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Review

Best Practices for Monitoring and Assessing the Ecological Response to River Restoration

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Abstract: Nature-based solutions are widely advocated for freshwater ecosystem conservation and restoration. As increasing amounts of river restoration are undertaken, the need to understand the ecological response to different measures and where measures are best applied becomes more pressing. It is essential that appraisal methods follow a sound scientific approach. Here, experienced restoration appraisal experts review current best practice and academic knowledge to make recommendations and provide guidance that will enable practitioners to gather and analyse meaningful data, using scientific rigor to appraise restoration success. What should be monitored depends on the river type and the type and scale of intervention. By understanding how habitats are likely to change we can anticipate what species, life stages, and communities are likely to be affected. Monitoring should therefore be integrated and include both environmental/habitat and biota assessments. A robust scientific approach to monitoring and appraisal is resource intensive. We recommend that appraisal efforts be directed to where they will provide the greatest evidence, including 'flagship' restoration schemes for detailed long-term monitoring. Such an approach will provide the evidence needed to understand which restoration measures work where and ensure that they can be applied with confidence elsewhere.

Keywords: river restoration; monitoring; appraisal; best practice; BACI

1. Introduction

Despite their critical role in maintaining biodiversity and the essential socioeconomic services they provide, the importance of freshwaters and the need to treat them responsibly is often overlooked. Indeed, according to the Living Planet Index, there was an 84% decline in freshwater vertebrate populations 1970–2016, and almost one in three freshwater species is threatened with extinction [1]. Increasing attention is now being paid to the restoration of ecosystems to help limit and mitigate the effects of climate change, to ensure the sustainable provision of essential ecosystem services, and to stem the loss of habitats and species. The United Nations has proclaimed 2021–2030 to be the Decade on Ecosystem Restoration [2], with freshwater ecosystem conservation and restoration a major theme [2].

In 2013, the River Restoration and Biodiversity Programme was established under the auspices of the International Union for the Conservation of Nature National Committee United Kingdom (IUCN NCUK [3]). The aim of the Programme is to provide robust evidence for the biodiversity benefits of restoring rivers. The Programme defines river restoration as "the re-establishment of natural physical processes (e.g., variation of flow and sediment movement), features (e.g., sediment sizes and river shape) and physical habitats of a river system (including submerged, bank and floodplain areas)". This approach uses nature-based solutions to restore natural processes to create a characteristic, self-sustaining, dynamic physical habitat that facilitates ecological recovery [4,5].

Understanding the response of biota to river restoration intervention is important when determining whether ecological objectives have been met, whether adaptive management is necessary, and to learn lessons for future projects [6,7]. It requires the collection of meaningful data to determine whether a project has been successful [8,9]. However, most projects have not implemented effective monitoring to assess the outcome of restoration [7,10], and there has been a reliance on subjective perceptions of success [11]. If we are to understand and implement restoration measures effectively, their success must be rigorously evaluated [5,12].

The ongoing lack of research and monitoring following the recovery of degraded ecosystems means that theories about the trajectories of ecosystem change following restoration remain unclear [13,14]. Without confidence in the theoretical framework, developing generalised strategies for the evaluation of change following a restoration intervention is difficult. In short, we remain in a data gathering phase.

To address these gaps, in October 2018 as part of the IUCN (NCUK) River Restoration and Biodiversity Programme, a workshop of invited river restoration appraisal academics and practitioners was held. Its aim was to explore best practices and incorporate academic knowledge to develop a scientifically robust monitoring protocol for appraising the biodiversity benefits of restoration [15]. This review builds on the findings of the workshop. The recommendations are intended to inform robust assessments of restoration effectiveness by both academics and practitioners worldwide.

2. History of Restoration Appraisal

In the 1990s, river restoration became established as an important method for the rehabilitation of river ecosystems [16–19]. Concurrent with this increase in restoration activity was the call for comprehensive monitoring, including flag-ship demonstration projects [20] and well-structured monitoring and appraisal [21] that take an ecosystem approach [19]. Despite the recognition of the importance of monitoring change, restoration measures were often implemented on the assumption that the restoration of habitats would be followed by improvements in biodiversity. This approach is characterised by the phrase "if you build it, they will come", otherwise known as the "Field of Dreams hypothesis" [22]. The lack of appraisal meant that the success of restoration measures was poorly understood. A 2007 review found 89% of project contacts reported success but only 11% of the projects were considered successful due to a measurable ecological response [23]. Similarly, in 2016, the UK National River Restoration Inventory compiled by the River Restoration Centre contained over 2800 completed projects with only 21% reporting any monitoring. Of the 179 projects added to this inventory in 2017, only 5% specifically reported any monitoring outcomes [24]. A review of restoration work in California, USA, found that very few projects had been subjected to post-project evaluation resulting in a lost opportunity to learn and improve future design [25]. This view was supported by others who also concluded that poorly planned appraisals can be misleading [26].

Despite an increase in the number of published restoration appraisals [27], there is still a noted lack of monitoring and appraisal [12,28]. There is also a lack of consideration of how to monitor project success effectively and the inherent difficulties in doing this [29]. These appraisals are illustrated by poorly planned inappropriate monitoring strategies [7,30] and recommendations to undertake monitoring with more rigor to increase the likelihood of detecting actual changes in biodiversity [5,31], as well as linking hydromorphological changes to ecological responses [32,33].

3. Towards More Effective Appraisal of River Restoration

Discussions at the 2018 IUCN (NCUK) workshop concentrated on developing recommendations to complement existing guidance and established best practices. Specifically, all restoration activity should be undertaken within an integrated project framework. This framework should ensure there are sufficient baseline data to characterise the current status, identify causes of degradation, plan effective solutions, and set restoration targets [12,34,35].

Once restoration targets have been established they should be turned into clear SMART (Specific, Measurable, Achievable, Realistic, and Time-bound (e.g., [36]) objectives that are linked to project goals and predicted outcomes [17,21]. A lack of defined objectives and success criteria or end points against which to measure success has also been identified as a problem in river restoration appraisal [12,29].

The development of target outcomes or 'expectations', therefore, requires either historical information about the system that is to be restored, information from ecologically similar but undisturbed 'reference' sites, or expert opinion based on empirical and/or theoretical models [26]. Quantified expectations allow the testing of scientific hypotheses about how systems respond to restoration [37,38]. The expectations must be set in the context of catchment condition and processes and should consider restoring both structural complexity and functional integrity [39] (Figure 1). Setting expectations or targets in a catchment context allows the interactions with other anthropogenic stressors to be considered [32,40,41]. Expectations should also consider projected future changes within the catchments of restored rivers including climate change and likely land use changes such as urban development.

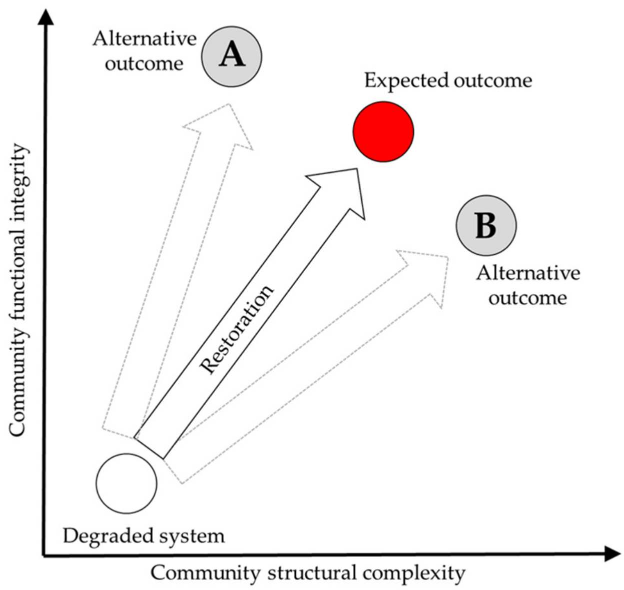

Figure 1. A general model of ecological restoration, where the objective is to increase structural and/or functional complexity.

Exactly what is monitored to support the appraisal of restoration outcomes will depend on the impetus for a scheme and the scale of the restoration [5]. However, it should follow an integrated ecosystem approach [18] that includes geomorphological, habitat, and biota assessments [4,5,17]. Where practicable, assessments points should be colocated [29] to help understand biotic responses to habitat change.

Legitimacy of restoration appraisal requires the scientific review and public dissemination of findings [5], yet appraisals are often poorly documented [34]. There are two main dissemination routes: publications in peer-journals and less formal forums. Journal publication ensures scientific robustness and knowledge sharing. Less formal routes such as the EU-RiverWiki [42], (an online tool used for sharing information on river restoration projects) allow wider dissemination and the sharing of less detailed studies, which can contribute to the weight of evidence of restoration success. To ensure the field of river restoration continues to advance, results should be shared regardless of whether they are positive, negative, or ambiguous [11,13,21,29,34,43]. The importance of engaging project stakeholders at this stage should not be overlooked as this can be critical to promoting buy-in for future projects.

4. Monitoring Strategies

There are two broad types of monitoring for restoration: confirmatory and investigative. Confirmatory monitoring is a process of confirming ecological expectations, for example, the presence of xylophagous (feeding on or boring into wood) invertebrates following the addition of large woody material. Confirmatory monitoring is simple but cannot answer fundamental ecological questions or make predictions; this capability is the domain of investigative monitoring, which is more complex and involves the collection of data on several related variables to answer questions associated with the outcome of habitat restoration.

Evaluation of change should be achieved through the collection of high quality information. "High quality" in this case means representative data gathered with sufficient replication over appropriate time and spatial scales relevant to the indicator or process, i.e., physical, biological, or ecological. To cover the range of scales required it is likely that a combination of different types of data and monitoring will be required [44]. The information gathered must be able to account for the multiple influences on plausible recovery trajectories.

Before any data are collected, the factors causing variability within the system need to be identified and defined, and suitable indicators of interest must be determined. This will provide insight into the sampling effort required to gain a significant result—in statistical parlance, power analysis [45]. This is of particular importance in river restoration projects where the restoration "signal" may be difficult to discern from the "noise" of uncontrolled confounding factors such as land use changes, climate change, interannual variation, natural disturbance, erratic events (e.g., La Nina), and observer-variability.

Both natural and anthropogenic stressors have been shown to generate contrasting patterns in the overall dissimilarity of species assemblages, species turnover, and assemblage nestedness (i.e., beta diversity factors; [46]). For example, the increasing intensity of stress has been shown to reduce variability in the occurrence of subsets of sensitive species, particularly through anthropogenic stressors [46].

Rivers exhibit gradients of change in hydromorphological and ecological attributes over their course, which poses a potential problem for locating suitable control or reference sites to determine the changes resulting from restoration intervention. This limitation can be reduced through the use of a paired river design and multiple controls in similar habitats, including neighbouring rivers [47–49] and, for example [50].

Pre-restoration data are also important, because they allow the assessment of whether a restoration project has been successful against a baseline [51]; understanding variability in the data improves confidence in assessments of success [32,52]. Whilst the pre-intervention data should cover as long a period as possible [43], the actual number of years over which it is gathered is often arbitrarily set at three. This 3-year period is a compromise between understanding the current condition of the site, the resources (both money and time) available [53], and statistical criteria. In many cases, there is simply no or very little pre-restoration data.

To ensure a true representation of the background natural variability in river condition (i.e., controls), multiple sites, sampled at the same time across similar habitats and/or rivers, could assist in understanding existing or underlying attributes. As well as enabling the success of an individual project to be evaluated, the information gathered also contributes to the development of wider understanding, i.e., to the building of a theoretical framework [45]. Following restoration, the frequency and duration of monitoring should be consistent with the life histories of the target organisms and the timescale for exhibiting responses (i.e., the lag time). The magnitude and duration of responses vary from rapidly responding algae, through moderately responsive fish, to slowly responding riparian trees [54], Figure 2 [55].

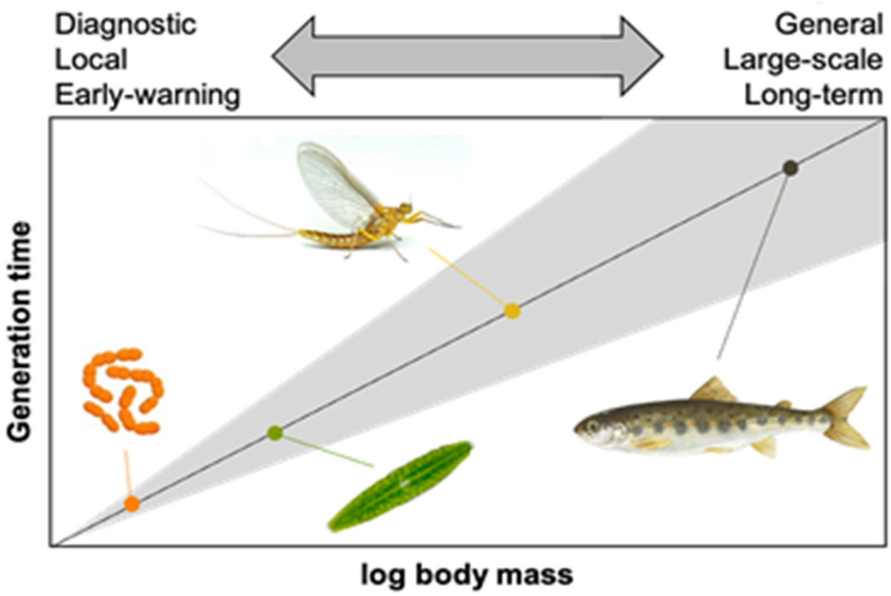

Figure 2. Capabilities in biological monitoring across the spectrum of body sizes. Relatively small-bodied, short-lived, and widely dispersed organisms such as microbes and diatoms can indicate short-term localised changes in the environment with potentially high specificity to particular stressors. On the other hand, larger-bodied, long-lived organisms such as macroinvertebrates and fish can be indicative of larger-scale longer-term environmental changes (from [55]).

Taking the aspects outlined above into account when monitoring will increase the likelihood that data of adequate quality will be collected to summarize restoration outcome with sufficient precision. The Before–After–Control–Impact (BACI) monitoring design [47,48] coupled with stratified random sampling [56], is often appropriate, especially when data need to be gathered over a long period to inform future generalised monitoring strategies [56]. Variations of the BACI design exist but have inherent assumptions which must be recognised. For example, in the absence of controls, Before–After studies must collect information for long enough before and after restoration to allow the quantification of natural variability (e.g., high and low flows); this has become known as the "intensively monitored watershed" [49]. In the absence of "Before" information, assumptions have been made that Control and Impact sites were of comparable condition before any restoration intervention. To address this assumption extensive post-treatment (EPT; [49]) monitoring has been undertaken to attempt to adequately quantify spatial variability. A related alternative design is the Before–After–Gradient (BAG) approach. This allows determination of the spatial (i.e., lateral and longitudinal) and temporal extent of change associated with restoration and improves statistical power over control–impact and BACI designs by incorporating distance as an independent variable in the analysis [57,58]. The purpose of the controls used in a monitoring programme must be considered. A positive control (often described in experimental design as the treatment control) represents the best example of what the restoration work is trying to achieve, providing some indication of how a restoration site is changing to meet an ideal. A negative control represents the pre-restoration state of a site and provides a baseline against which change in a restored site can be compared. In the absence of control sites, establishing whether any observed changes are due to restoration or other environmental changes is difficult [59]. However, control site selection will unavoidably entail compromise, and understanding the aspects that differ from the restoration site is essential in order to interpret BACI results.

Monitoring strategy—recommendations:

- Follow a Before–After–Control–Impact (BACI) approach.
- Controls can be positive (the best example of what the restoration work is trying to achieve), negative (the state of a restoration site before the restoration intervention), or a combination of both.
- Base evaluations on representative data gathered over an appropriate length of time and at spatial scales relevant to the change of interest (i.e., physical, biological, and ecological).
- Identify factors causing variability in the system (catchment context) to help identify suitable indicators of interest; this includes consideration of multiple pressures.
- Collect pre-restoration data to quantify baseline variability and ensure that appropriate target outcomes are set. Three years of pre-intervention data is a pragmatic choice, but multiple control sites can help give an understanding of background spatial variability.
- Ensure post-restoration monitoring design is appropriate for the the life histories of the target organisms.

5. Appraisal Methods

Sample collection generally falls along a continuum from quantitative to qualitative. Quantitative biological sampling often involves an intensive sampling effort using replicated small sample units and provides relatively precise information about the density or abundance of common species. It provides information about the components of variation in a system [60], meaning that the information collected provides an insight into the functioning and dynamics of the community under investigation [61]. As quantitative sampling may not sample all habitats it may fail to record less common and rare species and may not therefore be appropriate for surveys aimed at rare species conservation. At the other end of the continuum, qualitative sampling involves the collection of fewer, larger samples, where the presence of a much broader range of species is recorded. This sampling is appropriate for surveying larger areas and provides an insight into the distribution of species. It does not provide enough information about the variability in a system and is thus unable to provide fine scale information about the functioning and dynamics of the community [61].

5.1. Riverine Vegetation

Riverine vegetation is of interest at restoration sites as an indicator of water quality, for its conservation value, and because it can influence fluvial geomorphological processes. Vegetation can stabilise and affect the accumulation of sediment and so influence the formation of characteristic bed forms. Therefore, the interaction between vegetation and physical processes may strongly influence the trajectory of a restoration project. The monitoring approach taken will reflect which of the aspects (water quality, conservation value, and fluvial geomorphology) are of interest. In the following discussion, a distinction is made between instream and riparian vegetation as monitoring methods have developed separately for the two types.

5.1.1. Monitoring for Water Quality and Conservation Value

Monitoring instream vegetation (macrophytes) is often a key element in assessment programmes [62]. Macrophytes may be used as a semiquantitative indicator of water quality. Standard survey techniques can be applied and typically involve a visual assessment of cover over a reach of standardised length, typically 100 m or more [63]. A number of standardised techniques are used across Europe [64,65]; the transect based approach used by Danish monitoring agencies is recommended, as it provides quantitative data that can also be used to investigate some instream biogeomorphic processes [66]. As with invertebrate sampling, there is a wealth of supporting information for many of these methods on sources of error, statistical interpretation, and indicator metrics [67]. Comparisons with other sites sampled with the same method within a national network are easily made.

Aquatic vegetation morphotypes (e.g., submerged broad-leaf, emergent narrow-leaf, etc.) are strongly associated with hydraulic and hydrological habitat [68]. There is some evidence that aquatic vegetation responses to restoration are best detected by examining changes in plant morphotypes rather than species responses [69].

5.1.2. Monitoring Biogeomorphic Processes

To check that biofluvial geomorphological processes are developing as expected, it is important to monitor vegetation in concert with physical processes. There is no widely applied and standardised approach for doing this, although there are rapid assessment techniques that show promise [70,71]. There is a strong conceptual understanding of the topic that takes account of vegetation succession, the formation of bed features, and the role of disturbance [72]. These conceptual models indicate that the trajectory of change will depend on river type. Thus, rather than prescribing a particular method, here, the recommendation is to consult with a fluvial geomorphologist and aquatic botanist familiar with biofluvial geomorphological processes and together develop a monitoring approach suited to the site and river type. Monitoring may be undertaken using traditional survey techniques, aerial photography, and remote sensing (e.g., LiDAR).

Significant advances in modelling biofluvial geomorphological processes have been made in the last two decades, and collecting data suitable for use in one of the emerging modelling techniques should be considered [73,74]. Once the trajectory of change for a system has been modelled, the management can be altered as necessary to achieve the required goal.

River vegetation can be very dynamic, especially following the physical disturbance of restoration. It is therefore expected that vegetation will go through a succession of different stages. Restoration sites are especially vulnerable to invasion by alien species; this risk should be monitored so that swift remedial action can be taken. Important explanatory variables are often not recorded. For example, riparian shading of aquatic vegetation can be hugely influential, and often overlooked is the structuring influence of grazing and trampling [75].

Riverine vegetation—recommendations:

- Assess both species and morphotypes.
- Take succession into account when setting expectations and planning post-restoration appraisal.
- Use aerial photography, hydroacoustic methods, remote sensing, and modelling to complement more traditional approaches.
- Incorporate geomorphological interactions with riverine vegetation and controlling factors such as shading and grazing when assessing vegetation response to restoration.

5.2. Invertebrates

5.2.1. Qualitative Monitoring

Representative samples are collected with kick nets over a large habitat unit. Traditionally, this would be within a wadable habitat (i.e., a riffle [76]), but it is now more common to cover multiple habitats [77]. Sampling effort (time taken) can be allocated across the habitats included in the survey unit, in proportion to the area of each habitat. Invertebrates collected in each sample are then sorted and identified to species or, more efficiently, to easily identifiable taxonomic levels, termed Operational Taxonomic Units (OTUs). This approach is widely applied in national monitoring programmes [64]. However, whether these data are suitable for illustrating changes resulting from river restoration activity needs to be considered carefully. They may, for example, be best for assessing catchment scale intervention, as a large geographic area can easily be covered (e.g., [78]).

Qualitative (or semiquantitative) techniques are best applied following a BACI approach and in situations where substantial changes in habitat are anticipated, such as those associated with a reduction in impoundment following the removal of a weir. These techniques are often insensitive to changes in the areal extent of a habitat. The qualitative, or time-standardised, nature of the approach makes it impossible to compare invertebrate densities and underrepresents taxa abundance.

5.2.2. Quantitative Monitoring

Quantitative sampling can be used to derive relationships between invertebrate metrics and physical habitat measures, including ordinal or continuous hydraulic and hydrological variables and geomorphological units. Fully quantitative samples are typically collected using a quadrat with an attached net. The quadrat may be open (Surber—for bare substrate [77]) or enclosed (Lambourn—for vegetated substrate [77]). Suction techniques can be used to collect animals in deeper water, and grab samplers can be used in fine sediment [77]. The size of the quadrat must take account of the heterogeneity and distribution of invertebrates [79]. Data collected from quadrats provide a measure of density (number of animals per unit area) and lend themselves to a range of analytical approaches including the analysis of food webs and the quantification of ecohydraulic relationships [78].

For restoration appraisal the most effective application of quantitative surveys will follow a BACI or experimental design. A stratified random approach is recommended; the river is divided into areas, which may represent different habitats (e.g., pools and riffles) [80], and each habitat is randomly sampled. This can be labour intensive when many habitats are present. Alternatively, selecting a larger area, such as the mid-channel, allows randomly placed samples to be collected across a range of conditions (e.g., substrate and velocity) and assessments against habitat gradients made.

Quantitative monitoring needs substantially more sampling effort than qualitative monitoring and also requires the expert selection of sampling locations in a site. Where the relationship between invertebrate responses and the development of geomorphological forms is of interest, quantitative invertebrate and fluvial geomorphological sampling locations need to be sampled in a spatially and temporally coordinated manner.

Whether a quantitative or qualitative approach is taken, the influence of season must be taken into account with any invertebrate sampling. Traditional assessments (e.g., national monitoring programmes) are undertaken in both spring (March–May) and autumn (September–November). For restoration appraisal, a narrower (one month) sampling window is recommended for each season. If resources are limited, a more detailed once a year monitoring programme is recommended rather than collecting fewer samples per season.

Invertebrates—recommendations:

- Undertake quantitative sampling using a stratified random approach.
- Incorporate positive and negative controls.
- Sample within the same one month window.

5.3. Fish

The approach to monitoring the response of fish populations to river restoration should reflect the restoration aim, and take account of the spatial and temporal scale over which changes are expected to occur and the life history stages and essential habitat requirements of the species affected [6,81]. Assessing the effectiveness of some fish habitat-focused restoration, such as removing a barrier to improve connectivity or recreating spawning areas, can be straightforward. However, quantifying the benefits for fish of restoring natural processes can be challenging [12]. Understanding whether restoration is aimed at general ecological improvement, focused on a specific species of fish (e.g., salmonid habitat restoration), or the improvement of the fish community (e.g., coarse fish abundance) will provide clear direction for the approach to monitoring and allow suitable methods to be chosen.

For restoration aimed at general ecological improvement, and 'better fish habitat', understanding the 'current' and 'expected' characteristics of a river and catchment context from the source to estuary (e.g., Huets Fish Zonation [82]) provides the basis to assess 'baseline' against 'expected' diversity of fish habitat and different fish assemblages (including life stages in response to river restoration.

Fish have distinct seasonal habitat preferences; these vary according to species-specific life cycles and life histories [81]. For example, the juveniles of some species (e.g., sea lamprey Petromyzon marinus) will occupy low energy river margins with macrophytes or backwaters; those of other species (e.g., Atlantic salmon *Salmo salar*) or the adult rheophilic fish such as gudgeon (*Gobio gobio*) will occupy faster flowing riffles; and limnophilic species (e.g., bream *Abramis brama*) will inhabit slower flowing pools. The time of year also defines when some species are present or just simply migrating through an area. A robust monitoring plan will take account of these factors; it should also consider other catchment pressures that could undermine the otherwise beneficial restoration effects on fish.

5.3.1. Monitoring Considerations

As with other species, a replicated BACI is the strongest statistical approach for quantitatively assessing a fisheries response to river restoration, as it incorporates both the spatial and temporal dimensions of assessment [28].

Fish can move over many kilometres and, therefore, finding suitable within-river control or reference sites is often difficult. Fish surveys of restored or control reaches may be unreliable as some individuals could be passing through rather than inhabiting them. Potential solutions such as statistical power analysis [83] can ensure that the number of surveys is suitable. Reference sites could be upstream or downstream of a restored reach at a distance that is further than the distance over which the fish will be expected to move within a set period of time taken to collect concurrent samples. A survey design could be applied, where monitoring occurs at different distances upstream and downstream from the restored site to determine the gradient of change or difference between the restored site and the adjacent sections of the river. Alternatively, samples from control sites in other rivers could be used, and by using more than one river for this, some of the variability associated error can be removed [84].

When monitoring is undertaken will depend on whether the target species are migratory, either seasonally or diurnally. Spatial and temporal differences in habitat use according to life stage will have significant implications for monitoring and, therefore, understanding the species' natural history is crucial. Understanding the baseline status of the fish population (usually estimated through density and biomass determination methods [84]) will be essential. Fish population increase (i.e., recruitment) and decrease (i.e., mortality) is notoriously variable and includes immigration as well as emigration. Knowledge of the baseline fish population age structure will be important and allow the strength of each year class to be understood. It can help to highlight existing issues with the maintenance of a sustainable population.

5.3.2. Monitoring Methods

Effective fisheries monitoring requires the sampling techniques used to assess the effects on both the fish *and* their habitat. The quality and availability of fisheries habitat can be assessed directly using approaches such as Hendry-Cragg-Hine, HABSCORE, or 1D hydrological modelling [35] that incorporate the habitat preferences of chosen species.

The principal methods used for fish assemblage/community sampling include: netting a fixed length of river or shoreline habitat; electrofishing different habitats; hydroacoustic surveys for density and size distribution; and fish counters or in situ cameras to monitor fish passage through a specific section of the river, e.g., [85]. If the objective is species-specific, then typically used methods include: netting (e.g., eel traps); passive tagging, where identification markers are attached externally or inserted into fish and records are kept of where and when they are recaptured; and active radio/acoustic tracking of individuals' fine scale movements and behaviour. More contemporary methods, such as environmental DNA (eDNA) metabarcoding, can be used to determine the presence of different fish species and can show whether a specific species has moved into a new upstream area [86]. Fishery assessment methods result in a variety of data outputs. Nevertheless, combining fish habitat and fisheries stock/fish movement assessments is an efficient way to illustrate the success of a restoration project for fish.

Fish survey methods vary according to the objective of the restoration being assessed and the length of time the response is predicted to take [87]. For example, fish may respond immediately when a barrier to movement is removed, whereas changes associated with projects aimed at longer-term improvements to population age structure or cohort strength may not become clear for several years. Regardless of the objective, knowledge of the species' seasonal requirements in relation to the hydrological regime will determine which method is the most appropriate. Furthermore, the timing of monitoring needs to be matched to hydrological changes, life stages and when fish will be present; it is important to take account of both the longitudinal and lateral use of the river environment which vary according to the time of year (e.g., lateral floodplain use during spawning season).

Fish—recommendations:

- Understand the local hydrological regime of the catchment.
- Decide whether the fish community or specific species need(s) to be monitored.

5.4. Riparian Zone

Riparian biota, especially vegetation, responds relatively readily to restoration [88,89]. Riparian vegetation has proven a reliable indicator of restoration effectiveness [90], though restoration effects may take some time to manifest [91]. Riparian vegetation can be monitored with a variety of standard techniques that are typically applied to terrestrial vegetation. Both quadrat and transect-based surveys can be used [92–94]. It is important to take account of zonation and succession patterns to ensure that the entire flora of the riparian zone is adequately represented.

Riparian invertebrates are also considered suitable indicators of the effects of hydromorphological restoration [95]. In particular ground beetles, sampled between late June and August using pitfall traps and hand searches, have been found to respond strongly to restoration measures [96]. Following a standard protocol incorporating both pitfall traps and hand searches enhances the capacity of invertebrate communities to characterize riparian habitat quality and thus restoration activity [97].

Riparian zone—recommendations:

- Assess riparian vegetation taking into account expected timescales of response.
- Assess ground beetle response using a combination of pit-fall traps and hand searches.

5.5. Hyporheic Zone

The hyporheic zone (the transition zone between stream and river beds and ground waters) is an integral component of a river's ecosystem; it plays a major role in river functioning, and must be considered in river restoration schemes and their appraisal [98,99]. The few studies that have monitored hyporheic zone reaction to river restoration indicate that the hyporheos does respond to it [100] and in potentially different ways to the benthos, and thus both should be included in future monitoring protocols [99]. Approaches to monitoring the hyporheos are given in the Hypoerheic Handbook [101]. The limited number of examples of assessing how the hyporheos responds to river restoration means that a monitoring approach cannot yet be recommended, although a BACI approach should be followed.

Hyporheic zone—recommendations:

- Assess the hyporheos using a BACI approach.
- Trial different sampling methods to determine which are most effective in restoration appraisals.

6. Analysis

Biological data can be analysed and summarized using both taxonomic (e.g., species richness) and trait-based (e.g., functional richness) approaches. The consideration of functional traits (inherent biological characteristics) is often ignored in post-project appraisals [102], yet, it could help elucidate the mechanistic understanding of biotic responses to restoration [100,102], Studies and reviews have shown that the effect of restoration on community structure, traits, and functional indicators can be more pronounced than the effect on taxonomic composition or diversity [80,102]. Whereas others have found that functional outcomes are harder to achieve, e.g., [9], take longer, or that neither were achieved [103].

The two most common approaches to the analysis of biological community data collected from restoration programmes are model-based and algorithm-based. A model-based approach results in a statistical model, based on the observed data. With the potential to separate the signal from the noise (error), statistical approaches may be better suited to answering well-defined ecological questions. Model-based approaches (e.g., linear regression methods) provide the framework for prediction (i.e., for a unit increase in x there is a change in y) and can be used to quantify a priori expectations of restoration action (e.g., [104]). An algorithm-based approach uses summary statistics (e.g., pair-wise measures of dissimilarity) generated from the observed data to look for patterns of association [105]. Algorithm-based approaches (e.g., discriminant analysis) provide measurements of association (i.e., a community of type x is associated with a habitat of type y). Algorithm-based approaches can provide a framework for prediction when broad scale (spatial and/or temporal) information is available against which to compare collected data (e.g., RIVPACS; [106]). Historically, these two methods were commonly split into multivariate (algorithm-based) and univariate (model-based) methods, but recent advances in the last decade have seen the application of model-based approaches to multivariate data, e.g., [107]. Modelling observed data directly means important ecological relationships can be directly quantified and predicted [105], the importance of which, at this early stage of understanding the biota's response to restoration intervention, cannot be overstated.

Analysis—recommendations:

- Consult a statistician as early as possible, ideally at the project and appraisal planning stage.
- Identify which modelling approach (model-based or algorithm-based) will provide the appropriate answers to the project.
- Assess results in terms of both taxonomic and functional response.

7. Timescales of Recovery

Post-restoration recovery time is influenced by a number of factors including the type of restoration activity (Figure 3), morphological response [108], sources of colonisers [80,109], spatial scale of restoration [110], and the presence of other pressures [40,41,111]. Understanding and anticipating these influences will help identify the appropriate temporal scale for monitoring [13].

The majority of monitoring and appraisal studies take place over short timescales (<1–3 years), with some involving medium (up to 10 years), and a few much longer commitments (~20 years) [80,112]. The short-term nature of most monitoring rarely reflects the timescale of ecosystem recovery [113,114]. For example, habitat conditions are likely to temporarily deteriorate following restoration, generally associated with loss of plant cover, which may affect invertebrates and fish populations, which could affect results [115]. This focus on short-term evaluation means that some relatively ineffective/unsustainable restoration methods may continue to be used [34]. Long-term monitoring is strongly recommended, ideally for a minimum of 10 years [29]; more rigorous and longer monitoring will increase the likelihood of accurately detecting changes [31,111]. When a pressing operational need to understand the effectiveness of restoration arises, perhaps to inform adaptive management and future restoration measures, shorter-term expectations or indications of restoration success may be incorporated in an appraisal strategy; these will necessitate repeated temporal monitoring and appraisal. In a meta-analysis of salmonid abundance to in-stream restoration structures, 45% of the 211 projects reviewed were monitored only once [116]. For more accurate and reliable results, restoration evaluation should be a continual activity [34], although it is recognised that the costs associated are significant.

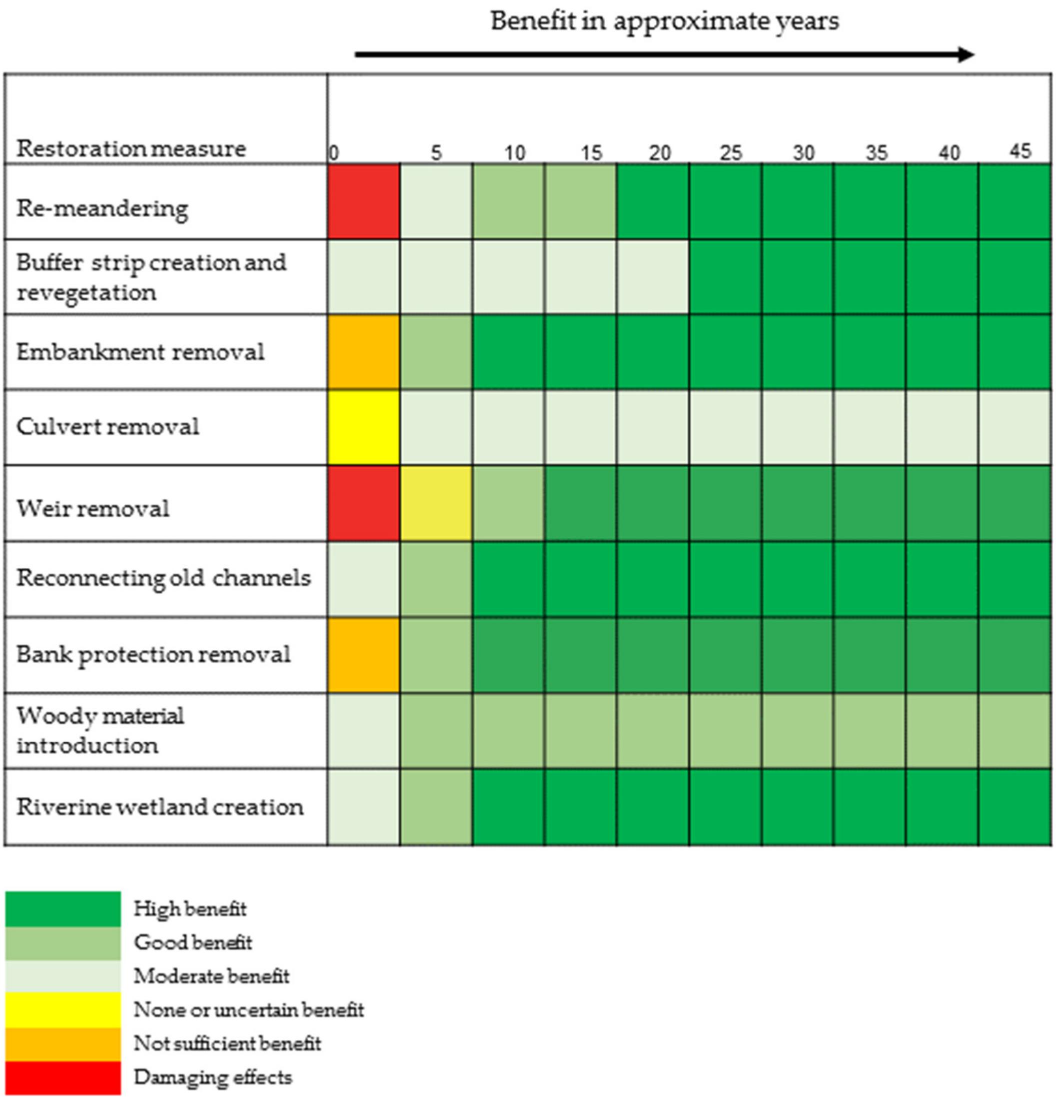

Figure 3. Timescales of biodiversity response, adapted from [112]. * Woody material introduction refers to the one-off addition of large wood to mimic fallen trees or act as flow deflections. The long term uncertainty reflects the decomposition of the wood.

Where long-term monitoring and assessment is undertaken it is important the interim targets are set and appraised. Recording and publicising interim activities and findings are essential to stimulate public interest, inform discussion, and inspire buy-in to related projects. Reporting on key sightings and monitoring activities is vital to maintain stakeholder support and can be as powerful in securing buy-in as the 'final' appraisal results; it can also be a powerful stimulus.

Temporal monitoring—recommendations:

- Always integrate hydroecological and hydromorphological assessments.
- Plan for long-term monitoring to allow meaningful knowledge on rates of river recovery following restoration.
- Plan an appraisal period that is long enough to illustrate the ecological response to restoration. The length of time needed will vary by group or species.
- Collect repeat information at similar times (ideally identical) in the year to avoid adding variability (i.e., error) to the data.
- Consider life history and seasonal trends when monitoring specific species and/or communities.

8. Future Consideration/Development

8.1. Empirical and Theoretical Modelling Frameworks

Modern ecological theory proposes roles for a wide range of "community assembly" processes in shaping biological communities, including processes which are independent or only partially dependent on the local abiotic environment [117]. Among the ecological theories that have risen to prominence in the last decade, the metacommunity framework is of particular relevance to river restoration [118]. Metacommunity theory states that local community structure is not only a function of local conditions at any one point in time but is also influenced by spatial and demographic processes occurring over a range of spatial and temporal scales. Dispersal is the key factor: if dispersal rates are high, species may live in local conditions that are far from optimal for fitness ("mass effects"); if they are low, species may be absent from many habitat patches with suitable conditions for growth and reproduction ("patch dynamics").

Only when dispersal rates are high enough to allow species access to all suitable habitat patches, but low enough so that they are not present in unsuitable patches, can we expect the local community to fully reflect local environmental conditions. This optimal case is known as "species sorting". Ultimately, the "field of dreams" [22] approach to river restoration assumes efficient species sorting; yet, previous work has shown that this assumption is flawed in a range of settings [119,120], and particularly in rivers where the connecting effects of flow (mass effects) and the fragmenting effects of barriers and droughts (patch dynamics) mean that conditions for species sorting rarely occur [121,122]. Thus, expectations in terms of biodiversity responses to river restoration must account for species' population distributions, dispersal capacities, and river network connectivity, in addition to species' environmental niches.

Modelling—recommendations:

- Take account of ecological theory when interpreting monitoring results.
- Gather background information on species' population distributions, environmental niches, traits, and phylogenetic relationships.
- Use statistical and theoretical models to set biodiversity targets for restoration as benchmarks for project appraisal.

Statistical modelling approaches may be used to better understand the influence of community assembly processes, including the niche-based and spatial mechanisms influencing biodiversity responses to river restoration. In particular, species distribution modelling encapsulates a variety of statistical approaches useful for predicting biodiversity under a given set of environmental conditions. These include well-established single-species models such as Maxent, linear models, and additive models, as well as joint species distribution models, which may be fitted to multiple species simultaneously, such as Hierarchical Modelling of Species Communities (HMSC; [123]). HMSC has been shown to produce strong predictive performance by integrating background information on species' traits, evolutionary relationships, biotic interactions, and spatial and temporal processes [124]. Models such as HMSC can be used to predict the biodiversity changes that result from restoration interventions, and so allow for quantitative target-setting [125].

8.2. DNA-Based Approaches

Emerging DNA-based approaches have the potential to contribute towards evaluating river restoration success in several ways. DNA metabarcoding has repeatedly been shown to detect a greater number of species than traditional monitoring approaches such as kick-sampling and electrofishing [126]. Field, laboratory, and bioinformatic protocols to optimise the process are becoming better established for a range of taxa, from diatoms to fish and mammals. Whilst many applications are focusing on bulk DNA sampling (i.e., biological material), analysis of eDNA (e.g., from water samples) can provide a nonintrusive broad-spectrum picture of the species present at the sample location or at nearby locations upstream.

Whilst DNA metabarcoding is already revolutionising biological monitoring, it is just one of several molecular techniques with the potential to provide valuable data to inform river restoration. For example, genomic (DNA) and transcriptomic (RNA) analysis of fungal and bacterial communities can be used to quantify functional potential and actual functioning at a site respectively. Certain genes and transcripts have known ecological functions (e.g., cellulose degradation) and have been shown to respond with high specificity to particular stressors [127]. For example, the bacterial organophosphate hydrolase gene (opd) indicates pesticide degradation, whilst the ammonia monoxygenase gene (amoA) is activated during periods of intense organic matter breakdown [126]. New applications of these approaches from microbial ecology could be used to identify the main stressors on potential restoration sites and to monitor the status of those stressors at restored sites. These approaches could also shed light on the effects of restoration on population viability, food webs, and ecosystem functioning.

DNA approaches—recommendations:

- Embrace DNA metabarcoding to complement traditional monitoring approaches
- Explore and trial different DNA- and RNA- based applications sampling methods to determine which are most effective in restoration appraisals, especially for assessing food webs and ecosystem functioning

8.3. Ecosystem Services

Ehrlich and Ehrlich coined the term ecosystem services [128] and subsequent publications raised their profile [129,130]. Global recognition of the ecosystem services concept led to the Millennium Ecosystem Assessment [131]. River restoration to promote healthy rivers is now associated with ecosystem services because of the benefits for society [132–134]. In particular, the potential value of river restoration to flood risk reduction has emerged via 'natural flood management' [135,136]. Restored healthy river systems, however, bring a variety of other ecosystem services such as improved water quality and recreational opportunities. These include both tangible and intangible benefits across provisioning, cultural, regulating, and supporting ecosystem services [137]. As such, the linking of natural and socioeconomic systems in fluvial environments [138] through the process of restoration and ecosystem services should be integral to 21st century river management.

Despite the progress made, there are challenges in river restoration–ecosystem service appraisal. Firstly, the scientific evidence of the restoration-derived benefits for some ecosystem services is limited [139]; research and monitoring are needed to enhance our understanding. Secondly, the appropriateness of the ecosystem services appraisal and valuation methods selected can be disputed [140]. Scale is important when using river-focused methods due to frequent spatial mismatches between restoration locations and societal benefit. This emphasises the need for catchment based or river source-to-mouth appraisals (e.g., [141–143]). Valuation can have different connotations, notably economic valuation versus cultural importance [144]. Traditional approaches to economic valuation struggle to cope with the intangible benefits of many cultural ecosystem services and so need to be supported by appraisals including social and ecological perspectives. The restoration of river flows [145–147], for example, can return the social fabric of indigenous communities to their traditional river-focused ways of life [148]. Some people argue that such benefits are 'priceless' and assigning monetary values is unethical. This implies that there is a need to value services relative to each other in a common framework acceptable to all river restoration stakeholders. Moreover, some believe that we should have moral obligations to species beyond any economic value. The World Conservation Strategy (IUCN, 1980) promotes species diversity to maintain biological stability and to keep options open for the future. Within the realm of river restoration this implies that the promotion of anthropocentric ecosystem service delivery and biodiversity conservation needs to be complementary [149]. By creating habitat heterogeneity and net biodiversity gain, biodiversity focused restoration is likely to enhance the range and level of ecosystem services in rivers [70,142,150,151]. However, societal choices and values are integral to river management and the success of restoration measures (Figure 4).

Ecosystem services—recommendations:

- Appraise the ecosystem service benefits of river restoration at reach and wider river network scales.
- Use methods that allow comparison of provisioning, supporting, regulating, and cultural services.
- Link ecosystem services to geomorphological river types when mapping river network wide ecosystem services.

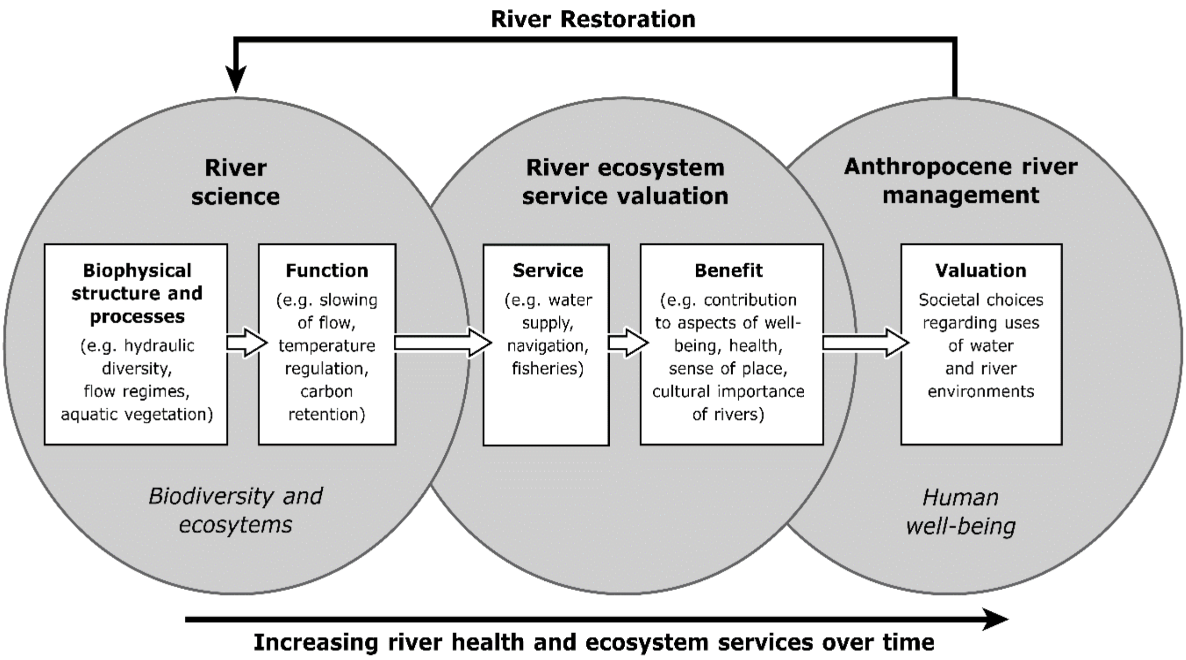

Figure 4. The links between societal choices and values in river management and restoration.

8.4. Community Engagement and Citizen Science

Engaging with and including communities in the decision-making process of river restoration planning can often aid the success of projects [12]. Such engagement can change the views of those involved in the project [152]. Involving communities through citizen science can provide valuable information, connect people with river environments [153], and help them to understand the natural processes and associated benefits [5,71]. The Modular River Survey [154] is a citizen science survey specifically designed for monitoring the physical characteristics and outcomes of physical interventions at scales that complement biological surveys, e.g., RiverFly. Such surveys can improve understanding of river environments, facilitate engagement [71], and, when applied using a robust scientific approach (such as BACI), can contribute to evidence for restoration impact [5]. Studies are underway to explore how well the river habitats characterised by the Modular River Survey relate to river biota assessments and how such approaches can be used in river restoration appraisal (e.g., [155]). Communicating early records from a restoration site can be especially important in early years when the site is recovering from construction and environmental benefits are not immediately obvious, and the involvement of communities in gathering these records is a powerful way to achieve support for future projects.

Citizen science—recommendations:

- Incorporate citizen science surveys using a robust study design (e.g., BACI) to provide additional evidence.
- Incorporate less formally structured citizen science to inspire public involvement and enhance the understanding of river processes.
- Ensure timely and ongoing community engagement with the project.

9. Key Messages/Conclusions

Including monitoring and appraisal in a restoration scheme will demonstrate project effectiveness, allow an adaptive management approach, identify needs for further restoration work, and contribute to the wider evidence base. Appraisals should aim to assess the relationships between physical changes and ecological responses; this will necessitate sequential monitoring from physical change to biological response, and will enable the telling of a clear story about the evidence basis of river restoration.

Such approaches will not be possible everywhere but should instead be directed to where they will provide the greatest evidence [53], such as 'flagship' or demonstration restoration sites for detailed long-term (>5 years) monitoring [5]. A flagship approach would provide the robust evidence needed to understand what restoration works where, and the knowledge gained could be incorporated in conservation practice [156]. Understanding which restoration measures work in which catchment contexts will enable them to be applied more widely with greater confidence and reduce the need for further appraisal.

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