

Bridging science and society: Developing a citizen science biomonitoring approach for river ecosystems in Italy

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ABSTRACT

Rivers are among the most altered and impacted freshwater ecosystems on Earth, so that collective efforts should be fuelled by professionals and societies to implement their biomonitoring and conservation. Citizen science is recognized as a powerful approach but its application in river biomonitoring is still scarce, especially in Italy. This study was aimed at developing and validating a citizen science biomonitoring approach for river ecosystems based on the analysis of benthic macroinvertebrate communities. By using a calibration dataset composed of 932 sampling events performed by professionals, a simplified macroinvertebrate community was first obtained by selecting only 36 representative taxa. Four different, but routinely applied, metrics were calculated on both the simplified and calibration communities and showed strong and significant correlations. Thresholds for the four selected metrics were statistically derived and offered a good agreement in discriminating not-impacted and impacted conditions according to the official methodology. The performance of the proposed approach was validated on ten independent sampling campaigns with citizen science volunteers and compared to benchmark sites. Since 33 out of 36 taxa were recorded at least once, results showed that the simplified macroinvertebrate community was effective and representative. The ecological status assessment and the selected metrics were generally comparable to the values of the benchmark sites, despite some differences being observed depending on the metric. This study represents one of the first efforts in the direction of developing a citizen science macroinvertebrate-based methodology for river biomonitoring in Italy and it supports the adoption of a multi-metric approach.

1. Introduction

Rivers are unique and irreplaceable ecosystems on Earth (Allan and Castillo, 2007). They play a fundamental role in the global water cycle, host diverse and highly-specialized life forms, and support the social and economic growth of human societies by providing several ecosystem services, such as water purification, water supplies, fisheries, and recreational activities (Hanna et al., 2018). However, rivers are also among the most impacted, modified, and over-exploited environments (Dudgeon, 2019; Albert et al., 2021). Anthropogenic pressures on river ecosystems include: alterations of the natural flow and sediment regimes (Poff et al., 1997; Dewson et al., 2007; Surian et al., 2009), water abstraction and pollution (Schinegger et al., 2012; Di Nica et al., 2021; Marino et al., 2023), damming (Comiti, 2012; Espa et al., 2015; Doretto et al., 2022), morphological alterations of the channel, banks and

riparian vegetation (Miserendino and Pizzolon, 2004; Del Tánago et al., 2021), and introduction of invasive species (Francis and Chadwick, 2012; Larson et al., 2022). Moreover, climate change is widely recognized as an additional and superimposing pressure with potentially dramatic consequences (Tonkin et al., 2019).

Since rivers are typically affected by multiple stressors with potential additive and synergic effects (Laini et al., 2018; Leitner et al., 2021), common consequences include: reduced habitat heterogeneity and suitability, the loss of aquatic biodiversity, especially among the most sensitive species, and the loss of ecosystem services (Grizzetti et al., 2019). Thus, improving the monitoring effort and preserving the ecological integrity of rivers are pivotal challenges for the sustainable development (Karr 1993; Dudgeon, 2010; Karr et al., 2022; Rohwer and Marris, 2021).

In the last few decades, the application of biomonitoring techniques,

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that is the variety of methodologies based on the response of living organisms, has blossomed and exceeded the traditional and chemically-oriented ones (Heiskanen et al., 2004; Bennett et al., 2011). In Europe, the Water Framework Directive (2000/60/CE – WFD) represents the main normative act in terms of protection and monitoring of river ecosystems. This Directive sets common standards and methodological approaches for EU Countries as well as shared goals. Moreover, one of the main novelties of the WFD is the emphasis on the role of the Biological Quality Elements (i.e. BQEs), such as macroinvertebrates, fish, diatoms, and macrophytes, in assessing the ecological status. Biomonitoring techniques provide many advantages: they are generally cheaper than chemical analyses, and offer complementary information on the overall effects of contaminants and alterations on different levels of biological organization (e.g. from cellular to community and/or ecosystem level). Several authors have also recognized that biomonitoring can serve as a rapid way to obtain integrated responses that a disturbance is occurring, or as a cost-effective way to assess the success of restoration actions over time (Moerke et al., 2004; Montuelle, et al., 2010; Besse et al., 2012; Pander and Geist, 2013; Hamza-Chaffai, 2014). Among riverine BQEs, benthic macroinvertebrates are the far most used target group (Buss et al., 2015; Bo et al., 2017). In a review on the advances in stream biodiversity research since the publication of the River Continuum Concept (Vannote et al., 1980), Tornwall et al. (2015) found that benthic macroinvertebrates were the most studied taxonomic group outreaching all the other organisms. Main reasons for the wide use and versatility of macroinvertebrates include: their ease of collection and systematic identification, at least to family or genus level, their ubiquity and reduced mobility, and their long-lasting aquatic stages. Moreover, macroinvertebrate taxa show different degrees of sensitivity to alterations, allowing thus a rapid evaluation of shifts from sensitive-dominated communities to tolerant-dominated ones when alterations occur.

Similarly, the above-mentioned advantages of macroinvertebrates make this target group ideal for citizen science activities. Previous research has shown that macroinvertebrates are commonly used in biomonitoring programs with volunteers and their application has increased in the last years (Edwards, 2016; Burgess et al., 2017; Ramírez et al., 2023). For example, von Gönner et al. (2023) developed a citizen science program that enables volunteers to collect data on stream hydromorphology, physicochemical status and benthic macroinvertebrates to calculate the SPEARpesticides indicator for quantifying pesticide exposure. A further example of a successful citizen science project is “The Riverfly Partnership”, that aims at assessing the ecological status of British rivers using benthic macroinvertebrates. This project uses the ARMI’s protocol, a simplified version of the Biological Monitoring Working Party (BMWP) (Cahill, 2019). Since 2004, when it started, to 2019, over 2,000 volunteers were involved in the biomonitoring of approximately 1,600 British streams (riverflies.org). Hence, citizen science has been invoked as a powerful approach to advance the conservation of freshwater biodiversity by offering both occasions of education for a generic audience and implementing the data collection (Metcalfe et al., 2022). This assumes a particular importance especially where regular and official data acquired by the local authorities and professionals are spatially and temporally limited, or where data are even lacking. Adopting an effective and evenly-distributed monitoring scheme is fundamental to obtain informative and realistic data that, in turn, can be used to lead management and political actions, especially in relation to ecosystems affected by multiple stressors like rivers (Tricarico, 2022). Thus, collective efforts should be fuelled by professionals, researchers, and stakeholders to implement the river biomonitoring, including the adoption of innovative and participative approaches such as citizen science activities.

The aim of this study was to develop and validate a citizen science biomonitoring approach for river ecosystems using benthic macroinvertebrates. To this end, a simplified macroinvertebrate community was first obtained by selecting only 36 taxa among the most frequent,

representative, and easy-to-identify ones in the area of study. Then, four different biodiversity and biomonitoring metrics were calculated on the simplified community and their correlation with those obtained with the whole community sampled by professionals in the same area of study was statistically tested. Hence, thresholds for the selected metrics discriminating not-impacted and impacted conditions were statistically derived, and their accordance with the official methodology was tested. Finally, from November 2023 to June 2024 this approach was validated on ten independent sampling campaigns with citizen science volunteers and results were discussed and compared with benchmark sites in the area of study.

2. Materials and methods

2.1. Area of study

Piedmont Region covers a surface area of 25.391,67 Km² and is the seventh most-populated administrative area in Italy (Fig. 1). This Region is characterized by a great heterogeneity of natural areas and topographic gradients, including mountain chains (i.e. Alps and Apennines), hilly landscapes, and lowland areas. According to the river-type classification introduced by the Water Framework Directive (Moog et al., 2004; Hering et al., 2006), seven different hydro-ecoregions (HER) are hosted in Piedmont: Western Alps (HER1), Southern Alps (HER4), Monferrato (HER5), Pianura Padana (HER6), Piedmont Apennines (HER8), Mediterranean Alps (HER9), and Northern Apennines (HER10), highlighting thus the high heterogeneity of rivers in this Region.

This study focused solely on river ecosystems belonging to HER6, that is a variety of lowland watercourses ranging from the mid-order

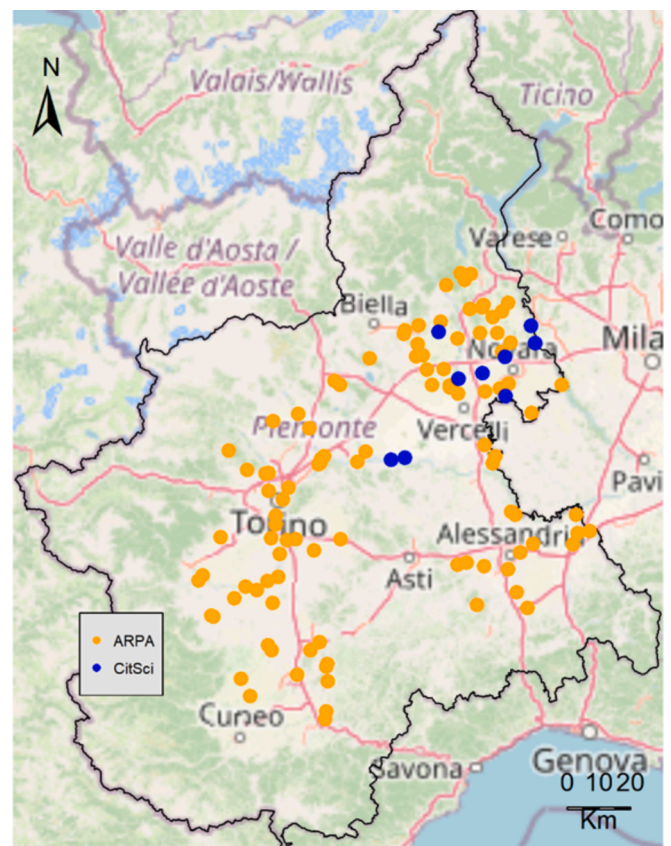


Fig. 1. Map of the Piedmont Region (Northwestern Italy) and location of the sampling sites. Orange dots represent the official sampling sites of the regional agency for environmental protection (ARPA Piemonte) belonging to HER6 and here used for the calibration dataset. Blue dots represent the sampling sites on watercourses surveyed with citizen science volunteers (validation dataset).

(Strahler, 1952; 1957) rivers to agricultural streams and ditches. Data were gained from two independent databases: at first, publicly available data on benthic macroinvertebrates in the HER6 sampling stations were downloaded from the official website of the regional agency for environmental protection (ARPA Piemonte). These data were used as calibration dataset to define the simplified list of selected taxa (hereafter simplified community) and metrics to be used in the citizen science activities. Then, ten macroinvertebrate sampling campaigns were performed with citizen science volunteers in different sites and these data were used as validation dataset to test the performance and reliability of the selected metrics.

2.2. Calibration dataset

Starting from the official website of the regional agency for environmental protection (ARPA Piemonte) data from 932 sampling events since 2009 to 2019, across 101 different sampling sites (Fig. 1), were obtained and used as calibration dataset. This dataset included 116 different taxa (families and/or genera) colonizing the selected rivers and represented the taxonomic pool of macroinvertebrates of the HER6 (i.e. Pianura Padana). According to the Italian normative, five ecological status classes (i.e. High, Good, Moderate, Poor, Bad) are provided depending on the numeric value of STAR_ICMi, the official macroinvertebrate-based index (Buffagni et al., 2001; Buffagni & Furse, 2006). STAR_ICMi is a multi-metric index that aggregates six different metrics: total family richness, EPT (Ephemeroptera, Plecoptera, Trichoptera) family richness, ASPT (Average Score Per Taxon), 1-GOLD (i.e. the relative abundance of Gastropoda, Oligochaeta and Diptera), logSel EPTD + 1 (i.e. logarithm of the abundance of selected Ephemeroptera, Plecoptera, Trichoptera and Diptera plus one), and Shannon index (Bo et al., 2023). Moreover, sampling events covered all the ecological status gradients (High: N = 88, Good: N = 337, Moderate: N = 305, Poor: N = 178, Bad: N = 24). In accordance with the methodology of previous citizen science research (Ramírez et al., 2023), a simplified macroinvertebrate community was identified to facilitate the systematic identification by volunteers. The taxonomic level was set at family rank, with the exception of a few taxa that were grouped at higher taxonomic levels, such as Bivalves, Oligochaeta, Hirudinea, and Tricladida.

The frequency of each taxon was calculated as the percentage of occurrence among sampling events. Therefore, only 36 taxa were selected to be representative of the macroinvertebrate fauna of the study area based on their frequency rank (Table 1). Although their low percentage abundance (<4%), Aphelocheiridae, Coenagrionidae, Bivalves, and Ecnomidae were included in the simplified community because typical of some river ecosystems (e.g., agricultural ditches) in the study area but underrepresented in the calibration dataset. Indicator Species Analysis (ISA; Dufrene and Legendre, 1997) was run to evaluate whether both sensitive and tolerant taxa were included within the simplified community. Before performing ISA, the ecological status class of each sampling event was grouped into two categories: “Not-impacted” (i.e. High + Good; N = 425) and “Impacted” (i.e. Moderate + Poor + Bad; N = 507), and indicator taxa were searched for these two latter categories in order to verify whether among the 36 selected taxa there were representatives of both conditions.

Moreover, the following biodiversity and biomonitoring metrics were obtained for both the whole and simplified community: total taxon richness, EPT (Ephemeroptera, Plecoptera and Trichoptera) richness, ASPT (Average Score Per Taxon), and BMWP (Biological Monitoring Working Party). These represent worldwide commonly used metrics in river biomonitoring with macroinvertebrates (Bonada et al., 2006; Verdonshot and Moog, 2006; O’Callaghan & Kelly-Quinn, 2017; Eriksen et al., 2021; Fenoglio and Doretto, 2021). Moreover, three of them, namely total taxon richness, EPT richness, and ASPT are sub-metrics of the STAR_ICMi index and were thus chosen to guarantee, at least partially, a link with the official methodology for Italian rivers. When

Table 1

List of the selected families/taxa of the simplified macroinvertebrate community. % Occurrence = percentage of occurrence of each taxon in the calibration dataset.

Taxonomic group	Family / taxon	% Occurrence
Plecoptera	Leuctridae	50
Ephemeroptera	Ephemeridae	18
	Ephemerellidae	55
	Baetidae	95
	Caenidae	59
	Heptageniidae	70
Trichoptera	Hydropsychidae	87
	Ecnomidae	4
	Goeridae	15
	Leptoceridae	14
	Limnephilidae	16
	Odontoceridae	10
	Psychomyiidae	15
	Rhyacophilidae	54
Coleoptera	Dytiscidae	61
	Dryopidae	11
	Gyrinidae	14
Odonata	Gomphidae	29
	Calopterygidae	13
	Coenagrionidae	1
Hemiptera	Corixidae	12
	Aphelocheiridae	4
Diptera	Limoniidae	49
	Chironomidae	99
	Empididae	19
	Simuliidae	75
	Tabanidae	27
	Tipulidae	27
Crustacea	Asellidae	18
	Gammaridae	38
Gastropoda	Ancylidae	13
	Physidae	16
Others	Bivalves	3
	Hirudinea	19
	Oligochaeta	84
	Tricladida	26

calculating BMWP on the simplified community, the approach of Alba-Tercedor and Sánchez-Ortega (1988) allowed to assign each taxon its own score with exception of Bivalves. Because in this study all the families were pooled together and analysed as Bivalves, a conservative score of 3 was assigned this taxon. It corresponds to the lowest score for the bivalve mollusks in Italian rivers (i.e. Sphaeriidae). For each sampling event in the calibration dataset, significant correlations between the metrics calculated on the whole and simplified communities were statistically evaluated. Similarly, the correlations between the metrics calculated on the simplified community and STAR_ICMi index calculated on the whole community were tested. Pearson correlation index was used for ASPT, while Spearman correlation index was used for total taxon richness, EPT richness, BMWP and STAR_ICMi.

Generalized linear models with binomial distribution were used to identify thresholds in the four selected metrics calculated on the simplified community discriminating between “Not-impacted” and “Impacted” conditions based on the ecological status assessment gained from the whole community. Thresholds were derived from the equation (Eq. (1)) of the regression models as the inflection point of the logistic curve of the model.

$$\frac{P}{1-P} = e^{\beta_0 X + \beta_1} \quad (1)$$

The analysis conducted returned the values of β_0 and β_1 , used to define the abscissa of the inflection point with ordinate 0.5, which corresponds to the threshold value (Peng et al., 2002). To evaluate the degree of agreement in assessing the ecological status (i.e. “Impacted” vs “Not-impacted”) between the STAR_ICMi index and the derived thresholds, Cohen’s Kappa coefficient (Cohen, 1960) and the percentages of

correctly classified instances (CCI%) were calculated. With respect to its interpretation, it was adopted the approach proposed by Fleiss et al. (2003): $Kappa < 0.4 =$ poor agreement, $0.4 < Kappa < 0.75 =$ good agreement, and $Kappa > 0.75 =$ excellent agreement.

2.3. Validation dataset

From November 2023 to June 2024 ten sampling campaigns with citizen science volunteers were performed in nine different river ecosystems in the study area, especially within the Vercelli and Novara Provinces (Fig. 1; Supplementary Materials Table S1). None of these sampling sites overlapped with those of the calibration dataset. Sampling sites were selected according to their accessibility and ranged from mid-order river stretches to agricultural streams and ditches. No data on the ecological status of selected sites were available, but preliminary and personal observations allowed us to assume that their ecological status ranged from Good to Poor (Chiorino et al., 2024). They varied in wetted width and showed some differences in the substrate composition, but they were all wadeable and representative of HER6 (i.e. Pianura Padana). A total of 197 volunteers were involved, including high-school and college students, anglers, rangers, children and parents, and volunteers of NGOs. The number of volunteers per sampling event varied from 10 to 29 (Supplementary Materials Table S1).

On each sampling occasion, benthic macroinvertebrates were always sampled by the same operators (i.e. AD, AL, SR) collecting from 10 to 12 Surber samples (surface area: 0.05 m^2 , mesh size: $500 \mu\text{m}$; Doretto et al., 2020) across all the representative substrates. Then, the collected material was transferred into different plastic trays for sorting. Volunteers were divided into small sub-groups, assigned to one or two trays, and actively involved in the systematic identification of macroinvertebrates. To this end, specific and simplified atlas and dichotomous keys, based solely on the simplified community, were created and provided with volunteers along with lens, forceps, and a field sheet for recording all the sampled taxa (i.e. presence/absence). Systematic identification was performed by volunteers and experts (i.e. AD, AL, SR) verified the accuracy of their identification. At the end of the sorting phase (on average 2–3 h), all the data recorded by each sub-group of volunteers were aggregated to obtain a total macroinvertebrate community. Based on this latter one, the total taxon richness, EPT richness, BMWP and ASPT were calculated and discussed with volunteers.

To validate the proposed methodology, macroinvertebrate data from 11 benchmark sites ($N = 41$ sampling events; time period: 2020–2022) were downloaded from the website of the regional agency for environmental protection (ARPA Piemonte). These sites were chosen because of their strong geographical proximity with those monitored with volunteers (Supplementary Materials Fig. S1) and represented the latest available information that were not included in the calibration dataset. Benchmark sites were also representative of both “Not-impacted” (27 %) and “Impacted” conditions (73 %). Cohen’s Kappa coefficient was calculated to verify the degree of agreement with the ecological status assessment based on the official methodology and that obtained from the proposed metrics based on the simplified community. Moreover, for all the benchmark sites the mean (\pm SD) values of the proposed metrics were calculated and compared to those obtained with volunteers to better contextualize the results at local scale.

All the statistical analyses (significant threshold: $p\text{-value} < 0.05$) were performed with the R software (R Core Team, 2022) by using the basic functions and those of the following R packages: biomonitoR (Laini et al., 2022), indicpecies (Cáceres and Legendre, 2009), ggplot2 (Wickham, 2011), terra (Hijmans et al., 2022), vcd (Meyer et al., 2020), and maptiles (Giraud, 2022).

3. Results

3.1. Calibration dataset

Among the 36 taxa composing the simplified community, Indicator Species Analysis identified 18 taxa as indicative of “Not-impacted” or “Impacted” conditions (Table 2). Sixteen taxa were significantly associated with the “Not-impacted” conditions and, among these, 8 taxa belong to the EPT group. By contrast, Hirudinea and Bivalves were statistically representative of “Impacted” conditions.

Overall, all the selected metrics calculated on the simplified community were positively and significantly correlated with those obtained from the whole community (Fig. 2a-d). The strength of these correlations was generally high and varied from 0.894 (ASPT sel vs ASPT tot) to 0.930 (BMWP sel vs BMWP tot). Similarly, all the selected metrics calculated on the simplified community were statistically and positively correlated with STAR_ICMi (Fig. 2e-h), with the strength of these associations varying from 0.740 (N. taxa sel vs STAR_ICMi) to 0.831 (N. EPT sel vs STAR_ICMi).

Logistic regression models showed significant variations in the selected metrics from “Not-impacted” to “Impacted” conditions. Therefore, thresholds were obtained for all the four metrics (Table 3). When testing the degree of agreement in assessing the ecological status between the official methodology and the derived thresholds of the selected metrics, Cohen’s Kappa was always higher than 0.40, despite some differences being found depending on the metric (Table 3). ASPT showed the lowest Kappa as well as the lowest percentage of correctly classified instances (CCI%). Taxon richness and EPT richness showed similar K values, despite the percentage of correctly classified instances was higher for EPT richness (80.5 %). On the contrary, BMWP was the metric with the highest K and CCI% (Table 3).

3.2. Validation dataset

A total of 44 different macroinvertebrate taxa were collected on the ten sampling campaigns with citizen science volunteers (Table 4). Among these, 33 taxa belonged to the simplified community defined prior to the sampling activity. The most frequent taxa were: Gomphidae, Calopterygidae, Baetidae, Hydropsychidae, Goeridae, Gammaridae, Chironomidae, Simuliidae, and Bivalves. It should be acknowledged that Bivalves were uniquely represented by the invasive species *Corbicula fluminea*. On the contrary, 11 taxa out of 44 were not included in the simplified community: Aeshnidae, Corduliidae, Lepidostomatidae, Elmidae, Haliplidae, Hydrophilidae, Nepidae, Pleidae, Planorbidae, Valvatidae, and the invasive species *Procambarus clarkii*. However, six of

Table 2

Results of the ISA: list of the indicator taxa for the two conditions (“Not-impacted” and “Impacted”) and their statistics.

Water quality class category	Taxon	Ind. Val.	p-value
“Not-impacted”	Heptageniidae	0.940	0.001
	Leuctridae	0.843	0.001
	Rhyacophilidae	0.839	0.001
	Dytiscidae	0.837	0.001
	Ephemerelellidae	0.807	0.001
	Limoniidae	0.729	0.001
	Tabanidae	0.593	0.001
	Ephemeridae	0.586	0.001
	Goeridae	0.523	0.001
	Gyrinidae	0.521	0.001
	Empididae	0.497	0.001
	Limnephilidae	0.480	0.001
	Odontoceridae	0.459	0.001
	Ancyliidae	0.446	0.001
	Tricladida	0.361	0.001
	Oligochaeta	0.222	0.002
“Impacted”	Hirudinea	0.248	0.001
	Bivalves	0.210	0.004

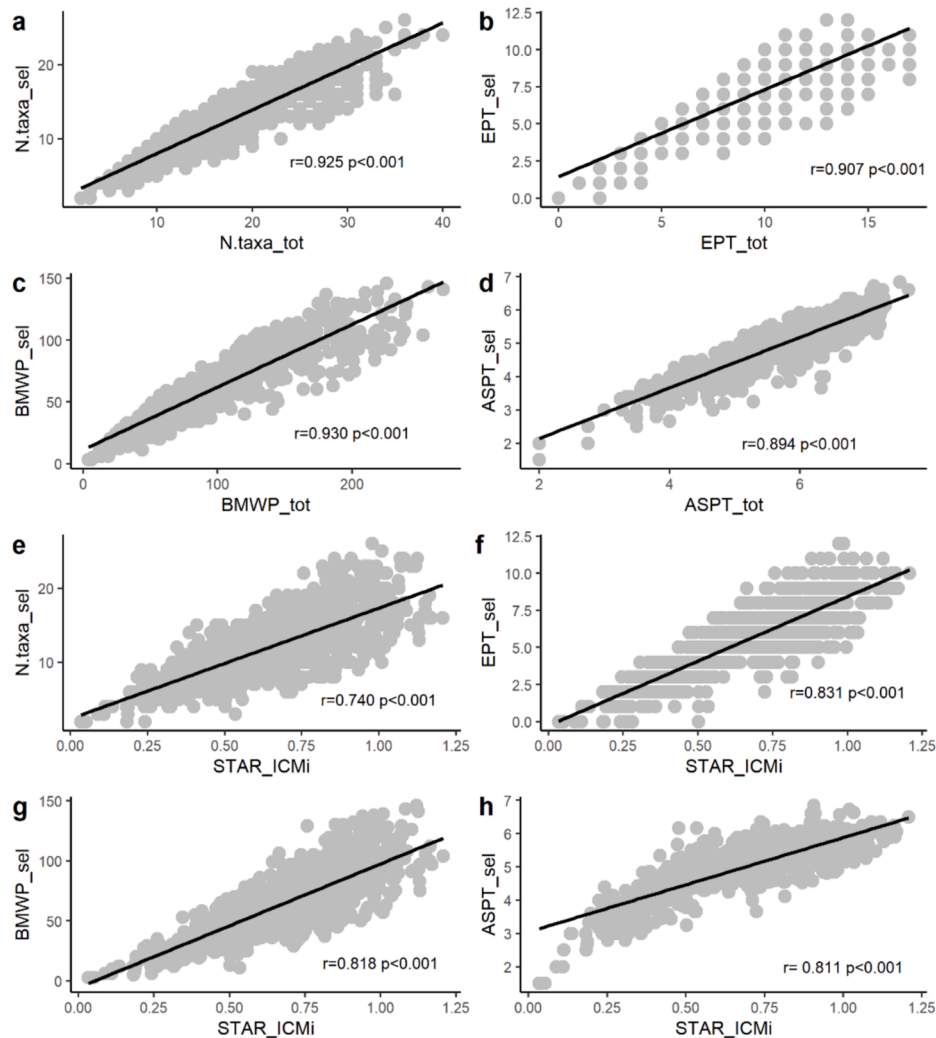


Fig. 2. Scatter plots illustrate the correlations between the selected metrics calculated on the whole and simplified communities (2a-d) and the correlations between the selected metrics based on the simplified community and STAR_ICMi (2e-h). Black line represents the regression line, while r and p are the rho coefficient and p -value, respectively.

Table 3

Output of the logistic regression models for the four selected macroinvertebrate metrics. Thresholds were derived by using Equation (1) as the inflection point of the logistic curve of the model. K = Cohen's Kappa coefficient illustrating the degree of accordance in the ecological status assessment between the derived threshold and that obtained by the official method (i.e. STAR_ICMi). CCI% = percentages of correctly classified instances.

Metric	β_0	β_1	p-value	Threshold		K	CCI%
Total taxon richness	-5.712	0.439	<0.001	13	>13: "Not-impacted" ≤13: "Impacted"	0.558	78.3
EPT richness	-6.462	1.089	<0.001	6	>6: "Not-impacted" ≤6: "Impacted"	0.559	80.5
BMWP	-14.158	2.753	<0.001	67	>67: "Not-impacted" ≤67: "Impacted"	0.613	80.9
ASPT	-5.667	0.085	<0.001	5.14	>5.14: "Not-impacted" ≤5.14: "Impacted"	0.521	76.2

them occurred only on one sampling occasion, and other four on two sampling occasions out of ten. Only *Procambarus clarkii* was recorded more than two times. The average number of taxa collected per sampling event was $14.4(\pm 3.204$ SD) considering the simplified community (SC), a value that increased to $16.5(\pm 3.171$ SD) when including the taxa that were not a-priori selected in the simplified community.

Based on the derived thresholds for the selected metrics, only sites 1b (Doretta Morta on 4th April 2024) and 8 (Risorgiva Darè) were consistently classified as "Non-impacted" with both the simplified community

and the entire sampled community (Fig. 3). Sites 2 (Fontana Pietta) and 7 (Mulino San Giovanni), instead, represented the worst conditions: they were always classified as "Impacted" by using both all the collected taxa and the simplified community (Fig. 3). For the remaining sites the ecological status assessment varied depending on the metric as well as the input macroinvertebrate community. When looking at the taxon richness, EPT richness, and BMWP, the identified thresholds were always higher than the mean(+SD) values of the benchmark sites classified as "Impacted" in the study area (Fig. 3). By contrast, the identified

Table 4

List of taxa recorded on the sampling campaigns with citizen science volunteers. Macroinvertebrate taxa that were not originally included in the simplified community are in bold.

	Doretta morta		Fontana Pietta	Torrente Agogna	Cavo Busca	Roggia Molinara	Parco Lame del Sesia	Mulino San Giovanni	Risorgiva Daré	Torrente Rovasenda
	a	b								
Leuctridae										+
Gomphidae	+		+	+	+	+	+		+	+
Aeshnidae						+			+	
Corduliidae							+			
Calopterygidae	+	+	+	+	+		+		+	+
Coenagrionidae				+			+		+	
Heptageniidae	+	+		+						+
Baetidae	+	+	+	+	+	+	+	+	+	+
Caenidae										+
Ephemerellidae		+		+		+	+		+	
Epheremidae									+	
Hydropsychidae	+	+	+	+	+	+	+		+	+
Rhyacophilidae		+				+			+	+
Limnephilidae					+	+	+			+
Odontoceridae	+	+				+			+	
Goeridae	+	+		+	+				+	
Leptoceridae									+	
Psychomyidae	+									
Ecnomidae										
Lepidostomidae				+						
Hydrophilidae					+					
Elmidae	+									
Halplidae						+		+		
Dryopidae		+		+	+					+
Gyrinidae	+									
Dytiscidae	+			+	+					+
Nepidae					+			+		
Pleidae						+		+		
Aphelocheiridae			+		+			+	+	
Corixidae										
Gammaridae	+	+	+	+	+				+	+
Asellidae			+	+				+		
P. clarkii						+		+	+	
Ancylidae									+	
Physidae	+	+					+	+		
Planorbidae				+						
Valvatidae	+									
Bivalves	+	+	+	+	+	+	+		+	
Tricladida		+								
Chironomidae	+	+	+	+	+	+	+	+	+	+
Simuliidae	+	+		+		+	+	+	+	+
Limoniidae			+	+						
Empididae							+			
Tabanidae										
Tipulidae	+					+	+	+	+	+
Hirudinea	+	+			+	+	+			+
Oligochaeta	+	+	+	+	+	+	+	+	+	+

threshold for ASPT was very close to the average value of this metric observed for the “Impacted” benchmark sites. ASPT values obtained in the sampling sites monitored with volunteers were always included in the range of mean \pm SD of the “Impacted” benchmark sites, with exception of site 8 (Risorgiva Daré) (Fig. 3). When evaluating the degree of accordance between the official methodology and the proposed metrics on the data from the benchmark sites, the lowest Kappa values were obtained for taxon richness ($K = 0.341$; $CCI\%=75.6\%$) and ASPT ($K = 0.412$; $CCI\%=68.3\%$). On the contrary, the highest agreement with the official methodology was found for EPT richness ($K = 0.492$; $CCI\%=82.9\%$) and BMWP ($K = 0.627$; $CCI\%=85.4\%$).

4. Discussion

Biomonitoring is one of the most cost-effective approaches to evaluate the ecological status of rivers worldwide (Buss et al., 2015; Resh, 2007). The amount of data produced through biomonitoring has increased considerably in the last decades insofar as, nowadays, this approach is officially included in the national legislation of many

countries (Nguyen et al., 2019). Also, previous studies have shown that biomonitoring data offer pivotal information and science-based knowledge to guide political decisions on environmental management, species and nature conservation, and habitat restoration (Darwall et al., 2018; Deacon et al., 2023). However, river biomonitoring loses its effectiveness when data collection is spatially or temporally inconsistent or even limited. Hence, joint and collective efforts should be performed by researchers, professionals, and societies to implement the river biomonitoring techniques and approaches, especially under the current “freshwater biodiversity crisis” (Tickner et al., 2020; Arthington, 2021; Ottoni et al., 2023).

The aim of this study was to develop and validate a citizen science approach to implement the ecological status assessment of rivers by using benthic macroinvertebrates and related community metrics. Citizen science projects dealing with benthic macroinvertebrates are still scarce in Italy, despite the variety of river ecosystems and the long tradition in biomonitoring (Bo et al., 2017). For instance, Grano et al. (2023) involved volunteers in the collection of mussel species along the Tevere River, but this occasional experience was carried out solely on a

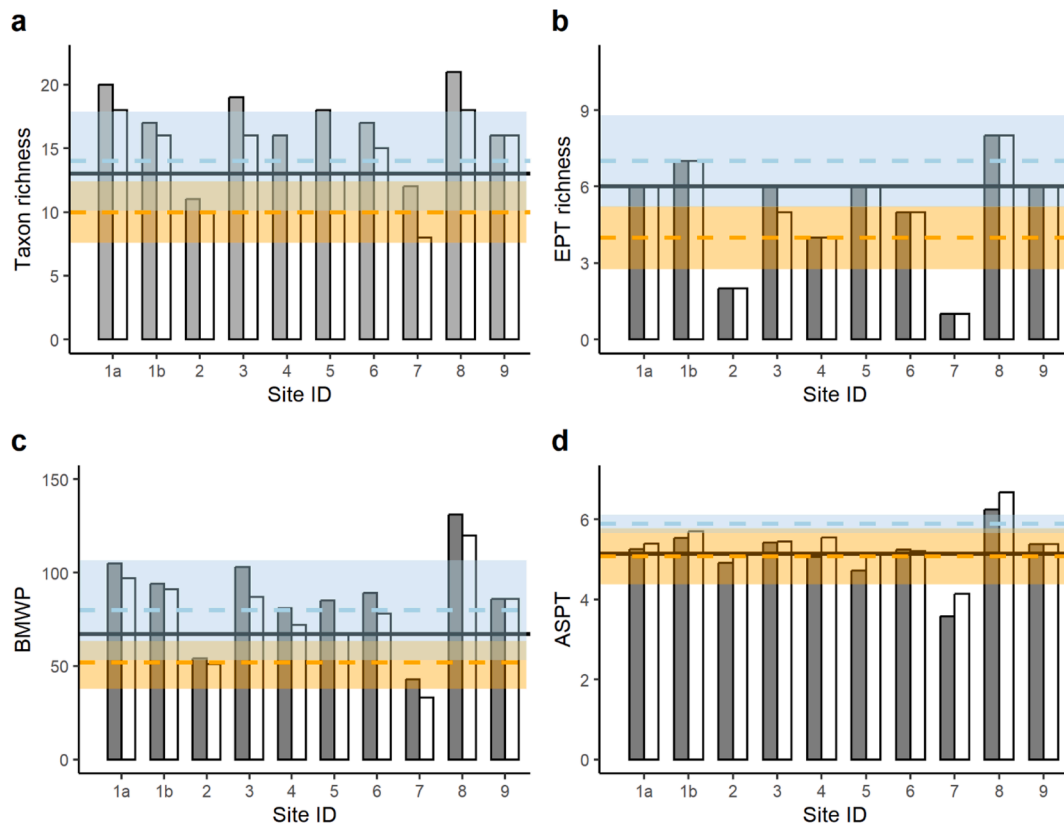


Fig. 3. Bars illustrate the variation of the four selected metrics across the sampling sites surveyed with citizen science volunteers (validation dataset): Doretta Morta (1a, 1b), Fontana Pietta (2), Torrente Agogna (3), Cavo Busca (4), Roggia Molinara (5), Parco Lama del Sesia (6), Mulino San Giovanni (7), Risorgiva Darè (8), Torrente Rovasenda (9). Grey bars indicate the value calculated with all the taxa collected, while white bars indicate the value calculated by using only the taxa of simplified community. Horizontal black lines indicate the derived thresholds discriminating the “Not-impacted” and “Impacted” conditions. Dashed orange and light-blue lines indicate the mean value of the metric for the “Impacted” and “Not-impacted” benchmark sites in the study area, respectively. Orange and light-blue areas indicate the mean \pm SD of the metric for the “Impacted” and “Not-impacted” benchmark sites in the study area, respectively.

specific taxonomic group. Similarly, most of the current projects aim at monitoring of flow conditions (Ferri et al., 2020) or the riparian vegetation (Gumiero et al., 2023, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4663192). Therefore, this study likely represents one of the first attempts, especially in Northern Italy, trying to engage volunteers in the river biomonitoring activities using benthic macroinvertebrate communities.

By following the approach proposed in previous studies (McSorley, 2022; Ramírez et al., 2023; von Gönner et al., 2023), we first defined a simplified macroinvertebrate community composed of 36 taxa. Data gained from the sampling campaigns with citizen science volunteers showed that 33 out of the 36 macroinvertebrate taxa originally included in the simplified communities were found at least once, thus confirming their representativeness for the monitored rivers. Among these taxa there were also two invasive species: *P. clarkii* and the mussel *Corbicula fluminea*. This aspect confirms the utility of citizen science for recording the presence and spread of invasive species, as previously shown in other studies (Encarnaçao et al., 2021; Faraone et al., 2017; Trichkova et al., 2021). As expected, 11 additional taxa were also found but, with the exception of the invasive species *P. clarkii*, restricted to a single site. Among the eleven additional taxa, only Lepidostomatidae and Planorbidae showed a percentage of occurrence equal to 7 % in the calibration dataset, while the other taxa were less than 3 % frequent. These findings indicate that the simplified community was adequately representative of the pool of macroinvertebrates. Also, it served as a simple and practical taxonomic list for volunteers. Previous studies have noticed the data collection and, when necessary, data processing should be as simple as possible to make them effective and reliable (Ramírez et al., 2023). For instance, in a river biomonitoring project with citizen

scientists, Moolna et al. (2020) applied the ARMI index, that is a simplified version of the BMWP index, based on only seven macroinvertebrate taxa. Similarly, a large-scale citizen science project on the water quality assessment of South-African rivers focussed on 14 macroinvertebrate taxa (Taylor et al., 2022, <https://minisass.org/#/howto>). Onion et al. (2023), instead, developed a citizen-based methodology for evaluating the ecological status of rivers in the New York State (USA). Similar to the approach here used, the authors first identified 36 and 12 macroinvertebrate taxa statistically associated with pristine and impacted conditions, respectively. Then, relevant thresholds in selected biomonitoring metrics based on the abundance of the indicator taxa were derived (Onion et al., 2023).

Results of the ISA confirmed and even strengthened the previous ones on the representativeness of the simplified community. In fact, 18 taxa (i.e. 50 %) out of the 36 originally selected were statistically associated with “Not-impacted” (16 taxa) or “Impacted” (2 taxa) conditions. Among the former ones, eight belonged to the EPT group, namely Leuctridae, Heptageniidae, Ephemeridae, Ephemerellidae, Rhyacophilidae, Limnephilidae, Goeridae, and Odontoceridae. These findings are corroborated by previous studies highlighting how the EPT taxa are the most sensitive riverine macroinvertebrates (Akamagwuna et al., 2019; Marino et al., 2024). However, we found also not-EPT taxa associated with the “Not-impacted” conditions, including two families of Coleoptera (i.e. Dytiscidae and Gyrinidae), three Dipteran families (i.e. Tabanidae, Empididae, and Tipulidae), Ancyliidae, Tricadida, and Oligochaeta. While the result for Oligochaeta disagrees with the scientific literature because these organisms are usually considered as tolerant (Rimcheska and Vidinova, 2020), previous studies have demonstrated that some Coleopterans and Dipterans can be considered sensitive

(Chang et al., 2014; Berger et al., 2018). By contrast, Hirudinea and Bivalves were identified as indicative taxa of “Impacted” conditions, thus confirming evidence of previous research on their tolerance to chemical pollution and physical disturbance (Waykar and Deshmukh, 2012; Cortelezzi et al., 2018).

When comparing our proposed citizen science approach with the official methodology for river biomonitoring with macroinvertebrates in Italy, strong positive correlations between the selected metrics calculated on the simplified communities and the STAR_ICMi index were found. Moreover, results from the calibration dataset showed a good agreement in the ecological status assessment between the derived thresholds of the selected metrics and the official methodology. Cohen’s Kappa values obtained for the selected metrics were always higher than 0.40 with the percentage of correctly classified instances ranging between 76.2 % and 80.9 %. In accordance with previous research, $K > 0.40$ with $CCI\% = 80\%$ are considered reliable results in ecological studies (Randin et al., 2006; Gabriels et al., 2007; Mereta et al., 2013; Gezie et al., 2020). Overall, these findings indicate that our proposed metrics and their derived thresholds are, potentially, reliable proxies of the official monitoring index (i.e. STAR_ICMi).

When the proposed citizen science approach was validated at local scale, little to negligible variation in the ecological status assessment were observed between the metrics calculated on the simplified community only and those obtained by including even the additional taxa. This suggests that, likely, the simplified community here proposed is weakly affected by the presence of occasional taxa. However, contrasting results on the reliability of the selected metrics arose. ASPT showed poor agreement with the official methodology, as proven by the low values of Cohen’s Kappa and percentage of correctly classified instances. ASPT values in the sites monitored by volunteers were comparable to the average values of the benchmark sites classified as “Impacted”, thus limiting its reliability. Taxon richness showed a poor agreement with the official methodology, despite its derived threshold and the values observed in the sites monitored by volunteers approached those of the “Not-impacted” benchmark sites in the study area. By contrast, EPT richness and, especially, BMWP showed a good agreement with the official methodology as proven by the high values of Cohen’s Kappa and percentages of correctly classified instances (always higher than 80 %). In the sites monitored by volunteers, the derived thresholds as well as the values of these metrics were similar to those observed for the “Not-impacted” benchmark sites in the study area.

Therefore, the ecological status assessment in this study benefited by the choice of adopting four different metrics. With respect to the official methodology, the derived thresholds for BMWP and EPT richness offered the most reliable and coherent results. These findings corroborate the large-scale application of these metrics in river biomonitoring, as previously observed in scientific literature (Chiorino et al., 2024; Clarke and Murphy, 2006; Yu et al., 2017). On the contrary, the derived thresholds for taxon richness and ASPT showed limited agreement with the official methodology and need further validations. In a review on the success factors of citizen science projects in water monitoring, Capdevila et al. (2020) found that the institutions’ motivation was a relevant aspect affecting the effectiveness and long-term establishment of biomonitoring activity with volunteers. Since taxon richness, EPT richness, and ASPT are sub-metrics of the official macroinvertebrate-based index (STAR_ICMi) in Italy, we believe that our approach may offer real chances to foster the collaboration between local groups of citizen science volunteers and professionals, with the ultimate goal of increasing the number of rivers to be monitored as well as contributing to the further validation of the proposed approach. For instance, rivers in the geographical area of this study are typically monitored by professionals every three years (Bo et al., 2017). In the light of this, the simplified approach here proposed for groups of trained volunteers may contribute to increase the frequency of data collection. This, in turn, assumes a particular importance in relation to the current climate change and the increased anthropogenic pressures on water supplies.

The citizen science approach has grown exponentially in the last years (Larson et al., 2020; Orchard, 2018), despite there is still no single and universally accepted definition of what exactly citizen science is (Heigl et al., 2019). Generally speaking, this term indicates the active and autonomous involvement of people in the collection and, at least partly, processing of scientific data under the supervision and coordination of researchers (Burgess et al., 2017; Strasser et al., 2019; Vohland, 2021). It should be acknowledged that in our study the active involvement of citizens was limited to the sorting and taxonomic identification of benthic macroinvertebrates, while biomonitoring metrics were calculated with the assistance of the experts. Yet, our study represents the first attempt aimed at developing a citizen science approach for river biomonitoring in the study area where, to our knowledge, previous and similar experiences and groups of active volunteers did not exist. Our volunteer-driven approach is therefore justified by the need of validating an effective and practical method, which may be used independently by the volunteers in the next future. To this end, we found that the adoption of simplified taxonomic keys and atlas for the selected community coupled with the calculation of different and qualitative metrics facilitated the active participation of volunteers. In fact, many of them joined several sampling campaigns because of the increased interest in the experience along with enhanced familiarity with the approach (personal observation). Further studies will be necessary to further test the effectiveness of the proposed approach. Nonetheless, the results and the experience gained so far, although preliminary, contributed to mobilize and raise awareness of groups of local people. This substantially agrees with the general objectives and philosophy of the citizen science as reported in previous research (Abhijith et al., 2024; Jordan et al. 2011; Locritani et al., 2019; Moedas, 2018; Phillips et al., 2021).

CRediT authorship contribution statement

Samuele Roccatello: Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Alessandro Lagrotteria:** Writing – review & editing, Writing – original draft, Methodology. **Chiara Andrà:** Writing – review & editing, Writing – original draft, Methodology. **Alberto Doretto:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Originate” which has received funding from European Commission - NextGeneration EU and Compagnia di San Paolo.

Author contributions

Conceptualization, A.D., Methodology, formal analysis, writing—original draft preparation, A.D., S.R., A.L., C.A.; Data collection, writing—review and editing, A.D., S.R., A.L., C.A. All authors have read and agreed to the published version of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2025.113199>.

Data availability

Data will be made available on request.

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