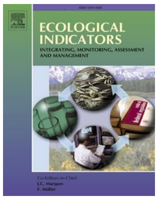
Ecological Indicators 153 (2023) 110433

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Unveiling relationships between ecosystem services and aquatic communities in urban streams

Ana Raquel Calapez [a,*], Sónia R.Q. Serra [a], Andreia Mortágua [b], Salomé F.P. Almeida [b], Maria João Feio [a]

[a] MARE – Marine and Environmental Sciences Centre, Laboratório Associado ARNET, Department of Life Sciences, University of Coimbra, Portugal
[b] GeoBioTec & Department of Biology, University of Aveiro, Portugal

ARTICLE INFO

Keywords:
Urbanization
Indicators
Macroinvertebrates
Diatoms
Ecosystem services

ABSTRACT

River and stream ecosystems within cities can provide important Ecosystem Services (ES) to urban population along with the maintenance of biodiversity. Increasing urbanization with land use change can affect biodiversity, impacting ES provision, but the relationships between biota and ES are complex and poorly understood. This study aims to explore relationships between aquatic biodiversity (communities' composition and structure), urbanization and ES provided by urban streams. Nine streams were surveyed within a city area (up to 8 km of the city centre) focusing on common biological indicators (i.e., macroinvertebrates and diatoms), as well as several indicators of Provisioning ($N = 7$), Regulation ($N = 14$) and Cultural ($N = 23$) services for this type of ecosystem. Urban stream sampling sites were also assessed in terms of their urbanization degree, according to the surrounding imperviousness area (IMD). Pearson correlations showed trends of negative relationships between IMD and both Provisioning and Regulating services. Yet, urbanization effects on the biota seemed to be mitigated due to enhanced hidromorphological site features. The community structure and composition of invertebrates and diatoms was differently associated to ES (BIOENV analysis). Whereas macroinvertebrate communities related specifically with Provisioning and Regulating indicators, the diatom responded just to regulating indicators. Overall, this study showed that aquatic biodiversity is linkable with ES provided by urban streams, and such relationship depends on specific ES indicators mainly for Provisioning and Regulating services. Additionally, macroinvertebrate communities can be used as a suitable indicator for the potential of streams in supplying Provisioning and Regulating ecosystem services. This shows that their indicator value goes beyond their known potential as indicators of structural and functional integrity of river ecosystems. These results also reinforce the need to protect nature associated to running water ecosystems in urbanized areas, as they provide green and blue solutions for the sustainability of cities.

1. Introduction

Both natural and managed ecosystems provide a wide variety of benefits to people (MEA, 2005), from food, clean water, flood protection and climate change mitigation to cultural heritage. Such benefits known as "Ecosystem Services" (ES) are essential for human life and the well-being of human population (Díaz et al., 2018; Haines-Young and Potschin 2018; MEA, 2003, 2005).

Particularly, urban river and stream ecosystems have a great potential in providing important ES to their inhabitants and promoting the sustainability of cities (Elmqvist et al., 2015; Grimm et al., 2008; Haase, 2015). Riverine ecosystems are composed of blue and green areas which includes the flowing water and its aquatic communities (fauna and flora), but also corridors of riparian vegetation and associated terrestrial or semi-aquatic fauna. Thus, urban streams have the potential of maintaining urban biodiversity, improving aesthetics and air quality, mitigating floods and extreme temperatures, establishing recreational areas and promoting the well-being and health of the population, among other important ES (Brauman et al., 2007). These include Provisioning, Regulating, and Cultural services. Provisioning services are products that are obtained from an ecosystem (e.g. water, food, raw materials), and Regulating services are mainly benefits derived from the biophysical ecosystem properties (e.g. climate regulation, flood risk mitigation). Cultural services refer to nonmaterial benefits including both physical

---

* Corresponding author.
E-mail address: anacalapez@uc.pt (A. Raquel Calapez).

https://doi.org/10.1016/j.ecolind.2023.110433
Received 23 January 2023; Received in revised form 16 May 2023; Accepted 25 May 2023
Available online 6 June 2023
1470-160X/© 2023 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

and mental amenities for inhabitants (e.g. aesthetics, recreation, tourism and cultural heritage) (MEA, 2005).

However, the provision of many of these ES are under severe threat from anthropogenic pressures (Keyes et al., 2021). Among the various types of land-uses, urbanization arises with a complex mixture of changes, including land-use modifications (e.g. increasing soil sealing, decreasing natural habitats), and environmental disturbances (e.g. hazardous substances, higher temperatures). These alterations increase the stress on local species diversity and ecological processes (Del Arco et al., 2012; Serra et al., 2019), inducing the establishment of different ecological communities and the so-called novel ecosystems (Evers et al., 2018; Swan et al., 2011). As urban areas are expanding faster than urban populations in several areas of the world, the effect of urbanization is acknowledged as a key driver of biodiversity change and ecosystems services loss at a global scale (Seto et al., 2013; Zari, 2018).

The importance of biodiversity behind the delivery of ES is well recognised (Díaz et al., 2006, 2018; MEA, 2005), with effects of biodiversity loss on the provision of ES (e.g. Balvanera et al., 2006, 2014; Cardinale, 2012). In fact, biological diversity is closely associated to ecosystem functioning and expected to positively influence the provision of certain ES (Cardinale et al., 2012; Vaughn, 2010; Worm et al., 2006). For instance, ES that improve water quality and flow regulation are enhanced by increasing community and habitat area (Harrison et al., 2014), and biodiversity should also stabilise the provision supply of ES over time (Chapin et al., 2000; Hooper et al., 2005; Tilman, 1996). Thus, there is great concern about the effects of biodiversity decay, not only for ecosystems, but also for human well-being and sustainability (Balvanera et al., 2014; Cardinale et al., 2012). In this context, the ecosystem services approach enables to assess the relationship between the environment and human populations providing a more comprehensive approach for decision-making. Several approaches have been taken in an attempt to measure and value ecosystem services aiming at integrating both natural and social systems (e.g. MEA, 2005; UNEP, 2007; TEEB, 2010; IPBES in Díaz et al., 2015), among which is a recent framework and assessment tool designated Urban stream Assessment system (UsAs; Ranta et al., 2021), based on the Millennium Ecosystem Assessment (MEA, 2005) and the Common International Classification of Ecosystem Services (CICES; Haines-Young and Potschin, 2018). This ecological assessment tool (UsAs) was developed specifically for urban streams and contemplates surveys of the several services provided by the ecosystem (including Provisioning, Regulating and Cultural services among others).

Despite the recognition of the importance of biodiversity and ecosystem services in urban areas, there is a lack of studies that allows a clear understanding of how one influences the other, which leads to disagreements on the adequate management of urban freshwater ecosystems (e.g. Evers et al., 2018; Murcia et al., 2014).

Thus, in this study, the overall objective is to assess the relationships between biodiversity and ES, while characterizing them in urban streams based on UsAs framework (Ranta et al., 2021). For that, we investigate the relation between Provisioning, Regulating and Cultural services and two important biological elements of aquatic communities and bioindicators, the benthic macroinvertebrates and diatoms. We assess community structure and composition and ES indicators of urban streams with different urbanization degrees according to their imperviousness area. Specifically we investigate a) which is the type of relationship between urban biodiversity and ES (does biodiversity influence negatively or positively the provision of ES?); b) which ES indicators are more and less related with aquatic bioindicators (diatoms and invertebrates), c) whether streams with enhanced biodiversity and better ecological quality are able to provide more ES than those with worse biodiversity and ecological quality, and d) how does the degree of urbanization influence biodiversity and ES? We hypothesized that 1) specific ES are influenced by lower biodiversity and by urbanization intensity, 2) aquatic communities and ecological quality can reflect ecosystem services provision 3) urbanization affects biodiversity in proportion to its degree of influence in streams' alterations.

2. Methods

2.1. Study area

In order to assess aquatic communities and the Ecosystem Services (ES) we surveyed nine urban streams (uS) within river Mondego catchment in Coimbra (central Portugal) (Fig. 1). The municipality of Coimbra comprises an area of 319.40 km^2 with ca. 140 838 inhabitants (ine.pt, 2021), located in both banks of river Mondego and is considered the fourth-largest urban centre in the country. Geographically, Coimbra region is influenced by a Temperate-Mediterranean climate alternating between a cold, rainy season and a hot dry season with mean annual precipitation ranging from 348.4 mm in winter and 71.6 mm in summer and a mean monthly temperature from 10.1 °C (winter) to 21.3 °C (summer) (IPMA, long data series at "https://www.ipma.pt/en/oclima/series.longas/?loc=Coimbra/Geof%C3%ADsico&type=raw".

The sampling sites of the urban streams are located up to a distance of 8 km from the city centre and cover different watershed tributaries of the main river Mondego (Fig. 1) presenting different degrees of urbanization (measured as soil % of imperviousness density; IMD) and environmental conditions (Table 1; Fig. 2). Accordingly, less urbanized stream sites (i.e. uS8 and uS9; Table 1; Fig. 2a,b) presented adjacent margins of semi-continuous riparian vegetation composed by adult trees, scrubs and rank vegetation, and were characterized with larger areas of available land to natural floods (i. e., areas that can receive water in high precipitation periods without causing damages in constructed areas), whereas more urbanized stream sites such as uS3, uS4 and uS5 (Table 1, Fig. 2c,d) presented extensive construction on the banks, such as viaducts and roads and residential buildings, with little riparian vegetation, mostly composed by invasive species (e.g. *Arundo donax*) when present, and very reduced areas of available land to natural floods.

2.2. Biological sampling and processing

For aquatic communities, we considered two important biological indicators and representatives of different trophic levels, the benthic macroinvertebrates and the microalgae diatoms (Almeida and Feio, 2012; Feio et al., 2021; Feio et al., 2022a). Sampling of macroinvertebrates and diatom communities took place in November 2019 in each sampling site (uS).

Macroinvertebrate samples were collected with a hand-net (500 µm mesh size, 0.25 × 0.25 m opening) by kick sampling covering 6 × 1 m of available habitats (organic and inorganic) (INAG, 2008a), and preserved with 10% formalin. Macroinvertebrates were identified to the lowest possible taxonomic resolution/level and counted. Identification, under a stereomicroscope (magnification 60 ×), was mostly to genus level except for Diptera (sub-family) and Oligochaeta (class).

Diatom samples were collected from the epilithic biofilms from the upper surfaces of submerged stones (an area of ~100 cm^2) by scraping with a toothbrush and washed with running water (INAG, 2008b). Samples were preserved with 10% formaldehyde and oxidised with nitric acid and potassium dichromate. Thereafter, permanent slide mounts in Naphrax® were prepared and a light microscope (100 × objective N. A. 1.32) was used to count about 400 diatom valves per sample at species or infra-specific rank.

2.3. Assessment of ecosystem services and environmental pressures data collection

Field surveys for ecosystem services assessment in each sampling site took place between November 2019 and June 2020 in order to minimise seasonal variances in ES indicators, and were performed following the Urban stream Assessment system (UsAs) methodology according to

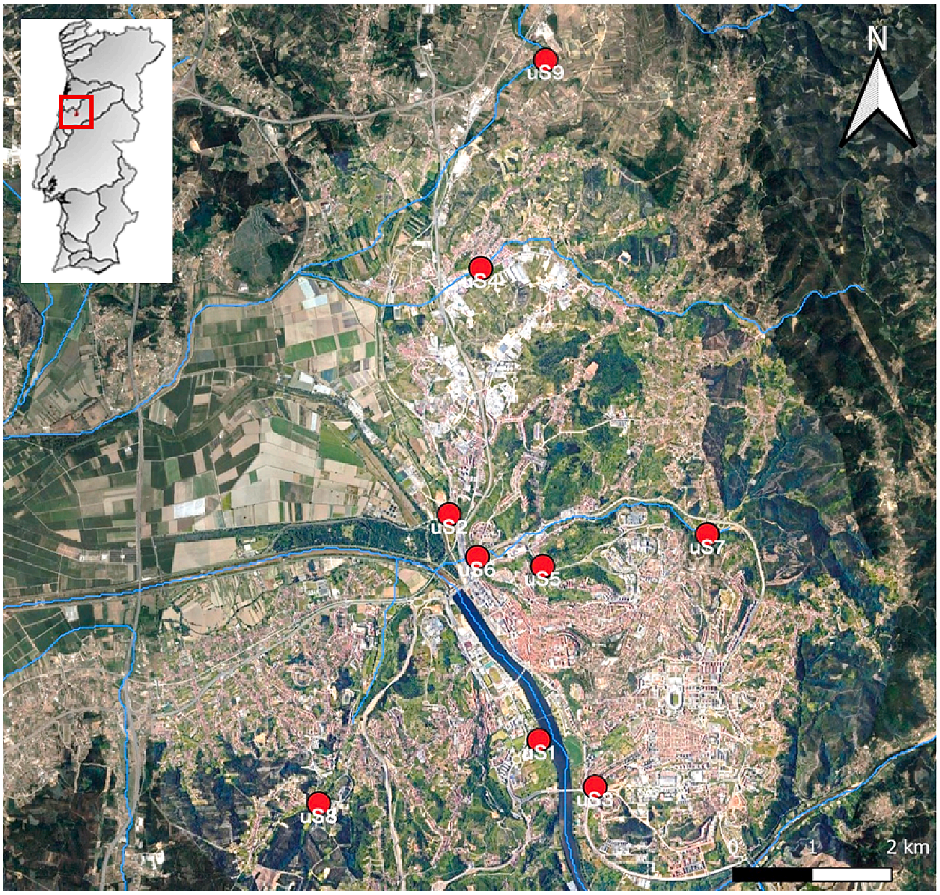


Fig. 1. Location of stream sampling sites (uS; N = 9; red circles) within the urban area of Coimbra, Portugal. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Urban stream sampling site characterization.

Site code	Site Name	Watershed (stream name)	Longitude (N)	Latitude (W)	Elevation (m)	Distance to source (km)	Soil imperviousness density - IMD (%)
uS1	Exploratório	Vala Real	−8.4278	40.19852	20	1.82	31.4
uS2	Estação Cbr-B	Ribeira de Gorgulhão	−8.44123	40.22451	14	3.05	23.8
uS3	Vale Flores	Ribeira Vale das Flores	−8.41946	40.19313	22	2.31	32.1
uS4	Eiras	Rio Fornos	−8.43666	40.25291	17	9.47	31.9
uS5	Mina Hospital	Ribeira de Coselhas	−8.42732	40.21857	27	1.13	39.2
uS6	Casa do Sal	Ribeira de Coselhas	−8.43703	40.21962	16	6.3	32.6
uS7	São Romão	Ribeira de Coselhas	−8.40295	40.2223	53	3.04	23.6
uS8	Covões	Ribeira de Covões	−8.46041	40.19112	74	1.97	16.9
uS9	Fornos	Rio Fornos	−8.42715	40.27697	19	9.44	12.5

Ranta et al. (2021). Briefly, this method incorporates a step-by-step scoring system that can provide a final classification score for a selection of ES indicators (Table 2) that were surveyed within a segment section of 100 m in each stream site. Accordingly, we surveyed ES proxies/indicators for two main Provisioning services (i.e., water and food supply), six Regulating services (i.e., climate regulation, flood mitigation, air quality, water quality, carbon sequestration, and pollination) and six Cultural services (i.e., education and cognitive development, tourism and recreation, heritage and prestige, amenity and aesthetic enjoyment, therapeutic services, and health and well-being) (Table 2).

Urban stream sites (uS) were also characterized in terms of their level of urbanization and physicochemical parameters. As an urbanization measurement, soil sealing data (imperviousness density, IMD; mean %; Table 1) was obtained by GIS (https://land.copernicus.eu/pan-european) considering a buffer zone of 1 km radius from each stream sampling site, comprising a surrounding area of approximately 3.14 km^2. Accordingly, higher IMD values were assumed to reflect a greater urbanization degree. Current velocity (m/s), water temperature (°C), pH, conductivity (μS/cm) and dissolved oxygen (mg/L) were monitored *in situ* at each stream site, in parallel with the biological sampling, using portable meters (HANNA's multiparameter probe HI 9812–5 and oxygen probe HI98193, and FP101 Global Water Instrumentation digital water velocity meter). Water samples were collected, preserved in cooling boxes and later processed for analysis of nutrients (i.e., nitrate, nitrite, ammonia, phosphate, total phosphorous, total nitrogen) and total suspended solids (TSS; mg/L).

2.4. *Data analysis*

2.4.1. *Biological and environmental characterization*

Diversity indices (Shannon-Wiener, Margalef's richness and Pielou's evenness) were used to characterize macroinvertebrate (MINV) and diatom (DIAT) communities as a measure of biodiversity. To assess the

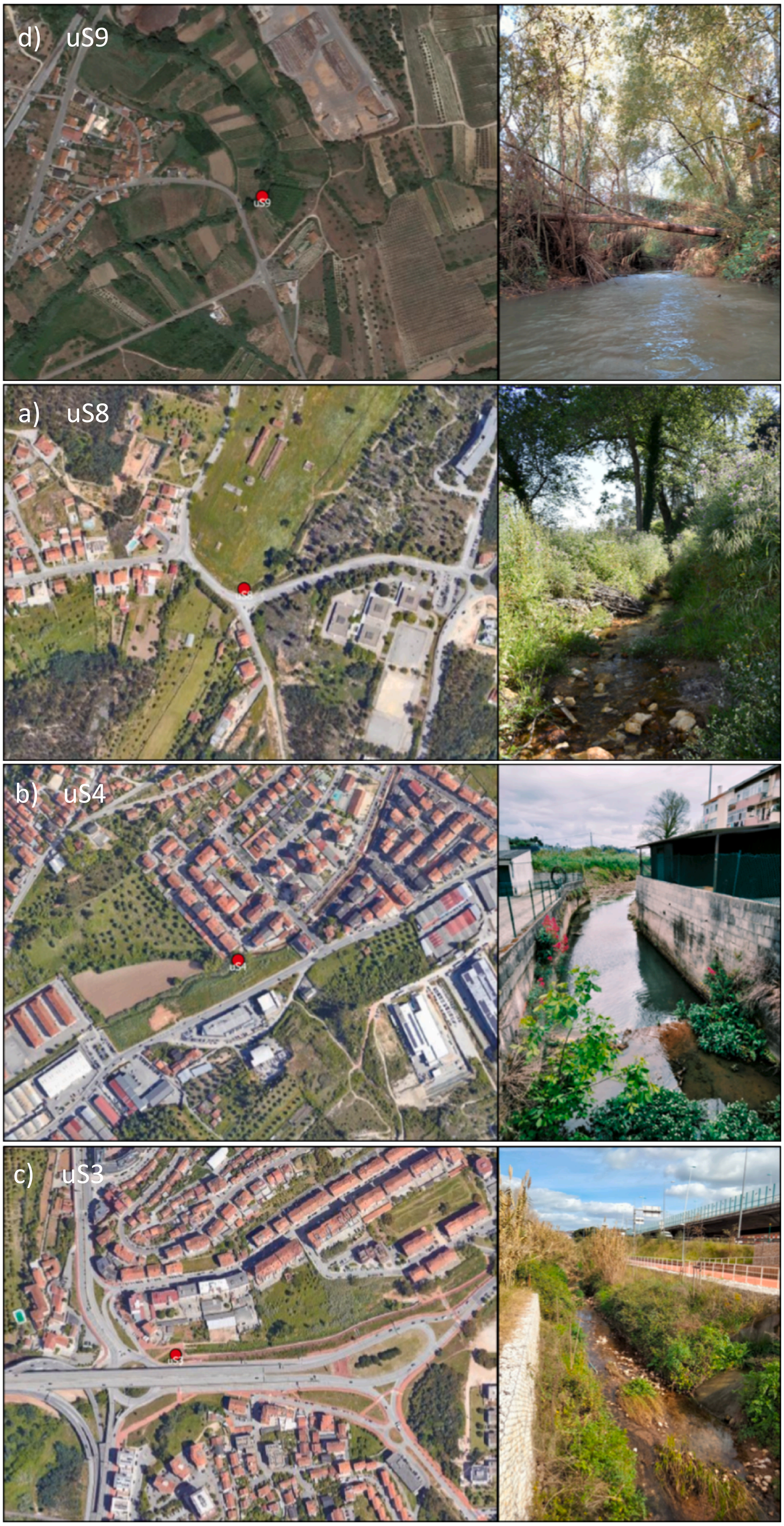


Fig. 2. Satellite overview and correspondent site picture of representative urban stream sampling sites presenting an increasing urbanization gradient from low (uS9 - a, uS8 - b) to high (uS4 - c, uS3 - d) soil % of imperviousness density.

Table 2

Ecosystem Services indicators/proxies for Provisioning (N = 7), Regulating (N = 14) and Cultural Services (N = 23) surveyed in this study, according to the UsAs tool (more details in Ranta et al. 2021).

Ecosystem Services	Goods or services provided	Indicator/proxy
Provisioning (P)	Water supply (WS)	Irrigation of crops
		Groundwater recharge
		Transversal connectivity (water from channel to the margins)
	Food supply (FS)	Natural plants with a nutritional, aromatic, medicinal value
		Fish
		Other aquatic animals with nutritional value
		Urban orchards
Regulating (R)	Climate regulation (Cl)	Air temperature variation
		Air humidity variation
	Flood mitigation (F)	Flood capacity
		Floodplain availability
	Air quality (AQ)	Integrity of the riparian corridor
		Lichen functional groups
	Water quality (WQ)	Nutrients in the water
		Tolerant invertebrates
		Ecological quality
		Total suspended solids
		Acidification
	Carbon sequestration (C)	Dissolved CO_2 in the water
	Pollination (P)	Bees
		Nectariferous plants
Cultural (C)	Education and cognitive development (Ed)	Distance from school to a stream
		Distance to an urban stream from home
		Excursions by schools (annually)
		Environmental volunteer projects to rehabilitate and restore the stream
	Tourism and recreation (T)	Scouts activity
		Recreational fishing
		Museums
		Restaurants, cafes, shops
		Touristic activity + water based activities
	Heritage and prestige (H)	Washhouses
		Water wheel/mill
		Historical bridges
		Restoration projects by institutions
		Naturalness of the streams
	Amenity and aesthetic enjoyment (A)	Open spaces with vistas, photopoints
		Charismatic birds and mammals to observe
	Therapeutic services (Ther)	Babbling of water
		Birdsong
		Calm and tranquil locations
		Temporal getaway
	Health and well-being (Hea)	Jogging, football, other sports
		View to a stream from home/workplace
		Feeling of safety

biological quality of the sampling sites based on invertebrates and diatom communities the official Portuguese index for Invertebrates (IPtIS; Ferreira et al., 2008) and the diatom index IPS (Coste in CEMAGREF, 1982) expressed in Ecology Quality Ratios (EQRs) and corresponding Ecological Quality Classes (High, Good, Moderate, Poor or Bad) were calculated. All metrics and indices were determined using AMIIB@software for MINV (AMIIB@n.d.) and OMINIDIA software for DIAT (Lecointe et al., 1993). In addition, patterns in MINV and DIAT communities' distribution were analysed through non-metric multidimensional scaling analysis (NMDS; Bray-Curtis dissimilarity; Log(x + 1) transformed).

Correlation analyses (Pearson) were performed between IMD (proxy of urbanization degree) and final score of ES for Provisioning, Regulating and Cultural. A Principal Component Analysis (PCA) was performed on indicators of ES_Provisioning, ES_Regulating and ES_Cultural (partial score per indicator) in order to summarize the sampling sites regarding ES information.

2.4.2. *Relationship between environment, services and aquatic biota*

The relationship between the ES indicators and the aquatic community composition was analysed with BIOENV-BEST relating the species abundance matrix to the Euclidean distance matrix of ES indicators. BIOENV function also finds the best subset of environmental variables (here the ES indicators), so that the Euclidean distances of scaled environmental variables have the maximum (rank) correlation with community dissimilarities. As result, BIOENV analysis was used to obtain the smallest sub set of ES indicators that better correlated with biological communities.

Statistical and graphical analyses were performed using PRIMER 6 & PERMANOVA + software (PRIMER-E Lda, Plymouth UK) (Anderson and Robinson, 2001) and STATISTICA 8 software (Weiß, StatSoft Inc., 2007).

3. Results

3.1. *Biological characterization & ecological quality assessment*

Macroinvertebrate (MINV) taxonomic identification resulted in a total of 2546 individuals distributed by 39 families in the overall urban stream sites. Among these, the number of families ranged from 4 (uS2) to 22 (uS5 and uS8). Most abundant taxa were Diptera (24.7%, mainly represented by Chironomidae and Simuliidae), Gastropoda (22.9%, mostly the exotic *Potamopyrgus antipodarium*), Oligochaeta (20.7%, represented at all sampling sites), and Ephemeroptera (15.8%, comprising only Baetidae and a few Caenidae).

Biodiversity indices obtained for macroinvertebrates and diatom communities are plotted in Fig. 3. Macroinvertebrate Margalef's richness ranged from 0.85 (uS1) to 3.50 (uS8), while diversity varied between 0.82 (uS2) and 2.09 (uS5). Pielou's evenness ranged from 0.50, for both uS3 and uS9, to 0.71 in uS7. Overall, sites with lower Diversity and Richness of MINV (uS2 and uS1) reveal a tendency for medium (23.8%) and higher IMD values (31.4%), with the exception of uS5, that presented high values for both biodiversity metrics (Diversity 2.09; Richness 3.11; Evenness 0.68) and urbanization (IMD 39.2%) (Fig. 3a).

Diatom community was represented by 111 species in the overall study area. The number of species ranged from 16 (uS5) to 47 (uS6). The most abundant species, totalizing 58% of the community, were also the most frequent and included *Amphora pediculus* (Kützing) Grunow (12.9%), *Achnanthidium minutissimum* (Kützing) Czarnecki (12.7%), *Eolimna minima* (Grunow) Lange-Bertalot (9.3%) and *Nitzschia palea* (Kützing) W. Smith (7.7%), in all 9 sites; *Sellaphora seminulum* (Grunow) D.G.Mann (11.1%) and *Planothidium frequentissimum* (Lange-Bertalot) Lange-Bertalot (4.3%) were present in 8 sampling sites.. All diatom biodiversity indices presented the lowest values for uS5 and the highest values for uS6, ranging from 2.48 to 7.62 for richness, 1.46 to 3.13 for diversity and 0.53 to 0.81 for evenness. Urbanization degree presented the lower value of IMD (12.5%) in uS9 (corresponding to high values for DIAT biodiversity metrics) and the highest values in uS5 (39.2%), that presented the lowest values of biodiversity metrics (Fig. 3b).

Focusing on macroinvertebrate communities, NMDS plot showed, as expected, a clear segregation between uS classified with good/excellent ecological condition (uS8, uS9, uS5) and the remaining sites with bad/poor classifications according MINV ecological assessment (giving the respective EQR values) (Fig. 4a). Pressure variables that contributed the most for segregating sites with the better ecological condition classification (Pearson correlations > 0.5), include dissolved oxygen (mg/L), pH and flow velocity (m/s), while worst classified sites were correlated with nutrients (i.e. nitrate, nitrite, ammonia, phosphate, total nitrogen, total phosphorus; mg/L) and alkalinity (mg/L $CaCO_3$).

Diatom community showed the same pattern as invertebrates, segregating uS classified with "good" ecological condition (uS5, uS7, uS8, uS9) from the remaining sites classified with "moderate" and "bad"

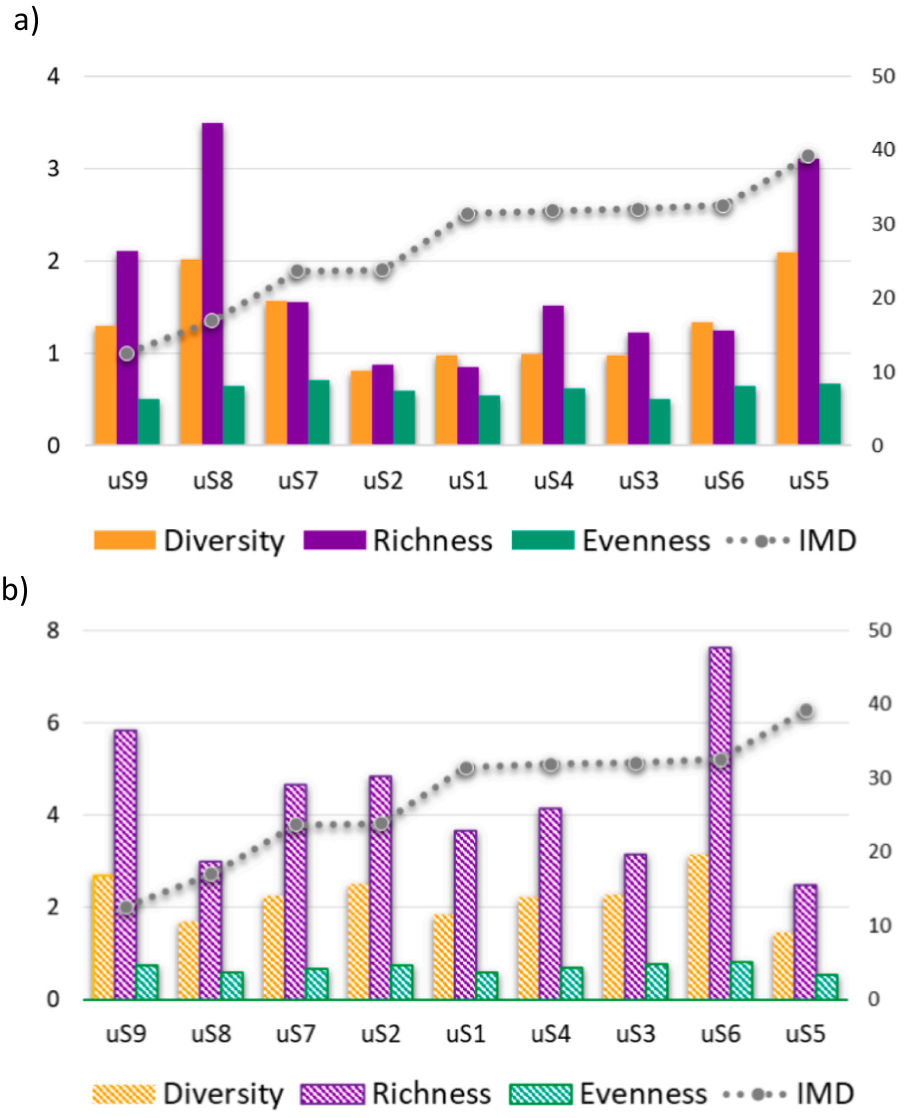


Fig. 3. Biodiversity indices (Diversity of Shannon-Wiener, Richness of Margalef, Pieloús Evenness) obtained for macroinvertebrates (a) and diatoms (b) – left yy axis; and soil imperviousness density (IMD, %) – right yy axis, for each sampling site (uS) within a buffer zone of 3.14 km^2. Sites ordenation is displayed according increasing IMD values.

(Fig. 4b). Accordingly, pH, flow velocity (m/s) and water dissolved oxygen (mg/L) were correlated (Pearson correlations $>$ 0.5) with diatom communities responsible for the better ecological classification, while nutrients (i.e. nitrate, nitrite, ammonia, phosphate, total nitrogen, total phosphorus; mg/l), alkalinity, total suspended solids (TSS) and soil imperviousness related with the worst classified sites.

Final ecological quality assessment classification based on both bioindicator communities (macroinvertebrates and diatoms), according to respective EQR values, showed that urban sites are classified as good (uS5, uS8, uS9), bad (uS3, uS6, uS7) and poor (uS1, uS2, uS4).

3.2. Environmental pressure variables, ecosystem services and urbanization

A wide range of values of water physical and chemical variables were observed. The urban streams sampling sites showed different degrees of organic and inorganic water contamination as inferred by the nutrient concentration and parameters measured (Appendix A. Supplementary data). Ammonia concentration in the water varied between 0.05 and 0.28 mg/L, nitrate concentration ranged from 4.20 to 13 mg/L and phosphates varied between 0.01 and 0.11 mg/L. Dissolved oxygen concentration in the water ranged from 5.63 to 11.09 mg/L, pH varied between 7.25 and 8.81, while conductivity and TSS ranged from 281.5 to 569 mg/L and from 2.0 to 73.6 mg/L, respectively.

The Ecosystem Services final scores (%) based on the *UsAs* tool (Ranta et al., 2021) assessment (Fig. 5), which took into account partial scores given for all indicators/proxies considered (Table 2), varied between 25.0% (uS5) and 58.3% (uS4 and uS9) for Provisioning services, 45.8% (uS4) and 86.7% (uS8) for Regulating services, and 16.9% (uS5) and 52.8% (uS1) for Cultural services.

Correlations (Table 3) showed a general trend for negative relations between urbanization degree level (IMD) and ES. A moderate negative correlation between soil imperviousness (IMD) and Provisioning (Pearson, $r = -0.37$) and Regulating (Pearson, $r = -0.50$) services was obtained.

When correlating IMD with biodiversity metrics, a weak correlation was found, though presenting an overall negative relation between urbanization and biological communities.

A Principal Component Analysis (PCA) on ecosystem services indicators displaying the pressure variables (normalized) in uS

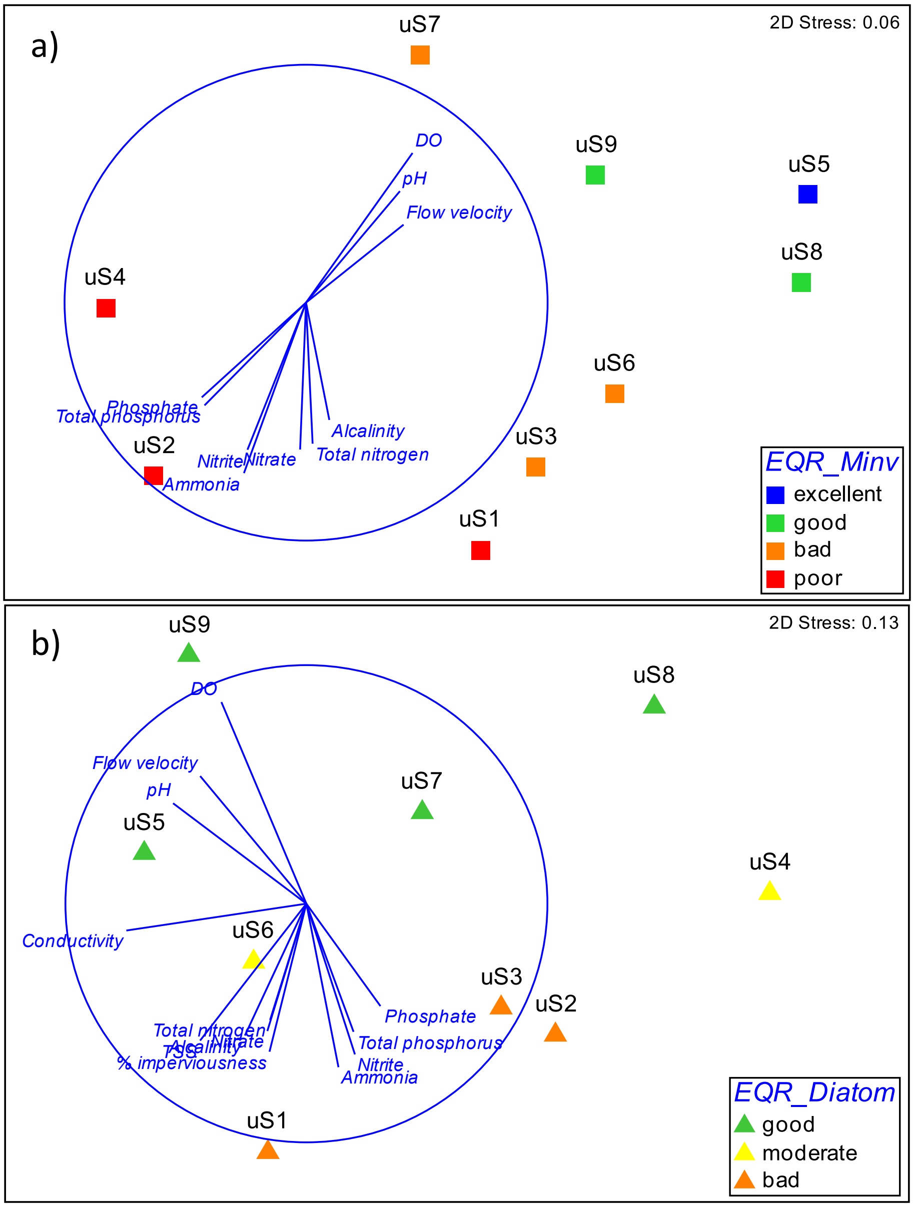


Fig. 4. Two-dimensional non-metric Multi-Dimensional Scaling (NMDS) ordination of macroinvertebrate (a) and diatom (b) communities in the urban streams sites (uS) displaying the ecological quality classification based in the EQR and projecting the environmental parameters better correlated with the NMDS axes (Pearson correlations > 0.5).

distribution is presented in Fig. 6. The PCA performed on ES indicators yield a first and second axis that explained 35.9% and 20.4%, respectively of the total variability (56.3%). Accordingly, three sampling sites were grouped (uS1, uS2, uS6) and segregated from the remaining according to their ES indicators, related with Provisional services (P) indicators for water supply (WS; by groundwater recharge and by transversal connectivity) and food supply (FS; by other aquatic animals with nutritional value), and also relating with Cultural services (C) amenity and aesthetic enjoyment proxy (A; open spaces with vistas, photopoints). Looking at the overlap of pressure variables on the ES values for sampling sites in Fig. 6, it's perceptible that sites with lower ES scores are better related with higher water nutrient concentrations (e.g., ammonia, total phosphorus, nitrate, nitrite) and % IMD in opposition to lower pH and dissolved oxygen concentration (DO).

3.3. Relating bioindicators & ES

The BIOENV analysis used to investigate the relationship between aquatic biota communities and ES, indicates that aquatic community composition is associated to a combination of different ES indicators (Table 4). Accordingly, the most important ES in the relationship with macroinvertebrate communities were 4 Provisioning indicators (related to water and food supply) and 7 Regulating indicators (correlations 0.65 and 0.76 respectively; $p < 0.05$; Table 4). Specifically, indicators for provision services were: “Transversal connectivity” (water supply); “Plants with a nutritional, aromatic, medicinal value”, “Fish” and “Other aquatic animals with nutritional value” (food supply). As for diatoms, BIOENV selected 8 indicators of Regulating services ($r = 0.6$; $p < 0.05$) that were best correlated with these communities. Both macroinvertebrate and diatom communities were associated to Regulating Services of climate regulation, flood mitigation, water quality and pollination (assessed by the shared indicators “Air humidity variation”, “Flood capacity”,”Tolerant invertebrates”, “Ecological quality”, “Acidification”, “Nectariferous plants”; Table 4).

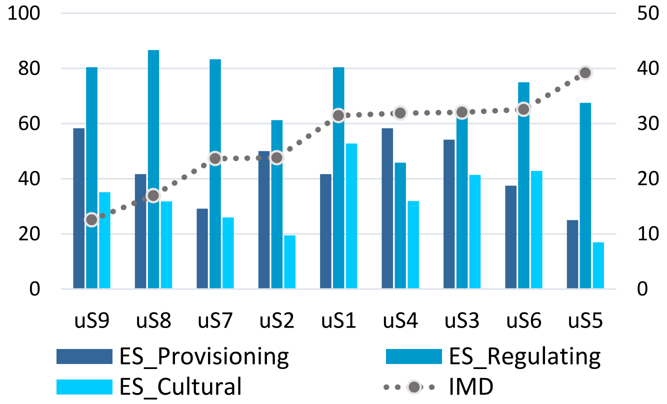


Fig. 5. Final scores (%) of Provisioning, Regulating and Cultural ecosystem services (ES) based on the UsAs tool (Ranta et al., 2021) on the left yy axis and soil imperviousness density (IMD; %) on the right yy axis for the urban stream sites (uS) assessed. Sités ordenation is displayed according increasing IMD values.

Table 3
Correlations (Pearson, *r*) between urbanization degree level as soil imperviousness (IMD; %) and Ecosystem Services final scores (ES_Provisioning, ES_Regulating, ES_Cultural) and biodiversity metrics (Shannon-Wiener diversity, Margalef́s richness and Pielou's evenness) for macroinvertebrate (MINV) and diatom (DIAT) communities.

		Imperviousness density (IMD)
ES_Provisioning		−0.37
ES_Regulating		−0.50
ES_Cultural		0.04
Diversity	**MINV**	−0.04
	DIAT	−0.22
Richness	**MINV**	−0.21
	DIAT	−0.23
Evenness	**MINV**	0.20
	DIAT	−0.16

4. Discussion

River and stream ecosystems within cities have a great potential in providing important ES to their inhabitants (Elmqvist et al., 2015; Grimm et al., 2008; Haase, 2015) and can host a high richness and diversity of flora and fauna (e.g. Aronson et al., 2014; Ives et al., 2016) despite the "urban stream syndrome" (*sensu* Walsh et al., 2005), that often translates into soil imperviousness, pollution, flash floods, lack of riparian vegetation (Miller et al., 2014; Walsh et al. 2005). Our results go beyond the state of the art by demonstrating that biodiversity and aquatic communities influence positively the provision of ES, namely Regulating and Provisioning services of urban stream ecosystems.

4.1. Biological communities and ecological quality assessment

An enhanced urban biodiversity is intricately related to city sustainable development and human wellbeing (Kowarik et al., 2020). Accordingly, our findings showed that stream sites with the better ecological condition and biodiversity in urban context also presented a potential high delivery for Provision and Regulating services alongside with lower urbanization as impervious area, as initially hypothesized. Moreover, our study sitеś impervious area correlated negatively with Provisioning and Regulating services that potentially can be delivered. In accordance, the decrease of ES due to land use conversion towards urbanized areas (e.g. Crespin and Simonetti, 2016; Ekka et al., 2020; Mendoza-González et al., 2012; Tianhong et al., 2010; Yi et al., 2017; Zhang et al., 2022) has been commonly reported in developing countries.

As expected, and given the ability of the sampled communities as reliable indicators of biological condition of waterbodies including urbanized ecosystems (e.g. Chen et al., 2016; Serra et al., 2019; Walsh et al., 2006), MINV and DIAT reflected the ecological quality of urban sites corroborating environmental parameters measured. Regarding the community structure and ecological quality, our main findings showed that both biological indicators exposed a clear discrimination between sites classified with better ecological condition correlated with dissolved oxygen and pH, from sites classified with worse ecological condition that were mostly correlated with nutrients. Sites with better ecological

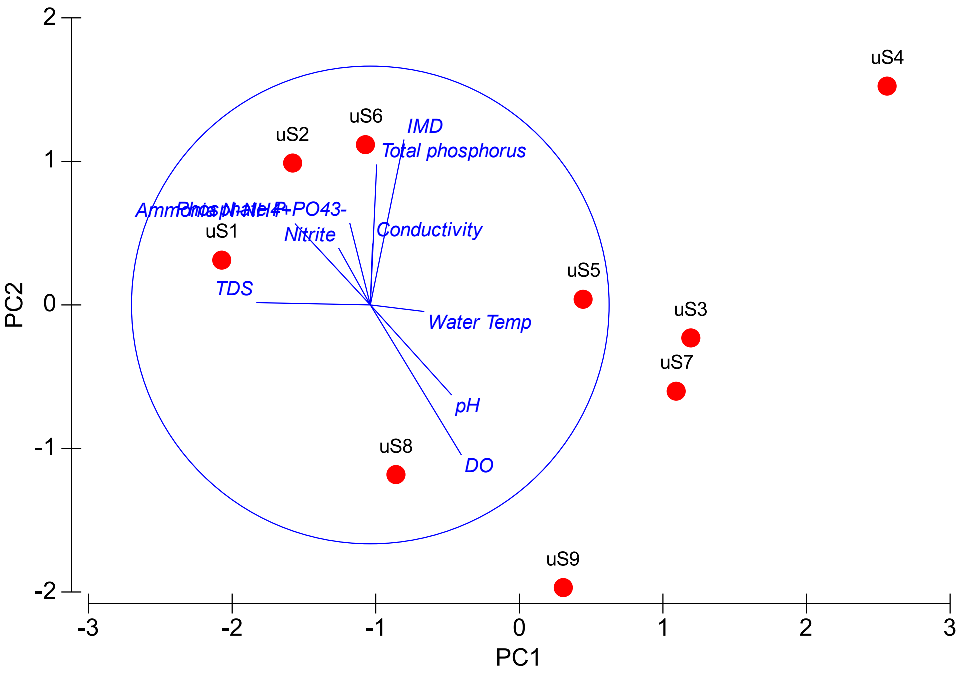


Fig. 6. Principal Component Analysis (PCA) on the distribution of ecosystem services indicators (●) in urban stream sites (uS; N = 9) with overlapping vectors of pressure variables (normalized; Pearson correlations above 0.2).

Table 4
Results of BIOENV analysis showing the best Ecosystem Services (ES_Provisioning, ES_Regulating, ES_Cultural) indicator variables related to the patterns in macroinvertebrate (MINV) and diatom (DIAT) communities (rank correlation Spearman).

BIOENV		Rank correlation	p-value	Variable combinations; indicators*
MINV	**ES_Provisioning**	0.650	**0.004**	P_WS_Transversal connectivity; P_FS_Plants with a nutritional, aromatic, medicinal value; P_FS_Fish; P_FS_Other aquatic animals with nutritional value.
	ES_Regulating	0.763	**0.002**	R_Cl_Air humidity variation; R_F_Flood capacity; R_AQ_Lichen functional groups; R_WQ_Tolerant invertebrates; R_WQ_Ecological quality; R_WQ_Acidification; R_P_Nectariferous plants.
	ES_Cultural	0.311	0.918	-
DIAT	**ES_Provisioning**	0.421	0.132	-
	ES_Regulating	0.597	**0.014**	R_Cl_Air temperature variation; R_Cl_Air humidity variation; R_F_Flood capacity; R_WQ_Tolerant invertebrates; R_WQ_Ecological quality; R_WQ_Acidification; R_C_Dissolved CO_2 in water; R_P_Nectariferous plants.
	ES_Cultural	0.514	0.377	-

*Indicators - Provisioning: water supply (P_WS) and food supply (P_FS); Regulating: climate regulation (R_Cl), flood mitigation (R_F), air quality (R_AQ), water quality (R_WQ) and pollination (R_P).

condition (namely uS8 and us9) were also characterized by a high potential of ES supply, which is in agreement with the study of Grizzetti et al. (2019) showing higher ES delivery mostly correlated to better ecological condition.

In general, urban streams associated with the city of Coimbra, were characterized by a relatively lower diversity (1.34 ± 0.46; mean ± SD) of macroinvertebrates but a higher richness (1.78 ± 0.95), when compared with non-urban streams in the same region and season (2.21 ± 0.57 and 1.03 ± 0.36 for diversity and richness, respectively; Graça et al., 2004). This can reflect the potential for urban or novel ecosystems to support a diverse biological community, sometimes even higher than of reference state (Evers et al., 2018). However, this is often due to a noteworthy abundance of tolerant species (i.e. Chironomidae, Oligochaeta and Baetidae) and exotic specimens (Gastropoda *Potamopyrgus antipodarium*), which is in linewith other studies showing that disturbed and impacted sites, as streams in urbanized context, subsidy the prevalence of such communities (Serra et al., 2019, Vermonden et al., 2009). For diatom communities, the most represented taxa (displaying overall higher relative abundances and frequency) are generally considered cosmopolitan and near ubiquitous in continental waters (Potapova and Charles, 2002) and commonly found in a wide range of urbanized environments (e.g. Chen et al., 2016; Teittinen et al., 2015; Walker and Pan, 2006). Nevertheless, diatom diversity and richness were lowest in the most urbanized site (uS5) and high in the least urbanized site (uS9). Despite the unexpected highest diversity and richness for one of the most urbanized sites (uS6), the most abundant diatoms at uS6 are very tolerant to aquatic degradation indicating high levels of nutrients and organic contamination (ie. *Nitzschia palea, Eolimna minima, Navicula veneta*). The occurrence of nutrients in the water promotes the growth of primary producers in general, including diatoms, which may explain the high number of species and diversity registered. In fact, Leira et al. (2009) refer that nutrient-rich lakes were generally more taxonomically diverse than less eutrophicated ones.

4.2. Urbanization, biological and ES indicators

The assessed urbanization metric (i.e. IMD) assigned a high degree of urbanization to 5 of the sites studied (out of 9), which can explain the biological aquatic communities found (e.g. high abundance of tolerant and exotic macroinvertebrate species and relatively low diversity; high abundance of tolerant diatom species). Although most correlations found were not statistically significant, probably due to the low number of samples (uS N = 9), we cannot overlook the overall negative correlations between soil surrounding impervious area (proxy of urbanization) and both ES (mainly Regulating and Provisioning) and biodiversity.

Urbanization is greatly related with the artificialization of land use with imperviousness and soil sealing, which naturally impose limitations into supporting riparian vegetation. Previously, Cao and Natuhara (2020) identified the proportion of impervious surface in artificial habitats, as the strongest predictor for the variation in species richness, associating it to the richness of alien, native, and riparian species. The integrity of riparian corridors, and their composition is well known as a major key to stream ecosystem functioning and habitat availability supporting more diverse aquatic communities as diatoms and macroinvertebrates (Allan, 2004; Mesa, 2014; Mutinova et al., 2020; Rios et al., 2006), that can support a better global ecological quality. Accordingly, our findings also showed that urban stream sites with better ecological classification given by bioindicators' assessment (i.e. uS8 and uS9), corresponded to sites presenting less urbanization given by lower soil impervious values, with the exception of uS5 (classified with "excellent" ecological quality by MINV and classified as "good" ecological quality by DIAT but showing the highest density of imperviousness). This can be related with local stream features, since uS5 particularly presented a relatively semi-continuous riparian corridor and *in stream* habitat variability with different substrate types (e.g. cobbles, gravel, clay, macrophytes, underwater tree roots) and fast flow velocity with turbulence and good oxygenation (supplementary material table S1). In this specific case, urbanization effects on the biota seemed to be mitigated due to enhanced hidromorphological characteristics of the site.

We also found that macroinvertebrate communities related specifically with indicators for water and food supply (Provisioning), climate regulation, flood mitigation, air and water quality, and pollination (Regulating), while diatom communities only correlated to Regulating indicators of climate regulation, flood mitigation, water quality and pollination. Moreover, urban stream sites displaying higher biodiversity obtained higher scores of mainly Regulating ecosystem services, but also Provisioning, confirming that a biodiverse urban environment generates and supports a broad array of ecosystem services (Haase et al., 2014).

Some of these relationships are easier to explain than others. For example, biological indicatorś link with water quality is well-established as both diatoms and macroinvertebrates are known to be affected by water pollution and river impairment (e.g. Calapez et al., 2019; Tornés et al., 2018). Moreover, these communities are at the basis of riverine food chains, being primary producers (i.e. diatoms) and primary consumers (i.e. invertebrates herbivores), and being themselves a food source for higher trophic levels, either for fish or even for humans, such as the bivalves or crayfish. Thus, their presence can be related to the ability of a stream to provide food supply. On the other hand, many benthic invertebrates depend on the presence of riparian vegetation, as one of their most important trophic groups are the shredders that decompose fallen leaves and wood from the riparian trees being key players in the ecosystem functioning through the decomposition of leaf litter (Graça, 2001). The presence of full corridors of riparian vegetation in the riverine banks is an important factor for the service of climate regulation, increasing the humidity and decreasing the air and water temperature in hot days (Riis et al., 2020; Trimmel et al., 2018). Simultaneously, this vegetation improves the air quality by sequestering carbon and pollutants and releasing oxygen (Dybala et al., 2019; Riis et al., 2020). An enhanced riparian vegetation may also include nectariferous plants which will promote the presence of pollinators. Finally, when a floodplain is available, the presence of riparian vegetation is more likely, and therefore, more water infiltrating in the soils and feeding the streams along with better water quality due to the retention of fine sediments and pollutants before their entry into the streams (Dosskey et al., 2010; Nakamura and Yamada, 2005). All these functions associated to riparian vegetation will promote more diverse invertebrate and diatom communities contributing to improve ecosystem biodiversity (Naiman et al., 1993). Indeed, more biodiverse urban ecosystems, are also expected to sustain people's connection to nature, provide areas for relaxation or physical activity near homes, promoting their physical and mental health (Feio et al., 2022b; Ives et al., 2017; Jimenez et al., 2021). Yet, in this study, Cultural services did not show a clear relation with biodiversity or the urbanization metric. That could be mainly for two reasons: 1) some indicators of Cultural services are more based in the potential that the urban stream sites have to supply given services than to the quality of the ecosystems (for example, number of houses or cafes with a view to a stream – aesthetic value; or number of schools within 1 km distance – potential of using the stream for environmental education); and 2) some indicators, for example those related to health and well-being that measure the possibility of playing sports in the streams, can also be valuing the eventual presence of artificial structures, such as cycle paths or sports fields which occupy floodplains and are often constructed with impervious or semi-impervious materials but that have a negative impact on the ecosystem. These are examples of potential conflicts of interests between nature preservation and Cultural services, which are especially relevant in urban areas and that deserve a special attention to avoid promoting further degradation of the ecosystems. As a matter of fact, while some defend that the concept of ecosystem services reconnects society to ecosystems, others also point out that it may conflict with biodiversity conservation objectives (Schröter et al., 2014). These conflicts have been addressed in the literature but mostly for larger rivers, regarding the redevelopment of waterfronts or the management of dams, where the land ownership, heritage and cultural, social and environmental justice and environment, and resilience are indicated as the main challenges to be addressed (e.g. Avni and Teschner, 2019; Jorda-Capdevila and Rodríguez-Labajos, 2015). Here we defend that given the high potential of the urban streams to bring nature into cities and to provide Provisioning and Regulating services, a greater emphasis should be given to the ecosystem preservation, accepting only the promotion of Cultural services that do not conflict with biodiversity preservation, considering the great impact that grey infrastructures have on these fragile ecosystems. For example, urban stream ecosystems in better condition could promote a higher social justice, as these constitute small natural areas accessible to all, from younger to older adults, and could bring additional value to houses located in lower income and neglected neighbourhoods.

4.3. *Conclusions*

According to our main findings, it is possible to infer that urbanization can affect communities in proportion to its degree of influence of alterations in streams. As initially hypothesized, this study found that the sitesʹ imperviousness density (proxy of urbanization) was negatively related with urban streams' potential for providing Ecosystem Services, especially Provisioning and Regulating services. Moreover, this study confirmed that aquatic communities and ecological quality can reflect ecosystem services provision in urban context, and such relationship depends on specific ES indicators mainly for Provisioning and Regulating services, though further research is needed. Also, a lower urbanization land-use is positively related to a higher biodiversity and a higher potential of streams to supply Provisioning and Regulating services. The effects of highly impervious areas surrounding the watercourses (proxy of high urbanization) on biota, may be softened in some extent to improved hydromorphological conditions, mainly related with riparian vegetation integrity and instream habitat heterogeneity. Nevertheless, additional assessment of relationships between biota and ES is important, and should include other biological groups, key inhabitants of these ecosystems (e.g. fish, aquatic and riparian vegetation, fungi, amphibians, birds, etc).

The use of Urban stream Assessment system (UsAs; Ranta et al., 2021) in this study was found to be a simple and standardized tool for surveying a great amount of services supplied by these ecosystems resulting in a broad characterization (and comparable) of each stream site. By providing intermediate and final scores of the diverse indicators and Ecosystem Services, it allowed for a simplified demonstration of a complex reality of an urban stream, with great potential for adaptability and comparisons between urban stream ecosystems worldwide.

Overall, our results support the need to protect and rehabilitate (whenever possible) urban river ecosystems as green and blue solutions for the sustainability of cities. And while our study has demonstrated the relationship between biodiversity and Provisioning and Regulating services, care must be taken when considering Cultural services, as the enhancement of some of the latest may lead to further artificialization. Participatory approaches engaging local stakeholders should be used to clarify the nature of conflicts and assure the conservation of urban aquatic ecosystems (e.g. Brummer et al., 2017; King et al., 2015).

CRediT authorship contribution statement

Ana Raquel Calapez: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft. **Sónia R.Q. Serra:** Investigation. **Andreia Mortágua:** Investigation. **Salomé F.P. Almeida:** Resources, Supervision, Writing – review & editing, Funding acquisition. **Maria João Feio:** Conceptualization, Resources, Supervision, Funding acquisition, Project administration, Writing – review & editing.

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.

Data availability

Data will be made available on request.

Acknowledgements

Funding: This research has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 857188 (PHArA-ON Project), and support of national funds through Fundação para a Ciência e Tecnologia, I. P (FCT), under the projects UIDB/04292/2020, UIDP/04292/2020, granted to MARE, LA/P/0069/2020, granted to the Associate Laboratory ARNET, UID/GEO/04035/2019 granted to GeoBioTec and a Principal Investigator CEEC contract granted to MJF. ARC was supported by a research grant from PROAQUA (REVIVE2021_PhD) and SRQS was supported by a research grant under the project PHArA-ON (H2020-SC1-FA-DTS-2018-2).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110433.

References

Allan, J.D., 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Ann. Rev. Ecol. Evol. Syst. 35 (1), 257–284.

Almeida, S.F.P., Feio, M.J., 2012. DIATMOD: Diatom predictive model for quality assessment of Portuguese running waters. Hydrobiologia 695 (1), 185–197.

Anderson, M.J., Robinson, J., 2001. Permutation tests for linear models. Aust. N. Z. J. Stat. 43, 75–88.

Aronson, M.F.J., La Sorte, F.A., Nilon, C.H., Katti, M., Goddard, M.A., Lepczyk, C.A., Warren, P.S., Williams, N.S.G., Cilliers, S., Clarkson, B., Dobbs, C., Dolan, R., Hedblom, M., Klotz, S., Kooijmans, J.L., Kühn, I., MacGregor-Fors, I., McDonnell, M., Mörtberg, U., Pyšek, P., Siebert, S., Sushinsky, J., Werner, P., Winter, M., 2014. A global analysis of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers. Proc. R. Soc. B Biol. Sci. 281 (1780), 20133330.

Avni, N., Teschner, N., 2019. Urban Waterfronts: Contemporary Streams of Planning Conflicts. J. Plan. Lit. 34 (4), 408–420. https://doi.org/10.1177/0885412219850891.

Balvanera, P., Pfisterer, A.B., Buchmann, N., He, J.S., Nakashizuka, T., Raffaelli, D., Schmid, B., 2006. Quantifying the evidence for biodiversity effects on ecosystem functioning and services. Ecol. Lett. 9, 1146–1156.

Balvanera, P., Siddique, I., Dee, L., Paquette, A., Isbell, F., Gonzalez, A., Byrnes, J., O'Connor, M.I., Hungate, B.A., Griffin, J.N., 2014. Linking Biodiversity and Ecosystem Services: Current Uncertainties and the Necessary Next Steps. Bioscience 64 (1), 49–57. https://doi.org/10.1093/biosci/bit003.

Brauman, K.A., Daily, G.C., Duarte, T.K., Mooney, H.A., 2007. The nature and value of ecosystem services: an overview highlighting hydrologic services. Annu. Rev. Env. Resour. 32, 67–98.

Brumer, M., Rodríguez-Labajos, B., Nguyen, T.T., Jorda-Capdevila, D., 2017. They have kidnapped our river": Dam removal conflicts in Catalonia and their relation to ecosystem services perceptions. Water Altern. 10 (3), 744–768.

Calapez, A.R., Elias, C.L., Almeida, S.F.P., Brito, A.G., Feio, M.J., 2019. Sewage contamination under water scarcity effects on stream biota: biofilm, grazers, and their interaction. Environ. Sci. Pollut. Res. 26, 26636–26645. https://doi.org/10.1007/s11356-019-05876-7.

Cao, Y., Natuhara, Y., 2020. Effect of urbanization on vegetation in riparian area: Plant communities in artificial and semi-natural habitats. Sustainability 12, 204.

Cardinale, B.J., 2012. Impacts of Biodiversity Loss. Science 336 (6081), 552–553. https://doi.org/10.1126/science.1222102.

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Loreau, M., Grace, J.B., 2012. Biodiversity loss and its impact on humanity. Nature 486 (7401).

CEMAGREF (1982). Etude des Méthodes Biologiques d'Appréciation Quantitative de la Qualité des Eaux. Ministere de l'Agriculture, CEMAGREF, Division Qualité des Eaux, Peche et Pisciculture, Lyon StatSoft, Inc. (2007). STATISTICA (data analysis software system), version 8.0. www.statsoft.com.

Chapin III, F.S., Zavaleta, E.S., Eviner, V.T., Naylor, R.L., Vitousek, P.M., Reynolds, H.L., Hooper, D.U., Lavorel, S., Sala, O.E., Hobbie, S.E., Mack, M.C., Díaz, S., 2000. Consequences of changing biodiversity. Nature 405 (6783), 234–242.

Chen, X., Zhou, W., Pickett, S.T.A., Li, W., Han, L., Ren, Y., 2016. Diatoms are better indicators of urban stream conditions: A case study in Beijing, China. Ecol. Ind. 60, 265–274.

Crespin, S.J., Simonetti, J.A., 2016. Loss of ecosystem services and the decapitalization of nature in El Salvador. Ecosyst. Serv. 17, 5–13.

Del Arco, A.I., Ferreira, V., Graça, M.A.S., 2012. The performance of biological indicators in assessing the ecological state of streams with varying catchment urbanisation levels in Coimbra, Portugal. Limnetica 31, 141–154.

Díaz, S., Fargione, J., Chapin III, F.S., Tilman, D., 2006. Biodiversity loss threatens human well-being PLOS. Biol. 4 (8), e277.

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., Larigauderie, A., Adhikari, J.R., Arico, S., Báldi, A., Bartuska, A., Baste, I.A., Bilgin, A., Brondizio, E., Chan, K.MA., Figueroa, V.E., Duraiappah, A., Fischer, M., Hill, R., Koetz, T., Leadley, P., Lyver, P., Mace, G.M., Martin-Lopez, B., Okumura, M., Pacheco, D., Pascual, U., Pérez, E.S., Reyers, B., Roth, E., Saito, O., Scholes, R.J., Sharma, N., Tallis, H., Thaman, R., Watson, R., Yahara, T., Hamid, Z.A., Akosim, C., Al-Hafedh, Y., Allahverdiyev, R., Amankwah, E., Asah, S.T., Asfaw, Z., Bartus, G., Brooks, L.A., Caillaux, J., Dalle, G., Darnaedi, D., Driver, A., Erpul, G., Escobar-Eyzaguirre, P., Failler, P., Fouda, A.M.M., Fu, B., Gundimeda, H., Hashimoto, S., Homer, F., Lavorel, S., Lichtenstein, G., Mala, W.A., Mandivenyi, W., Matczak, P., Mbizvo, C., Mehrdadi, M., Metzger, J.P., Mikissa, J.B., Moller, H., Mooney, H.A., Mumby, P., Nagendra, H., Nesshover, C., Oteng-Yeboah, A.A., Pataki, G., Roué, M., Rubis, J., Schultz, M., Smith, P., Sumaila, R., Takeuchi, K., Thomas, S., Verma, M., Yeo-Chang, Y., Zlatanova, D., 2015. The IPBES Conceptual Framework — connecting nature and people. Curr. Opin. Environ. Sustain. 14, 1–16.

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R.T., Molnár, Z., Hill, R., Chan, K.M.A., Baste, I.A., Brauman, K.A., Polasky, S., Church, A., Lonsdale, M., Larigauderie, A., Leadley, P.W., van Oudenhoven, A.P.E., van der Plaat, F., Schröter, M., Lavorel, S., Aumeeruddy-Thomas, Y., Bukvareva, E., Davies, K., Demissew, S., Erpul, G., Failler, P., Guerra, C.A., Hewitt, C.L., Keune, H., Lindley, S., Shirayama, Y., 2018. Assessing nature's contributions to people. Science 359, 6373. https://doi.org/10.1126/science.aap8826.

Dosskey, M.G., Vidon, P., Gurwick, N.P., Allan, C.J., Duval, T.P., Lowrance, R., 2010. The Role of Riparian Vegetation in Protecting and Improving Chemical Water Quality in Streams. J. Am. Water Resour. Assoc. (JAWRA) 46 (2), 261–277. https://doi.org/10.1111/j.1752-1688.2010.00419.x.

Dybala, K.E., Matzek, V., Gardali, T., Seavy, N.E., 2019. Carbon sequestration in riparian forests: A global synthesis and meta-analysis. Glob. Chang. Biol. 25, 57–67. https://doi.org/10.1111/gcb.14475.

Ekka, A., Pande, S., Jiang, Y., van der Zaag, P., 2020. Anthropogenic Modifications and River Ecosystem Services: A Landscape Perspective. Water 12, 2706. https://doi.org/10.3390/w12102706.

Elmqvist, T, Setälä, H, Handel, SN, van der Ploeg, S, Aronson, J, Blignaut, JN, Gómez-Baggethun, E, Nowak, DJ, Kronenberg, J, de Groot, R, 2015. Benefits of restoring ecosystem services in urban areas. Current Opinion in Environmental Sustainability ISSN. ISSN: 1877-3435 14, 101–108. https://doi.org/10.1016/j.cosust.2015.05.001.

Evers, C.R., Wardropper, C.B., Branoff, B., Granek, E.F., Hirsch, S.L., Link, T.E., Olivero-Lora, S., Wilson, C., 2018. The ecosystem services and biodiversity of novel ecosystems: A literature review. Glob. Ecol. Conserv. 13, e00362.

Feio, M.J., Hughes, R.M., Callisto, M., Nichols, S.J., Odume, O.N., Quintella, B.R., Kuemmerlen, M., Aguiar, F.C., Almeida, S.F.P., Alonso-EguíaLis, P., Arimoro, F.O., Dyer, F.J., Harding, J.S., Jang, S., Kaufmann, P.R., Lee, S., Li, J., Macedo, D.R., Mendes, A., Mercado-Silva, N., Monk, W., Nakamura, K., Ndiritu, G.G., Ogden, R., Peat, M., Reynoldson, T.B., Rios-Touma, B., Segurado, P., Yates, A.G., 2021. The biological assessment and rehabilitation of the world's rivers: an overview. Water 13, 371. https://doi.org/10.3390/w13030371.

Feio, M.J., Hughes, R.M., Serra, S.R.Q., Nichols, S.J., Kefford, B.J., Lintermans, M., Robinson, W., Odume, O.N., Callisto, M., Macedo, D.R., Harding, J.S., Yates, A.G., Monk, W., Nakamura, K., Mori, T., Sueyoshi, M., Mercado-Silva, N., Chen, K., Baek, M.J., Bae, Y.J., Tachamo-Shah, R.D., Shah, D.N., Campbell, I., Moya, N., Arimoro, F.O., Keke, U.N., Martins, R.T., Alves, C.B.M., Pompeu, P.S., Sharma, S., 2022a. Fish and macroinvertebrate assemblages reveal extensive degradation of the world's rivers. Glob. Chang. Biol. 29 (2), 355–374.

Feio, M.J., Mantas, A.I., Serra, S.R.Q., Calapez, A.R., Almeida, S.F.P., Sales, M.C., Montenegro, M., Moreira, F., Hepp, L.U., 2022b. Effect of environmental education on the knowledge of aquatic ecosystems and reconnection with nature in early childhood. PLoS One 17 (4), e0266776.

Ferreira J, Bernardo JM, Alves MH (2008) Exercício de Intercalibração em rios no âmbito da Directiva Quadro da Água. 9° Congresso da Água: desafios de hoje, exigências de amanhã. Associação Portuguesa de Recursos Hídricos. Estoril.

Graça, M.A.S., Pinto, P., Cortes, R., Coimbra, N., Oliveira, S., Morais, M., Carvalho, M.J., Malo, J., 2004. Factors Affecting Macroinvertebrate Richness and Diversity in Portuguese Streams: a Two-Scale Analysis. Internat. Rev. Hydrobiol. 89 (2), 151–164.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs, J.M., 2008. Global change and the ecology of cities. Science 319 (5864), 756–760.

Grizzetti, B., Liquete, C., Pistocchi, A., Vigiak, O., Zulian, G., Bouraoui, F., De Roo, A., Cardoso, A.C., 2019. Relationship between ecological condition and ecosystem services in European rivers, lakes and coastal waters. Sci. Total Environ. 671, 452–465.

Haase, D., 2015. Reflections about blue ecosystem services in cities. Sustain. Water Qual. Ecol. 5, 77–83. https://doi.org/10.1016/j.swaqe.2015.02.003.

Haase D, Larondelle N, Andersson E, Artmann M, Borgström S, Breuste J, Gomez-Baggethun E, Gren A, Hamstead Z, Hansen R et al. (2014). A Quantitative Review of Urban Ecosystem Service Assessments: Concepts, Models, and Implementation. AMBIO, 43, 413–433.

Haines-Young R, Potschin MB (2018). Common International Classification of Ecosystem Services (CICES) V5 1 and Guidance on the Application of the Revised Structure. European Environment Agency. https://cices eu.

Harrison, P.A., Berry, P.M., Simpson, G., Haslett, J.R., Blicharska, M., Bucur, M., Dunford, R., Egoh, B., Garcia-Llorente, M., Geamănă, N., Geertsema, W., Lommelen, E., Meiresonne, L., Turkelboom, F., 2014. Linkages between biodiversity attributes and ecosystem services: a systematic review. Ecosyst. Serv. 9, 191–203.

Hooper, D.U., Chapin III, F.S., Ewel, J.J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J. H., Lodge, D.M., Loreau, M., Naeem, S., Schmid, B., Setälä, H., Symstad, A.J., Vandermeer, J., Wardle, D.A., 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. Ecol. Monogr. 75, 3–35. https://doi.org/10.1890/04-0922.

INAG (2008a). Manual para a avaliação biológica da qualidade da água em sistemas fluviais segundo a directiva quadro da água. Protocolo de amostragem e análise para os macroinvertebrados bentónicos. Ministério do Ambiente, do Ordenamento do Território e do Desenvolvimento Regional, Instituto da Água, I. P. Portugal.

INAG (2008b). Manual para a avaliação biológica da qualidade da água em sistemas fluviais segundo a directiva quadro da água. Protocolo de amostragem e análise para o fitobentos-diatomáceas. Ministério do Ambiente, do Ordenamento do Território e do Desenvolvimento Regional, Instituto da Água, I. P. Portugal.

Ives, C.D., Lentini, P.E., Threlfall, C.G., Ikin, K., Shanahan, D.F., Garrard, G.E., Bekessy, S.A., Fuller, R.A., Mumaw, L., Rayner, L., Rowe, R., Valentine, L.E., Kendal, D., 2016. Cities are hotspots for threatened species. Glob. Ecol. Biogeogr. 25 (1), 117–126.

Ives, C.D., Giusti, M., Fischer, J., Abson, D.J., Klaniecki, K., Dorninger, C., Laudan, J., Barthel, S., Abernethy, P., Martín-López, B., Raymond, C.M., Kendal, D., von Wehrden, H., 2017. Human–nature connection: A multidisciplinary review. Curr. Opin. Environ. Sustain. 26-27, 106–113.

Jimenez, M.P., DeVille, N.V., Elliott, E.G., Schiff, J.E., Wilt, G.E., Hart, J.E., James, P., 2021. Associations between Nature Exposure and Health: A Review of the Evidence.

Int. J. Environ. Res. Public Health 18 (9), 4790. https://doi.org/10.3390/ijerph18094790.

Jorda-Capdeviça, D., Rodríguez-Labajos, B., 2015. An ecosystem service approach to understand conflicts on river flows: local views on the Ter River (Catalonia). Suistainability Science 10, 463–477. https://doi.org/10.1007/s11625-014-0286-0.

Keyes, A.A., McLaughlin, J.P., Barner, A.K., et al., 2021. An ecological network approach to predict ecosystem service vulnerability to species losses. Nat. Commun. 12, 1586. https://doi.org/10.1038/s41467-021-21824-x.

King, E., Cavender-Bares, J., Balvanera, P., Mwampamba, T.H., Polasky, S., 2015. Trade-offs in ecosystem services and varying stakeholder preferences: evaluating conflicts, obstacles, and opportunities. Ecol. Soc. 20 (3). https://www.jstor.org/stable/26270263.

Kowarik, I., Fischer, L.K., Kendal, D., 2020. Biodiversity Conservation and Sustainable Urban Development. Sustainability 12, 4964.

Lecointe, C., Coste, M., Prygiel, J., 1993. Omnidia: software for taxonomy, calculation of diatom indexes and inventories management. Hydrobiologia 269, 509–513.

Leira, M., Chen, G., Dalton, C., Irvine, K., Taylor, D., 2009. Patterns in freshwater diatom taxonomic distinctness along an eutrophication gradient. Freshw. Biol. 54, 1–14. https://doi.org/10.1111/j.1365-2427.2008.02086.x.

Mendoza-González, G., Martínez, M.L., Lithgow, D., Pérez-Maqueo, O., Simonin, P., 2012. Land use change and its effects on the value of ecosystem services along the coast of the Gulf of Mexico. Ecol. Econ. 82, 23–32.

Mesa, L.M., 2014. Influence of riparian quality on macroinvertebrate assemblages in subtropical mountain streams. J. Nat. Hist. 48 (19–20), 1153–1167. https://doi.org/10.1080/00222933.2013.861937.

Millennium Ecosystem Assessment, 2003. Ecosystems and Human Well-Being: a Framework for Assessment. Island, Washington, DC.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.

Miller, J.D., Kim, H., Kjeldsen, T.R., Packman, J., Grebby, S., Dearden, R., 2014. Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. J. Hydrol. 515, 59–70. https://doi.org/10.1016/j.jhydrol.2014.04.011.

Murcia, C., Aronson, J., Kattan, G.H., Moreno-Mateos, D., Dixon, K., Simberloff, D., 2014. A critique of the 'novel ecosystem' concept. Trends Ecol. Evol. 29 (10), 548–553. https://doi.org/10.1016/j.tree.2014.07.006.

Mutinova, P.T., Kahlert, M., Kupilas, B., McKie, B.G., Friberg, N., Burdon, F.J., 2020. Benthic Diatom Communities in Urban Streams and the Role of Riparian Buffers. Water 12, 2799. https://doi.org/10.3390/w12102799.

Naiman, R.J., Decamps, H., Pollock, M., 1993. The Role of Riparian Corridors in Maintaining Regional Biodiversity. Ecol. Appl. 3, 209–212. https://doi.org/10.2307/1941822.

Nakamura, F., Yamada, H., 2005. The effects of pasture development on the ecological functions of riparian forests in Hokkaido in northern Japan. Ecol. Eng. 24 (5), 539–550.

Potapova, M.G., Charles, D.F., 2002. Benthic diatoms in USA rivers: distributions along spatial and environmental gradients. J. Biogeogr. 29 (2), 167–187.

Ranta, E., Vidal-Abarca, M.R., Calapez, A.R., Feio, M.J., 2021. Urban stream assessment system (UsAs): An integrative tool to assess biodiversity, ecosystem functions and services. Ecol. Ind. 121, 106980 https://doi.org/10.1016/j.ecolind.2020.106980.

Riis, T., Kelly-Quinn, M., Aguiar, F.C., Manolaki, P., Bruno, D., Bejarano, M.D., Clerici, N., Fernandes, M.R., Franco, J.C., Pettit, N., Portela, A.P., Tammeorg, O., Tammeorg, P., Rodríguez-González, P.M., Dufour, S., 2020. Global Overview of Ecosystem Services Provided by Riparian Vegetation. Bioscience 70, 501–514. https://doi.org/10.1093/biosci/biaa041.

Rios, S.L., Bailey, R.C., 2006. Relationship between Riparian Vegetation and Stream Benthic Communities at Three Spatial Scales. Hydrobiologia 553, 153–160. https://doi.org/10.1007/s10750-005-0868-z.

Schröter, M., van der Zanden, E.H., van Oudenhoven, A.P.E., Remme, R.P., Serna-Chavez, H.M., de Groot, R.S., Opdam, P., 2014. Ecosystem Services as a Contested Concept: a Synthesis of Critique and Counter-Arguments. Conserv. Lett. 7 (6), 514–523.

Serra, S.R.Q., Calapez, A.R., Simões, N.E., Marques, J.A.A.S., Laranjo, M., Feio, M.J., 2019. Effects of variations in water quantity and quality in structure and functions of invertebrates' community of a Mediterranean urban stream. Urban Ecosystems 22, 1173–1186. https://doi.org/10.1007/s11252-019-00892-4.

Seto, K.C., Parnell, S., Elmqvist, T., 2013. A Global Outlook on Urbanization. In: Biodiversity and Ecosystem Services: Challenges and Opportunities. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-7088-1_1.

Swan, C.M., Pickett, S.T.A., Slavecz, K., Warren, P., Willey, K.T., 2011. Biodiversity and community composition in urban ecosystems: coupled human, spatial and metacommunity processes. In: Niemelä, J. (Ed.), Handbook of Urban Ecology. Oxford University Press, Oxford.

TEEB (2010). The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A synthesis of the approach, conclusions and recommendations of TEEB. http://www.teebweb.org.

Teittinen, A., Taka, M., Ruth, O., Soininen, J., 2015. Variation in stream diatom communities in relation to water quality and catchment variables in a boreal, urbanized region. Sci. Total Environ. 530–531, 279–289.

Tianhong, L.i., Wenkai, L.i., Zhenghan, Q., 2010. Variations in ecosystem service value in response to land use changes in Shenzhen. Ecol. Econ. 69 (7), 1427–1435.

Tilman, D., 1996. Biodiversity: population versus ecosystem stability. Ecology 77 (2), 350–363.

Tornés, E., Mor, J.-R., Mandaric, L., Sabater, S., 2018. Diatom responses to sewage inputs and hydrological alteration in Mediterranean streams. Environ. Pollut. 238, 369–378.

Trimmel, H., Weihs, P., Leidinger, D., Formayer, H., Kalny, G., Melcher, A., 2018. Can riparian vegetation shade mitigate the expected rise in stream temperatures due to climate change during heat waves in a human-impacted pre-alpine river? Hydrol. Earth Syst. Sci. 22, 437–461. https://doi.org/10.5194/hess-22-437-2018.

United Nations Environment Programme (2008). UNEP 2007 annual report. https://wedocs.unep.org/20.500.11822/7647.

Vaughn, C.C., 2010. Biodiversity Losses and Ecosystem Function in Freshwaters: Emerging Conclusions and Research Directions. Bioscience 60 (1), 25–35.

Vermonden, K., Leuven, R.S.E.W., van der Velde, G., van Katwijk, M.M., Roelofs, J.G.M., Jan Hendriks, A., 2009. Urban drainage systems: An undervalued habitat for aquatic macroinvertebrates. Biol. Conserv. 142 (5), 1105–1115.

Walker, C.E., Pan, Y., 2006. Using diatom assemblages to assess urban stream conditions. Hydrobiologia 561, 179–189. https://doi.org/10.1007/s10750-005-1613-3.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Morgan, R.P., 2005. The urban stream syndrome: current knowledge and the search for a cure. JN Am Benthol Soc 24 (3), 706–723.

Weiß CH, StatSoft Inc., Tulsa OK (2007). STATISTICA, Version 8. *AStA* **91**, 339-341. https://doi.org/10.1007/s10182-007-0038-x.

Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S., Jackson, J.B.C., Lotze, H.K., Micheli, F., Palumbi, S.R., Sala, E., Selkoe, K.A., Stachowicz, J.J., Watson, R., 2006. Impacts of biodiversity loss on ocean ecosystem services. Science 314 (5800), 787–790. https://doi.org/10.1126/science.1132294.

Yi, H., Güneralp, B., Filippi, A.M., Kreuter, U.P., Güneralp, İ., 2017. Impacts of land change on ecosystem services in the San Antonio River Basin, Texas, from 1984 to 2010. Ecol. Econ. 135, 125–135.

Zari, M.P., 2018. The importance of urban biodiversity – an ecosystem services approach. Biodivers. Int. J. 2 (4), 357–360.

Zhang, H., Deng, W., Zhang, S., Peng, L.i., Liu, Y., 2022. Impacts of urbanization on ecosystem services in the Chengdu-Chongqing Urban Agglomeration: Changes and trade-offs. Ecol. Ind. 139, 108920.