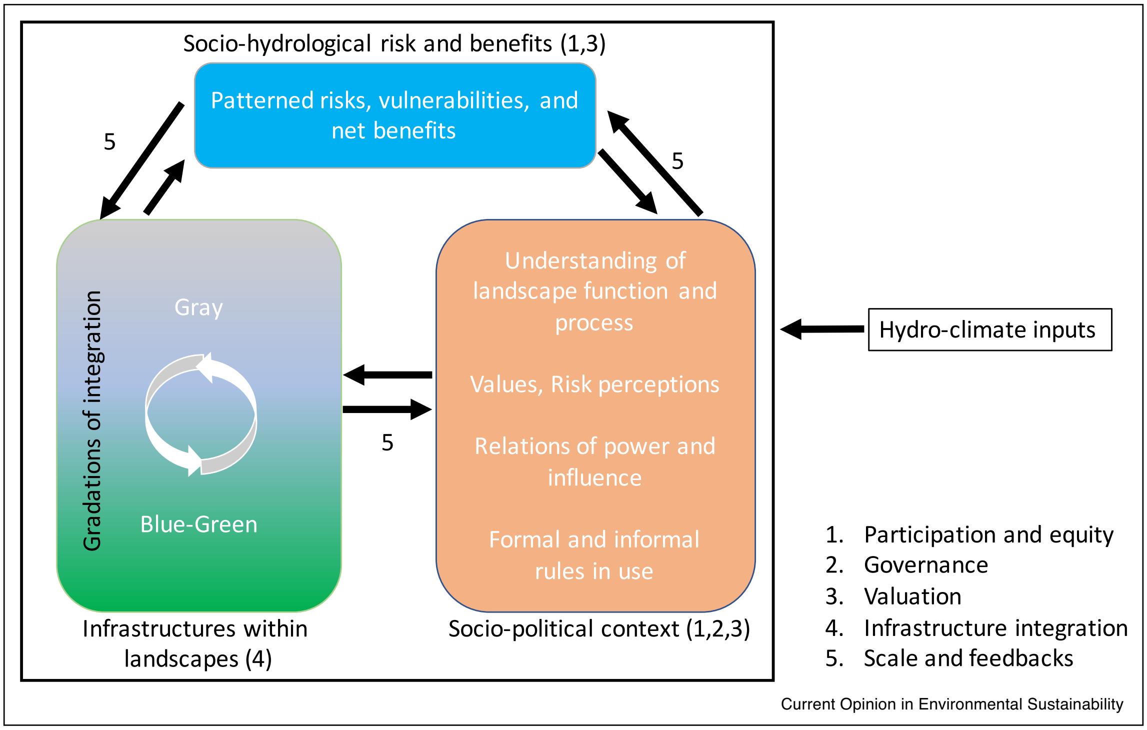
Examples of NBS challenges and emerging responses[a]

Challenges	Emerging responses
Participation and equity	
Lack of public understanding, unclear definitions and concepts [18••,58,59]	Expand research in stakeholder perceptions [58], broaden stakeholder base [60]
Fear of the unknown and change [12]	Sustained engagement that valorizes different knowledges [12]
Limited stakeholder involvement [61]	Purposeful inclusion of diverse actors, including the private sector [61], increasing awareness [10]
Unequal relations among actors [62]	Develop mechanisms to address justice and social cohesion issues [12]
Recognition that social and cultural elements are as important as biophysical elements [59]	Applying a complex systems lens to NBS [11••]
Governance	
Incomplete frameworks do not address novel challenges NBS (e.g. dynamics, participation) [18••]	More comprehensive frameworks that includes the missing components [18••]
Socio-political infrastructure creates patterns of behavior and action that shape the built environment [22]	Sustainability science can help; incorporates the complexities of social-hydrological risk in vulnerability assessment and planning [22]
While there is increasing political will at various scales (local, national, regional, and global), there may not be sufficient commitment to implementation [62]	Use reflexive approaches, which bring together NBS ambassadors, practitioners, other stakeholders to help build political will [12]
Water governance is dispersed and complex, with many competing interests, hindering integrated visions [62]	The Global Environmental Facility and associated programs (e.g. Transboundary Water Assessment Programme (www.geftwap.org), developed principles of integrated management [62]
Valuation	
Long term horizons for benefit accrual [11••]	Use of declining discount rates and dual discounting [44], application of transfer costs [63]
Need of a framework for full accounting of multifunctionality of NBS [17,44]	Account for non-market non-use values [45], Apply a system perspective [44], participatory multi-criteria analysis [46]
Complexity of estimating benefits/costs	Incorporate knowledge of ecological production functions, and uncertainties [21,38••]
Conventional markets can underprovide ecosystem services [38••]	Develop approaches to create markets (e.g. Payments of Ecosystem Services) [38••]
Infrastructure integration	
Knowledge gaps in terms of effectiveness, implementation, and design [10–12]	Develop evidence base through monitoring and evaluation [12], develop repository of best practices [10]; Sustained commitment to an evidence-based approach to increase the likelihood that programs will attain their goals. [61]
Lack of confidence and certainty regarding the ability of natural infrastructure to reduce risk [3••]	Integration of science, designs, and policy to establish evidence based eco-engineering standards [3••]
Path dependence has strong influence on decision making [54]	Education of infrastructure professionals, community-empowered [54]
NBS considered separate from conventional infrastructure despite significant potential for resilient hybrid systems	Develop compelling examples of integrating green and gray infrastructure [1••,64], build awareness and evidence through demonstrations [65]
Scale and feedbacks	
Disconnect between short term action and long term goals/outcomes [12]	Sustainability science incorporates complexities of social-hydrological risk [22] through a systems-based approach [17–19], including an ecosystem approach, with integrated planning from the early stages [16,20,32]
Mismatch between the timeframes of evaluation and project duration reduces incentives to account for long-term impacts [63]	Framework that considers future change, such as climate change [21]
Scale of intervention may differ from the scale of institutions thus limiting potential for effective change [32]	Integrated, cross-scale planning, application of planning-shed approach [3••,17,20]
Processes are complex, include diverse stakeholders, and extend beyond political boundaries [3••]	Examples of planning and implementation across scales and jurisdictional boundaries [17], including Building with Nature Indonesia [3••]

[a] Challenges and responses listed are exemplary, and not exhaustive.

determining, implementing, and managing solutions. This entails inclusion of a multitude of perspectives, including stakeholders whose voices are frequently unheard. Indeed, the effectiveness of NBS relies on stakeholder engagement to provide substantive, instrumental and normative benefits [8,13] to help meet all dimensions of sustainability. To increase participatory space and promote ownership of these decision-making processes, researchers argue for a focus on understanding risk perceptions before conducting vulnerability outcome assessments, and provide examples for how to do so [13,22,25]. Hydrological risks and vulnerabilities are

Figure 1



Current Opinion in Environmental Sustainability

NBS heuristic system diagram with associated challenge categories.
Adapted from Ref. [22].

patterned through social structures and institutional process [31,32]. Because sustainability and equity are interlinked and interdependent [33], sustainable NBS must work to address social and systemic inequities, and may frequently engage with environmental justice approaches [12]. The transdisciplinary umbrella of NBS research and applications also requires broad disciplinary participation, including natural, physical, social sciences, the humanities, and engineering [8,12].

Governance

The system-based complexities of NBS require broad integration, including conceptual, functional, methodological and disciplinary [34]. This entails developing legal and governance structures that can account for dynamic change, ensure effective participation, and support social learning to promote the definition and pursuit of collective goals. The emerging evidence in SES research demonstrates that much of this responsive, transformative capacity will be informal, through social networks and cultural knowledge [35]. It requires space for human agency and self-organization to envision desired futures [35], and, through participation, evaluate and influence the ongoing enactment of those futures. Simultaneously, SES scholars are beginning to understand the ways in which the enactment of formal statutory and regulatory law can be more responsive [36]. Nevertheless, to date, there has been less focus within the NBS literature on how societies should organize and act to sustain the provision of ecosystem services [37]. One well-documented mechanism is payment for ecosystem services. However, institutional imperfections such as ill-defined property rights or poorly functioning financial services and credit markets undermine these schemes [38••,39]. Furthermore, while effective monitoring and sanctioning of non-compliance are key governance elements [8,16,39], few programs sanction non-compliance regularly [39], likely due to political costs and administrative complexity. In contrast, the monitoring and evaluation of gray infrastructure performance is relatively straightforward [40].

Valuation

A precondition for the efficient provision of any NBS is that benefits exceed costs [18••,38••,39]. NBS integrate management activities with landscape-scale planning and policy [18••], allowing a broad range of multifunctional solutions, simultaneously providing environmental, social and economic benefits [8,19,37,41]. However, NBS do not offer win–win scenarios, and the desire to simultaneously achieve these benefits must be met with a realistic acknowledgment of potential losses as well as gains (for places, people, or valued outcomes) for the long term success of projects. Centering discussions of trade-offs can promote creativity and learning [42] and incentivize ongoing participation. Although some posit that NBS can outperform other conventional interventions [3••,21] once co-benefits are considered, full economic or social evaluations to argue for the cost-effectiveness of NBS have not been forthcoming [19,37], and benefit-cost analyses that explicitly compare NBS to other 'hard' measures remain rare [10,15,37,38••]. Economic analyses of NBS require an understanding of ecological production functions and uncertainties and include benefits that typically accrue over longer time horizons than with conventional solutions [43]. The long-time horizons undermine assumptions in conventional discounting theory. While the use of declining discount rates has strong theoretical and empirical support for the evaluation of extremely long-horizon projects [44], its application is currently limited to a handful of OECD countries. Finally, economic analyses must account for non-market values, including non-use values [45], which may change over the life of NBS. The multi-dimensionality of values and distributional considerations leads to further arguments for increased participation [46]. Even when aggregate benefits exceed costs, net benefits may not be equitably distributed or positive for all [44]. The interdependence of sustainability and equity requires the consideration of promoting vertical equity, in which different populations (e.g. according to income) receive different treatments to account for discrepancies in resources, social position or political access, even though this may reduce efficiency [39].

Infrastructure integration

NBS are frequently considered separate from conventional infrastructure despite significant potential for hybrid designs that strengthen the overall system by increasing the resilience and functional life span of interconnected water, transportation, food, and energy infrastructures [3••,47,48]. Natural infrastructure generally does not catastrophically fail, even in extreme events, and has the capacity for self-repair [49]. However, NBS will not be perceived as essential and functionally equivalent elements of an integrated system until they are subjected to the same level of rigorous analytical processes, performance standards, and assessment criteria as conventional infrastructure [50]. This will be a long-term interdisciplinary challenge because NBS work differently and are inherently dynamic and heterogeneous compared to conventional hard infrastructure. The complexity and regenerative properties of natural and nature-based systems must ultimately be embraced by infrastructure engineering practitioners if NBS are to reach their full potential, as these attributes are what engender NBS with the capacity to serve multiple functions and perform robustly and cost-effectively under a wide range of potential future conditions [9].

Scale and feedbacks

NBS confront challenges common to other complex systems, which stem from social and ecological heterogeneities, connectivity and spatial flows, working across scales, and cross-domain feedbacks (e.g. between social and ecological domains) [23]. Scalar challenges include working across spatial and ecological scales [51], political boundaries [3••], and social structures [32] and the delayed accrual of some benefits generates temporal mismatches regarding the timing of actions and outcomes [12,15,32]. The literature acknowledges the variation in size/type [52] and scales [53] of projects but there remains a lack of knowledge regarding the scale of activity necessary for social-environmental sustainability [51]. Responses will require private sector engagement [54], in part because small-scale projects are unlikely to meet objectives unless implemented at broad scales [17]. For example, when resource ownership is fragmented, projects may underperform when each owner sets the price of access independently, creating a 'tragedy of the anticommons' [55]. This underscores the need to move from a small-scale, 'random acts of kindness' framing, to prioritize scales for which NBS has measurable impacts. Thus, there is a strong need for models to help prioritize national/global investments, and guide selection and implementation of NBS. Finally, there is a need to move from the conventional infrastructure 'command and control' mentality, to the recognition of the iterative relationship between society and nature in which project outcomes are dynamic and emergent, rather than preordained [56]. This again highlights the importance of intentional learning to evaluate goals and processes and respond accordingly.

Looking forward

We conclude with sobering, yet hopeful reflections on a way forward. NBS offer attractive possibilities for responding to adaptation challenges in the 21st Century. But we must be careful not to oversell NBS. The term 'solutions' permits a perception that NBS promote quick, tidy outcomes. But in truth, these solutions are ongoing processes that require dedicated efforts to revisit and learn from past decisions. Deep uncertainty — ecological and social — needs to be considered. Trade-offs in current and future equity considerations, intrinsic to sustainability, must be identified and evaluated, and the distribution of risks and benefits, must be made explicit. Researchers are continuing to build a suite of empirical evidence [see Ref. 57] and move from information gathering to knowledge building. Yet, a fundamental shift in the way that we think about our relationship to nature and our conceptions of infrastructure is required to fully achieve the lofty potential of NBS. This is more than just a scientific rethinking, but will challenge common cultural perceptions of separation from nature [56] and what we expect from infrastructure, and entails fundamental changes in the ways in which decisions are made.

These conceptual shifts will require focused communication efforts with the public and policy makers, and address not just possible benefits, but also the tough road to get there.

Conflict of interest statement

Nothing declared.

Funding

This work was supported by a Presidential Interdisciplinary Seed Grant from the University of Georgia.

Acknowledgements

We thank Sarah Buckleitner for constructive comments on the manuscript and appreciate insightful conversations with our colleagues from the Institute for Resilient Infrastructure Systems at the University of Georgia.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest

1. •• Browder G *et al.*: *Integrating Green and Gray: Creating Next Generation Infrastructure*. Washington, DC: World Bank and World Resources Institute; 2019.

This document serves to guide stakeholders on methods for integrating green and gray infrastructure to address existing infrastructure development challenges such as water supply, flood management, and so on. Technical, environmental, social, and economic co-benefits are detailed within the context of existing financial and policy frameworks. Global case studies provide examples for how the presented framework for green infrastructure integration can be implemented to address the various challenges across diverse settings.

2. WWAP, UN-Water: *The United Nations World Water Development Report, Nature-based Solutions for Water*. Paris: UNESCO; 2018.
3. •• Whelchel AW *et al.*: **Advancing disaster risk reduction through the integration of science, design, and policy into eco-engineering and several global resource management processes**. *Int J Disaster Risk Reduct* 2018, **32**:29-41.

This paper presents a clear and relatively holistic description of NBS from an eco-engineering perspective. It covers origins, basis for risk reduction, current challenges, and a suite of compelling examples. Finally, they offer a set of recommendations to advance eco-engineering through science, design, policy, and multiscalar processes.

4. Krutilla JV: **Conservation reconsidered**. *Am Econ Rev* 1967, **57**:777-786.
5. Kairo J *et al.*: **Restoration and management of mangrove systems—a lesson for and from the East African region**. *South Afr J Bot* 2001, **64**:383-389.
6. Jordan WR, Lubick GM: *Making Nature Whole: A History of Ecological Restoration*. Island Press; 2011.
7. Westman WE: **How much are nature's services worth?** *Science* 1977, **197**:960-964.
8. Nesshover C *et al.*: **The science, policy and practice of nature-based solutions: an interdisciplinary perspective**. *Sci Total Environ* 2017, **579**:1215-1227.
9. van Wesenbeeck BK *et al.*: **Nature-based approaches in coastal flood risk management: physical restrictions and engineering challenges**. *Ecosystem-based Disaster Risk Reduction and Adaptation in Practice*. Springer; 2016:181-198.
10. Faivre N *et al.*: **Nature-based solutions in the EU: innovating with nature to address social, economic and environmental challenges**. *Environ Res* 2017, **159**:509-518.
11. •• Fernandes JP, Guiomar N: **Nature-based solutions: the need to increase the knowledge on their potentialities and limits**. *Land Degrad Dev* 2018, **29**:1925-1939.

This paper provides an exploration of why NBS require fundamental changes in how we approach infrastructure. It highlights processes and challenges of reintroducing nature into the built environment. The authors also discuss social and governance implications of a move to NBS and offers some potential pathways forward.

12. Kabisch N *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* 2016, **21**.
13. Santoro S *et al.*: **Assessing stakeholders' risk perception to promote nature based solutions as flood protection strategies: the case of the Glinscica river (Slovenia)**. *Sci Total Environ* 2019, **655**:188-201.
14. Pacanowsky M: **Team tools for wicked problems**. *Organ Dyn* 1995, **23**:36-51.
15. Ojea E: **Challenges for mainstreaming ecosystem-based adaptation into the international climate agenda**. *Curr Opin Environ Sustain* 2015, **14**:41-48.
16. Nalau J, Becken S, Mackey B: **Ecosystem-based adaptation: a review of the constraints**. *Environ Sci Policy* 2018, **89**:357-364.
17. Xing Y, Jones P, Donnison I: **Characterisation of nature-based solutions for the built environment**. *Sustainability* 2017, **9**.
18. •• Cohen-Shacham E *et al.*: **Core principles for successfully implementing and upscaling nature-based solutions**. *Environ Sci Policy* 2019, **98**:20-29.

This paper presents a general framework and eight principles of nature-based solutions, comparing them to related ecosystem-based approaches. These comparisons showcase how NBS can be an umbrella for other approaches by expanding the spatial scale, applicability to policy, and compatibility with other methods. It emphasizes social-ecological systems at the landscape scale, incorporating key social science concepts.

19. Colléony A, Shwartz A: **Beyond assuming co-benefits in nature-based solutions: a human-centered approach to optimize social and ecological outcomes for advancing sustainable urban planning**. *Sustainability* 2019, **11**.
20. Krauze K, Wagner I: **From classical water-ecosystem theories to nature-based solutions - contextualizing nature-based solutions for sustainable city**. *Sci Total Environ* 2019, **655**:697-706.
21. Calliari E, Staccione A, Mysiak J: **An assessment framework for climate-proof nature-based solutions**. *Sci Total Environ* 2019, **656**:691-700.
22. Eakin H *et al.*: **Opinion: urban resilience efforts must consider social and political forces**. *Proc Natl Acad Sci U S A* 2017, **114**:186-189.
23. King EG, Nelson DR, McGreevy JR: **Advancing the integration of ecosystem services and livelihood adaptation**. *Environ Res Lett* 2019, **14**.
24. Sterk M, van de Leemput IA, Peeters ETHM: **How to conceptualize and operationalize resilience in socio-ecological systems?** *Curr Opin Environ Sustain* 2017, **28**:108-113.
25. Tellman B *et al.*: **Adaptive pathways and coupled infrastructure: seven centuries of adaptation to water risk and the production of vulnerability in Mexico City**. *Ecol Soc* 2018, **23**.
26. Auad G *et al.*: **A dynamic management framework for socio-ecological system stewardship: a case study for the United States Bureau of Ocean Energy Management**. *J Environ Manage* 2018, **225**:32-45.
27. De Kraker J: **Social learning for resilience in social–ecological systems**. *Curr Opin Environ Sustain* 2017, **28**:100-107.
28. Yu DJ *et al.*: **Learning for resilience-based management: generating hypotheses from a behavioral study**. *Global Environ Change* 2016, **37**:69-78.
29. Angelstam P *et al.*: **Collaborative learning to unlock investments for functional ecological infrastructure: bridging barriers in social-ecological systems in South Africa**. *Ecosyst Serv* 2017, **27**:291-304.

30. van der Merwe SE, Biggs R, Preiser R: **A framework for conceptualizing and assessing the resilience of essential services produced by socio-technical systems**. *Ecol Soc* 2018, **23**.

31. Sanderson MR: **Everything flows . . . unevenly: social stratification in coupled socio-ecological systems**. *Curr Opin Environ Sustain* 2018, **33**:51-57.

32. Woroniecki S, Wamsler C, Boyd E: **The promises and pitfalls of ecosystem-based adaptation to climate change as a vehicle for social empowerment**. *Ecol Soc* 2019, **24**.

33. Leach M *et al.*: **Equity and sustainability in the anthropocene: a social–ecological systems perspective on their intertwined futures**. *Global Sustain* 2018, **1**.

34. Guerrero AM *et al.*: **Achieving the promise of integration in social-ecological research: a review and prospectus**. *Ecol Soc* 2018, **23**.

35. Garmestani A *et al.*: **Untapped capacity for resilience in environmental law**. *Proc Natl Acad Sci U S A* 2019, **116**:19899-19904.

36. Chaffin BC *et al.*: **Transformative environmental governance**. *Annu Rev Environ Resour* 2016, **41**:399-423.

37. Brink E *et al.*: **Cascades of green: a review of ecosystem-based adaptation in urban areas**. *Global Environ Change* 2016, **36**:111-123.

38. Adamowicz W *et al.*: **Assessing ecological infrastructure
•• investments**. *Proc Natl Acad Sci U S A* 2019, **116**:5254-5261.
This provides an example of a state-of-the-art*ex ante* benefit-cost assessment of ecological infrastructure investment in the Panama Canal Watershed, illustrating the challenges to forecasting the market-clearing prices and quantities for PES contracts.

39. Wunder S *et al.*: **From principles to practice in paying for nature's services**. *Nat Sustain* 2018, **1**:145-150.

40. Bassi AM, McDougal K, Uzsoki D: *Sustainable Asset Valuation Tool*. International Institute for Sustainable Development; 2017.

41. Raymond CM *et al.*: **A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas**. *Environ Sci Policy* 2017, **77**:15-24.

42. Hirsch PD *et al.*: **Acknowledging conservation trade-offs and embracing complexity**. *Conserv Biol* 2010:259-264.

43. Gray E *et al.*: *Green-Gray Assessment: How to Assess the Costs and Benefits of Green Infrastructure for Water Supply Systems*. 2019.

44. Atkinson G *et al.*: *Cost Benefits Analysis and the Environment: Further Developments and Policy Use*. Organisation for Economic Co-operation and Development; 2018.

45. Johnston RJ *et al.*: **Contemporary guidance for stated preference studies**. *J Assoc Environ Resour Econ* 2017, **4**:319-405.

46. Dallimer M *et al.*: **Taking stock of the empirical evidence on the insurance value of ecosystems**. *Ecol Econ* 2020, **167**.

47. Depietri Y, McPhearson T: **Integrating the grey, green, and blue in cities: nature-based solutions for climate change adaptation and risk reduction**. *Nature-based Solutions to Climate Change Adaptation in Urban Areas*. Cham: Springer; 2017, 91-109.

48. Janssen MA *et al.*: **Highways as coupled infrastructure systems: an integrated approach to address sustainability challenges**. *Sustain Resilient Infrastruct* 2019:1-12.

49. Sutton-Grier AE, Wowk K, Bamford H: **Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems**. *Environ Sci Policy* 2015, **51**:137-148.

50. Seddon N *et al.*: **Understanding the value and limits of nature-based solutions to climate change and other global challenges**. *Philos Trans R Soc B* 2020, **375** 20190120.

51. Thorslund J *et al.*: **Wetlands as large-scale nature-based solutions: status and challenges for research, engineering and management**. *Ecol Eng* 2017, **108**:489-497.

52. Gómez Martín E, Máñez Costa M, Schwerdtner Máñez K: **An operationalized classification of nature based solutions for water-related hazards: from theory to practice**. *Ecol Econ* 2020, **167**.

53. Keeler BL *et al.*: **Social-ecological and technological factors moderate the value of urban nature**. *Nat Sustain* 2019, **2**:29-38.

54. Davies C, Lafortezza R: **Transitional path to the adoption of nature-based solutions**. *Land Use Policy* 2019, **80**:406-409.

55. Heller M: **The tragedy of the anticommons: a concise introduction and lexicon**. *Modern Law Rev* 2013, **76**:6-25.

56. Nelson DR, Bledsoe BP, Shepherd JM: **From hubris to humility: transcending original sin in managing hydroclimatic risk**. *Anthropocene* 2020:100239.

57. Oppla. EU Repository of Nature-based Solutions. Available from: https://oppla.eu/.

58. Gray JDE, O'Neill K, Qiu Z: **Coastal residents' perceptions of the function of and relationship between engineered and natural infrastructure for coastal hazard mitigation**. *Ocean Coastal Manage* 2017, **146**:144-156.

59. Bridgewater P: **Whose nature? What solutions? Linking ecohydrology to nature-based solutions**. *Ecohydrol Hydrobiol* 2018, **18**:311-316.

60. Ozment S, DiFrancesco K, Gartner T: *Natural Infrastructure in the Nexus*. 2015.

61. Bremer LL *et al.*: **One size does not fit all: natural infrastructure investments within the Latin American water funds partnership**. *Ecosyst Serv* 2016, **17**:217-236.

62. Boelee E *et al.*: **Overcoming water challenges through nature-based solutions**. *Water Policy* 2017, **19**:820-836.

63. Haasnoot M *et al.*: **Investments under non-stationarity: economic evaluation of adaptation pathways**. *Clim Change* 2019:1-13.

64. Gartner T *et al.*: **Protecting forested watersheds is smart economics for water utilities**. *J Am Water Works Assoc* 2014, **106**:54-64.

65. Bridges TS *et al.*: *Engineering with Nature: An Atlas*. US Army Engineer Research and Development Center, Environmental Laboratory; 2018.