Opinion

Citizen science: from detecting pollution to evaluating ecological restoration

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The proliferation of citizen science water quality monitoring networks suggests there is potential for developing an equivalent river Restoration Assessment Initiative (RAI). This is currently lacking, especially at larger (e.g., national and international) scales. As such, the RAI would provide a much-needed new tool for stakeholders to evaluate and compare the efficacy of their restoration efforts. We propose a standardized protocol to quantify biotic responses (e.g., changes to the macroinvertebrate community) to restoration efforts, which would facilitate a large-scale, open-access database revealing success or failure of commonly used restoration techniques. By combining biotic and abiotic (e.g., habitat and water quality) assessments, a feature typically lacking from restoration monitoring schemes and cited as a major constraint limiting development of the field, integrative approaches (e.g., meta-analyses and coordinated field experiments) could help untangle their respective effects on restoration outcomes. Water quality initiatives (e.g., the Riverfly Monitoring Initiative) have paved the way for volunteer-driven pollution monitoring, and provide models designed for sustaining long-lasting volunteer participation in stream monitoring. These could be developed for the RAI to better detect restoration signals (e.g., adopt a before-after-control-impact (BACI) approach) while continuing to address the key practical challenges associated with implementing citizen science initiatives (e.g., volunteer skills and data quality assurance). Once established, the resultant infrastructure would facilitate expansion to an international scale, increasing the statistical power of the combined database enormously and allowing the addition of novel measures (e.g., ecosystem process rates) for assessing restoration. Clearly citizen scientists need a role in restoration assessment, especially as they are becoming increasingly important drivers of practices on the ground. Developing a coordinated citizen science RAI to ensure data are standardized and disseminated effectively will advance restoration on a more global scale, and also provides a timely solution to keep society and science connected.

How to cite this article:
WIREs Water 2016, 3:287–300. doi: 10.1002/wat2.1138

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Conflict of interest: The authors have declared no conflicts of interest for this article.

INTRODUCTION

Citizen science, in which volunteers participate in scientific investigations, is increasingly contributing to environmental research, as illustrated by the burgeoning growth in the peer-reviewed literature (Figure 1).[1–3] Volunteer water quality monitoring has been an integral part of the informal citizen science landscape for decades, attracting diverse river

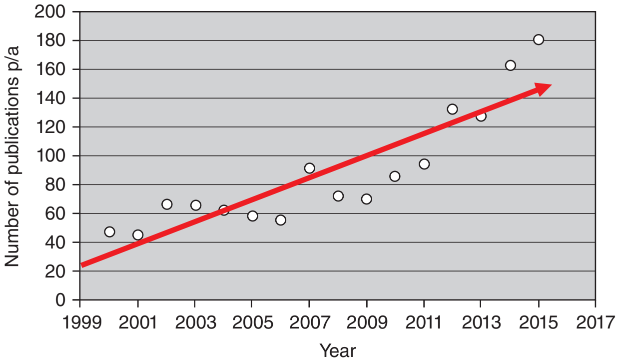

FIGURE 1 | The per annum number of peer reviewed papers concerning citizen science from 2000 to 2015. 'Citizen science' was searched within the 'Environmental Sciences, Ecology' subsection in Web of Knowledge (http://apps.webofknowledge.com/). Date of search 22/12/15.

stakeholders, such as angling associations, landowners and grassroots community groups, wanting to detect and prevent pollution.[4] Formalized national programs, such as the Riverfly Monitoring Initiative (RMI) (http://www.riverflies.org/rp-riverfly-monitoring-initiative) in the UK (see Box 1), and international programs, such as Freshwater Watch (https://freshwaterwatch.thewaterhub.org/), have established networks of coordinated volunteer teams monitoring water quality at unprecedented temporal and spatial scales.[3,5,6] The participating volunteers, stakeholders and organizations share a common goal to improve water quality, angling, amenity value, and biodiversity (e.g., species richness and abundance).[5] They often finance and support river habitat restoration in an attempt to achieve these goals. However, coordinated citizen science programs to assess the success of river restorations are lacking.

Restoring ecological integrity in degraded streams and rivers is urgent for both halting and reversing global declines in aquatic species[7] and providing ecosystem functions and services[7–9]; but has proved unexpectedly challenging.[10] The guiding paradigm is that degraded habitat diversity (e.g., following decades of channelization and over-widening) represents a constraint that limits ecosystem recovery.[11] Increasing habitat heterogeneity will thus help to restore biodiversity and ecological integrity, the so-called Field of Dreams hypothesis: 'If you build it, they will come.'[12] However, this theory has little supporting evidence; standardized monitoring and assessment remains the exception rather than the rule, and local habitat improvement is often eclipsed by large-scale drivers (e.g., water quality and catchment land-use).[12–14] As many as 90% of restorations in the US, Australia, and Europe are not monitored beyond visual examination.[15–18] This has been attributed to a lack of resources, i.e., time and money,[19] but could be successfully mitigated by engaging citizen scientists.[20]

A citizen science RAI employing a (standardized) monitoring protocol, using quantitative methods to measure relevant criteria (e.g., benthic macroinvertebrate community structure and diversity), would address this gap. If rolled out internationally, this would provide an invaluable new global perspective at comparatively little cost. Provision of a central database would facilitate large-scale analyses and meta-analyses to reveal the environmental and methodological drivers affecting restoration outcome; for instance, integrated studies have already associated catchment land-use (e.g., agricultural and forested) with river restoration outcomes.[17,21] The

BOX 1

THE RIVERFLY MONITORING INITIATIVE

The RMI, launched in 2004 by the Riverfly Partnership (http://www.riverflies.org/), is a national network of volunteers who are trained to carry out simple standardized biomonitoring to detect severe perturbations in water quality. This complements the routine statutory monitoring of UK environment agencies. RMI sampling is more frequent (monthly) and at a finer spatial scale but a coarser taxonomic resolution than the routine annual or biannual statutory monitoring. RMI monitoring therefore may detect pollution events that might otherwise be missed by agency sampling. In the event of a pollution incident, volunteers notify their local EA Ecological Officer who responds by carrying out a more detailed investigation of the site. The RMI has resulted in the successful prosecution of polluters and the presence of volunteers on the river acts as a deterrent to would-be polluters. RMI groups, under a local coordinator, are centered on a particular river and are often part of a regional hub covering an entire river catchment. The hubs are often hosted and coordinated by a rivers trust or wildlife trust. The RMI has a 'national coordinator' hosted by Salmon and Trout Conservation UK, and the post is funded by the Environment Agency of England. There are currently over 2000 active volunteers, monitoring over 900 sites, organized within 25 regional hubs.

resultant findings would feed into restoration design to enhance future interventions (Figure 2) and thus initiate a shift from the currently failing 'one-size-fits-all' approach to restoration, to more 'adaptive restoration,' in which documented failures and successes are used to inform future efforts and directions for research.[10] This latter approach has guided the restoration and management of coral reefs, marine reserves, and terrestrial biotopes, but has not yet been applied to rivers.[21] The interrelated potential scientific and societal benefits of engaging the public in such an initiative (4. Objectives: Figure 2) are similar to those identified in other citizen science monitoring projects, e.g., bird monitoring initiatives.[20]

In this opinion article, we outline how a coordinated citizen science restoration monitoring initiative would be an effective means for assessing river restoration projects at a local scale, while producing robust data that would advance river restoration science, river management and conservation globally (Figure 2). To be effective, river restoration monitoring will require a before-after-control-impact (BACI) design, quantitative sampling methods and assessment of process rates to measure success. Using the RMI (Box 1) as a template, we propose the use of training workshops to develop volunteer skills, feedback to sustain volunteer interest, data management and quality control measures, and review the likely set-up and running costs and how to meet these under a new river Restoration Assessment Initiative (RAI) that can be interwoven with the RMI or similar already-established schemes elsewhere.[20,22,23] Lastly, we discuss the broader societal and scientific benefits of the proposed RAI, including encouraging local stewardship of rivers, elevating public scientific understanding of river ecology, and ultimately meeting ecological goals and engagement targets laid out in national and international biodiversity plans (e.g., Table 1).

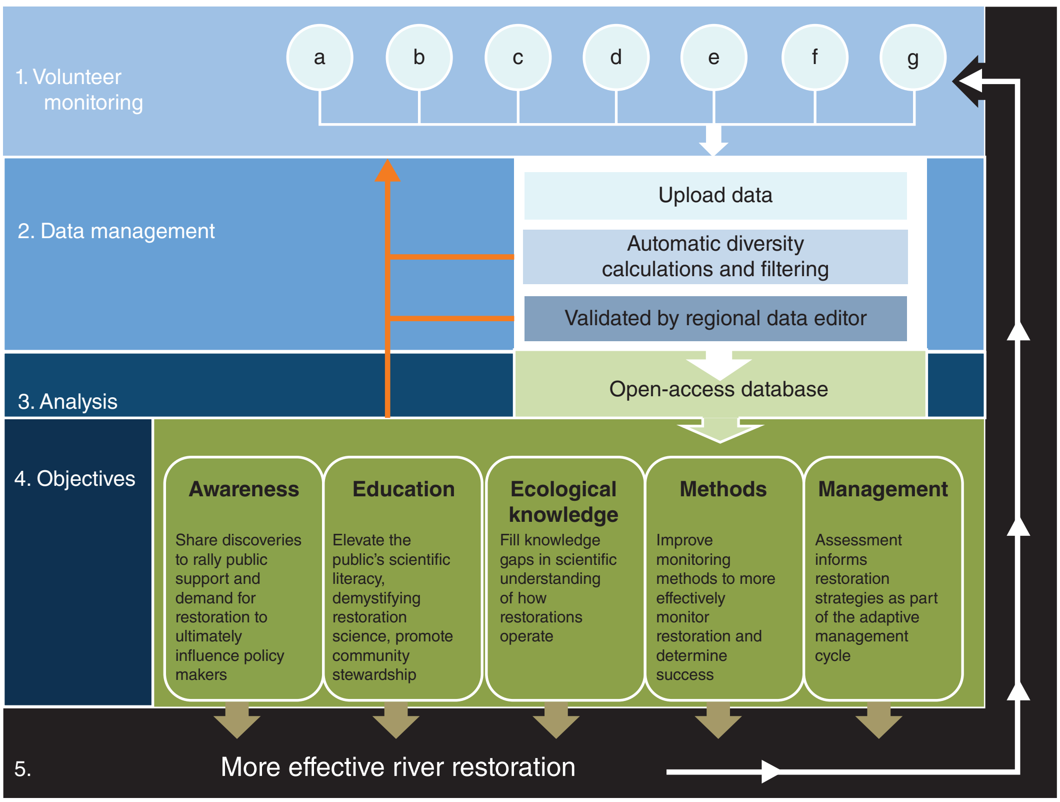

FIGURE 2 | Data flow toward more effective restoration for the proposed RAI. Starting at the top of the figure, 1. Volunteer Monitoring: teams are represented as circles (a–g) and monitor their local restoration projects; 2. Data Management: data are uploaded by the volunteers online, where they are automatically calculated into diversity metrics and passes through quality control filters, where flagged data are reported back to volunteers (red arrow), before being validated by the regional coordinator who loads them on to the main database, or if there are irregularities, contacts the volunteers (red arrow); 3. Analysis: data are freely available to researchers and actively analyzed by the initiative coordinators; 4. Objectives: Analyses will inform the five main and often-interlinked objectives of the initiative; 5. This would then feed back into future restoration projects, resulting in more effective river restoration.

THE REQUIREMENTS OF MONITORING POLLUTION AND RESTORATION

Benthic macroinvertebrates are useful for both pollution and restoration monitoring as they are sensitive to environmental change, are usually easy to collect and identify to a coarse taxonomic level (i.e., family or above), and are ubiquitous.[24] Biotic assessment has underpinned pollution monitoring for decades, as it provides an integrated, comprehensive assessment of water quality over time, rather than the 'snapshot' that is provided by physicochemical water sampling.[24] Organic or pesticide pollution events characteristically manifest as a decline in sensitive macroinvertebrate taxa. Routine statutory and citizen science monitoring usually requires semi-quantitative sampling methods, often keeping taxonomic resolution to the coarsest level necessary to detect perturbation (e.g., Table 2(e)). While this reduces errors, minimizes time and costs, and simplifies training, thus making pollution monitoring readily accessible to a wide-range of users with varying levels of skill (e.g., citizen scientists), the reduced sensitivity of these protocols and methods make them less likely to detect restoration success.

River restoration measures are often assumed to increase macroinvertebrate diversity and abundance, though these are rarely tested or validated.[11,17,21] Quantitative sampling methods and macroinvertebrate identification to higher taxonomic resolution are required to assess community change more comprehensively following restoration, especially because changes to diversity may only be manifested within lower taxonomic levels (e.g., genus or species) and within groups not currently included in pollution monitoring protocols.[24] Including a wider range of organisms and increasing taxonomic resolution for RAI monitoring are therefore necessary to increase the likelihood of detecting community change (Table 2(e)). The lack of documented increases in species richness (e.g., only 2 of 78 channel restoration projects were shown to significantly improve macroinvertebrate species richness) suggests the presence of hierarchical filters.[10,11,21] These may include a lack of source (re)colonists or other stressors and landscape factors that outweigh the effects of enhancing local habitat complexity on more sensitive species.[14,25–27] Thus, improved habitat and/or ecosystem functioning may manifest as increased abundance per unit area of species that are already present, yet schemes based on relative abundance or presence/absence cannot detect this. Easily replicated measures of abundance or biomass are therefore vital in river restoration assessment (and thus, the proposed RAI) as they provide a direct link to ecosystem functioning, as many processes drive, or are driven by, abundance (or biomass) per unit area, rather than species richness.[28,29] These are best estimated using quantitative sampling methods (i.e., using Hess or Surber samplers), either instead of, or alongside, the more widely used semi-quantitative techniques, which often correspond well with existing statutory monitoring methods, such as kick-samples used in the Water Framework Directive (Table 2(d)).

A focused and replicated monitoring design, combined with experimental approaches, is essential for identifying the causal links between restoration actions and ecological responses. Like pollution monitoring, detecting a response requires knowledge of before (baseline) and after conditions. However, additional untreated (i.e., control) monitoring sites (Table 2(b)) help to distinguish ecological responses to restoration from those due to other confounding variables in space and time, such as seasonal or longitudinal shifts. This constitutes the statistically robust BACI design used by ecologists to detect and measure drivers of ecological change.[11] Indeed, a BACI design is the only way to demonstrate unequivocally whether or not restoration has worked while ruling out the potentially confounding effects of natural background changes over space or time. Before-and-after studies are compromised by potential underlying temporal changes that are conflated with the restoration itself (e.g., differences among seasons, years etc.), whereas control-impact studies that rely on the assumption of space-for-time substitution are similarly compromised by potential underlying spatial confounds (e.g., natural upstream vs. downstream changes in biotic and abiotic variables): BACI designs avoid the inherent weaknesses of both these other commonly used approaches.[11]

As an example of an effective BACI design in practice, the detection of a pollution event on the River Kennet in the UK, by Action for the River Kennet (ARK), a citizen scientist organization that campaigns for the protection and conservation of the River Thames' largest tributary (http://www.riverkennet.org/) (Figure 3).[6] Here the recovery of invertebrate communities was tracked after a pollution event over both space and time: the presence of upstream RMI monitoring sites and data collected before and after the event providing spatial and temporal controls (see Ref 30 for further details). The trajectory of recovery toward pre-perturbation conditions offers a means of quantifying a system's resilience, and highlights the importance of monitoring

TABLE 1 | Examples of National and International Biodiversity Strategies and Targets, including Their Relevance to River Restoration and Public Engagement Components The bold entries are target titles of biodiversity strategies.

Name	Area	River Restoration Relevance	Public Participation	Citation
Water Framework Directive (WFD)	EU	Headline target is for all rivers of member states to reach 'ecologically good status'	Public participation has always been recognized as a key component for ensuring the WFD's success. (14, EC, 2000).	Official Journal 2000 L 327/1 European Commission, Brussels (2000)
Convention on Biological Diversity	190 Countries Globally	**Target 14** Restore and safeguard ecosystems that provide essential services. **Target 15** Enhance ecosystem resilience through conservation and restoration of at least 15% of degraded ecosystems	**Target 1** Raise public awareness of the values of biodiversity and the steps they can take to conserve and use it sustainably.	https://www.cbd.int/sp/targets/
EU Biodiversity Strategy to 2020	EU	**Target 2** Maintain and restore ecosystems and their services	Encourage the active involvement of civil society at all levels of implementation. Recognizes the value of citizen science initiatives for gathering high-quality data while mobilizing citizens to get involved in biodiversity conservation activities	http://ec.europa.eu/environment/nature/info/pubs/docs/brochures/2020%20Biod%20brochure%20final%20lowres.pdf
UK Biodiversity Strategy to 2020	England	See EU above	Engage more people in biodiversity; work with civil society organizations to engage more people and empower them to make a difference. Invest in data sharing, and biodiversity recording in the voluntary sector and develop new and innovative approaches to biodiversity recording.	https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69446/pb13583-biodiversity-strategy-2020-111111.pdf
Australia Biodiversity Conservation Strategy 2010–2030	Australia	1000 km^2 of fragmented landscapes and aquatic systems are being restored to improve ecological connectivity.	**Action 1 Engaging all Australians**: By 2015, achieve a 25% increase in the number of Australians and public and private organizations that participate in biodiversity conservation activities.	http://www.environment.gov.au/biodiversity/publications/australias-biodiversity-conservation-strategy-summary

TABLE 2 | Differences in the Requirements of Sampling and Data Collection for Pollution Monitoring Initiatives (e.g., RMI) and the Proposed Restoration Assessment Initiative. The bold entries highlight the main differences between restoration monitoring and pollution monitoring.

	Riverfly Monitoring Initiative	Restoration Assessment Initiative
a) Equipment	• Invertebrate sampling kit: a D-net, white trays, magnifying glasses, identification chart	• Invertebrate identification kit, but also **quantitative** samplers, e.g., Hess or Surber, and higher resolution identification charts • Ruler and measuring tape for planform and habitat monitoring
b) Time and Spatial Scale	• Typically rivers are monitored at the same location for a year to acquire baseline data, followed by continuous sampling. Chosen sites are usually those most at risk of pollution, i.e., below potential pollution entry points (e.g., sewage treatment works)	• 'Before' (i.e., pre-restoration) spring sampling at both **control**, **impact** and (where available) **reference** sites for baseline data and continuous spring sampling 'After' (i.e., post restoration). • The spatial scale of monitoring should be scaled to the spatial scale of restoration
c) Frequency	• **Monthly**, in order to increase the likelihood of detecting and sourcing a pollution or other perturbation event	• **Annually**, at the same time of year, usually in spring when invertebrates have attained sizes ideal for identification and before summer hatches, or biannual (autumn optional)
d) Method	• **3-minute semi-quantitative** cross sectional **kick-samples** using standard D-nets, followed by a 1 minute hand search	• **Quantitative sampling** using Surber or Hess samplers, minimum **3x replicates** for midstream and marginal habitats at all sites • **Process measures** such as decomposition, production, detrital retention • **In-stream habitat assessment** survey habitats and measure water chemistry
e) Identification	• Abundance of **8 invertebrate taxa**: cased caddis, caseless caddis, Ephemeridae, Baetidae, Heptageniidae, Ephemerellidae, Plecoptera, *Gammarus*.	• Should aim to expand taxonomic scope to incorporate **all easily identifiable macroinvertebrate taxa**, this could include Odonata, Mollusca, and Diptera etc. • Increase the taxonomic resolution where reasonably possible, e.g., identifying molluscs into gastropods and bivalves • Species counted to acquire density estimates
f) Data collection	• Raw data uploaded to the central online database by teams	
g) Data analysis	• Automated scoring system based on abundance and occurrence of taxa, autoelectronic notification if trigger breached	• Automated **species richness** and **density estimates** calculated for macroinvertebrate data at each site within project for comparison • Project data integrated into **database** and analyzed as part of a wider study aiming to establish links between methodological and environmental factors and project outcome
h) Feedback	• Team data displayed as timeline graphs on free to access website allowing teams to visualize and chart their rivers progress	• Similar to that of RMI: project specific feedback displayed so that teams can visualize the trajectory of their restoration • Wider findings from analysis of the database also shared via email newsletters on website

for several years after restoration, which has been ignored in almost all restoration studies to date.[6] For restoration monitoring, the inclusion of a 'reference' site provides a realistic and ultimately achievable target state (Table 2(b)); this state, and the time taken for impact sites to reach it (or at least their rate of approach toward it), can also provide an indicator for restoration potential within the catchment and therefore support further investment in restoration within the locale.[11,24]

Recording environmental and methodological factors for each RAI project is also crucial; if high-level environmental filters, such as climate, catchment land-use, or diffuse pollutants are not suitable then the restoration is likely to fail.[25,26] Therefore abiotic drivers of macroinvertebrate communities need to be assessed; data on hierarchical environmental filters such as ammonia, nitrate, and pH that inhibit recovery may already be being recorded by water managers, or can otherwise be measured using simple test kits similar to those used in the aquarium trade. Recording these will assist efforts to link restoration responses to abiotic factors to identify the boundaries of the environmental 'Goldilocks zone,' i.e., the optimum range in environmental conditions in which biotic responses can be expressed to their fullest extent, and thus this delimits the bounding envelope under which restoration practices are most likely to succeed. For instance, there is little to be gained by investing in restoration when the biotic responses are constrained by nutrient limitation at one extreme or toxic effects of pollutants at the other: the highest return per unit effort is in the mid-range, where responses can be manifested to their full extent, as can be seen from a continental study of the effects of nutrient pollution on decomposition rates in 100 streams across Europe.[31] This will further improve our ability to make predictions about a catchment's restoration potential. More in-depth analysis as the database expands would advance understanding of how these filters operate; at present we have huge gaps in our knowledge about the causes of restoration success or failure.[14,21]

In addition to these issues related to physical implementation of restoration schemes, current restoration efforts are additionally confounded in a statistical sense by the bias toward Type I errors, as significant positive results are far more likely to be reported than negative or neutral outcomes, especially as there is an underlying 'expectation bias' and many schemes are judged to be successful simply on the basis of having been implemented.[18] For the RAI to achieve a realistic measure of river restoration effectiveness the replicated, coordinated, standardized monitoring and reporting of both successes and failures are essential.[10,32] This would prevent the expensive repetition of unsuccessful restoration strategies, allowing stakeholders and organizations to optimize the use of (often limited) resources for maximum ecological benefit.

ALTERNATIVE AND NOVEL METRICS

The initial goal of habitat restoration is returning hydromorphological heterogeneity to the river channel to create diverse habitats, under the assumption that this will improve the river's ability to support desired biological assemblages.[12,21] This makes habitat monitoring an essential component of river restoration assessment (Table 2(d)) and a readymade protocol that can be easily adapted for the RIA is the River Habitat Survey (RHS) currently used in routine (e.g., by the English Environment Agency) monitoring to assess the character and habitat quality of rivers.[33] The high variability of the spatial distribution of biota within rivers means this approach for monitoring changes works best when surveyed at fixed points, and where possible supported by photographic records for pre- and post-project appraisal of habitat restoration. Elements of the RHS should be adopted for the RAI; surveying features of the channel (both in-stream and bank) and riparian zone, including channel substrate, habitat features, aquatic vegetation types and the complexity of bank vegetation structure and their extent.[33] This would compare well with statutory data both past and present, facilitating integration into wider studies. It would also provide valuable information on the sustainability of restoration practices, i.e., the expected lifetime, and further assist efforts to characterize ecological responses expected from habitat restoration measures by linking restored biotopes with changes to species assemblages.

The recovery of fish populations is often another major driving force behind restoration efforts, and often supersedes that of restoring overall biodiversity.[34,35] However, these taxa are often too challenging, hazardous and expensive for citizen scientists to monitor. Still, restoration practitioners are likely to have contacts with experienced personnel (i.e., with access to electrofishing gear) who could either voluntarily or contractually carry out fish surveys to complement the invertebrate monitoring, even if at a lower frequency than for invertebrate sampling. At the base of the food web, monitoring macrophytes, filamentous algae and diatoms would also be informative, as they may respond faster and more strongly to restoration than other groups at higher trophic levels, and are comparatively easy to identify using field guides.[17,36] These data, when combined, can provide far greater insights into the influence that restoration has on interactions and energy fluxes that underpin community structure at the whole-system level.[37]

In light of the currently equivocal community responses to river restoration, more emphasis is now being placed on process-based measures of ecosystem functioning.[15,37,38] A multitude of biotic, physical, and chemical processes, interacting over many spatial and temporal scales, control the river ecosystem.[37,39] Nutrient cycling and detrital processing are especially sensitive to the effects of restoration, and often determine community assembly.[39] Changes in these processes can thus be measured indirectly by monitoring functional groups and feeding guilds. For example, an additional increase in the abundance of detritivores to a community (with no detected change to other feeding groups) could suggest enhanced detrital retention associated with large woody debris (LWD) additions.[39,40] However, measuring these processes directly would provide a clearer understanding of how river restoration links to ecosystem functioning. There is a growing range of functional indicators that could be useful (and relatively inexpensive) for RAI purposes, including measuring algal growth on colonization tiles to quantify primary production, or percentage weight loss from leaf-litter to get decomposition rates, [see The Leaf Pack Network (www.stroudcenter.org/lpn)].[37,39,41] Quantifying macroinvertebrate abundances within leaf litterbags will additionally provide an estimate of consumption rates and energy transfer into the 'brown' detrital pathways at the base of the food web, and which may stabilize the food web's dynamics. For a more standardized decomposition substrate, cotton strips could be used, in which the loss of tensile strength is used to measure decomposition; this is currently being trialed on a global scale in the ongoing CELLDEX project.[42]

PRACTICAL CHALLENGES OF MEETING THESE REQUIREMENTS

Attracting Volunteers and Organizations

In addition to improving statistical design and the reliability and power of the metrics described above, a key step is to increase the currently limited sample size, as too many river restorations are still *ad hoc* and unreplicated. By effectively coordinating citizen scientists via the RAI the field could be transformed into a far more powerful, large-scale meta-experiment.[3,43] Implementing the proposed RAI (Table 1) on a national or international scale presents multiple challenges, not least attracting participation at volunteer and organizational levels. Fortunately, rivers and streams are features of cultural and ecological significance and offer a focal point for appreciating nature and participating in outdoor activities. The large number of volunteer water quality monitoring and stakeholder organizations operating at various scales demonstrates this. For example, there are over 4000 water-related nonprofit organizations in North America alone, the majority of which are grassroots community groups that focus on the stewardship of local rivers (See http://yosemite.epa.gov/water/volmon.nsf/Home and http://www.rivernetwork.org/our-history).[44] To succeed, the RAI must seek the sustained support and engagement of citizen science and community groups, as they provide a potentially large pool from which to recruit volunteers, and a regional focal point from which to coordinate workshops and other activities. The initiative would appeal to volunteers and stakeholders who are keen to improve their skills and ecological knowledge, and participate in activities that align with their interests to improve river ecology. For example, a 2012 survey revealed that of >29,000 UK anglers, 23.3% currently volunteered and 26% wanted to volunteer for environmental work; these are likely to participate in rehabilitation or habitat creation schemes that increase resources for desirable fish species.[35,45] A river restoration monitoring initiative would provide them with a clear means to assess their personal efforts and achievement.

Volunteer Skills

There are inevitable trade-offs in citizen science initiatives between data quality and quantity, variation in skill and ability between volunteers, standardization of sampling methods, and quantification and replication.[23] For instance, macroinvertebrate data quality can be affected by sampling method and expertise of the person sampling.[46] However, expert training can improve citizen science data quality markedly.[22,47,48] In common with other stream monitoring initiatives (e.g., Missouri Stream Team (http://www.mostreamteam.org/) Virginia Save our Streams (www.vasos.org), and the RMI), the RAI volunteers' skills can be raised through workshops taught by accredited tutors. The workshops would provide training in the monitoring technique and identification. Customized supporting literature providing details on the RAI's monitoring protocols and taxonomic guides is also crucial. Workshop costs are likely to be in the order of $1550 USD, which covers tutor fees and travel expenses, as well as the supporting guides, information and sampling kit. Funds to meet these costs can often be raised locally from water authorities, government agencies, or community funding bodies, such as lottery heritage awards in the UK. The RAI accredited tutors can visit proposed restoration sites with the volunteers to demonstrate quantitative sampling, give advice on restoration design, assist in selecting appropriate control sites and instruct on potential health and safety hazards associated with river sampling. Easily accessible post-workshop support is critical for maintaining data quality and motivating volunteers, and could be provided by regional coordinators.[22]

Data Collection, Management, Quality Control and Feedback

The challenge of efficiently collating data from projects across the world has been considerably reduced by the growth of internet use and communication technology. Websites are now associated with most citizen science projects to disseminate and publicize project information, collect raw data (typically uploaded by volunteers to a central online database), and share results—and this can now be done almost instantaneously in some cases.[22,49] To create a global database of river restoration results the RAI's website would need multiple language options. Developing recording websites is also becoming less challenging; the open source project Indicia specifically aims to simplify developing biological recording websites, which can be customized to meet the specifications of the RAI (http://www.indicia.org.uk/).

Data quality is always a key concern for a monitoring initiative hoping to inform not only local restoration strategies, but also research and policy, which require appropriate auditing and verification measures.[20,50] 'Regional RAI coordinators' with editing access could help data screening, an approach already used by the RMI, and eBird, which has over 400 volunteer regional data editors who validate flagged submissions.[51] These could be assisted by automated features such as 'smart filters' that flag records that fall outside the known temporal or spatial distribution, or abundance measures that are excessively high or low, for a species are also useful.[52] Automated richness and density calculations from raw data would assist data management and provide feedback to teams. Feedback, such as online time-series graphs that allow participants to visualize their results (e.g., Figure 3), is crucial for volunteer motivation and sustaining long-term participation.[3,22] Openness and transparency are essential components of citizen science, and as a minimum requirement for joining the global RAI database metadata should be made available to all participants on access, with further data either made freely available on site, or accessible on request.[53]

Dissemination of Results and Feedback

The results from studies that use the RAI database should be widely publicized to expedite new restoration activities and findings into practice. As well as publication on its main website and in newsletters to participants, engaging platforms that seek to provide a focal point for the exchange and dissemination of knowledge and best practice between restoration practitioners, planners, policymakers and engineers, is ideal for disseminating results, these include the UK and Australian River Restoration Centre (http://www.therrc.co.uk and http://www.arrc.com.au), and the European Centre for River Restoration (http://www.ecrr.org/). Not only do these have newsletters and live news streams, but they also arrange conferences and events in which results can be showcased. More mainstream social media hubs such as Twitter and Facebook can also be utilized, providing a free and instantaneous outreach to global audiences. Lastly, links with academic and research organizations would provide access to publication in peer-reviewed journals, these not only legitimize the research but also have global readership.[51,52]

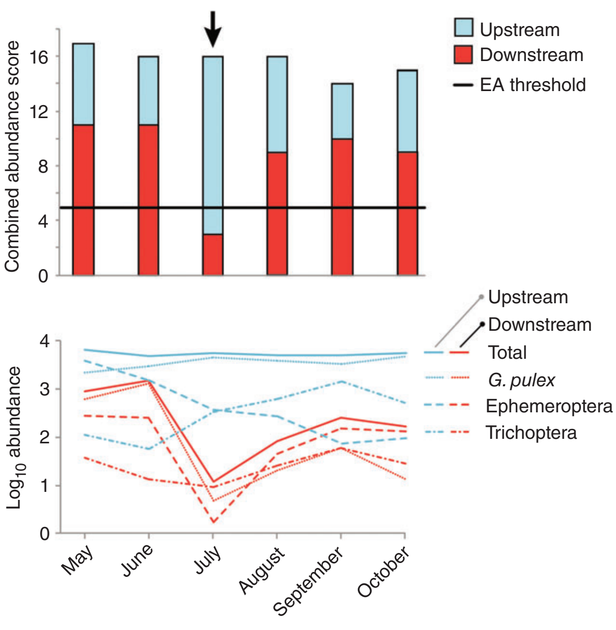

FIGURE 3 | Chlorpyrifos spill detected by citizen scientists on the *R. Kennet* near Marlborough UK. Top: Routine RMI volunteer data collected by ARK show the detection of a chlorpyrifos pollution event on the *R. Kennet*. Invertebrate scores before (up to the black arrow) and after the spill at unaffected upstream (blue) and affected downstream (red) sites, based on the sum abundance of target taxa. The black line represents an Environment Agency pre-set 'trigger level' for substantial ecological perturbation that when breached stimulates a site visit and investigation. Bottom: abundance of key taxa in relation to scores from an upstream control and downstream impact site respectively illustrating the drop in taxa on July.[30]

Initiative Coordination and Long-Term Sustainability

Central coordination of the RAI is essential for start-up and development once launched, and this often requires equivalent to at least one full-time funded post to manage each national database. Duties are likely to include correspondence with volunteers, regional coordinators and participating organizations, communications (articles/websites), database maintenance, and the development of new initiatives as well as fundraising. The annual sampling frequency for restoration monitoring (Table 2(c)) means web traffic (e.g., uploading raw data) is likely to peak during the sampling season. Regional coordinators will be required on a seasonal basis and can be sourced from both participating organizations and volunteers. These regional coordinators would be responsible for organizing workshops with team leaders; communicating with, and assisting, the teams on the ground; local fundraising for workshops; data verification within their catchment; and could also be trained as workshop tutors. This hierarchical structure not only facilitates the further expansion of the RAI via a locally engaged support network, but also helps to maintain robust standardization of the protocol, and therefore data, across spatial scales, which is crucial if the database is to advance restoration science and policy globally.

MEETING THE FINANCIAL COSTS OF RESTORATION MONITORING INITIATIVES

Volunteers are extremely cost-effective for environmental monitoring in terms of the volume of data produced and the spatiotemporal scales covered.[3,22,47] In-kind contributions by volunteers are also important and a recent study of 388 citizen science projects estimated the 1.3 million participating volunteers each average an in-kind contribution of $1900 p.a.[48] The RMI currently costs approximately $80k p.a. to operate and the volunteers provide in-kind contributions of roughly $1.9 million. However, project launching and maintenance costs are often substantial, for example, Roy et al. (2012) estimated that the cost of maintaining national citizen science projects to be between $109k and 235k p.a., and eBird costs approximately $300,000 p.a. to maintain.[22,51] Thus, securing funding is likely to be one of the biggest challenges for the proposed RAI.

Outgoings include the website and database set up, the RMI's cost over $70,000, with continuing costs for site maintenance.[22,50] Additionally, funds are needed to support full-time salaried staff and other operational costs.[20] These costs are common to most citizen science projects, but well-run projects can attract grants. Donors are likely to be organizations or individuals whose objectives are aligned to river restoration, including conservation organizations and river trusts, philanthropists, research grant bodies, or commercial companies. Citizen science and science outreach also appeals to large foundations, for example the Esmée Fairbairn Foundation funds environmental projects that aim to connect people with nature, and donated over $9 million in grants to the environmental sector in 2014 in the UK alone (esmeefairbairn.org.uk). Large businesses may have funds available via their corporate responsibility policy, e.g., Coca-Cola.[53] Collaborating with academic institutions and organizations can reduce operating costs and also provide direct funds for initiatives, for instance the Cornell Lab of Ornithology provides financial services and office space to eBird, funding a third ($100,000) of its annual operating costs, and Salmon and Trout Conservation UK hosts the RMI national office.[5,51,52]

International and governmental sources can also provide financial assistance. In the UK, the Environment Agency supports the RMI financially, providing $80,000 in its first year and also contributes to annual costs. For governments committed to national and international biodiversity targets (Table 1), the costs or punitive fines imposed for failing to meet targets can be substantial, so there is a strong incentive for these to invest in palliative efforts such as restoration. For instance, the EU's LIFE program has co-financed a large number of river restoration projects to meet the Water Framework Directive's ecological requirements.[54] Integrating the RAI into river restoration programs would meet the public and/or stakeholder engagement and participation component, which is often stressed as key for achieving these targets (See Public Participation, Table 1), as well as identifying and developing more curative and so sustainable restoration practices.

BROADER SCIENTIFIC AND SOCIETAL BENEFITS OF ESTABLISHING THE INITIATIVE

The benefits that can be expected from successfully establishing the initiative are outlined in Figure 2. These range from volunteer engagement in improving the ecological integrity of a single river, to river agencies restoring ecosystem function across a whole catchment and restoration scientists exploring broad trends and patterns across regional to global scales, as well as achieving criteria set out in national and international restoration strategies (Table 1).[17,22] A more sophisticated understanding of the prerequisites that determine restoration success and the spatiotemporal scales at which they operate could assist the development of models to predict desirable outcomes and hence to inform project design to those that are most likely to succeed. This stands in stark contrast to the current practice of applying habitat restoration in vastly different contexts, yet still naively expecting identical and successful outcomes. The RAI therefore serves to advance restoration science through scientific characterization of the still poorly understood relationship between habitat structure and heterogeneity and ecological integrity.[11] This should then feed back into restoration management and policy at both local and national scales to improve restoration outcomes, in a 'virtuous circle' of volunteer engagement, to subsequent knowledge generation, to implementation and validation in the field.[19]

Estimating the societal benefit of the RAI includes the five key objectives summarized in Figure 2, which act both alone and in synergy. The value to participating volunteers and organizations are numerous. First, the RAI improves assessment of restoration responses directly. In terms of management, this is beneficial to restoration practitioners regardless of the direction or strength of the ecological outcomes, as positive responses in biota reassures practitioners that their restoration strategy is working. Conversely, evidence of failure, can initiate a revision of restoration strategy, preventing repetition of ineffective practices in the future.[10,19] Secondly, the initiative could serve an important educational role, elevating the scientific literacy of volunteers and the general public through project co-design, dissemination of results in nontechnical articles and closer interaction with scientists and other experts.[3] This would transcend the more prosaic workshop topics related to sampling methods and taxonomy, and would help to develop general awareness of more complex themes surrounding the controls on river ecosystems and how human interventions not only create environmental problems but can help to solve them. This would fulfill the goals of many biodiversity strategies (Table 1) leading to more informed attitudes and behavior toward river conservation by encouraging stewardship and further stakeholder involvement as active participants in the management and policy-making process at the basin scale.[37]

FUTURE HORIZONS

Cutting-edge technologies provide an exciting opportunity to collect low-effort data to complement data collected by citizen scientists, and/or to vastly increase the volume of data collected. For example, analysis of environmental DNA (eDNA), nuclear or mitochondrial DNA that is released from an organism into the environment, is rapidly developing as a commercially viable survey technique. A recent study trialing the use of eDNA sampling for detecting the presence of protected Great Crested Newts found it to be more effective than standard survey methods, with no false positives. Volunteers were able to collect samples successfully with little training.[55] Incorporating this technology into future restoration assessments could massively increase taxonomic resolution of sampling while mitigating taxonomic error.[56] The use of eDNA for restoration assessment is currently limited; analysis is expensive, complicated due to eDNA transport in rivers, and weak at estimating abundance.[55,57] Genomics databases are also currently lacking species barcodes for many aquatic invertebrates; this is likely to be a bigger problem in developing nations. However, plummeting costs and efforts to build up databases (which could be assisted by volunteer monitoring and specimen collection) will increase its viability. eDNA in its current form can also supplement macroinvertebrate sampling by providing information on fish and mammals, providing a snapshot of total species richness at the start and end of the monitoring life-time.[57] It could also detect invasive, rare, elusive, and/or charismatic species such as otters, water-voles, salmonids and kingfishers and thus act as a powerful tool for raising awareness, public interest and participation, and attracting funding.[57]

The increasingly higher-resolution imagery used in remote sensing and technologies such as 'Structure from Motion' using commercial digital cameras, also provides opportunities for cost-effective, rapid and repeatable habitat mapping and monitoring using volunteers.[58,59] For the RAI, this could mean volunteers tracking recovery of rivers and their riparian zones before and after restoration, as well as recording and measuring seasonal variation and environmental events. As the ideal environmental factors for successful restoration are established, volunteers could remotely identify catchments or reaches that are more favorable conditions for restoration, e.g., forested catchments.[17,25] The online community could also be instrumental in developing affordable sampling and monitoring equipment to assess restorations. For example, Public Lab (publiclab.org) is an open network of 'DIY activists and explorers' working together to create low-cost solutions to monitoring water. Their 'Riffle' datalogger aims to monitor temperature, water turbidity and electrical conductivity over a set period of time using standard 500-ml water bottles to house cheap components (http://publiclab.org/wiki/riffle).

CONCLUSION

Engaging volunteers in restoration monitoring via the proposed RAI is an opportune approach to help restoration science benefit both in theory and practice. There is an urgent need for ecologically effective river restorations as river ecosystems are among the most degraded in the world and the threats they face will intensify rather than diminish.[7,9] Establishing a standardized approach to monitoring restorations and recording and collating data, would address the current lack of robust standardized data which is frequently cited in literature as the main factor constraining the advance of restoration science.[18,19,60] This approach would also facilitate the development of a database that covers temporal and spatial scales otherwise unachievable.[19] Moreover, combining data from multiple restorations and across multiple catchments could enable a better understanding of the conditions that optimize restoration success, in general, and demonstrate which techniques are most likely to succeed, and where. This would result in making restoration practice more ecologically effective and economically efficient.[14,17,21] The public have established their role as 'environmental sentinels,' but scientists need to develop more sophisticated, and structured societal engagement in restoration ecology.[6] Citizen scientists will then be more effective contributors to the scientific evidence base, and better equipped to assist in the discovery of solutions to address future problems, such as climate change.[48] Our RAI approach seeks to move river restoration and citizen science toward a collaborative process that is underpinned by stakeholder participation, and has a philosophy of equity, trust and learning between volunteers and scientists. This will lead to a comprehensive understanding of intrinsically complex and dynamic river systems and how to repair them; ultimately helping to maintain and enhance riverine ecosystems and the services they provide, for future generations.[61]

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