Integrating ecosystem functioning into the assessment of stream and river health

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Key words: Stream and river assessment, ecological functions, ecological processes, functional indicators, restoration success

Abstract

Assessing the ecological status of streams and rivers is key to deriving appropriate restoration measures and evaluating restoration success. Established assessment methods are usually based on 'structural indicators', most often focused on the composition of biological communities in restored versus reference sites or reaches. Yet, in recent years, an increasing number of studies have demonstrated the response of ecological functions (e.g., metabolism, nutrient uptake, decomposition) to a range of stressors, highlighting the potential use of these as more realistic and dynamic descriptors of restoration outcomes. Despite this progress, we still lack clear criteria for the use of functional measures as tools to assess restoration. Here, we reflect on the benefits and limitations of integrating ecological functions into assessments of restoration and identify steps and research questions to solve if we aim to use these to judge success. We identify three major benefits associated with functional assessments: First, many ecosystem functions respond faster to restoration when compared to structural indicators, i.e., at timescales more relevant for communication and possible adjustment. Second, shifting boundary conditions, as a result of climate change and the establishment of invasive species, make it less likely that a system will return to past reference communities in the future. Thus, generating targets for functional properties that support the most essential characteristics of river systems may be crucial for maintaining ecological health under environmental change. Finally, integrating functions into structural assessment may increase our diagnostic potential and thus provide a more ecosystem-wide perspective on restoration or mitigation responses. However, to implement functional assessments in a management context, we need to agree on a roadmap and solve two main challenges. First, given the large number of potential functions, we need to resolve a set of core processes that are relevant to managers. Here we suggest a set of functions that fulfill the criteria of being relatively easy to measure, yet provide a meaningful and integrative representation of the ecosystem and its changes following restoration. Second, we

need clear and objective functional goals, e.g. in relation to reference conditions, or reference to emerging water quality challenges. Given the strong benefits of integrating functions into aquatic ecosystem assessment, we strongly encourage scientists and practitioners to further co-develop their broader implementation and consider this paper a roadmap to tackle the next steps towards a broader implementation.

Assessment of stream and river health

Globally, streams and rivers are under stress from a wide range of physical, hydrological, and chemical alterations, which affect their biodiversity and functionality and the services they provide to society (e.g., Vörösmarty et al., 2010). Monitoring and assessment are key to detecting river degradation, deriving appropriate restoration measures, and subsequently judging the success of restoration measures. Such assessments can focus on a range of aspects, including water quality, biodiversity, or performance of specific taxonomic groups of interest. Yet, given that this range of endpoints may generate competing societal interests and unwanted tradeoffs, there is an increasing interest in using more inclusive assessments, e.g., of 'ecological integrity' and 'health' as management goals, with the assumption that these integrate and encapsulate the diversity of ecosystem services rivers provide. In this context, ecological integrity in running waters can be judged in terms of both *structural* variables, including the composition and biodiversity of various organismal groups, and *functional* variables (e.g., organic matter decomposition, primary productivity), which reflect how a system actually works ecologically or biogeochemically. Yet, despite recent calls for greater consideration of functional responses (e.g., Palmer and Ruhi 2019), most assessments of river health continue to be based on community structure, assuming that structural metrics are a reasonable proxy for ecosystem integrity overall (e.g., the ecological health assessment in the context of the EU-Water Framework directive, Hering et al., 2010).

The longstanding emphasis on structural responses to assess river condition and judge the outcome of restoration is not necessarily misplaced: such metrics are well-known to capture changes in water and habitat quality in response to a range of anthropogenic stressors (e.g., Bonada et al. 2006). Further, knowledge about structural properties from past assessments of a given system, or from suitable reference systems, can provide relatively straightforward ‘targets’ for managers. However, despite this track record, diversity and composition metrics also routinely fail to show clear responses to restoration (Leps et al. 2016; Palmer et al. 2010) or help us mechanistically understand how an ecosystem has changed as a result of degradation or recovery after management. We think this shortcoming reflects three key problems:

First, a lack of response can occur when system stressors or restoration actions do not fully target the indicator used and/or its requirements for recovery (Hering et al., 2010; Palmer et al., 2010). This is a notable issue for structural metrics, like community composition and diversity, which in river systems can be linked to multiple drivers beyond the local habitat, including properties of the broader catchment and drainage system (Bernhardt and Palmer 2011) and even the broader species pool and the dispersal capacity of species (Poff 1997). Such complexity makes it difficult to understand what attributes of the river and surrounding landscape should be restored to realize recovery in structural metrics locally. This can be a particular problem for restoration when (i) there are strong constraints to biotic communities operating at scales larger than the restoration effort (Griffith and McManus 2020a and b; Polvi et al. 2020) or if (ii) that broader environmental conditions are shifted such that the composition of species best adapted for a given ecosystem has also changed (Schindler et al. 2015). With respect to shifting boundary conditions, especially in the context of climate change, there is ongoing debate about whether current reference conditions can (or should) be considered as structural targets for the future (Harris et al. 2006). To maintain core ecological processes that underpin ecological integrity, it will be necessary that communities change to include species better adapted to new sets of baseline conditions.

Second, a strictly structural focus can also limit our ability to evaluate and communicate ecosystem change or restoration success at short enough time scales to enable adaptive management. Recovery times in response to river restoration can vary greatly within and amongst the taxonomic groups often used to evaluate recovery (e.g., algae vs. macroinvertebrates vs. riparian plants), and such differences can contribute to seemingly weak responses to management actions, depending on when this is assessed. For plants or animals with longer inherent recovery rates, it may be difficult to know if a restoration measure was simply unsuccessful or if communities needed more time to recover due to dispersal limitation or the slow rates of ecological succession (e.g., Muotka et al. 2002; Hasselquist et al. 2015). By comparison, foundational ecosystem processes mediated by communities of algae and bacteria (e.g., primary production or community respiration) have the potential to respond to restoration more rapidly (Arroita et al. 2018), allowing communication of outcomes that can enable management responses.

Third, our ability to *diagnose*, or mechanistically understand, which particular stressor or stressor combination explains the observed degradation can be limited when based solely on structural variables. As noted, compositional indices can be difficult to link to proximate drivers, which makes informed management decisions difficult. By comparison, ecosystem process rates are often directly responsive to changes in the physical and/or chemical environment, enabling us to detect specific stressors that alter a given ecosystem process. These responses can be highly predictive and are often well-grounded in theory, including the temperature dependence of biological processes (Cross et al. 2015), photosynthesis-irradiance (PI) relationships (Hill et al. 1995), nutrient uptake kinetics (Dodds et al. 2002), and the thermodynamics of microbial metabolism (Hedin et al. 1998). Such relationships provide a means of understanding and predicting how stressors act and how the release of stressors, as achieved by restoration mechanisms, mechanistically reshape basal processes that underpin a range of structural properties over longer periods (e.g., Dudley et al. 1986). In this sense, the inclusion of functional variables may help us detect relevant stressors.

For all of these reasons, there is a call to incorporate functional indicators into stream assessment in general and into the assessment of restoration success in particular (e.g., Palmer and Ruhi 2019, von Schiller et al. 2017). Indeed, given the list of ecosystem services that we rely on from running waters, a singular focus on recovery of biodiversity and viable populations is likely insufficient to inform us on how restoration alters other key functions these systems support (e.g., nutrient uptake). Despite this, including measures of functioning as assessment tools is often not straightforward and is plagued by both practical and conceptual limitations. Here, we critically analyze the potential strengths and limitations of applying ecological functioning as a tool to assess river restoration success. On this basis, we present what we see as key steps that may be taken to better implement function-oriented assessments.

Consideration of ecological functioning in stream assessment

Current environmental legislation (e.g., the European Water Framework Directive; WFD) already includes a recommendation that structural *and* functional attributes be considered in assessments of healthy aquatic ecosystems. In fact, there is a surprising discrepancy between the targets of existing water and nature legislations and the targets that are, in practice, most often implemented into current freshwater management. For example, the European Water Framework Directive (art. 21) defines the ecological status as '…*an expression of the quality of the structure and functioning of aquatic ecosystems* …'. The European Biodiversity Strategy 2030 (art. 2.2.7) mandates that '*Greater efforts are needed to restore freshwater ecosystems and the natural functions of rivers* …'. Finally, the Convention on Biological Diversity (Strategic Goal B, target 8) requests that '*By 2020, pollution, including from excess nutrients,* *has been brought to levels that are not detrimental to ecosystem function and biodiversity*.' Ironically, while ecosystem functions are explicitly mentioned as targets for protection in these respective texts, current methods to assess ecosystems or restoration success often lack consideration of any measure of functioning.

'Function' and 'functioning' as terms in ecology can be ambiguous, refer to a range of phenomena, and be difficult to operationalize empirically (Jax 2005). In river science, functioning *writ large* can include a wide diversity of potential variables connected to a range of scientific disciplines, from primarily physical processes related to hydrology and sediment dynamics, to microbial processes that govern biogeochemical transformations and material retention, to processes reflecting resource consumption and energy transfer by communities and food webs (e.g., Palmer and Ruhi 2019, von Schiller et al. 2017). This potential set of functions operates across a broad range of spatial and temporal scales, incorporates different levels of organization, and is shaped by varying contributions from abiotic and biotic drivers. Further, inherent differences in the scale at which we measure different processes (e.g., litter decomposition vs. ecosystem metabolism) complicate our ability to connect a given functional metric to local restoration efforts with confidence (Young et al. 2008). Finally, because these processes underpin different ecosystem services that rivers provide (e.g., from flood mitigation to water purification to healthy food webs), whether strongly optimizing for one such goal may enhance or diminish other goals is not always clear, and may cause unwanted ecological or environmental quality outcomes. Thus, despite calls for incorporating functioning into assessments of river restoration outcomes, deciding on which functions we should consider and how to interpret them remains a limitation.

In our view, successfully implementing functional measures into assessments of stream and river restoration is currently limited by two main issues. First, we need a clearer foundation for selecting core functions. These functions should be sufficiently sensitive to capture environmental changes caused by degradation and recovery following management actions and align with the precise monitoring targets and restoration goals (see below). However, they should also be practical in the sense that they are relatively easy to estimate by scientists and managers alike. While the field at large continues to develop and refine ever-advanced methods to characterize stream and river functioning, the practicalities of incorporating these into management require scrutiny. Second, we need to advance a clearer framework for judging or interpreting functional metrics with appropriate goals and values. Goals could be either narrowly focused (e.g., optimizing a given function) or more broadly seek ecosystem health. The latter goal needs a clear framework for deciding which functions and which values of these functions actually capture ecosystem health. Finally, it may be important to advance beyond a pure indication of ecosystem health and consider how ecological functioning can aid in efforts of diagnosis, i.e., in detecting which are the most important stressors causing ecosystem degradation in a multi-stressor context.

Moving forward, I: Selection of appropriate functions

To comprehensively assess river ecological health and its recovery following restoration, we suggest selecting key ecosystem functions following the criteria of 1) alignment with management objectives, 2) practicality and suitability, and 3) integrative insight and potential value for diagnosis.

Criterion 1: Alignment with management objectives

Functional assessments need to be anchored by metrics that are clearly aligned with the intended ecological or water quality target and specific restoration goals. If restoration aims emphasize or optimize certain functions and services, then indicators need to be clearly linked. For example, if the goal is to improve the quality of receiving waters such as drinking water reservoirs, functions such as nutrient retention and transformation are key. Functional metrics that are related to nutrient uptake rates or key transformations (e.g., primary production or denitrification) as well as hydrological correlates (e.g., water residence time) should be prioritized over metrics like consumer biodiversity or food web stability (Bernot et al. 2010). By comparison, restoration in remote settings without major water chemistry problems could be explicitly aimed at improving habitat quality, connectivity, and recruitment of stream and riparian organisms (Nilsson et al. 2015), and here, metrics linked to the functioning of consumers should be prioritized (Franier et al. 2018). Aligning metrics with objectives will strengthen the feedback loop between restoration actions and environmental outcomes, enhancing the accuracy of functional indicators as proxies for restoration success, allowing for more targeted improvements to river health.

However, assessment and restoration often target more general quality goals such as "ecological health" or "ecological status" rather than a specific goal such as self-purification or fish production. This holistic approach is useful as it optimizes multiple attributes of an ecosystem with fewer risks for unwanted tradeoffs. Such a perspective is, for instance, central to assessments in the context of the European Water Framework Directive, which assesses the "ecological status" based on different communities including benthic micro-algae, invertebrates and fish (Hering et al. 2010). Integrating functions into such assessments of the ecological status raises the question of which functions represent the aquatic ecosystem in total and which of these should we select for a meaningful assessment? According to the broad definition of ecological functions (see section *Consideration of ecological functioning in stream assessment*), several options exist in the literature (e.g., von Schiller et al. 2017). Here, we argue that this large number of functions needs to be boiled down to a select few, which together represent the ecosystem with a focus on biological processes (Table 1). Further, this selection could span core processes of an ecosystem, from low to high trophic positions of the food web, including: (1) (primary) production with rates of GPP or accumulation of pigments as measures, (2) decomposition, with microbially dominated processes such as ER or microbial decay of standardized organic matter (e.g., cotton strips, leaf litter breakdown in fine litter bags) and processes dominated by the macrofauna (e.g., leaf litter breakdown in coarse litter bags), (3) nutrient removal, with quantified or estimated (e.g., from metabolism) uptake rate as a measure, and (4) processing of resources within the broader food web with food web complexity (or related proxies) as a potential measure. These ecological measures would be usefully supplemented by adding a core set of hydrodynamical measures (Table 1), which are often lacking in standard assessments, but which strongly regulate biological communities and processes (Anlanger et al. 2021). The proposed measures would integrate the different levels of food webs while being at the same time focused, given the huge number of functions that could be measured. We see this as a starting point for further discussions and will not exclude that functions can be exchanged or other functions be added, depending on future discussions and methodological developments.

As management goals change, new sets of more specific riverine functions may become prioritized by stakeholders and policy makers. For instance, functioning related to carbon (C) cycling, including mineralization, burial, and greenhouse gas (GHG) emissions to the atmosphere, has not been a major focus of stream and river restoration assessments, despite this being the primary impetus for restoration of other ecosystems (e.g., wetlands; Evans et al.

2021). However, this emphasis may change with growing recognition that rivers play an important role in the regional-to-global C cycle and that this role is at least partially mediated by aquatic biological processes (Battin et al. 2023). We also know that significant amounts of carbon dioxide (CO_2; Raymond et al. 2013), methane (CH_4; Rocher-Ros et al. 2023), and nitrous oxide (N_2O, Beulieu et al. 2011) are emitted from streams and rivers to the atmosphere. Streams with high pollutant loads, such as those receiving urban and agricultural run-off, may be hotspots of GHG concentrations and emissions (e.g, Xu et al. 2024), and restoration efforts, particularly those resulting in a reduction of sewage input and nutrient loads, may effectively reduce these emissions (Wang et al. 2023). Considering functions related to C cycling is also a key component of understanding and motivating dam removal efforts, where the transition from a lentic to a lotic environment is associated with physical and redox changes that have important implications for GHG emissions (McGinnis et al. 2016, Ammani et al. 2022, Bega et al. 2024a). Beyond the active channel margins, river corridors can also be hotspots of carbon storage (e.g., in floodplains) and GHG emissions (McGinnis et al. 2016) and this recognition has raised the question of how and whether restoration of this storage function could be used to obtain carbon credits (Hinsha and Wohl 2023; Lininger and Lave 2024). Taken together, the growing interest in the regional-to-global C cycle by society and policymakers may motivate greater focus on C cycling functions in assessments of river restoration outcomes in the future.

Criterion 2: Practicality and spatial and temporal relevance

Effective functional indicators must be practical while yielding meaningful insights, either into specific management targets or into an ecosystem's overall state. Commonly suggested functional metrics, such as organic matter decomposition and ecosystem metabolism, could meet such standards due to their relatively straightforward measurement techniques and equipment requirements, including modern optical dissolved oxygen (DO) sensors, the availability of software for data analysis, and well-established protocols (Battin et al. 2023, Tiegs et al. 2024). However, rates of whole-system metabolism are not always possible to generate with confidence and require a range of supporting data related to the hydrology and physics of a stream (Demars et al. 2015). Thus, proxy metrics using algal biomass accumulation or high-frequency DO data (e.g., Canadell et al. 2021), as well as chamber-based approaches (e.g., Lopez et al. 2025), could be more viable for practical use. Similarly, while often aligned with restoration objectives, functional metrics related to stream nutrient retention and denitrification rates also require specialized field and laboratory assays, making them less practical for routine monitoring. Such issues could be overcome by developing more time- and/or cost-effective methods (e.g., Covino et al. 2010). Further, increasing use of automated sensors for water chemistry (e.g., nitrate; Kunz et al. 2017), as well as methods that leverage nutrient mass-balance approaches (Von Schiller et al. 2015; Valett et al. 2021) could open up new opportunities for assessing restoration effects on nutrient cycling and retention.

One challenge to using functional metrics for assessment is the potential mismatch between the inherent scale of a given process (or process measurement) and the extent of the degradation and management action (Wright 2021). The length of stream sections under consideration can be highly variable, but is most often less than 500 m (Morandi et al. 2017), which, depending on drainage size, may be insufficient to isolate functional responses using whole-system approaches. For example, estimates of ecosystem metabolism from single-station DO methods typically have a 'footprint' of 100's of meters to kilometers, depending on ecosystem size, and may thus greatly exceed the length of restored reaches (e.g., Hall et al. 2016). Two-station approaches are an option here, provided sufficient travel time within the target reach, but these require more care and effort to execute (Demars et al. 2015) and may be less practical for managers. Similarly, while nutrient uptake lengths can be relatively short (10^1-10^2 m) for small, nutrient-poor streams, these can also greatly exceed the length of a restored reach, depending on the solute in question, nutrient supply relative to demand, and the physical and hydrological attributes of the system (Ensign and Doyle 2006). Conversely, functional metrics based on litter decomposition or algal accumulation on tiles require measurements at relatively small scales (e.g., sub-meter) and subsequent scaling up to the reach. Targeted microbial functions (e.g., denitrification) may be dynamic at even finer scales (mm). In contrast, the characteristic scales at which consumer-driven functions operate can be highly variable, depending on the life history traits of the relevant groups (e.g., Finlay et al. 2000). The point here is not to discourage the use of any particular metric, but to highlight that selecting functions requires aligning the inherent spatial scales of various processes with the scope of restoration.

The appropriate *temporal* scale for measuring functional responses is also a key consideration. This is particularly true for microbial functions, which can show strong seasonal dynamics, while traditional metrics rooted in the community structure of macrofauna integrate over longer time scales. Generally, for biologically mediated functions, the timing and frequency of sampling should reflect the life cycles of the organisms involved. Microbial-driven functions (e.g., biofilm production) may require early and frequent sampling after restoration as these recovery processes are likely to be rapid and are often seasonally variable (Bernhardt et al. 2018). By comparison, functions shaped by macroinvertebrate communities may be assessed less frequently, but could take longer (5+ years) to respond to restoration (Pilotto et al. 2018). Importantly, for both microbial- and macro-consumer-driven functions, any changes to riparian cover that co-occur with restoration efforts may create even longer-term responses driven by potential changes in incident light and/or inputs of organic matter resources as streamside vegetation recovers (e.g., Bega et al. 2024b, Ramiao et al. 2022). The different temporal responses are not a unique phenomenon for functional indicators, as also different structural indicators (e.g, macro-invertebrate communities vs. micro-algae communities) also integrate over time in very different ways. Nevertheless, integrating functions into assessment schemes enhances the variation of time scales integrated by the indicators, as some functions, such as metabolism, can respond to stressors almost immediately. This requires awareness of the different temporal scales and matching the time scales of interest with those of the indicator response. At the same time, there is an opportunity here to incorporate functional indicators that are dynamic at short time scales, as these can potentially act as early warning indicators after environmental change and early success indicators after restoration.

Criterion 3: Integration, complementary functionality, and diagnosis

Unless restoration efforts have a specific aim (e.g., rehabilitating a given species), we argue that functional metrics should target those that encompass multiple processes that integrate trophic levels, ecosystems compartments, biological communities, and abiotic factors, including hydromorphological and habitat diversity, while being focused on core metrics at the same time (see above; Table 1). Such a 'multi-functionality' approach includes metrics related to primary productivity, ecosystem respiration, decomposition, nutrient processing, and food web processes, all of which capture complementary aspects of ecosystem health and integrate biotic and abiotic interactions (Brauns et al. 2022). These metrics provide a comprehensive view of stream ecosystems, linking nutrient cycling, energy flow, and resource consumption. Such processes can capture the stability of a stream in terms of water quality, energy flow, and food web support, which can in turn shed light on resilience and functional redundancy as ecological attributes (Vugteveen et al. 2006). A multifunctional approach does not merely substitute structural metrics with isolated functional ones but rather encompasses the dynamic and interdependent nature of ecological processes. Multi-functionality also serves as an insurance mechanism, safeguarding the ecosystem's ability to function under diverse environmental conditions and across temporal scales (Vugteveen et al. 2006, Brauns et al. 2022). Several recent publications suggest procedures to calculate multi-metric indices for assessment of ecosystems (e.g., Assefa et al. 2023; Martins et al. 2020). Such metrics can be a useful measure to communicate ecological health to the public and to the political arena. From the ecosystem assessment and diagnostic perspective, however, multi-functional indices are less useful as they may be too general to detect processes and underlying drivers linked to degradation and recovery. Therefore, we do not elaborate on the calculation of integrative multi-functional metrics here but rather recommend evaluating the different ecosystem processes separately.

Functional metrics derived from ecosystem metabolism and organic matter decomposition are notable in reflecting short- to longer-term ecosystem dynamics that integrate across levels of organization (Young et al. 2008; Ferreira et al. 2020). Organic matter decomposition offers insight into the activity of both microbial and invertebrate communities, linking terrestrial and aquatic ecosystems through nutrient cycling and energy transfer processes (Rosemond et al. 2015). Metrics from ecosystem metabolism, including gross primary productivity (GPP) and ecosystem respiration (ER), provide a more immediate measure of carbon production and consumption within a system, capturing the functional balance between autotrophic and heterotrophic processes (Bernhardt et al. 2018). Both sets of functional metrics reflect extant ecosystem state but can also reveal shifts in function due to temporal change, such as those following restoration, land use change, and natural seasonality (Griffith et al. 2013, Silva-Junior et al. 2014, Kupilas et al. 2017). Finally, these functions can provide direct insight into the mechanisms driving ecosystem change, serving as responsive indicators to various anthropogenic stressors stemming from wastewater inputs (Arroita et al. 2019; Pereda et al. 2020), pesticides and nutrient enrichment caused by agricultural activities (Rossi et al. 2018), wildfire (Betts & Jones Jr. 2009), as well as climate-induced hydrological extremes (Ulseth et al. 2017).

Functions should also be selected to aid in diagnosis, which refers to our ability to generate a mechanistic understanding of an ecosystem. Typically, functional metrics are more suitable for diagnosis than structural metrics, because causes and effects are often more directly connected. As one established approach, functional traits are used for diagnosis to identify relevant stressors (e.g., Schuwirth et al., 2015). However, traits represent a potential for functions (e.g., high contribution of the feeding trait "shredder" indicates high potential for leaf litter degradation) rather than a realized quantity of certain functions (e.g., the quantification of leaf litter degradation with litter bags). The diagnostic utility derived from the measurement of functions is not only useful in understanding restoration response, but is also crucial as it aligns with management objectives that require rapid and accurate feedback on outcomes (Palmer and Ruhi 2019). Obviously, not all functions are equally suitable as diagnostic indicators; nevertheless, most functions could aid diagnosis by revealing whether or not certain restoration measures result in changes to basal processes that are either directly related to desired outcomes (e.g., nutrient removal) or have clear indirect linkages to consumer communities (e.g., algal biomass accrual). Importantly, more work is needed that critically evaluates which functions are useful in providing diagnostic information in response to restoration, including whether and how different processes may help us anticipate future structural changes. For example, GPP and its relation to algae standing stocks might be a much better (because more directly related) indicator for eutrophication than changes in algal community composition. Seeking this diagnostic type of understanding will allow us to assess ecosystems' health more rapidly, to identify relevant stressors and corresponding tailored management measures and to decide whether or not we are moving toward restoration targets.

Moving forward II: valuation of functional goals

Once sets of functional metrics are selected, the next challenge is interpreting whether and how measured process rates or functional proxies indicate ecological health and success or failure of restoration or remediation. Importantly, how we judge functional indicators is closely linked to what we are aiming to achieve. For example, documented increases in fish abundance and biomass are straightforward hallmarks of success if the overall goal is to improve a river reach for fish production. Here, judging functional indicators (i.e., evaluating success) is tailored to a specific, pre-determined target. However, most monitoring programs and restoration efforts target ecosystem health in a holistic sense, assuming that a broad set of indicators is the best compromise to fulfill multiple functions and expectations (see above). Here, judging functional indicators becomes less objective, as targets may be linked to the availability and utility of reference systems and be sensitive to changing baselines. Our goal is not to argue for any particular approach, as this must be a decision taken by society. Instead, we present the pros and cons of the different approaches and essential steps to define appropriate goals.

Functional metrics can provide objective, concrete evidence of ecosystem recovery when management goals are narrow and distinct. Here, judging degradation and recovery based on single functions may be particularly easy for cases where overall water quality is good, and habitat restoration is used to optimize the production of a target species (Louhi et al. 2014), or if the goal is to remediate a severe water quality problem (e.g., hypoxia), unlocking a diverse set of positive ecological outcomes (e.g., Arroita et al. 2019). Yet, in many cases, judging success based on a single, focal function may be arbitrary, and optimization itself could come at a cost to other water quality considerations, as ecosystem processes typically do not operate in isolation. For example, judging success based solely on nitrogen removal (e.g., via denitrification) could come at a cost to structural measures (e.g., biodiversity of macroinvertebrates), but also create unwanted changes in greenhouse emissions, particularly of CH_4 and nitrous oxide (N_2O; e.g., Mander et al. 2014). Further complicating this challenge is that environmental drivers (e.g., nutrient loading) can have both positive and negative associations with a given functional measure (Woodward et al. 2012), making it difficult to judge whether an observed rate indicates management success or failure. More broadly, because diversity measures like species richness are in many cases only weakly connected to a given function (e.g., Cardinale et al. 2012), highly disturbed ecosystems may perform as well as pristine ones, even if they have lost most of their diversity. Thus, having a single functional metric as the only guideline may lead to a species-poor ecosystem, engineered to do one thing well. Without accounting for potentially important biotic redundancy (e.g., a portfolio effect; Schindler et al. 2015), we risk creating systems in which even the target function of interest has low resilience to future disturbance or environmental change.

If management goals instead target holistic improvements in ecosystem health, functional indicators are still critical to consider, but their valuation becomes more of a challenge as the targets are less obvious. In most restoration programs, the aim is to restore ecosystems to something approaching 'natural conditions', which in practice involves recovering a set of structural and functional properties that match a local and historic (pre-human influence) reference. This can be a challenge where the reference state is unclear and may require a reconstruction of historical conditions and the related ecological attributes. Even when possible, it is further problematic that reference conditions for functioning may be less evident than for structural counterparts and may be particularly sensitive to shifting baselines (e.g., linked to climate warming). One option here could be to anchor our expectations and judgements based on a 'functional stream typology' where certain stream attributes result in predictable functions.

Such an effort could be guided by theory; for example, functioning related to metabolic rates and ratios (e.g., GPP/ER) could be derived from predictions based on ecosystem size (e.g., Vannote et al. 1980), the seasonal timing of measurements (Bernhardt et al. 2018), and/or the broader biome context (Dodds et al. 2015). In this context, we might derive desired endpoints by synthesizing published rates of ecosystem processes from streams considered to be 'near reference' in terms of human impacts. This approach would require testing at which spatial scale values from the literature tend to differ (e.g., by biome, ecoregion, catchment, etc.) and thus how reasonable these are for guiding targets locally. The advantage here could be the development of targets that are applicable over broader spatial scales and also over broader environmental gradients, including climate gradients.

Finally, in the event that restoration or remediation goals change, we may need to judge functional indicators in new ways. For example, rather than looking backward for target endpoints, functional indices may need to be assessed through the lens of how streams will respond to future environmental change and how we define ecosystem health under these conditions. This is hardly possible when having community structure-based indicators, as the composition of the communities will change in the future in an unpredictable way. However, using general functional properties of ecosystems, which are rooted in stream ecology theory (see above) and which are valid under different environmental conditions, could be a way forward to define functional goals that are robust towards shifting boundary conditions.

Conclusions

Integration of functional indicators into the ecological assessment of running waters provides clear additive value to present, structurally-focused assessments. Functions can (i) act as an early indicator for critical changes and restoration success, (ii) they still work as a quality indicator even under changing boundary conditions and corresponding changes in the species pool, and (iii) they increase, together with structural indicators, the potential for diagnosing ecosystems. We are, however, not yet ready to explore these clear benefits and to implement functional indicators into assessment routines. To reach this goal, future studies must shift the focus from the pure description of responses of ecosystem functions to stress and its release towards the implementation indicators into an assessment scheme. This paper should guide the future effort to solve two major challenges, namely the selection of appropriate functions and the definition and valuation of functional goals to provide the scientific basis for a broad implementation of functional indicators into stream management and assessment.

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Table 1: Core set of selected functional indicators, which in total address the key elements of the aquatic ecosystems along these categories: (0) Important abiotic variables, which are not represented in routine management today (1) (primary) production-related measures, (2) decomposition-related proxy either with microbial dominance of dominance of macrofauna mediated (3) nutrient-removal related measure, and (4) measures for food web structure/ complexity. In addition to these general descriptors of ecosystem health, we provide (5) one example of a specific functional measure of potential management interest, i.e., the greenhouse gas emission (see text for further details). This list is intended stimulate the discussion on the selection of a reduced set of appropriate indicators, which reasonably well describe ecosystem health in total and which fulfil other selection criteria (see text), including the practicability to measure the variables. It is explicitly not intended to cover a full set of all functional indicators, which are applied in aquatic science.

(category) Variables	**Example descriptors**	**Response time to stressors/ restoration**	**Operative scale**
(0) Hydrodynamics	Near-bed hydraulics Turbulent flow Vertical, lateral exchange Transient storage	Fast	Spot to reach
(1) Metabolism, GGP	Gross primary production	Fast	Reach to segment
(2) Metabolism, ER	Ecosystem respiration	Fast to Intermediate	Reach to segment
(2) Litter decomposition	Mass loss in coarse and fine mesh bags (macrofauna/ microfauna)	Intermediate	Spot
(3) Nutrient uptake	Total (U) Uptake efficiency (V_f)	Fast	Reach

(3) Secondary production	Microbial secondary production Macrofauna secondary production	Fast (micro) Intermediate (macro)	Spot
(4) Microbial functional diversity	Shannon diversity of OTUs Targets groups (e.g., cyanobactgeria) Fungi:bacteria Denitrifiers	Fast to intermediate	Spot
(4) Consumer functional diversity	Functional feeding groups	Slow	Spot
(4) Food web complexity	Niche compression Carbon transfer efficiency	Slow	Spot
(5) Greenhouse gas emissions	CO_2 emissions CH_4 emissions N_2O emissions	Fast to intermediate	Spot