Restoration Ecology
THE JOURNAL OF THE SOCIETY FOR ECOLOGICAL RESTORATION

OPINION ARTICLE

A unique role for citizen science in ecological restoration: a case study in streams

Patrick M. Edwards[1,2], Gail Shaloum[3], Daniel Bedell[1]

Citizen science has the potential to generate valuable biologic data for use in restoration monitoring, while also providing a unique opportunity for public participation in local restoration projects. In this article, we describe and evaluate a citizen science program designed to monitor the effect of stream restoration construction disturbance on the macroinvertebrate community. We present the results of a 7-year stream restoration study conducted by citizen scientists utilizing a Before-After-Control-Impact (BACI) design. Trait-based macroinvertebrate data showed a strong response to restoration construction disturbance and return to pre-restoration conditions within 2 years. The findings of this study suggest that citizen science can generate meaningful BACI-oriented data about ecological restoration; however, until more research is conducted, citizen data should only be used to augment professional data intended to demonstrate restoration success.

Key words: BACI, biologic traits, citizen monitoring, stream macroinvertebrates, stream restoration

Implications for Practice

- Citizen science can generate meaningful trait-based biologic data for use in stream restoration monitoring.
- Partnerships between municipalities, schools, and universities offer a unique opportunity to implement citizen-based programs focused on restoration monitoring.
- Citizen science programs have the potential to improve the practice and broaden the societal impact of ecological restoration.

Introduction

Over the last 30 years, the practice of restoration ecology has made substantial gains in solving the complex environmental issues associated with ecological degradation (Perring et al. 2015). However, the science and practice of restoration still face a number of challenges including limited regional information about the ecological effects of restoration, few long-term datasets. and a lack of studies incorporating ecological function (Rumps et al. 2007; Pander & Geist 2013; Perring et al. 2015; Kollmann et al. 2016). More importantly, there is growing realization that the human dimensions of ecological restoration such as public awareness, knowledge, and stewardship are critical components of successful restoration projects (Allen 2003; Bernhardt et al. 2005; Halle 2007; Hallett et al. 2013; Perring et al. 2015). Environmental citizen science, in which volunteer participants collect and analyze ecological data as part of a scientific inquiry (Cohn 2008; Silvertown 2009; Henderson 2012), provides an opportunity to contribute to both the scientific and societal goals of ecological restoration. This can be achieved through both contributory and collaborative citizen science programs (Shirk et al. 2012) and authentic learning experiences (Dickinson et al. 2012) in which students work directly with scientists to understand the impacts of ecological restoration, collect relevant data (Turnhout et al. 2016), and communicate their findings to the community.

The role citizen science could play in restoration ecology can be illustrated in the practice of stream restoration. Since 1990, more than 14 billion dollars has been spent on watershed and stream restoration in the United States; however, very few of these projects have been evaluated for effectiveness (Palmer et al. 2005; Pander & Geist 2013; Rumps et al. 2007). As a result, restoration scientists are calling for a greater effort in monitoring restoration outcomes and promoting effective practices across a range of ecological settings and landscapes (Palmer et al. 2005). The lack of information about the effects of restoration on ecological function provides a unique opportunity for citizen science programs to contribute biologic trait-based data (Laughlin et al. 2016) to the science of ecological restoration while simultaneously achieving important societal-related goals. In stream ecosystems, this could be achieved through citizen monitoring of restoration projects using stream macroinvertebrates.

A major challenge to the practice of ecological restoration is the lack of research based on an experimental approach known as the Before-After-Control-Impact (BACI). The BACI design utilizes data collected before and after restoration from both a

Author contributions: PME, DB designed the research, collected, and analyzed the data; all authors wrote and edited the manuscript.

[1]Environmental Science and Management, Portland State University, PO Box 751, Portland, OR 97207-0751, U.S.A.
[2]Address correspondence to P. M. Edwards, email patrick.edwards@pdx.edu
[3]Clackamas County Water Environment Services, 150 Beavercreek Road, Suite 430, Oregon City, OR 97045, U.S.A.

doi: 10.1111/rec.12622

control and the restored (impact) site (Underwood 1994). Owing to logistical and financial constraints, BACI studies are rarely implemented (Rumps et al. 2007; Miller et al. 2010). We propose that citizen science could play a role in generating data for BACI-oriented research while also increasing awareness and promoting stewardship of stream restoration efforts. Moreover, given the general lack of information about the ecological impacts of restoration, it is reasonable to suggest that a citizen-based monitoring program could also make important contributions to the science of stream restoration. For example, citizen monitoring could provide basic information about stream restoration such as determining adequate time periods for baseline monitoring, documenting ecological changes related to restoration efforts, and monitoring the recovery of the macroinvertebrate community.

In this article, we evaluate a citizen-based restoration monitoring program focused on macroinvertebrate traits at two streams using a BACI design. This study presents one of the few long-term stream macroinvertebrate datasets associated with stream restoration and, to our knowledge, the only example of a BACI-oriented citizen science program focused on ecological restoration. The design of this study is based on the premise that in order to generate useful information for restoration monitoring, citizen science programs must be able to detect the change in the macroinvertebrate community due to restoration construction disturbance at the impacted stream as well as collect useful BACI-oriented data from a control stream. Using flood disturbance as a theoretical framework (Resh et al. 1988) to explain the disturbance to the macroinvertebrate community caused by heavy machinery used during restoration construction (Muotka 2002), we tested several a priori predictions to evaluate the ability of citizen-generated data to detect the biologic impact of construction activities on the stream and the subsequent return of macroinvertebrates to baseline conditions.

Methods

Program Overview

The program described in this study represents both contributory and collaborative citizen science and was developed through a 7-year partnership between a county municipality, a high school, and a university. The overarching goal of the program is to increase students' awareness of stream health and to engage them in local efforts to improve surface water quality. The citizen science component of the program takes place during multiple classes, a field trip to the creek, and culminates with poster presentations by students at the end of the school year. The in-class curriculum is focused on developing students' content knowledge and research skills. Posters are created over the course of the school year and go through multiple drafts and revisions. All activities are facilitated and led by university scientists. Because participating students had no prior experience collecting macroinvertebrates, we considered their skills similar to those of citizen scientists (Edwards 2016).

Stream Characteristics and Restoration Approach

Macroinvertebrate data were collected at Rock Creek (45.41, −122.52) and Balch Creek (45.53, −122.52). Both streams are located in the maritime climate of western Oregon in the Pacific Northwest of the United States. The streams are shallow, less than 5 m wetted width and surrounded by heavily forested riparian zones; however, the watersheds of each creek reflect different land use intensities. The Balch Creek watershed is 6 km^2 and contains 5% light residential development and 93% forest cover. The Rock Creek watershed is 25 km^2 and contains more intensive land use including 27% development, 28% agriculture, and 33% forest cover (Homer et al. 2015). In the BACI design structure of this study, Balch Creek was considered the control stream and Rock Creek the impact stream. The purpose of the restoration at Rock Creek was to improve salmon-rearing habitat through native riparian plantings and the addition of approximately 140 logs, 30 habitat boulders, and 18 pools to the lower 600 m of stream (Fig. 1). Balch Creek was used as the BACI control because it is one of the few streams with minimal development and the only regional stream that has a similar long-term stream macroinvertebrate dataset generated by citizens using the same field sampling methodology.

Macroinvertebrate Data and Analysis

Students collected macroinvertebrate data using a randomized, nonlethal method described in Edwards (2016). Briefly, d-nets were used to collect multiple benthic samples in riffles. Macroinvertebrates were identified to the family level and identifications were verified in the field for each sample by an experienced taxonomist. Data were collected at Balch Creek ($n = 13$) and Rock Creek ($n = 12$) each spring and fall from 2010 to 2016 (Table 1). During each sampling event, participants collected an average of 575 macroinvertebrates (range = 104–3,512) from an average of 2.5 m^2 of substrate (range = 0.7–6.6 m^2). At both creeks, baseline data were collected from 2010 to 2013 and post-restoration construction data were collected from 2014 to 2016 (Table 1). Construction preparation at Rock Creek began in 2014; therefore, students could not access the site to collect data for the spring 2014 sample. Macroinvertebrate counts were expressed as abundance (0.1 m^{-2}) or as percent of total (relative abundance).

We evaluated the ability of citizen-generated invertebrate data to detect the impact of restoration construction on the macroinvertebrate community and subsequent return to baseline conditions. Citizen data were not compared to professional data. Across the same time span at both creeks, macroinvertebrate data were characterized using several metrics including abundance, richness, an index of biotic integrity (IBI), and biologic traits (life cycle length and pollution tolerance). The IBI is a multiple metric that ranges from 6 to 30 with higher numbers indicating better stream health (OWEB 1999). Macroinvertebrate life cycle was characterized as "long-slow" for macroinvertebrates that live more than 1 year and experience relatively slow larval growth (Poff et al. 2006). Macroinvertebrate tolerance was characterized using both the richness and relative

Figure 1. Pre-restoration reach (top panel) and same reach (bottom panel) after restoration at Rock Creek. Top panel image can be credited: Clackamas River Basin Council. Bottom panel image can be credited: Environmental Professional Program, Portland State University.

abundance of Ephemeroptera (E, Mayfly), Plecoptera (P, Stonefly), and Trichoptera (T, Caddisfly). The EPT taxa are sensitive to poor stream conditions and are well-known indicators of stream habitat degradation (Waite et al. 2010). Pollution tolerance was also evaluated using abundance of Diptera (True fly). True flies are rapid colonizers (Milner et al. 2008) and highly adapted to stream disturbance (Benke & Parsons 1990).

To determine if citizen-generated data could detect the impact of restoration construction disturbance on the macroinvertebrate community, we compared the first post-restoration metric value (fall 2014) to the pre-restoration (baseline) range for both creeks. Based on stream disturbance theory, we made predictions about the macroinvertebrate response to construction disturbance (Table 2). We tested predictions by determining if the post-restoration metric value was outside the minimum or maximum values observed in the baseline data. Five of the quantitative metrics (richness, IBI, long-slow density, Dipteran density, and EPT density) were statistically analyzed with a one-sample t test that compared the fall 2014 value to the median value of all the pre-restoration samples ($n = 7$) using the rank-based Mann–Whitney–Wilcoxon test. To account for the accumulating type 1 error due to multiple comparisons, a Bonferroni correction was applied so that the alpha value (α) was reduced to $\alpha = 0.01$. To graphically evaluate temporal patterns in the macroinvertebrate community, we examined time series plots of macroinvertebrate abundance and relative abundance data for both streams (Roni et al. 2005).

Results

Baseline Data and Post-Construction Response of Macroinvertebrates

Over the 7-year study period, more than 2,300 students participated in 25 sampling events at both streams and collected more than 14,000 macroinvertebrates from 50 m^2 of substrate (Table 1). Baseline sampling showed that several metrics (taxa richness, EPT richness, and IBI) at Rock Creek were generally higher than at Balch Creek. At Rock Creek, four of the IBI scores were near (i.e. within one point) or within the unimpaired category. This indicates that the invertebrate community at Rock Creek was in generally good condition prior to the restoration construction. At Balch Creek, none of the fall 2014 metrics were outside the minimum or maximum values observed in the baseline data. At Rock Creek, four of the seven values in fall 2014 were outside the minimum or maximum values observed in the baseline data and six of the seven a priori predictions were correct (Table 2). Abundance of macroinvertebrates with long-slow life cycles was slightly less in the fall of 2014 than the lowest value observed in the baseline data (0.8 vs. 0.9 per 0.1 m^{-2}, $p < 0.01$). True fly abundance was more than double the highest value observed in the baseline data (5.2 vs. 11.6 per 0.1 m^{-2}, $p < 0.01$). IBI scores for the baseline data ranged from 18 to 24. The IBI score for fall 2014 was four points less than the lowest value observed in the baseline data (14 vs. 18 $p = 0.01$), and EPT richness was slightly lower than the baseline data (9 vs. 10 $p = 0.01$). EPT abundance in fall 2014 was within the baseline range at both streams. All five of the metrics at Balch Creek had p values greater than 0.01; however, the p value for long-slow density was ($p = 0.02$), which was only slightly above the alpha value.

Stream Macroinvertebrate Temporal Patterns

Figure 2 shows the time series plots of macroinvertebrate abundance and relative abundance at both streams before and after restoration construction. At Rock Creek, 6 of the 10 macroinvertebrate measures showed the predicted response to restoration construction (panels D, E, G–J) and all measures showed return to baseline conditions within 1 year of construction. Richness, abundance, and EPT abundance did not show a response to the restoration construction at Rock Creek, except for spring 2016 when abundance was substantially higher than the baseline values (panels A–C). The variability and extreme values observed in the post-construction data (panels B, C, F, G) suggest that the macroinvertebrate community was still recovering up to 2 years after construction disturbance. In general, relative abundance appeared to be a more reliable indicator than abundance

Table 1. Macroinvertebrate data, sampling effort, and student participation for all samples at both Balch Creek and Rock Creek. Due to construction activities, data were not collected at Rock Creek during spring 2014. NA, Not Applicable.

Sample Date	*Balch Creek Abundance (Area, m^2)*	*Rock Creek Abundance (Area, m^2)*	*Balch Creek (No. of Students)*	*Rock Creek (No. of Students)*
Fall 2010	243 (1.0	104 (0.7)	40	30
Spring 2011	294 (1.1)	198 (1.8)	40	75
Fall 2011	265 (1.2)	730 (3.1)	40	150
Spring 2012	107 (0.5)	249 (2.9)	40	150
Fall 2012	173 (0.8)	710 (2.3)	40	120
Spring 2013	359 (1.0)	451 (1.8)	40	80
Fall 2013	270 (1.0)	1,139 (4.2)	40	220
Spring 2014	198 (1.1)	NA	40	NA
Fall 2014	214 (1.0)	896 (4.2)	40	220
Spring 2015	297 (0.8)	729 (2.1)	40	110
Fall 2015	815 (2.5)	301 (2.2)	80	250
Spring 2016	379 (1.2)	3,512 (5.3)	40	220
Fall 2016	460 (2.3)	1,213 (4.6)	40	180
Total	4,074 (15.5)	10,232 (35.2)	560	1,805
Mean	313 (1.2)	852 (2.9)	43	151

Table 2. Macroinvertebrate metrics used to test predictions and relevant references. Asterisk indicates a confirmed prediction.

Invertebrate Measure or Metric	*Description*	*Rock Creek Prediction for Fall 2014*	*References*
Total richness	Total number of unique taxa	No change*	Miller et al. (2010)
Abundance	Density (0.1 m^{-2})	No change*	Miller et al. (2010)
EPT	Mayfly, Stonefly, and Caddisfly abundance	Decrease	Waite et al. (2010)
Long-slow life cycle	Life cycle length and rate of development	Decrease*	Huryn and Wallace (2000), Gray (1981)
Diptera abundance	Dipteran abundance	Increase*	Benke and Parsons (1990), Milner et al. (2008)
IBI	Family level IBI	Decrease*	Kerans and Karr (1994)
EPT richness	Total number of EPT families	Decrease*	Waite et al. (2010)

for detecting the response and recovery of the macroinvertebrate community. The post-disturbance data observed in the Rock Creek and Balch Creek indicate that the changes in Rock Creek macroinvertebrate community were probably not due to large-scale environmental factors such as climate.

Discussion

Citizen Science Can Detect the Impacts of Restoration Construction

The observed changes in the stream macroinvertebrate community after the restoration construction activities at Rock Creek can be explained by flood disturbance ecology. The strong response of True flies to the restoration construction is likely due to the biologic traits of Simuliidae (Black Fly) and Chironomidae (Midge), which include rapid colonization (Milner et al. 2008), adaptation to disturbance (Benke & Parsons 1990), and fast life cycles (Poff et al. 2006). At Rock Creek, macroinvertebrate life cycle length and larval development also showed a strong response to the restoration disturbance. This finding is supported by other research that suggests flood disturbance can temporarily create habitats with low resource partitioning and reduced competition, thus resulting in a biotic community dominated by organisms with rapid growth rates and short life cycles (Benke & Parsons 1990; Huryn & Wallace 2000).

The results of our study illustrate the value of citizen-based monitoring to the practice of ecological restoration. At Rock Creek, trait-based macroinvertebrate data generated through citizen science could detect the impact and recovery of the stream macroinvertebrate community. These results are confirmed by the few other BACI-designed stream restoration studies conducted by professional stream scientists. For example, relatively rapid colonization and recovery of macroinvertebrates within 2 years of restoration construction have been observed in other investigations (Negishi & Richardson 2003; Pedersen et al. 2007; Nuttle et al. 2017). The post-restoration increase in abundance of Baetidae (Small Minnow Mayfly) observed at Rock Creek was also documented by Negishi and Richardson (2003) and Pedersen et al. (2007). In our study, traditional macroinvertebrate measures such as abundance, EPT abundance, and total richness were generally unable to detect the effect of restoration construction on macroinvertebrates. This finding was also observed in several other studies (Lemly & Hilderbrand 2000; Negishi & Richardson 2003; Pedersen et al. 2007; Louhi et al. 2011). The sensitivity of macroinvertebrate biologic traits to restoration activities has also been documented in other stream research (Lemly & Hilderbrand 2000; Muotka &

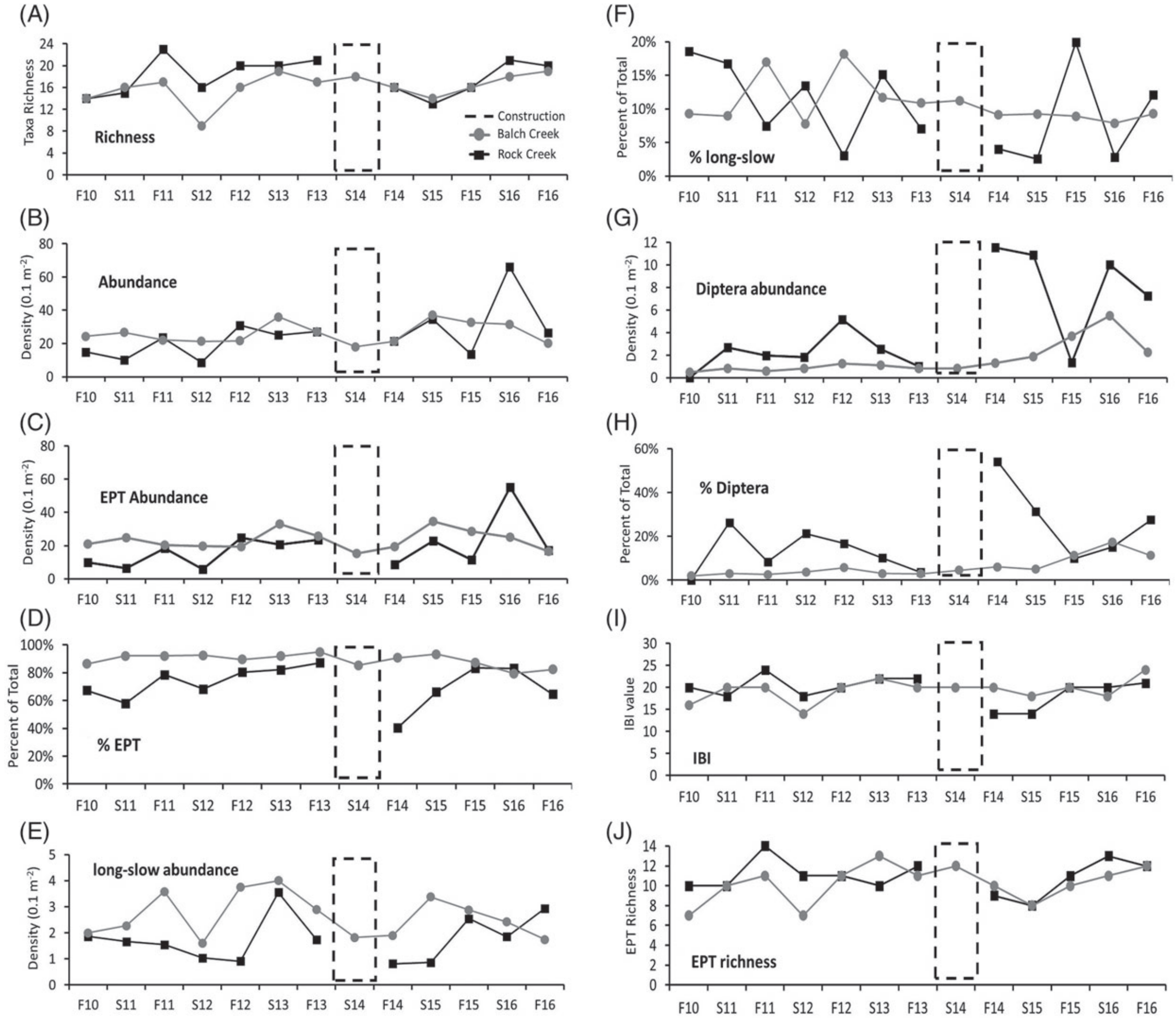

Figure 2. Temporal patterns of macroinvertebrate abundance, relative abundance (percent of total), and other metrics for Balch Creek (control) and Rock Creek (impact). Data were not collected at Rock Creek during construction (dashed lines). The *x*-axis labels indicate fall (F) and spring (S) seasons and two-digit year from 2010 to 2016.

Laasonen 2002; Lester et al. 2007; Pedersen et al. 2007). In our study, EPT abundance was the only metric that did not confirm the predicted macroinvertebrate response to construction disturbance. This finding may be related to the limitations of citizen identification skills, but it is more likely due to the ecology of Small Minnow Mayflies, which have a short-fast life cycle and rapidly colonize open habitat through drifting. In the fall 2014 sample, Small Minnow Mayflies represented 78% of the total EPT abundance.

The Value of Citizen Science Data to the Practice of Stream Restoration

The results of this study suggest that citizen science programs may be able to contribute valuable BACI-oriented data to the practice of stream restoration. For example, we envision that citizen science could generate multiple baseline datasets as part of an existing educational monitoring program, augment professionally collected data at an on-going restoration project, or monitor biologic conditions until baseline conditions return, after which professional monitoring could be implemented. One of the main advantages of using biological data for evaluating ecological restoration is the ability to utilize biologic traits. Not only does this provide meaningful information about the ecological impacts of restoration, it also creates a practical link between family-level data collected by citizen scientists and genus-level data collected by professionals. For example, in the appendix in Poff et al. (2006), it can be observed that many of the macroinvertebrate traits are the same across the genus and family taxonomic levels.

In this article, we mainly report on the quality of macroinvertebrate data collected by citizens; however, we recognize there are other important societal outcomes and benefits associated with citizen-based restoration monitoring programs. Although we do not present survey-based evidence about the societal effect of participating in restoration-focused citizen science, student interaction with scientists increases student awareness and understanding of the Rock Creek restoration and thus broadens the impacts of restoration efforts. For example, our program contains several aspects of citizen science that are known to increase environmental knowledge, awareness, and stewardship including authentic learning experiences, data collection and analysis, dissemination of results, and direct interaction with a scientist (Bonney et al. 2009; Dickinson et al. 2012; Shirk et al. 2012). Over the life of our project, more than 1,800 high school students participated in the Rock Creek restoration project and conducted authentic scientific inquiry under the guidance of a stream scientist at a local restoration site. This alone represents a substantial outreach and stewardship effort on the part of scientists, environmental managers, and educators. Through authentic scientific experiences, citizen science can support efforts to meet the societal and governance goals of restoration including: enhancing education, engaging and retaining students in science and engineering (STEM) fields, and inspiring public engagement (Groffman et al. 2010; Richardson & Lefroy 2016; Vince & Hardesty 2016).

The societal and scientific goals of citizen-based restoration monitoring are not mutually exclusive. Indeed, in our program, anecdotal evidence based on exams and teacher observations suggests that students have increased their awareness of the Rock Creek restoration, indicated by students' enhanced interest in restoration careers, information sharing with family members, and civic engagement including attendance at a county commissioners public meeting where they exhibited their posters and testified about the educational benefits of the program. These important societal benefits could be achieved in other programs and evaluated for success. Future research in this area should document the societal and educational impacts of citizen science programs focused on restoration from a wide range of ecological settings. The findings of our study suggest a knowledgeable and engaged citizenry will support efforts to restore damaged ecosystems and a citizen-based approach restoration monitoring could meet both the societal goals and data needs of restoration science.

One of the major limitations of this study is that we do not assess the ability of citizen science data to document the success of stream restoration. This is mainly due to the high quality of the macroinvertebrate community present at Rock Creek before restoration began, thus leaving little room for improvement in the metric scores. Furthermore, the purpose of the restoration project was to restore a single reach of Rock Creek. At this spatial scale, it is unlikely that the macroinvertebrate community would show drastic improvement without other watershed-wide restoration efforts and corresponding data. This is particularly true for Rock Creek where land development has accelerated over the last 10 years. Due to the lack of spatial replication in this study, evaluating the overall improvement in stream condition associated with the stream restoration efforts is beyond the scope of this research. Given these limitations, it is only possible to examine the impacts of restoration construction on stream macroinvertebrates and their return to baseline conditions. More research is needed in degraded stream systems to determine if citizen-generated data could be used to document improved ecological function due to restoration. Until that time, it is our belief that citizen data should only be used to augment professional data intended to demonstrate restoration success.

Strategies for Developing Citizen-Based Restoration Programs in Other Ecological Settings

The findings of this study provide insight into how citizen science can inform restoration practice in other ecological settings. While many of the current citizen science programs are focused on streams and lakes, restoration monitoring by citizens could be applied in vegetation-focused projects, wetland mitigation, or restoration of marine and estuarine systems. In our experience, the key to successful implementation of restoration-focused citizen science is to develop and utilize simple field collecting techniques that are randomized, nonlethal, and generally low impact. The challenge is that many of the existing methods and resources will need to be modified to fit the specific sampling and taxonomic requirements of citizen monitoring. Finally, all monitoring programs should incorporate the use of sample verification, either by a regional expert or through taxonomic training programs. This will ensure the quality of data collected by citizen scientists.

This article describes a restoration-focused citizen science program and presents one of the few BACI-oriented datasets focused on stream restoration and the only published example of citizen science restoration monitoring. Using stream disturbance theory, several hypotheses were tested about the impact of restoration construction disturbance on stream macroinvertebrate communities. Citizen data confirmed all but one of the predictions and could detect both temporal and spatial differences in stream macroinvertebrate communities. These findings suggest that citizen science programs could be used to collect valuable BACI-oriented data and contribute to the societal aspects of ecological restoration. Furthermore, the insight gained from this study can provide a model for citizen science programs in other ecological settings and thus promote a unique role for citizen science in the practice of environmental restoration.

Acknowledgments

The authors would like to thank the students at Clackamas High School and Portland State University for collecting the macroinvertebrate data used in this research. This project was funded by the RiverHealth Stewardship Program sponsored by Clackamas County Water Environment Services and supported by the Student Watershed Research Project at Portland State University. We also thank three anonymous reviewers whose comments greatly improved this manuscript.

LITERATURE CITED

Allen EB (2003) New directions and growth of restoration ecology. Restoration Ecology 11:1–2

Benke AC, Parsons KA (1990) Modelling black fly production dynamics in blackwater streams. Freshwater Biology 24:167–180

Bernhardt ES, Palmer MA, Allan JD, Alexander G, Barnas K, Brooks S, et al. (2005) Synthesizing U.S. river restoration efforts. Science 5722:636–637

Bonney R, Cooper CB, Dickinson J, Kelling S, Phillips T, Rosenberg KV, Shirk J (2009) Citizen science: a developing tool for expanding science knowledge and scientific literacy. Bioscience 59:977–984

Cohn JP (2008) Citizen science: can volunteers do real research? Bioscience 58:192–197

Dickinson JL, Shirk J, Bonter D, Bonney R, Crain RL, Martin J, Phillips T, Purcell K (2012) The current state of citizen science as a tool for ecological research and public engagement. Frontiers in Ecology and the Environment 10:291–297

Edwards P (2016) The value of long-term stream invertebrate data collected by citizen scientists. PLoS One 11:e0153713

Gray LJ (1981) Species composition and life histories of aquatic insects in a lowland Sonoran Desert stream. American Midland Naturalist 106:229–242

Groffman PM, Stylinski C, Nisbet MC, Duarte CM, Jordan R, Burgin A, Previtali MA, Coloso J (2010) Restarting the conversation: challenges at the interface between ecology and society. Frontiers in Ecology and the Environment 8:284–291

Halle S (2007) Science, art, or application—the "karma" of restoration ecology. Restoration Ecology 2:358–361

Hallett LM, Diver S, Eitzel MV, Olson JJ, Ramage BS, Sardinas H, Statman-Weil Z, Suding KN (2013) Do we practice what we preach? Goal setting for ecological restoration. Restoration Ecology 3:312–319

Henderson S (2012) Citizen science comes of age. Frontiers in Ecology and the Environment 10:283–283

Homer CG, Dewitz JA, Yang L, Jin S, Danielson P, Xian G, et al. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States – representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing 81:345–354

Huryn D, Wallace B (2000) Life history and production in stream insects. Annual Review of Entomology 45:83–110

Kerans BL, Karr JR (1994) A benthic index of biotic integrity (B-IBI) for rivers of the Tennessee Valley. Ecological Applications 4:768–785

Kollmann J, Meyer ST, Bateman R, Conradi T, Gossner MM, Souza Mendonça M, et al. (2016) Integrating ecosystem functions into restoration ecology—recent advances and future directions. Restoration Ecology 6:722–730

Laughlin DC, Strahan RT, Huffman DW, Sánchez Meador AJ (2016) Using trait-based ecology to restore resilient ecosystems: historical conditions and the future of montane forests in western North America. Restoration Ecology, doi:10.1111/rec.12342.

Lemly AD, Hilderbrand RH (2000) Influence of large woody debris on stream insect communities and benthic detritus. Hydrobiologia 1:179–185

Lester RE, Wright W, Jones-Lennon M (2007) Does adding wood to agricultural streams enhance biodiversity? An experimental approach. Marine and Freshwater Research 8:687–698

Louhi P, Mykrä H, Paavola R, Huusko A, Vehanen T, Mäki-Petäys A, Muotka T (2011) Twenty years of stream restoration in Finland: little response by benthic macroinvertebrate communities. Ecological Applications 6:1950–1961

Miller SW, Budy P, Schmidt JC (2010) Quantifying macroinvertebrate responses to in-stream habitat restoration: applications of meta-analysis to river restoration. Restoration Ecology 18:8–19

Milner AM, Robertson AL, Monaghan KA, Veal AJ, Flory EA (2008) Colonization and development of an Alaskan stream community over 28 years. Frontiers in Ecology and the Environment 6:413–419

Muotka T (2002) Long-term recovery of stream habitat structure and benthic invertebrate communities from in-stream restoration. Biological Conservation 105:243–253

Muotka T, Laasonen P (2002) Ecosystem recovery in restored headwater streams: the role of enhanced leaf retention. Journal of Applied Ecology 1:145–156

Negishi JN, Richardson JS (2003) Response of organic matter and macroinvertebrates to placements of boulder clusters in a small stream of southwestern British Columbia, Canada. Canadian Journal of Fisheries and Aquatic Sciences 60:247–258

Nuttle T, Logan MN, Parise DJ, Foltz DA, Silvis JM, Haibach MR (2017) Restoration of macroinvertebrates, fish, and habitats in streams following mining subsidence: replicated analysis across 18 mitigation sites. Restoration Ecology, doi: 10.1111/rec.12502

OWEB (Oregon Watershed Enhancement Board) (1999) Oregon watershed assessment Manual. Governor's Watershed Enhancement Board, Salem, Oregon www.oweb.state.or.us/publications/wa_manual99.shtml (accessed 16 Jul 2015)

Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, et al. (2005) Standards for ecologically successful river restoration. Journal of Applied Ecology 42:208–217

Pander J, Geist J (2013) Ecological indicators for stream restoration success. Ecological Indicators 30:106–118

Pedersen ML, Friberg N, Skiver J, Baattrup-Pedersen A, Larsen SE (2007) Restoration of Skjern River and its valley – short-term effects on river habitats, macrophytes and macroinvertebrates. Ecological Engineering 30:145–156

Perring MP, Standish RJ, Price JN, Craig MD, Erickson TE, Ruthrof KX, Whiteley AS, Valentine LE, Hobbs RJ (2015) Advances in restoration ecology: rising to the challenges of the coming decades. Ecosphere 6:1–25

Poff NL, Olden JD, Vieira NK, Finn DS, Simmons MP, Kondratieff BC (2006) Functional trait niches of North American lotic insects: traits-based ecological applications in light of phylogenetic relationships. Journal of the North American Benthological Society 25:730–755

Resh VH, Brown AV, Covich AP, Gurtz ME, Li HW, Minshall GW, Reice SR, Sheldon AL, Wallace JB, Wissmar RC (1988) The role of disturbance in stream ecology. Journal of the North American Benthological Society 7:433–455

Richardson BJ, Lefroy T (2016) Restoration dialogues: improving the governance of ecological restoration. Restoration Ecology 5:668–673

Roni P, Liermann MC, Jordan C, Steel EA (2005) Steps for designing a monitoring and evaluation program for aquatic restoration. Pages 14–30. In: Roni P (ed) Monitoring stream and watershed restoration. American Fisheries Society, Bethesda, Maryland

Rumps JM, Katz SL, Barnas K, Morehead MD, Jenkinson R, Clayton SR, Goodwin P (2007) Stream restoration in the Pacific Northwest: analysis of interviews with project managers. Restoration Ecology 3:506–515

Shirk J, Ballard H, Wilderman C, Phillips T, Wiggins A, Jordan R, et al. (2012) Public participation in scientific research: a framework for deliberate design. Ecology and Society 17:29

Silvertown J (2009) A new dawn for citizen science. Trends in Ecology & Evolution 24:467–471

Turnhout E, Lawrence A, Turnhout S (2016) Citizen science networks in natural history and the collective validation of biodiversity data. Conservation Biology 30:532–539

Underwood AJ (1994) On beyond BACI: sampling designs that might reliably detect environmental disturbances. Ecological Applications 4:3–15

Vince J, Hardesty BD (2016) Plastic pollution challenges in marine and coastal environments: from local to global governance. Restoration Ecology 25:123–128

Waite IR, Brown LR, Kennen JG, May JT, Cuffney TF, Orlando JL, Jones KA (2010) Comparison of watershed disturbance predictive models for stream benthic macroinvertebrates for three distinct ecoregions in western U.S. Ecological Indicators 10:1125–1136

Coordinating Editor: Jac. A.A. Swart

Received: 25 March, 2017; First decision: 27 May, 2017; Revised: 1 September, 2017; Accepted: 11 September, 2017