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Discussion

A strategic monitoring approach for learning to improve natural infrastructure

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ABSTRACT

Natural infrastructure (NI) development, including ecosystem restoration, is an increasingly popular approach to leverage ecosystem services for sustainable development, climate resilience, and biodiversity conservation goals. Although implementation and planning for these tools is accelerating, there is a critical need for effective post-implementation monitoring to accumulate performance data and evidence for best practices. The complexity and longer time scales associated with NI, compounded by differing disciplinary definitions and concepts of monitoring necessitate a deliberate and strategic approach to monitoring that encompasses different timeframes and objectives. This paper outlines a typology of monitoring classes differentiated by temporal scale, purpose of data collection, the information benefits of monitoring, and the responsible party. Next, we provide a framework and practical guidelines for designing monitoring plans for NI around learning objectives. In particular, we emphasize conducting research and development monitoring, which provides scientifically rigorous evidence for methodological improvement beyond the project scale. Wherever feasible, and where NI tools are relatively new and untested, such monitoring should avoid wasted effort and ensure progress and refinement of methodology and practice over time. Finally, we propose institutional changes that would promote greater adoption of research and development monitoring to increase the evidence base for NI implementation at larger scales.

1. Introduction

1.1. The need for monitoring and learning for advancing natural infrastructure

Natural Infrastructure (NI) systems are increasingly recognized as essential complements to conventional gray infrastructure that provide resilience under a changing climate in addition to other societal benefits, and are part of an integrated approach to achieving biodiversity conservation and sustainable development goals (Nesshöver et al., 2017; Nelson et al., 2020a, 2020b). NI (also known as nature-based solutions, nature-based features, Engineering with Nature®, or Working with Nature) are engineered or restored natural or semi-natural landscape features that provide key services (e.g., flood risk reduction, water purification, erosion protection) while providing ancillary benefits to biodiversity and society including habitat and recreational value (Bridges et al., 2015; Nelson et al., 2020a, 2020b). For the purposes of this paper, we include ecological restoration under this definition, because it similarly involves a deliberate manipulation or enhancement of ecosystem services or processes and operates on similar levels of ecological complexity and time scale. This operating definition also encompasses "green infrastructure," although the latter term often refers to a specific subset of NI in urban systems that provide the services of carbon sequestration, air quality improvement, and especially stormwater management (Grabowski et al., 2022).

NI can be employed in concert with conventional infrastructure to enable a self-repairing and self-sustaining system that allows for recovery after disturbance and adaptation to changing conditions over time. NI is being implemented worldwide, and is considered a priority part of sustainable development by the European Commission (Maes and Jacobs, 2017; Nesshöver et al., 2017), United States Army Corps of Engineers (Bridges et al., 2018, 2021), and international organizations (WWAP/UN-Water (United Nations World Water Assessment Program), 2018; World Wildlife Fund (WWF), 2020).

A wide range of NI applications includes increasing water security in semiarid regions (Everard et al., 2020), alleviating flood risks around rivers (Hartmann et al., 2019), managing urban stormwater for biophysical and social outcomes (Christman et al., 2018), and preventing coastal erosion and reducing storm surge risks (Slinger et al., 2021). Two frequently cited examples of natural infrastructure are restored floodplain wetlands from levee setbacks (Guida et al., 2015; Dahl et al., 2017), which reduce flood risk, and oyster beds and other natural elements of "living shorelines" that protect coastal communities and infrastructure from the effects of storm surge (Bridges et al., 2018). Urban forests are also considered natural infrastructure that buffer vulnerable communities from poor air quality and heat island effects while reducing storm water runoff (Kowarik et al., 2019). Many NI projects are considered "win-wins" for society and

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biodiversity because they generate functional habitat while mitigating risks associated with urbanization and climate change (Chausson et al., 2020; Girardin et al., 2021).

Despite the expanding application of NI, the research and evidence around NI performance and service delivery required to improve implementation in practice remain limited (Nesshöver et al., 2017; Nelson et al., 2020a; Albert et al., 2021; Bridges et al., 2021). There is a need to better understand NI methods themselves as well as their interactions with conventional infrastructure, and their role in enhancing the longevity and resilience of conventional infrastructure remains insufficiently explored. As with ecological restorations more broadly, developing an effective, applied understanding requires strategic monitoring of project outcomes over time and space (Stein and Bledsoe, 2013; Delaware Living Shorelines Committee, 2018; Davis et al., 2022). However, monitoring for learning is uncommon in many environmental management fields due to potentially high costs and long time scales (Bernhardt et al., 2007; Grantham et al., 2010; Wijsman et al., 2021). Knowledge acquired through this type of monitoring would not only improve NI implementation, but would also contribute to a broader understanding of the role of restored and artificial ecosystems to sustainability science (Yu et al., 2021).

Rigorous monitoring of NI presents additional challenges beyond conventional infrastructure. Gray infrastructure is often designed with static structural properties and performance objectives in mind, whereas natural or nature-based systems can and should change through time as they integrate with surrounding ecological systems and adjust to prevailing environmental conditions (Chausson et al., 2020; Seddon et al., 2020). This dynamism, combined with the inherent uncertainty in environmental management outcomes (Stein and Bledsoe, 2013; Galatowitsch and Bohnen, 2021) can lead to significant time lags between NI implementation and desired results as well as ambiguity about how and what to monitor (Giordano et al., 2020). The dynamic characteristics of NI may necessitate more frequent and more adaptable monitoring than conventional gray infrastructure.

The breadth of goals for which NI is designed and implemented also greatly multiplies the number of potential monitoring objectives and indicators. Ideally, these will include both lagging and leading (sensu Ota et al., 2021) indicators that give both a retrospective and predictive view of changes in system behavior. These should give useful information on the achievement of project outcomes across realms of benefits (social, environmental, economic), and which are applied using a standardized framework that allows comparison and synthesis across projects and studies (Eger et al., 2022). The multidisciplinary collaborations necessary for successful NI implementation also complicates monitoring because of the potentially conflicting terminology, definitions, and operational concepts among scientists, engineers, and project funders (Davis et al., 2022). Furthermore, natural systems are themselves inherently complex, displaying potentially unpredictable behavior (Kay et al., 1999), which adds a high degree of uncertainty to project outcomes and thus increases the number of appropriate monitoring indicators (Linkov et al., 2006). This uncertainty in ecological outcomes is further exacerbated by ongoing and accelerating climate change (Simonson et al., 2021). Consequently, incorporation of NI into the societal and geophysical systems of civil engineering has been described as a 'wicked' challenge necessitating multi- and transdisciplinary collaboration (Nesshöver et al., 2017).

Where monitoring is not carried out in a deliberate and organized fashion with the goal of improving future implementations, methods will fail to provide effective or reliable results for supporting decision-making or management (Webb et al., 2017). The field of stream restoration presents a cautionary example of the risk of widespread adoption of interventions without a deliberate approach to assessing their efficacy and to improving practices over time (Downs and Kondolf, 2002). Despite billions of US dollars in investment, stream and wetland restoration practices have largely failed to achieve their objectives (Wohl et al., 2005; Bernhardt et al., 2007). Restoration methods became "projectified" (sensu Hodge and Adams, 2016) and entrenched in practice, preventing adaptive management or refinement of methods from past experience (Galatowitsch and Bohnen, 2021). Once established as an industry, this trajectory became difficult to change, as actors had a vested interest in assuming success rather than spending funds on monitoring programs that risked demonstrating inefficacy (Lave and Doyle, 2021). Despite repeated calls for monitoring and project evaluation, these are still rarely implemented in restoration practice (Rubin et al., 2017).

As a relatively new form of ecological engineering, contemporary NI practice has limited monitoring data and a high need for evidence (Bernhardt et al., 2005; Palmer et al., 2007; Rubin et al., 2017; Davies et al., 2021). The massive, planned expenditures on global infrastructure, amounting to tens of trillions of US dollars as of this writing, have the potential to fuel extensive new implementation of NI projects. This offers an unprecedented opportunity for learning that should not be wasted. There is also the major risk of broader NI methods becoming entrenched and ineffective as stream and wetland restoration methods were in the past. This entrenchment could lead to an inefficient use of these crucial and timely resources and a failure to address the ongoing biodiversity crisis and work toward the sustainable development goals.

Given the multitude of potential motivations, benefits of monitoring, and potentially high costs of NI, a deliberate and strategic approach to monitoring design is needed (McDonald-Madden et al., 2010; Galatowitsch and Bohnen, 2021). Although a framework was recently developed for evaluating NI prior to implementation (i.e., selecting projects based on projected benefits; Sowińska-Świerkosz and García, 2021), no such generalized conceptual support exists for post-implementation monitoring of NI for research and learning purposes.

Overcoming the challenges of monitoring NI requires a conceptual guide that contextualizes and integrates various forms of monitoring and facilitates monitoring for learning and improvement. Monitoring protocols must be sufficiently flexible and adaptable to accommodate natural complexity as well as constraints related to cost and responsibility, while permitting the collection of meaningful data for institutional and disciplinary learning. A strategic approach to monitoring should monitor biophysical and socio-economic parameters that are feasible to collect and fund but also provide information that benefits long term learning (Wijsman et al., 2021). In this discussion paper, we present a strategic framework for developing monitoring plans for NI, ecological restoration programs, and related projects, and provide practical guidance for collecting evidence for NI research and development through systematic monitoring. We first present an inclusive typology of monitoring approaches across disciplines, then provide guidance on whether and how to implement monitoring for research, methodological development, and institutional or disciplinary learning. Because the specific choice of monitoring indicators will vary greatly across study systems, projects, and monitoring types, our goal is to encourage an explicit and organized accounting of monitoring goals for NI projects, rather than to provide specific guidance on indicators and methods.

This content is intended to provide flexible, practical guidance for interdisciplinary working groups to design effective and informative monitoring plans for natural infrastructure projects by providing a working vocabulary of monitoring types, and taking a deliberate step back to develop monitoring plans that avoid missed opportunities for learning, and cultivate a community of practice to promote NI research and development. Our framework is directed specifically toward a multidisciplinary audience including infrastructure planners, project engineers, landscape architects, environmental professionals, decision-makers and project managers, as well as restoration ecologists and conservation scientists engaged in natural infrastructure research and development. Where other recent work on monitoring ecological restorations provides general insights on the selection of indicators and workflows for adaptive management (Galatowitsch and Bohnen, 2021; Ota et al., 2021; Eger et al., 2022), we cater this paper to the broader, more interdisciplinary audience of practitioners and researchers involved in natural infrastructure projects. We expand upon previous frameworks by providing a guide for learning to improve natural infrastructure practice over time.

2. A typology for NI and restoration project monitoring

For the purposes of this paper, we define monitoring as the collection of empirical data (qualitative or quantitative) on the past and present condition of an ecological or infrastructure system, usually through repeated observations, using in-situ sampling and/or remote sensing. We treat this as distinct from forecasting future conditions (i.e., modeling). Monitoring is undertaken to accomplish a variety of practical goals and plays an essential role in formal decision making (e.g., Multi-Criteria Decision Analysis), project compliance, adaptive management, and collecting evidence for learning (Lyons et al., 2008; Stein et al., 2012; Marttunen et al., 2019). Much of the time, however, planners and practitioners are not explicit about the purpose, context and expectations of the monitoring strategies associated with a project.

Monitoring plan design begins with identifying monitoring objectives, which themselves stem from the intended outcomes of a project (end-points or management objectives) and the priorities and values of the project actors and stakeholders (Erwin et al., 2016; Delaware Living Shorelines Committee, 2018). A strategic approach to setting monitoring objectives should operate from a clear understanding of different types and purposes of monitoring, such that monitoring objectives match the questions and interests of project stakeholders. Such an intentional approach is particularly important for natural infrastructure projects, which require multidisciplinary approaches and therefore run the risk of miscommunications due to inconsistent terminology and contrasting disciplinary visions for monitoring goals (Corsair et al., 2009; Lindenmayer and Likens, 2009; Marttunen et al., 2019; Davies et al., 2021). A hallmark of a strategic approach is an “openness to learning” (sensu Galatowitsch and Bohnen, 2021) that marks effective adaptive management and avoids missed opportunities for learning and improvement.

Here, we provide a classification of monitoring types organized according to the time frame of monitoring activities, the parties typically responsible for carrying out monitoring, and the scale at which data are used (e.g., project scale, scale of the project's effect on a broader ecological or social system, or for broader research purposes). We describe three broad categories of monitoring: initial performance monitoring, long-term performance monitoring, and research and development monitoring (hereafter R&D monitoring), which themselves are based on the purpose or ultimate objective for which monitoring is undertaken (Fig. 1). The motivations and objectives of a monitoring plan, as well as intended time-frames and responsible parties, must be specified as part of the project design phase. All three types of monitoring can be conducted on the same project and use the same set of indicators or parameters, although alternative indicators operating at different temporal scales or focusing on different aspects of system behavior or function may be used to accomplish different monitoring objectives (Ota et al., 2021). In other words, although distinct objectives are necessary to achieve different types of monitoring goals, the monitored parameters and indicators may overlap significantly. A review of potential indicators and best practices for monitoring ecosystem condition is beyond the scope of this paper, and has been effectively presented elsewhere (e.g., Stein and Bledsoe, 2013; Prach et al., 2019; Science and Resilience Institute, 2020; Davis et al., 2022; Eger et al., 2022). To further clarify the differences between these types of monitoring objectives, we list example questions for each type in Table 1.

The first distinction in our typology separates monitoring to evaluate performance from monitoring for learning. Monitoring to evaluate performance involves collecting information about whether a project is meeting design objectives in order to take management actions accordingly. Project objectives could include the efficacy in delivery of expected benefits and values, the response to perturbations in the system (e.g., resistance, resilience), the need for maintenance, adjustment, or adaptive management, or changes in benefit delivery across time. For NI approaches, performance may also be based on how well a design replicates or behaves like a natural or reference system of interest. Conversely, NI may be expected to produce

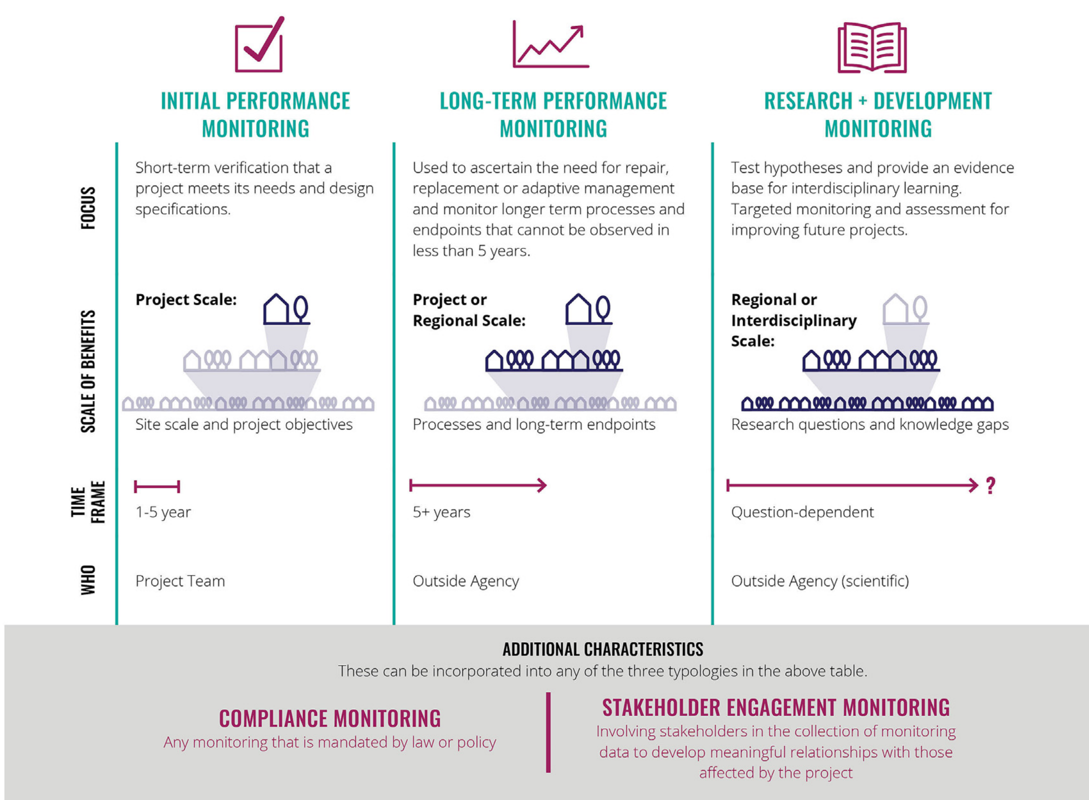

Fig. 1. A typology for common monitoring classifications used for natural infrastructure and ecological restoration organized by the purpose of monitoring, the scale of benefits accrued, the typical time frame, and the responsible party. The time scales suggested here are based on what is typically observed in the field, and are in no way prescriptive; actual monitoring time scales will depend on monitoring goals, chosen indicators, and the nature of the project.

specific benefits in excess of those expected from natural systems (e.g., treatment wetland designed for higher rates of denitrification than those observed in natural systems). These finer distinctions are highly dependent on the type of project (e.g., conventional or gray infrastructure, restoration, natural infrastructure) and its landscape context, so we combine these endpoints under a broader category of performance.

The highly dynamic nature of NI noted above implies that performance must be assessed through time, since the design will be evolving and adapting along with the dynamics of the surrounding system. Similarly, where there is significant uncertainty about whether a NI project will meet its design objectives, these monitoring efforts can effectively be monitoring for learning (see *Research and Development monitoring* below). Accordingly, the categories provided below are not necessarily mutually exclusive, but provide the conceptual basis for a more explicit and structured approach to NI monitoring, with a particular emphasis on monitoring for interdisciplinary learning.

We further divide performance monitoring into initial performance monitoring and long-term performance monitoring according to the time scale of monitoring practice. The objective of *initial performance monitoring* is the short-term verification that a project meets design specifications or is affecting a given system attribute as intended in the management objectives. Based on various definitions of performance, other authors have called this implementation, validation or effectiveness monitoring, in that it focuses on short-term metrics of project performance and impact (Stein and Bledsoe, 2013; Roni and Beechie, 2012; Theiling et al., 2015; Marttunen et al., 2019). Initial performance monitoring is differentiated from other forms of monitoring in our typology by its timeframe: typically, one to five years after project completion. This time frame is descriptive and approximate: that is, the time scales associated with initial performance monitoring are those that we typically associate with these sorts of monitoring questions (Table 1), and not a requirement for this type of monitoring. The actual time scale of any type of monitoring will depend on monitoring objectives, indicators, and the time scale at which the planned NI project operates and performs its desired functions.

Post-project inspections, in which the structural elements of a project are compared to the initial design goals (e.g., “as builts”), also fall under this definition. Initial performance monitoring can include examining the condition of structural or physical elements of the project, or ecosystem endpoints that the project is intended to affect. The permittees or actors responsible for project construction are typically responsible for this type of monitoring. This category of monitoring is most often legally mandated by funding or governmental bodies (see *Compliance* monitoring below). Consequently, monitoring activities are typically more intense at the early stages of project implementation, with a higher frequency of data collection on a wider range of variables.

Long-term performance monitoring is the ongoing assessment of longer-term (often more than five years beyond project completion) aspects of project performance relative to planned objectives or desired conditions. This category encompasses outcome monitoring, trends assessment, and surveillance monitoring (Bernhardt et al., 2007; Stein and Bledsoe, 2013; Vugteveen et al., 2014) in that it focuses on processes and longer-term endpoints as affected by the project through time. Repeated monitoring practices like condition monitoring, structural health monitoring, and asset management that assess the structural elements of projects for signs of long-term degradation or potential failure (e.g., Brownjohn, 2007) also fall within this category. This type of monitoring is done to ascertain the need for repair, replacement, or adaptive management. Long-term performance monitoring also includes evaluating the achievement of process-based objectives like the maintenance or provision of key ecosystem functions or services (benefits and values), and assessing how the design responds to changes and perturbations in the system.

Table 1
Examples of questions among different types of monitoring within the typology outlined in this paper.

Monitoring type	Example questions
Short-term performance	-Was the infrastructure constructed as designed and planned? -Is the project performing as expected?
Long-term performance	-How is project performance changing across time? -Are ecological, geological, hydrological or other dynamics behaving as expected? -How is the project affecting other aspects of the surrounding system?
Research & development	-What about this project worked well and could improve future implementation? -How effective is the implemented method at achieving the desired goals? -How can future projects be improved? -What mechanisms led to project performance or lack thereof?

Long-term performance monitoring is particularly important for NI, where short-term evaluations will likely fail to capture whether key biophysical processes were re-established over ecological time scales, missing trajectories of development and self-organization and leading to a premature designation of success (Herrick et al., 2006). Long-term performance monitoring is repeated on a consistent interval (e.g., every one to three years) to prevent catastrophic failures and gain insight into project performance over time (National Research Council, 1995). The iterative nature of long-term performance monitoring makes it highly relevant to adaptive management and refinement at the single-project scale (passive learning, sensu Grantham et al., 2010). The application of monitoring data beyond the present system is typically limited because this type of monitoring is not hypothesis-driven and does not necessarily include replication and controls (but see *Research and Development* monitoring, next section). Because of the longer time frame associated with this type of monitoring, a different agency is often responsible for this monitoring than the one responsible for construction. Notably, long-term performance monitoring data can be useful for learning if carried out rigorously in systems on which little empirical research has been carried out previously.

Research and Development monitoring is undertaken with the explicit goal of testing hypotheses on project performance in a way that is falsifiable, controlled, and repeatable (i.e., scientific) such that new knowledge and evidence are accumulated to improve project implementation beyond the current project system. This category encompasses similar monitoring strategies like investigative monitoring, monitoring for learning, and monitoring for science and management understanding (Suding, 2011; Friberg et al., 2016; Delaware Living Shorelines Committee, 2018; Weber et al., 2018). The goal of R&D monitoring is to provide an evidence base that is useful for learning at an (inter)disciplinary scale; this is also called social learning (Grantham et al., 2010). R&D monitoring is the informational foundation of an evidence-based approach to NI projects, and an important part of improving and encouraging their implementation for climate adaptation, biodiversity conservation, and other benefits (Nassauer and Opdam, 2008; Albert et al., 2021).

In R&D monitoring, practitioners view a project as an experiment from which stakeholders, managers, and researchers can learn more about how complex systems function in order to improve design and implementation in the future. This is parallel to Grantham et al. (2010)'s concept of active learning or active adaptive management, and involves setting specific learning objectives that correspond to research questions and focus monitoring on key knowledge gaps (Marttunen et al., 2019). Investment in R&D monitoring can help guide the management of a project based on present observations (active adaptive management), or inform, improve, or refine future projects by contributing to an evidence base (Kondolf, 1995; Bernhardt et al., 2005). The difference between these two applications of R&D monitoring is the scale; the former type pertains only to the management of a particular project, while the latter may be applied to future or ongoing projects elsewhere. For R&D monitoring data to be applicable beyond adaptive management of the project, a higher degree of methodological rigor is required.

R&D monitoring requires the delineation and recognition of explicit hypotheses or learning outcomes, and should be implemented with replication and controls or counterfactuals that are sufficient for hypothesis testing. The indicators and scale of this type of monitoring depend on the research question —that is, what the resource managers, decision-makers, research team, and other stakeholders desire to learn and improve in the future. The need for replication, controls, and an explicit experimental design potentially involve non-trivial expense and labor to be included in monitoring design. This can involve studying multiple sites, including controls where no action is taken, and reference sites where, for example, ecologically intact systems serve as a baseline for comparison (Delaware Living Shorelines Committee, 2018). Before-After-Control-Impact (BACI) designs, already applied in the context of ecological restorations (e.g., Block et al., 2001; Geist and Hawkins, 2016; Muller et al., 2016), are highly amenable to implementing R&D monitoring for learning. In particular, the deliberate collection of pre-implementation monitoring is essential for comparison and ascertaining project efficacy.

The degree to which R&D monitoring is necessary may depend on the responsible party's perception of the potential for learning or the value of generated knowledge to the broader management community. Highly experimental projects using untested or poorly understood methods may represent a large opportunity for learning, and thus may require extensive monitoring. Conversely, an iteration of a standard design might necessitate only sufficient monitoring for adaptive management, or as necessary to satisfy other monitoring needs (see above). As with long-term performance monitoring, the responsibility for R&D monitoring may fall to an agency other than the one responsible for initial project construction. The knowledge generated by R&D monitoring is a “public good,” and often these forms of monitoring fall under government and non-profit-led efforts.

Two additional secondary characteristics of monitoring plans, which in other frameworks have been treated as their own types of monitoring, are also worth mentioning to conceptually reconcile them with this typology. We consider both of these categories as characteristics of monitoring activities, and not types of monitoring in their own right given that their spatiotemporal scale and requirements can vary depending on the project, and could thus overlap with any of the three monitoring types outlined above. In other words, they are orthogonal to short- and long-term performance and R&D monitoring, and could be associated with a monitoring plan that was structured according to any of those three monitoring types.

Compliance monitoring refers to any monitoring practice that is mandated by law or policy (e.g., monitoring endangered species populations under the US Endangered Species Act; Malcom et al., 2017) or by the project funding agency. Any of the preceding three types of monitoring could have a component of compliance, although most compliance monitoring is focused on project implementation (e.g., endangered species “take” during construction), post-project inspections (initial performance monitoring) and condition and failure risk monitoring (long-term performance monitoring). *Stakeholder engagement monitoring* involves stakeholders as community scientists in the collection of monitoring data to develop meaningful participatory relationships with those who are affected by the project and its objectives (Martin and Lyons, 2018). Involving the community in the collection of monitoring data on a restoration or infrastructure project can increase project buy-in and legitimacy with the surrounding community, facilitate social cohesion, create a sense of place (Russ et al., 2015), or community of practice (Slough et al., 2021), and provide public education opportunities (Huddart et al., 2016; Buntaine et al., 2021). Stakeholder engagement monitoring is increasingly viewed as an attractive and viable approach to collecting valuable data while improving knowledge transfer and transparency in science (Irwin, 2018). Importantly, stakeholder engagement should always be considered an added benefit and not the primary purpose of monitoring. Involving stakeholders for collecting data that are trivial or will not be used for adaptive management or disciplinary development is disingenuous and could reduce trust and legitimacy.

3. General guidelines for monitoring natural infrastructure

Before focusing specifically on the design and implementation of R&D monitoring plans, it is valuable to briefly cover a set of considerations that are applicable to monitoring activities falling under any of the three categories described above. Concrete recommendations for monitoring design, indicator selection, and data collection for ecological restorations and specific types of NI are covered thoroughly elsewhere (e.g., Eger et al., 2022; Davis et al., 2022), so we treat these topics briefly here as a prelude to our guiding questions for R&D monitoring and to provide a general introduction to these topics for readers.

Practitioners should explicitly establish the purpose of monitoring (i.e., monitoring objectives; what questions monitoring data are intended to answer) as a first step in plan design. Ideally, planners will conduct project design and goal-setting using a repeatable and standardized approach like structured decision making (Kondolf, 1995; Palmer et al., 2007; Bernhardt and Palmer, 2011). Given the multiple desired outcomes and co-benefits across multiple sectors (e.g., ecological, hydrological, social) for which NI are constructed, the direct and comprehensive involvement of stakeholders in the goal-setting process is essential (Bridges et al., 2018; Nelson et al., 2020a). Along with stakeholder engagement monitoring, the intentional involvement of stakeholder groups and decision-makers in this process should manifest as a form of knowledge co-production (Nel et al., 2015).

Which management and monitoring objectives are considered most important will depend on the values and needs of stakeholder groups, decision-makers, planners, and other involved parties. Ideally, the process of stakeholder consultation and other stages of the broader co-production process will involve the elucidation, communication, and reconciliation of these different values to find common ground and acceptable compromises (Nel et al., 2015). This process is beyond the scope of this paper, but has been addressed elsewhere in the environmental management literature (e.g., Couix and Gonzalo-Turpin, 2015), especially in Integrated Water Resources Management (Agarwal et al., 2000; van Rees et al., 2019).

This participatory process establishes the criteria for monitoring success. In other words, the stakeholders, decision-makers, and other actors involved in designing the monitoring plan, in explicitly acknowledging their goals, also outline what information a successful monitoring plan will yield. A clear accounting of these priorities and objectives is important not only to ensure that monitoring delivers the necessary information, but also to enable broader reflection on what can, or should, be learned from a given project (see next section).

Project planners should also clearly delineate the spatial and jurisdictional scale of monitoring activities according to these objectives. For example, compliance monitoring may focus on structural aspects of a project at the sub-site scale, while performance monitoring questions might encompass an entire site (e.g., a section of coast for a living shoreline). Learning objectives for R&D (see next section) monitoring may extend well beyond the site scale to understanding broader landscape or watershed dynamics. Ultimately, the spatial scale is determined by the monitoring information needed to assess performance or compliance, or elucidate key dynamics for adaptive management or broader learning. These monitoring objectives are in turn dictated by the values and needs of planners, stakeholders, and other involved parties.

4. Guiding questions for research and design monitoring of natural infrastructure

Given the need for an evidence base for the efficacy of NI implementation, we present a set of guidelines for integrating R&D monitoring into monitoring plans for such projects (Fig. 2). Most existing guidance for monitoring environmental management projects is organized into questions that can be asked at various stages of monitoring (Stein et al., 2012; Delaware Living Shorelines Committee, 2018). We use this format to extend existing frameworks with five questions for planning R&D monitoring. Although they are organized to guide new monitoring plans, many of these considerations are also applicable to the modification and implementation of existing monitoring plans.

Our framework assumes that management and monitoring objectives have already been clearly delineated based on an analysis of potential benefits and constraints (e.g., as in Sowińska-Świerkosz and García, 2021). Among monitoring objectives, we focus specifically on learning objectives,

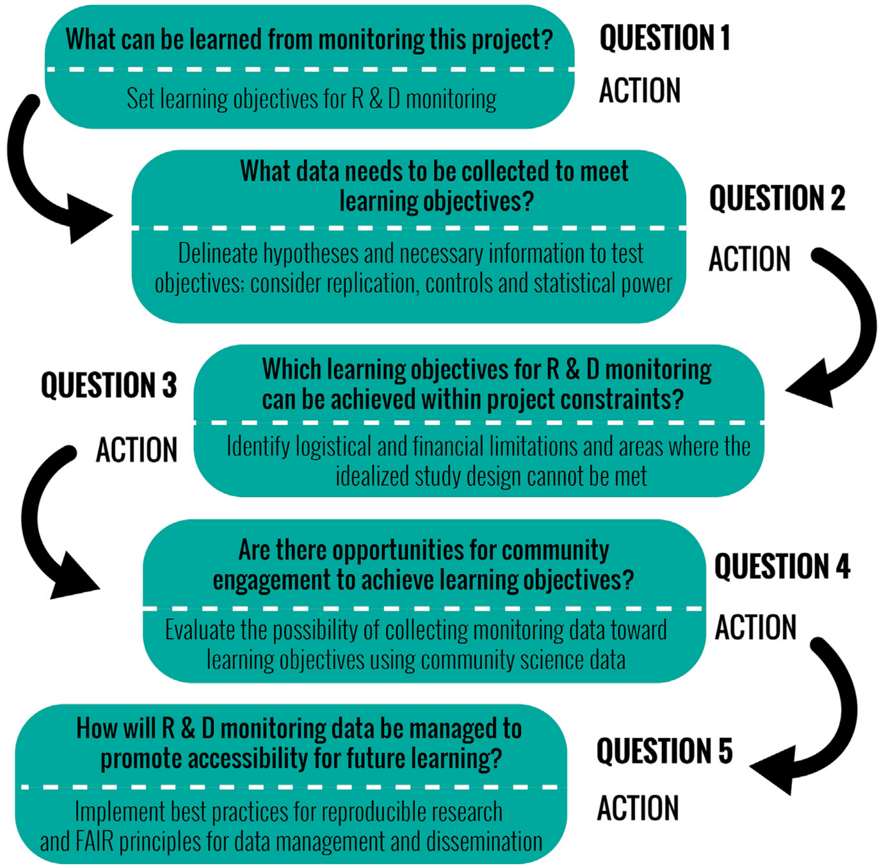

Fig. 2. A workflow with guiding questions and actions for designing monitoring plans for research and development monitoring of natural infrastructure and ecological restorations.

which are those objectives associated with the creation of new knowledge via R&D monitoring. This framework complements and broadens other published frameworks that provide more general guidance on setting monitoring objectives for living shorelines (Delaware Living Shorelines Committee, 2018; Science and Resilience Institute, 2020) and hydromodification monitoring (Stein et al., 2012; Stein and Bledsoe, 2013).

For practitioners and resource managers, this process begins with envisioning the idealized outcome of R&D monitoring within a project from the perspective of multiple stakeholders, and then allowing realistic constraints to determine what portions of this idealized vision can be implemented. This order of operations is intentional; it promotes the collection of a broad range of potential monitoring objectives for R&D first, followed by elimination steps based around existing constraints and resources, thus offering transparency in the selection of monitoring objectives and their corresponding metrics. An additional advantage of this approach is that it prevents the premature elimination of learning objectives that might have been feasible given additional resources and added value from other stakeholders.

As an additional note, we recommend carefully documenting decisions made in each step of this framework to archive the rationale and logic of the planned monitoring strategy. The motivations for particular monitoring approaches are often lost over the long monitoring windows typical of R&D monitoring (e.g., 10–20 years).

Question 1: What can be learned from monitoring this project?

Strategic monitoring begins with a careful articulation of monitoring objectives, which can fall into any of the classes of monitoring discussed above (e.g., compliance, short-term performance), but we focus here on the selection of learning objectives for R&D. The planning stage should begin with a consideration of what could be gained through R&D monitoring. Two major factors worth examining are whether the system to be studied or methods to be employed are well-established or relatively new, and whether there are significant uncertainties around project performance that could provide information for future projects (Stein and Bledsoe, 2013; Delaware Living Shoreline Committee, 2018). The existence of related projects or initiatives, for which data from the present project could be useful, may offer additional impetus for R&D monitoring, and could help establish new collaborations or avenues to support monitoring efforts. For example, restoration efforts by the U.S. Army Corps of Engineers in the Upper Mississippi River System are collectively monitored by a cooperative program involving the U.S. Geological Survey, U.S. Fish and Wildlife Service, U.S. Environmental Protection Agency and several others.

Stakeholder engagement in the form of transdisciplinary collaboration and knowledge co-creation is as key a part of planning monitoring for learning as it is for setting management goals and performance metrics. Co-production and stakeholder participation may reveal learning opportunities and resources that had not been integrated into the project at its outset (Wijsman et al., 2021). Academic researchers can benefit from such collaborations by learning about important research applications and new questions that they would not have encountered otherwise. The input of community stakeholders, including non-profit organizations and local governing bodies, is critical for prioritizing services provided by projects with multiple objectives because monitoring associated with services of particular local value can attract greater resources and support (Morandi et al., 2017). Engagement beyond the locale of the project—for example, with other organizations implementing or researching similar types of projects—can also be a highly productive activity, allowing resources to be pooled and research questions and study designs to be harmonized (Ferraro and Agrawal, 2021). This coordination is further enhanced by standardized indices and frameworks for data collection, enabling comparison and synthesis of monitoring data among sites across space and time (Eger et al., 2022), and communities of practice like the European Union's NetworkNature initiative (www.networknature.eu).

Question 2: What data need to be collected to meet learning objectives?

Once a project's monitoring objectives have been explicitly stated, the next task is to translate these objectives into indicators to be monitored along with associated protocols. If the project has learning objectives for R&D, it also becomes necessary to consider the sampling design necessary to achieve these objectives. Monitoring designs for learning goals include the use of controls, which may include reference sites or pre-implementation (e.g., pre-restoration, or pre-construction) data, as well as replicates for statistical inference (Stammel et al., 2012; Prach et al., 2019). Power analyses and simulations may be employed to determine the effect size detectable with a given sampling design (Green, 1989). Sampling designs will likely differ among learning objectives, and should be addressed separately for each. Once data needs and indicators have been established, it can be helpful to look for synergies among the data needs of learning objectives and other monitoring objectives. For example, water quality data collected for compliance monitoring of stormwater control structures (to evaluate whether these structures are efficiently reducing pollutants and meeting state water quality standards) could also be leveraged in building hydrologic models to learn how to maximize pollutant detention capacity through strategic placement of future structures. This could be done in conjunction with monitoring socioeconomic data such as recreational and cultural uses of natural wetlands with stormwater control and retention functions (e.g., van Rees, 2018).

Question 3: What learning objectives can be achieved within project constraints?

Logistical constraints are one of the most oft-cited limitations on monitoring implementation for river restoration projects (Bernhardt et al., 2007; Wohl et al., 2015), and are rarely explicitly addressed in the design of monitoring plans (McDonald-Madden et al., 2010). Such constraints, budgetary or otherwise, are inevitable in practice regardless of initial expectations, and require realistic consideration. After expansively outlining priorities and objectives for monitoring, it is necessary to confront the idealized vision of monitoring outcomes with the realities of institutional mandates, regulations, and material, financial, and human resources (Stein et al., 2012). Given the longer time frames necessary for R&D monitoring, especially in ecological and natural infrastructure systems for which nonstationary and long-term changes are common (Lindenmayer et al., 2008; Stammel et al., 2012), funding support beyond a small initial window (often on the order of 3–5 years) is frequently not available. Having personnel responsible for collecting data and maintaining a database is an especially costly component of monitoring and could present a major obstacle. In the following section, we propose broader structural and institutional changes to help alleviate these constraints.

After constraints have been identified and outlined, the initial, expansive list of monitoring objectives must be reduced to those that are feasible within these project boundaries. A key step in this process is to seek opportunities to leverage other resources, including existing datasets or active monitoring programs, stakeholder participation, and partnerships with other organizations. The strategic selection of low-cost monitoring metrics (i.e., those that involve small or one-time costs that do not accrue substantially over time) can also help maximize limited resources. Importantly, this step should consider a range of quantitative (e.g., empirical data collection), semi-quantitative (e.g., scoring systems), and qualitative (e.g., stakeholder surveys, photographs) monitoring approaches to maintain breadth sufficiently aligned with project objectives. Remote sensing technology can provide low-cost and regular surveillance of many habitat metrics that do not require in situ observations (Konrad et al., 2008). Community science initiatives, discussed in the next part of the framework, can also generate valuable data if strategically employed.

Question 4: Are there opportunities for community engagement to achieve learning objectives?

Community science volunteers can collect large amounts of monitoring data at very low cost, with the additional advantage of providing an avenue for outreach and engagement with the public (Edwards et al., 2018; Tulloch et al., 2013). Public engagement should be an integral part of planning the design and monitoring of any NI project, but stakeholder involvement in data collection itself can be a particularly valuable entry point for end-users and community members.

Opportunities for collaborative data collection can improve community buy-in and public interest in a project, increase legitimacy and trust, and contribute to the development of a community of practice (Slough et al., 2021). Though the effort involved varies based on the monitoring indicators and the system, community scientists have been trained to collect a wide variety of valuable monitoring data, including estimates of invertebrate community composition (Huddart et al., 2016), abundances of kelp ecosystem functional groups within a restored or protected area (Beas-Luna et al., 2020), microbial communities in river systems (Hassell et al., 2018); and debris in the environment (Jambeck and Johnsen, 2015).

Possible opportunities for community scientist participation should be carefully explored, with a particular focus on the overlap between data utility and the community's interest and willingness to participate. There will inevitably be some cases or systems in which community science monitoring is not cost effective, feasible, or appropriate, but its potential utility merits consideration. Conversely, there may be situations where community involvement is obligatory (e.g., due to site access, funding streams, or historical distrust between groups) and cannot be omitted.

Question 5: How will data be managed to promote accessibility for future learning and synthesis?

Even large amounts of high-quality monitoring data collected using rigorous protocols will make minimal contributions to institutional and disciplinary learning unless they are managed in a way that makes them accessible to researchers during and after project implementation. Monitoring data from individual projects should not only serve to guide adaptive management and inform future implementation, but should be made available for use in meta-analyses and large data syntheses for larger-scale inference. Morandi et al. (2017), in reviewing river restoration projects in Germany, emphasized that the dissemination of monitoring results is essential to promoting R&D. We strongly recommend that R&D monitoring data be managed according to the FAIR data principles (findable, accessible, interoperable, and reusable; Wilkinson et al., 2016) and be disseminated as soon as possible after collection. Data processing and analysis should follow best practices for reproducible research (Kitzes et al., 2017) and all code and metadata should be published alongside data products. Once data are collected and archived, it is important that they are ultimately used to inform future decision making. Many datasets, although already available, are never analyzed to extend the state-of-practice for designers.

5. Institutional and systemic changes in monitoring to advance the science of natural infrastructure

In the previous section we presented a series of guiding questions for strategically developing a monitoring plan that incorporates R&D monitoring. We acknowledge, however, that there are practical constraints and institutional barriers to developing monitoring plans, and these may be more limiting given the longer time frames and more exacting data requirements of R&D monitoring. These constraints may thus occasionally preclude R&D monitoring. Here we consider institutional and systemic changes that may remove barriers and reduce constraints to widespread R&D monitoring. In particular, we see opportunities to foster R&D monitoring through institutional structures and practices that 1) provide financial and logistical resources for R&D monitoring, and 2) encourage connections between practitioners and researchers for the co-production of knowledge.

R&D monitoring often operates at longer time scales and with additional requirements (replication, experimental controls) than initial performance monitoring, and its benefits extend beyond that of a single project. As such, it is unrealistic and perhaps unreasonable to expect that the agency responsible for project implementation and construction should bear the full financial burden. These costs should instead be borne by separate organizations or funding bodies with research as part of their core missions. These could take the form of cooperative monitoring groups united by a common geographic region or technical approach of interest (e.g., Stein and Bledsoe, 2013). Institutions operating at larger spatial scales are perhaps the most appropriate to support this type of work, and they could steward and allocate funding with a broad contextual understanding of which knowledge is new and beneficial to the larger field of practice. Funding to support R&D monitoring could be subsidized or cost-shared across scales and participating organizations.

Institutional structures already exist in many government agencies to support this model. For example, at the US Army Corps of Engineers, the Engineer Research and Development Center (ERDC) provides research support and technical guidance to Corps districts, the Department of Defense, and other agencies. In the US Forest Service, the Research Stations provide a similar role to the National Forest System, while the US Geological Survey provides analogous services to other units of the Department of the Interior. However, what is missing in each case is a substantial and reliable pool of funding that can be drawn upon to support both ongoing and novel science-based monitoring programs. Of course, the monitoring demand will still tend to exceed the available resources, so one of the roles of the research-oriented organizations should be to decide when R&D monitoring is *not* necessary (Bernhardt et al., 2007). Our R&D monitoring guidelines would make useful contributions to the selection process.

Relatedly, models already exist for reliably funding and executing monitoring in other contexts. Data collection efforts over large spatiotemporal scales are commonly supported by federal agencies in the United States and elsewhere. These programs were often developed for a given purpose but adopted by researchers for other applications including broader disciplinary learning. For example, the Landsat program and the USGS stream gaging network have both contributed invaluable data to research in multiple fields (e.g., Wulder et al., 2012; Sepulveda et al., 2019) and are supported by a cost-sharing model with contributions from dozens of institutions and agencies. A similar use of funds to intentionally draw useful data from planned NI projects would be a simple extension of this concept.

The European Union's NetworkNature community provides an excellent example of the type of large-scale support and coordination that will be necessary to facilitate research and development for widespread implementation of natural infrastructure. The network, funded by the European Commission through its Horizon 2020 initiative, brings together academic, non-profit, and governmental partners with the goal of mainstreaming nature-based solutions (NBS, used equivalently to NI) in EU countries. Of particular relevance to R&D monitoring is their primary activity of synthesizing and strengthening the evidence base for nature-based solutions, which includes strategic and organized monitoring. NetworkNature also includes specialized task forces, among which are groups for data and knowledge sharing and assessment of NBS projects. The network more broadly, and these task forces specifically, allows researchers to direct monitoring efforts and funding to projects that will yield informative results. This sort of coordination also allows for replicated or parallel monitoring for more powerful inference. Similar efforts at national, regional, or global scales would greatly improve the feasibility of useful R&D monitoring for NI.

Co-production of science among researchers, practitioners and stakeholders is essential to generating a solid knowledge-base and actionable understanding that are scientifically rigorous and relevant to real-world applications (Norström et al., 2020). Efforts to support the development of a community of practice—a social-professional network of stakeholders, researchers, practitioners and decision-makers who, through dialogue, achieve a shared understanding of a problem or field of inquiry—enhance project outcomes and increase learning for adaptive management or broader learning (Adelle et al., 2021). For example, strategies like collaborative adaptive management are amenable to R&D monitoring because they treat management projects as learning opportunities, involving research and implementation entities in monitoring (Allen and Garmestani, 2015; Barrett et al., 2021). The development and maintenance of interpersonal relationships among these groups is therefore a primary concern. A major obstacle to increased interactions between researchers and stakeholders is a bias in career incentives for academics, which tends to reward grant acquisition and academic publications more than applied products like decision-making tools, consultations and on-the-ground conservation results (Djenontin and Meadow, 2018). Likewise, many practitioners may also not be incentivized to publish monitoring data associated with their management actions due to constrained staff time, client priorities, or unfamiliarity with data analysis or publishing norms. Larger shifts in career incentives and the fostering of networking tools or bridge organizations to promote working relationships between practitioners and researchers across scales are needed to better promote co-production via R&D monitoring.

6. Harnessing opportunities and avoiding pitfalls

The inclusion of NI in recent infrastructure investment efforts in the United States, many European countries, and China indicates that current interest in NI is high and continuing to rise (H.R. 3684, Xia et al., 2017; O'Donnell et al., 2020; van Rees et al., 2021). Given continued urbanization and population growth and the escalating need for climate change adaptation, more than US$90 trillion in infrastructure investments is needed globally by 2040 (Global Infrastructure Hub, 2019). Major economic powers are now beginning to respond to this need with infrastructure investment programs of historic scale.

Harnessing this financial and political capital for long-term gains in the resilience of engineered systems and enhancement of biodiversity requires an investment in learning about the effectiveness of NI practices. The clear importance of ecosystem services and climate change adaptation to address Sustainable Development Goals and protect vulnerable populations implies that opportunities for learning cannot be missed (Nesshöver et al., 2017; Nelson et al., 2020a, 2020b). As a whole, the multidisciplinary community involved with natural infrastructure development cannot afford to repeat past errors seen in other branches of restoration ecology. To avoid "projectification" and the ineffective application of large economic investments, researchers and practitioners must collaborate to generate useful knowledge from this historic and crucial juncture.

Investment in developing an evidence base for NI is critical to its long-term successful implementation, as increasingly frequent natural hazards may diminish future interest in NI, which generally accrue benefits more slowly than conventional solutions (Nelson et al., 2020a). Promoting learning at the scale of individual projects, through the development of monitoring plans with clear learning objectives, and at the scale of institutions, through financial support for monitoring efforts, coordination and prioritization of key research questions, and the development of a community of practice, are timely interventions to realize the promises of NI.

The guiding questions and priorities outlined above also apply more broadly to ecological restorations in general and other environmental management strategies that operate under ecological complexity and longer time scales. Monitoring over these longer time scales offers the additional synergy of being easily compatible with learning and hypothesis testing about design performance and its variations across system conditions. Contemporary implementation of NI must employ monitoring that leads to better designs. The more strategic approach to monitoring presented in this paper, especially insofar as it encourages the judicious and deliberate application of R&D monitoring, offers one pathway to avoid missing additional opportunities for useful monitoring information. Ideally, the interdisciplinary scientific community can take advantage of the rising tide of support and funding for NI implementation and conduct meaningful monitoring to ensure the achievement of the multifaceted goals motivating this paradigm shift in infrastructure and conservation. Such a paradigm shift will make great contributions in better aligning the increasingly compatible goals of biodiversity conservation and sustainable, climate-resilient infrastructure development to secure a safer, healthier future for the global community and life-supporting ecosystems.

7. Conclusions

This discussion paper reviewed the importance of monitoring ecological restoration and natural infrastructure projects for improving practice in this rapidly growing and broadly important field, and highlighted the logistical difficulties it presents to researchers and practitioners. We provided a generalized typology that reconciles definitions of monitoring across the diverse disciplines involved in natural infrastructure research and practice, and a series of questions to facilitate the development of monitoring plans tailored toward learning. Further implementation of this type of monitoring will generate the necessary evidence base for broader applications of natural infrastructure needed to combat the ongoing biodiversity crisis and societal threats from climate change. Given the opportunities presented by massive infrastructure spending at the global scale in coming decades, it is essential that natural infrastructure development be implemented strategically and with deliberate attention to research and development.

CRediT authorship contribution statement

Charles B. van Rees: Conceptualization, Writing (Original Draft and Review & Editing), Visualization, Supervision, Project administration. **Laura Naslund**: Conceptualization, Writing (Original Draft and Review & Editing), Visualization. **Darixa D. Hernandez-Abrams**: Conceptualization, Writing (Original Draft and Review & Editing). **S. Kyle McKay**: Conceptualization, Writing (Review & Editing). **C. Brock Woodson**: Conceptualization, Writing (Review & Editing), Funding acquisition, Project administration. **Amy Rosemond**: Conceptualization, Writing (Review & Editing). **Brian McFall**: Conceptualization, Writing (Review & Editing). **Safra Altman**: Conceptualization, Writing (Review & Editing). **Seth J. Wenger**: Conceptualization, Writing (Review & Editing), Funding acquisition, Project administration, Supervision.

Declaration of competing interest

The authors of the submitted manuscript declare no conflict of interest.

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