Ecological Indicators 164 (2024) 112153

Contents lists available at ScienceDirect

Ecological Indicators

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

Review

Ecological responses of freshwater macroinvertebrates to augmented drought: A literature review and projections

Jorge Machuca-Sepúlveda [a,b], Matilde López [c], Pablo Fierro [d,e], Jorge F. Beltrán [b], Juan-Alejandro Norambuena [a,b], Ricardo Pinheiro S. Oliveira [f], Mauricio Zamorano [b], Jorge G. Farias [a,b,*]

[a] Doctoral Program on Natural Resources Sciences, Universidad de La Frontera, Avenida Francisco Salazar, 01145, P.O. Box 54-D, Temuco 4780000, Chile
[b] Department of Chemical Engineering, Faculty of Engineering and Science, Universidad de La Frontera, Temuco, Chile
[c] Laboratorio de Hidronomía, Universidad de Chile, Santiago, Chile
[d] Facultad de Ciencias, Instituto de Ciencias Marinas y Limnológicas, Universidad Austral de Chile, Valdivia, Chile
[e] Núcleo Milenio de Salmones Invasores (INVASAL), Concepción, Chile
[f] Laboratory of Microbial Biomolecules, School of Pharmaceutical Sciences, University of São Paulo, Rua Do Lago, 250, Cidade Universitária, São Paulo 05508 000, Brazil

ARTICLE INFO

Keywords:
Drought
Macroinvertebrate diversity
Bioassessments
Field-based studies
Experimental approaches

ABSTRACT

Drought significantly impacts freshwater ecosystems, disrupting all biological levels. In particular, freshwater macroinvertebrates undergo significant changes in taxonomic and functional diversity bioassessments. The effects often synergize with other stressors, such as pollution that drought can exacerbate. Several techniques have been well-developed (traditional) or have the potential (innovative) to address this issue. This review provides a comprehensive description of the impact of drought as a primary stressor on macroinvertebrate diversity. An overview of the research and projections are presented. Three conceptual pillars drive this study: taxonomic-functional responses, simultaneous pressure dynamics, and innovative techniques. Few studies have been conducted on lentic water bodies, arid and semi-arid systems, and on multiple continents. Common research keywords across continents are observed less frequently in experimental than in field studies. Most analyzed studies examine community structure, which is more common in field-based than experimental studies. Agricultural land use effect, urbanization, and invasive species are the stressors most associated with drought. Integrating traditional with advanced/innovative techniques that have hardly been applied makes it challenging to understand ecological responses comprehensively. If innovative techniques are employed to consider the dynamics of multiple stressors and to consistently estimate taxonomic and functional diversity, promising avenues for future research could be uncovered.

1. Introduction

The reduction in biodiversity within freshwater environments is an ecological issue mostly resulting from climate change and human activities (Jourdan et al., 2018; Roobavannan et al., 2018; Cid et al., 2020). Diversity is a fundamental metric of ecosystems (Chapin et al., 2000), and it is important to consider this attribute (Bonada et al., 2006) and its relationship with the degree of anthropogenic disturbance. This is necessary for ecological analysis and bioassessment practices (Hilsenhoff, 1988; Irfan and Alatawi, 2019). Macroinvertebrate diversity has been recognized as an indicator of the status of freshwater ecosystems (Vannote et al., 1980; Rosenberg and Resh, 1993). Studies in this area have been continuously reported, primarily through identifying taxa at different scales, bioassessments, and monitoring routines (Verkaik et al., 2013). Such feedback began to consider taxonomic and functional groups together regarding morphological, physiological, and behavioral traits, among others (Merritt et al., 2002). Bioassessments examine direct responses to environmental changes caused by effects such as pollution or land use change (Figueroa et al., 2003; Fierro et al., 2021).

* Corresponding author at: Doctoral Program on Natural Resources Sciences, Universidad de La Frontera, Avenida Francisco Salazar, 01145, P.O. Box 54-D, Temuco 4780000, Chile.
E-mail address: jorge.farias@ufrontera.cl (J.G. Farias).

https://doi.org/10.1016/j.ecolind.2024.112153
Received 18 January 2024; Received in revised form 15 May 2024; Accepted 16 May 2024
Available online 23 May 2024

Drought is related to anomalous flow intermittency, posing a significant issue to bioassessment frameworks (Crabot et al., 2021). The consensus is that drought is a water deficit condition below normal levels (White et al., 2022). According to Slette et al. (2019), drought has several definitions used by ecologists, such as quantifying differences between a reference and an abnormal condition, synonymous with dry conditions, reduced rainfall, characterized by low water flow, associated with low soil moisture, etc. Severity, defined as the degree of water deficit, and intensity, defined as the ratio of severity to the duration of the event (Cavus and Aksoy, 2020), are key variables in these definitions. Significant intensity and severity events of drought can have complex consequences, including reducing hydrological connectivity, enhancing siltation, changing the structure of aquatic vegetation, altering channel shape, increasing water temperature, decreasing dissolved oxygen availability, affecting water chemistry, and altering nutrient cycles (Ledger et al., 2011; Chessman, 2015). Also, drought has been noted for various characterizations used to describe its consequences in intermittent and regular systems, such as drying patterns (Wilding et al., 2018), extremely low flow levels (White et al., 2022), watershed water scarcity (Karaouzas et al., 2018), permanent drying (Carey et al., 2021), and others. In Mediterranean climate zones, intermittent watercourses denote a temporary or reduced flow in specific locations and periods (Banegas-Medina et al., 2021). Depending on climate-induced factors, drought has been increasing in frequency and intensity over the last few decades, as reported by Cunha et al. (2019) and Adámek et al. (2022). Additionally, the impact of drought on biota is influenced by several factors, including the chronic or semi-chronic duration, the severity and intensity of the disruption, and the availability of drought refugees (Boulton, 2003).

Hydroclimatic events, or natural intermittency, can be anomalous due to more severe and intensified droughts, leading to loss of macroinvertebrate diversity (Trenberth et al., 2014). Diversity can also be influenced by low flows, which can affect various processes, including migration, speciation, niche selection, and ecological drift (Green et al., 2022); it can also affect the life cycle, body size, biomass, and secondary production of macroinvertebrates (Ledger et al., 2011). There is evidence of changes in the trophic web resulting from certain functional feeding groups of macroinvertebrates being more sensitive than others (Piano et al., 2019; Ruiz et al., 2022). In this way, certain taxonomic groups, including crustaceans, leeches, and many species of Ephemeroptera, Plecoptera, and Trichoptera, are often the most vulnerable to drought (Aspin et al., 2019a). Therefore, each taxonomic and functional group responds differently to critical flow regimes with distinctive durations and intensities related to local aspects (Aspin et al., 2019a; McDaniel et al., 2019; Mormul et al., 2022). Drying patterns as natural processes have also been affected by drought, compromising resistance, resilience, and dispersal capacity, which is distinguishable among macroinvertebrates found in intermittent and perennial watercourses (Sarremejane et al., 2021; Hill et al., 2019).

There are numerous publications about field and controlled laboratory analyses for disentangling the effects of drought on abiotic and biotic changes in different freshwater systems. The study of macroinvertebrates has been more frequent in Mediterranean and temperate zones, both field-based and experimental approaches (Wilding et al., 2018). Using macroinvertebrate-based studies in field or controlled experiments involves primarily modeling the effects of anthropogenic pressures (Menbohan et al., 2022). Considering anthropogenic impacts as an important issue, especially given the increased risk of droughts that can exacerbate the damage to freshwater organisms, the complexity of responses and impacts in ecological processes also increases (Let et al., 2021). The multidimensional dynamics of the effects of stressors on communities pose a challenge, particularly for management planning and diagnostic purposes (Ormerod et al., 2010; Soria et al., 2017). In this context, advanced/innovative techniques represent a promising methodology that could complement traditional bioassessments (White et al., 2022). For example, biomonitoring 2.0 (Baird and Hajibabaei, 2012), "omics" techniques (Blackman et al., 2021), behavioral assessments (Guo et al., 2021), and physical/modeled simulations (Verdonschot et al., 2015; Patrick and Yuan, 2017) are some of the methods that can be used to tackle that complexity.

This review seeks to describe the most common ecological responses of freshwater macroinvertebrates to the increasing severity and intensity of droughts. The review is organized on three pillars of discussion that represent the most critical issues related to the topic: i) the responses of taxonomic and functional diversity, ii) the concurrent effect of drought with other stressors, and iii) the advanced/innovative diversity assessment techniques. It also provides an overview of the research, focusing on field-based and controlled experimental studies. Different types of analyses, such as overviews, reviews, empirical data analyses, and modeling techniques, are included. This knowledge would provide a comprehensive understanding of the effects of drought on macroinvertebrates based on evidence from multiple case studies. To account for the complexity of the responses of individual biotic groups and their diversity, this paper briefly outlines how research should proceed in the coming years.

2. Methods

As a first step, a comprehensive literature search was conducted including different types of scientific papers, such as primary research articles and reviews. The search was conducted using the Web of Science database provided by Clarivate Analytics. The Boolean search algorithm used was as follows: "macroinvertebrate OR *benthic OR macrozoobenthic AND drought AND *monitoring OR assess*", for highly cited articles only. The filters identified articles that matched the specified date and topic parameters. The selected papers were published between 1982 and May 2022. Also, articles mainly address the following issues, lead into three conceptual pillars: differential responses between taxonomic and functional groups, concurrent effects with other stressors, and potential applications related to advanced techniques. Each section relates to one of these pillars. Research on flow regulation, such as water abstraction during droughts, was included. Regarding macroinvertebrates, no filter was applied to the set of studies that analyzed their interactions with other communities such as microalgae or fish. Our analysis is also based on a systematic review of both field-based and experimental studies. Specific analysis in detail are as follows: i) for taxonomic and functional diversity, we quantified community versus one/few taxa analyzed in the studies, and ii) we ranked the most explores stressors analyzed simultaneously with drought events. Also, we described advanced/innovative techniques mostly recommended in the papers. First, this article provides a synoptic representation of the chronological development of research and a global map illustrating the number of studies conducted in each country. In addition, a heat map of the most frequently used study areas worldwide has been created. A brief overview of the current state is provided by a network map, to illustrate the relationships between the studies conducted in different locations and the progress made over the years. The network map, classified according to the co-occurrence of keywords, shows the main research objectives and identifies relationships between work focusing on field-based and experimental approaches. We used the programs R (https://www.R-project.org), VOSviewer (https://www.vosviewer.com) and QGIS (https://www.qgis.org) to perform all analyzes and create figures.

3. Results

3.1. Synoptic view of research

The 283 articles selected address the conceptual pillars in great detail and were reviewed to support the discussion. Fig. 1 summarizes the temporal distribution of articles for each year, considering the approach (field-based or experimental) they followed.

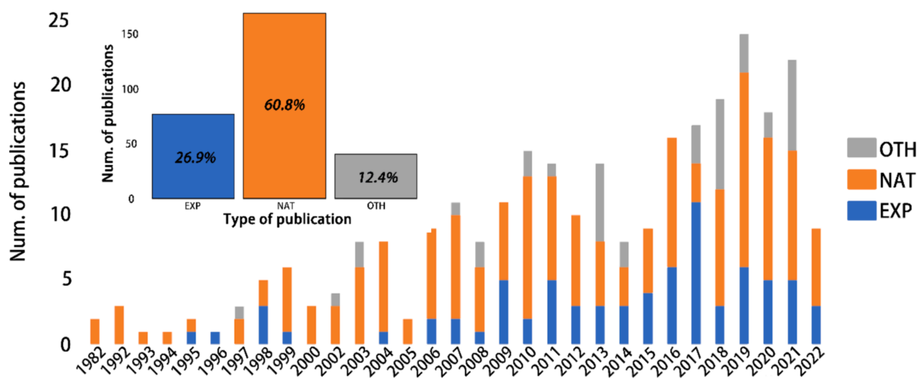

Fig. 1. Number of publications taken into account for this review, categorized by year of publication and type of assessment: direct assessments in natural environments (NAT), experimental (EXP), and other types of works (OTH). At the top left are the percentages associated with each type of publications.

Field-based studies constituted 60.8 % of the total, whereas experimental works accounted for 26.9 %. Other types of articles, such as reviews, overviews, empirical data evaluations, life history records, and modeling procedures, accounted for 12.4 % (Fig. 1). Hydrological conditions or freshwater systems include lotic systems (rivers, streams, channels, creeks, and springs) (75.2 % of the total), lentic systems (lagoons, lakes, ponds, pools, and floodplains) (11.4 %), coastal systems (estuaries and mangroves) (3.3 %), and wetland systems (10.2 %). Similarly, when it comes to climatic regions according to the Köppen climate classification, most field and experimental analyses were conducted in the Mediterranean (30.8 %) and temperate regions (30.3 %). This was followed by tropical/subtropical regions (19.2 %), arid/semi-arid regions (11.7 %), multiple regions simultaneously (5.6 %), and cold (high-altitude) regions (2.1 %). Fig. 2 illustrates all of these proportions across freshwater systems and climates.

The response of macroinvertebrates in terms of taxonomic and functional diversity is the first conceptual pillar to be addressed. Research development has primarily focused on assessing this response at the community level, with the main objective being to estimate the effect on ecological status that is either entirely or partially damaged by the consequences of drought. 10.6 % of the reviewed articles analyze one specific taxon or a few taxa. In Fig. 3, the analysis summarizes the community and taxa levels, including experimental, in-field, and other types of studies (represented as percentages of the total).

To determine the consequences on benthic macroinvertebrates, the dynamics of drought in combination with other stressors or anthropogenic pressures have been studied successively. This topic is discussed in 24.7 % of the articles reviewed. Overexploitation of certain human activities, such as the impacts of land use (mainly agricultural activities), urbanization, and invasive species (28.6 %,12.5 %, and 12.5 %, respectively), are the most reported. Fig. 4 summarizes the most observed effects in research regarding experimental, in-field, and other types of works, expressed as percentages.

Fig. 5 presents a heat map that synthesizes the number of publications produced between 1982 and 2022 across different study areas and locations of experiments achieved. Given the high ecosystem diversity of Asia and Africa and their vulnerability to drought, very limited research has been conducted.

The network maps across keywords are illustrated in Fig. 6. In addition to words such as “drought”, “benthic macroinvertebrates”, and “stream,” there is a high prominence of concepts such as “climate change”, “traits”, “intermittent/temporary streams/rivers”, “environmental flow”, “reference conditions”, “water quality”, “resilience”, and “flow alteration”. Field-based research (Fig. 6A) has recently begun to use the keyword “climate change” more frequently in opposition to the early 2010 s. In these years, “flow permanence”, “headwater stream”, “variability”, and “disturbance” are commonly utilized. “Resilience” is a keyword associated with recent works as well. This is similar to experimental research, where “resilience” and “resistance” become more well-known. Interestingly, in the experiments, the keyword “climate change” was employed more before field-based works.

Lastly, we cover a range of advanced techniques, including those already applied and those with potential for application in a projected understanding. This review considers advanced or innovative techniques as catalysts for technological, social, and cultural change within a defined thematic scheme (Edwards-Schachter, 2018). Therefore, we chose the following advanced/innovative techniques described because they are related to freshwater bioassessment and are frequently utilized in the literature acquired and revised. Consequently, we have decided to choose the following: molecular techniques, experiments of behavior movement, and physically modeled simulated drought. They include key articles on specific topics, their main findings, and associated disciplines or approaches. In this section, we describe some case studies from reviewed articles that comprehensively examine the three conceptual pillars from the two approaches explored and ecoregions.

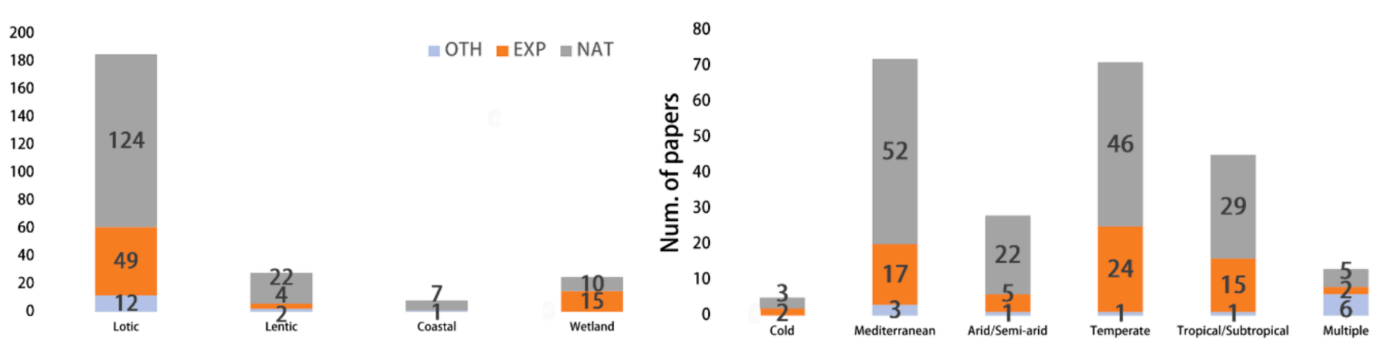

Fig. 2. Types of freshwater systems (lotic, lentic, coastal and wetland) (left) and climatic regions (Mediterranean, temperate, tropical/subtropical, arid/semi-arid, multiple, and cold regions) (right) in direct assessments in natural environments (NAT), experimental (EXP), and other types of works (OTH).

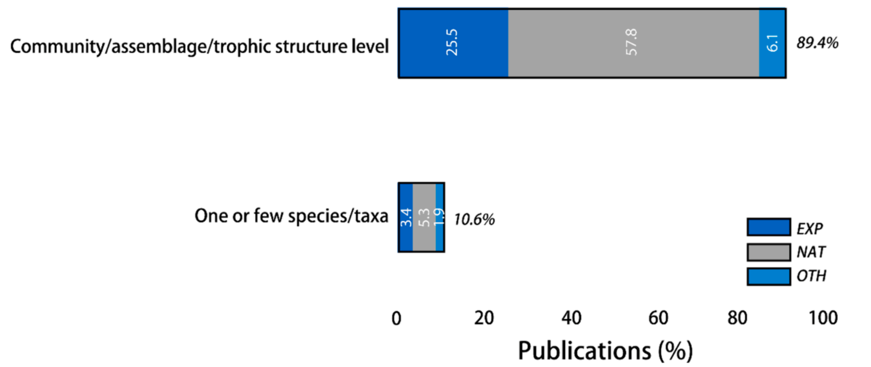

Fig. 3. Number of studies (in percentages) related to analysis addressed to community/assemblage/trophic structure level and one/few macroinvertebrates species or taxa, with respect to direct assessments in field or natural environments (NAT), experimental (EXP), and other types of works (OTH).

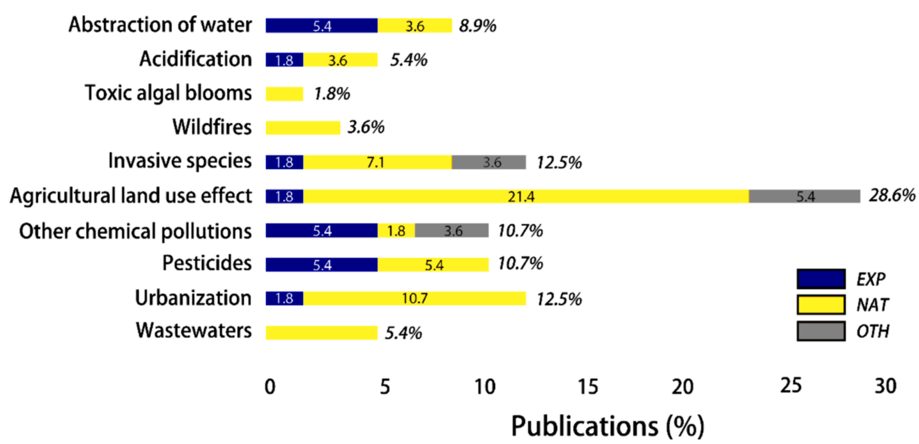

Fig. 4. Percentage of publications that focus directly on effects from several types of stressors simultaneously with drought. Of the total number of articles reviewed, 24.7% directly examine the effects of drought and at least one other stressor, from direct assessments in natural environments (NAT), experimental (EXP), and other types of work (OTH).

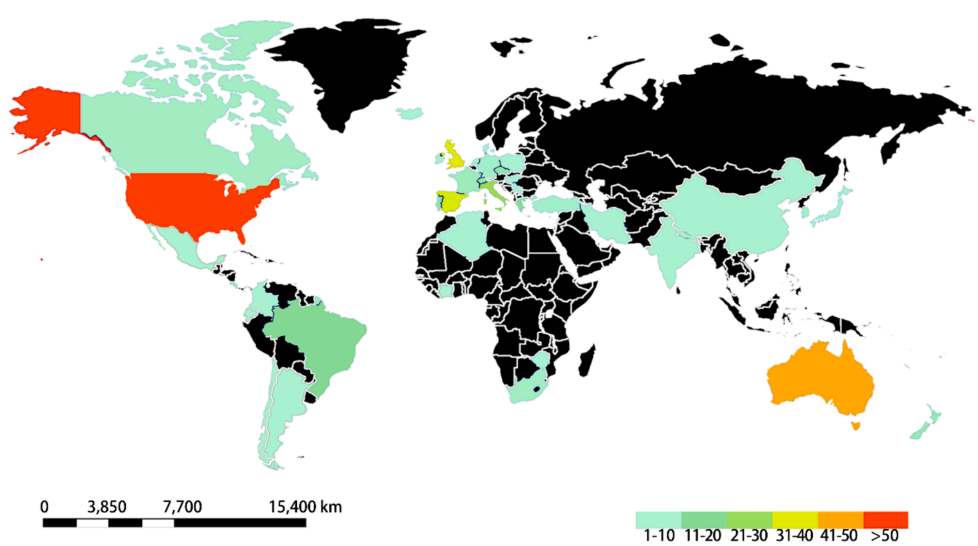

Fig. 5. Distributional geographic heat map of the study areas analyzed for the number of papers published. Black color represents countries without data or available data or studies.

3.2. Insights of taxonomical and functional responses

We describe some study cases from reviewed articles related to taxonomical and functional responses from macroinvertebrates to drought, mostly arthropods (Insecta and Crustacea class), followed secondarily by non-insects. Given the community or individual taxonomic levels of study, members of the phylum Arthropoda are the primary group explored. The complexity of responses between species, even within the same genus or family, makes it tremendously difficult to clarify specific trends of groups concerning increased drought severity

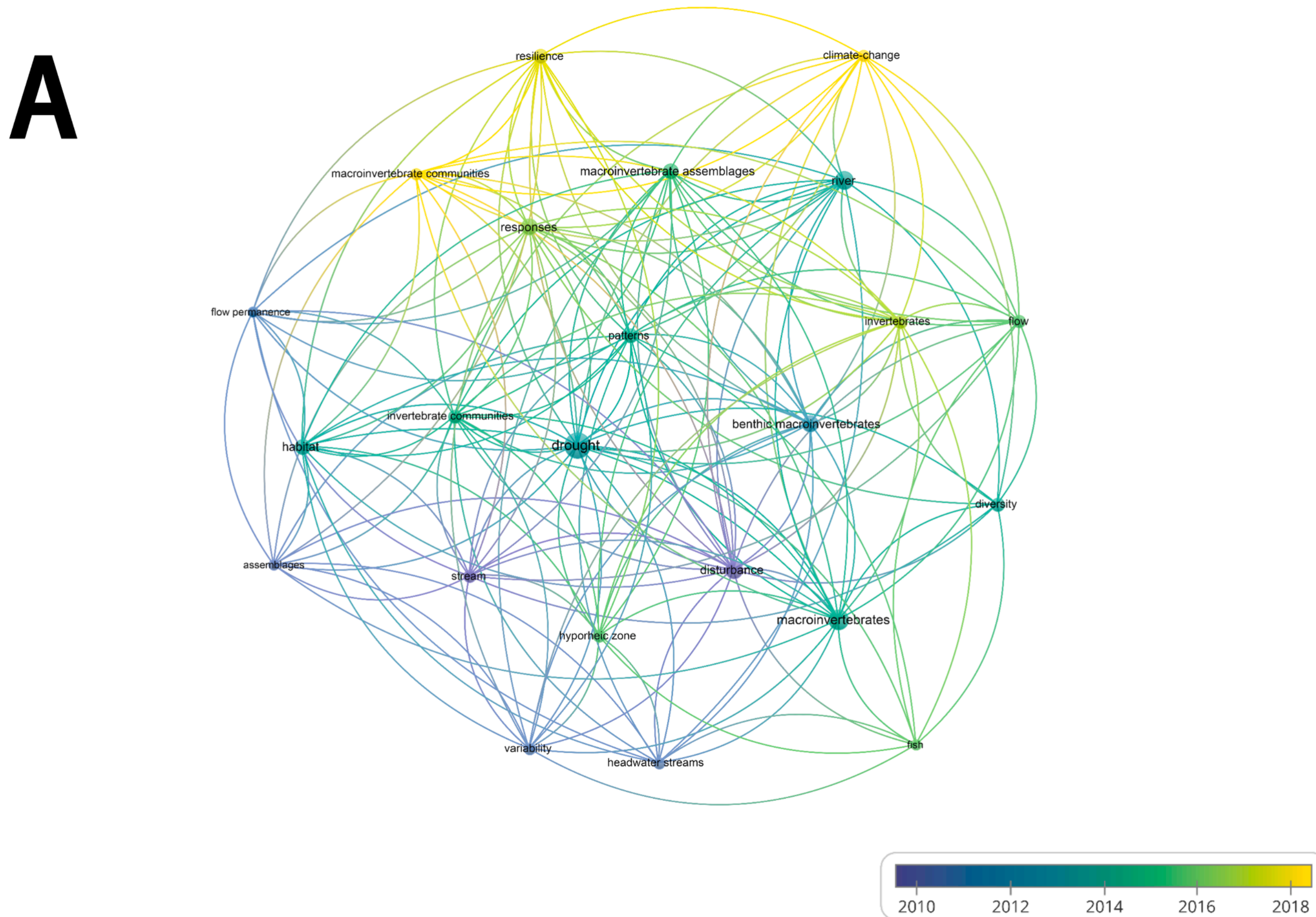

Fig. 6. Keyword analysis A) from works that emphasize field-based approaches, and B) which emphasize experimental approaches. Colors indicate the average publication year (from 2010 to 2018) in Fig. 6-A. Occurrences are related to the size of keywords and the size of circles.

and intensity. This is mainly due to differences in habitat conditions in different hydrological systems, climates, and biogeographical contexts.

Ephemeroptera, Plecoptera, Trichoptera, Diptera, and Coleoptera are the most commonly studied in relation to the effects of increased drought severity. The families Ephemeroptera, Plecoptera, and Trichoptera are primarily associated with perennial streams, widely found in riffles rather than pools (Verdonschot et al., 2015). Ephemeroptera, Plecoptera, and Trichoptera have been reported as drought-sensitive taxa in headwater intermittent streams of temperate climates (Storey, 2016). For example, drought incidents dramatically reduce the taxon richness of larval caddisflies, making them one of the most sensitive macroinvertebrates (Doretto et al., 2018). Nonetheless, in semi-arid intermittent streams, Ephemeroptera and Trichoptera show elevated richness compared to ephemeral sites (Chakona et al., 2008). This trend has been supported by experimental approaches, specifically in the effects of increased fine sediment on the silk of Hydropsychids, which are generally resilient to various environmental changes, such as drying events (Albertson and Daniels, 2016). Also, species of the genera *Hydropsyche* and *Rhyacophila*, which typically thrive in faster currents, can survive in altered habitats with reduced flow conditions (Dunbar et al., 2010). The main similarity among Ephemeroptera, Plecoptera, and Trichoptera is their dependence on water flow, sensitivity to dissolved oxygen, and intolerance to intensified drying events (Connolly et al., 2004; King et al., 2016; Peterson et al., 2017; Herbst et al., 2019).

As a basic finding from the reviewed articles, certain authors state that members of Diptera and Coleoptera can adapt well to temporary streams (López-Rodríguez et al., 2012; Verdonschot et al., 2015; Menció and Boix, 2018). In the case of Diptera, many authors have found that they are the most abundant and ubiquitous in different habitat types (García-Roger et al., 2011; Karaouzas et al., 2011; White et al., 2012; De Jong et al., 2015). For example, Dipterans can survive in reduced oxygen concentrations during extreme drought, increasing their capacity to colonize different habitats (Jovem-Azevêdo et al., 2019; Popović et al., 2022). The adaptability of Diptera and their life strategies to many environments allow them to persist in the cover of riparian vegetation in perennial sites during extreme droughts (Griswold et al., 2008; Cooper et al., 2021). Therefore, Chironomidae members can tolerate extreme environmental conditions, including drought (Irons et al., 1993; Frouz et al., 2003). The diversity of Chironomidae increases during low water-level periods but decreases during high water-level periods (Mormul et al., 2022). Some blackflies and midges dominate after rewetting (Bogan et al., 2013) and tanyponid *Zavrelimyia* (Ledger and Hildrew, 2001). Nonetheless, under experimental stagnant and drought conditions in the field, an abundance of Chironomidae increased, while other taxa, such as Simuliidae, decreased (Hille et al., 2014). Determining a general disposition is complicated by additional elements related to the effects of drought, such as ecological succession, dispersion capacities, and life span in chironomids (Cañedo-Argüelles and Rieradevall, 2011). In Coleoptera, most groups show adaptative reactions to drying in lentic water environments (Chadd et al., 2017). Coleoptera can exhibit unique behavior, such as consuming vertebrate carrion (some Dytiscids) in contracting pools (McDaniel et al., 2019). Particular taxa of Coleoptera can thrive in hypoxic conditions when a low flow scenario leads to fragmented habitats (disconnected pools) experiencing an increased

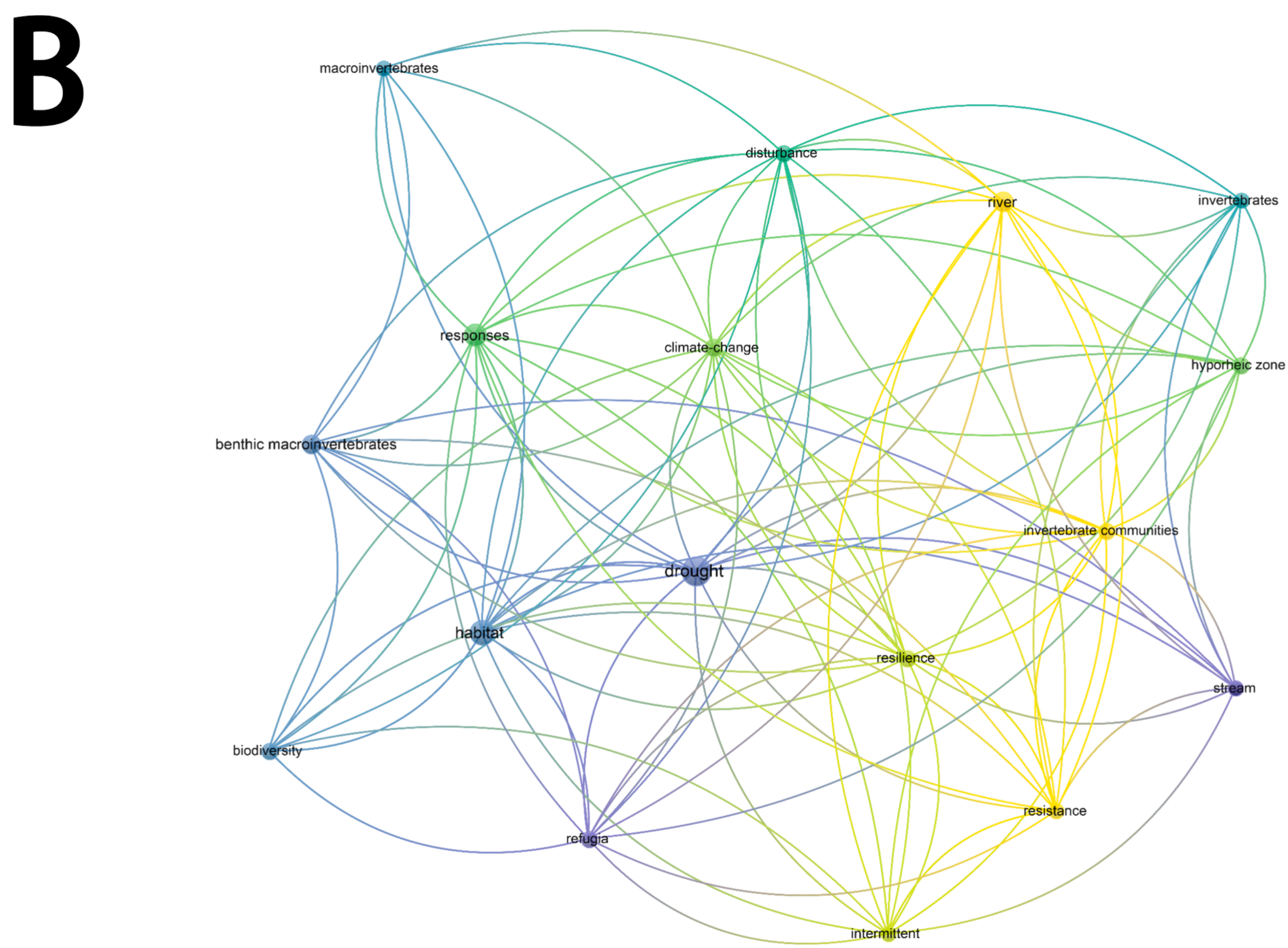

Fig. 6. (*continued*).

oxygen deficit (Buffagni, 2021). Together with Odonata species, a recolonization process in ponds is displayed within a couple of weeks of re-flooding (Chase and Knight, 2003).

The cases of non-insects such as Crustacea and Malacostraca are relevant examples of species models affected by drought that have been studied in terms of their recolonization dynamics (Adams and Warren, 2005). *Asellus aquaticus* dominates after dry episodes in ephemeral streams and *Gammarus pulex* in near perennial streams (Hill et al., 2019). Crayfish can survive desiccation through several strategies, involving vertical burrowing in the hyporheic zone (Kouba et al., 2016), sediment cracks for refugees (Strachan et al., 2015), and physiological limitations (Xu et al., 2022). Regarding amphipods, body size is important for migration processes, which can be affected by reduced water levels (Patel et al., 2021). According to Martínez et al. (2015), Oligochaetes dominate the community composition after rewetting but are presumed to have lower densities and biomasses than permanent streams. Other groups, such as bivalves, experience mortality during drought events, which is more remarkable in invasive species than native species (McDowell and Sousa, 2019). A myriad of responses are evidenced; the severity and intensity of drought alter ecological succession by recolonization, thermal tolerances, and hypoxic stress processes.

The taxonomic characteristics of macroinvertebrates in response to drought stressors are strongly influenced by their functional feeding conduct, as demonstrated in experimental (Ledger et al., 2011) and field-based research (Pinna et al., 2013). Some cases of shredders, collectors, scrapers, and predators are listed here. First, shredders are highly sensitive to episodes of drought disturbance; they are often replaced by other taxonomic groups (Carey et al., 2021). Shredders can be influenced by the biomechanical and stoichiometric characteristics of plants that grow on low-flow surfaces (Dehedin et al., 2013). After a drought event in perennial temperate streams, the recolonization process by shredders differs depending on the riparian vegetation type (Monroy et al., 2017). Direct and indirect consequences of drought, such as wildfires (Cooper et al., 2021), algal blooms resulting from hydrological variations (Burgazzi et al., 2020), and inter-seasonal drought periods (Reznickova et al., 2007), also have a negative impact on shredders. Notwithstanding the presence of shredders, the decline in leaf litter breakdown has also been directly attributed to drought conditions (Leberfinger et al., 2010). Hence, the loss of shredder taxa is presumed to alter the decomposition rate of leaf litter in streams, resulting in a modification of ecosystem functions (Wenisch et al., 2017). In the case of collectors, feed fine particulate organic matter has been extensively studied in the context of low-flow disturbances in seasonal variations (Boulton and Lake, 1992; Merritt et al., 2017). Collector-gatherers and filter feeders are the most dominant groups in terms of biomass in wetlands; however, they exhibit distinct temporal dynamics and recovery patterns (Meyer and Whiles, 2008). In tropical streams, drought causes an increase in the overall density of collector-gatherers (and some grazers) at the peak of the event, but the overall taxonomic richness remains unchanged (Gutiérrez-Fonseca et al., 2020). In mountain-Mediterranean streams, the relative abundance of collector-gatherers and predators increases during late drought, mainly tolerant Chironomidae that can benefit from enhanced food resources (Herbst et al., 2019). In experiments in wetlands disconnected from rivers, where coarse organic matter was manipulated during a severe drought, collector-gatherers were significantly modified in their trophic dynamics (Bush et al., 2017). Another study suggests a relationship between post-fire disturbance and drought conditions, which affects the composition of gathering collector assemblages in their functional characteristics (Verkaik et al., 2014). Other relevant functional feeding groups, such as scrapers, filterers, and predators, are closely linked to algal biomass and hydrological changes (DeColibus et al., 2017; Pardo and García, 2016). Scrapers are more common in streams where they rely on autotrophic materials for food, as noted by Sabater et al. (2008). Wright et al. (2003) and Let et al. (2021) report the effects of drought and other stressors for grazer-scrapers. Scrapers and attached algae form a robust trophic relationship, influenced by factors such as organism distribution and density, water flow, temperature, and sedimentation (Fenoglio et al., 2020). Scrapers are more abundant in permanent Mediterranean ponds than in temporary ones, which can affect the growth and diversity of algae and/or macrophytes (Bazzanti et al., 2009). Predator macroinvertebrates can be affected by extreme variations in water flow. For instance, López-Rodríguez et al. (2012) observed changes in food webs between wet and dry periods; the most remarkable is that the predators' role shifts to detritivores at the end of the wet season. Large specialist predators prefer isolated pools because deposit feeders' prey consume the organic matter that accumulates there (Gallardo et al., 2014). Table 1 summarizes the most recurrent characteristics and lessons of taxonomic and functional responses from the detailed study cases.

3.3. Drought synergistic effect with other stressors

The synergistic effect of drought with shifts in water chemistry caused by pesticides, wastewater discharge, and thermal pollution have a significant impact on the physical characteristics of habitats, some considered drought refugia (Humphries and Baldwin, 2003). Also, severely low flow events alter nutrient dynamics more than the wet years (Wetzel and Likens, 2000). For example, in regions with a semi-arid climate, the limited variety of species is associated with the quality of water, primarily influenced by total ammonia nitrogen, nitrate, total phosphorus, and total suspended solids. These factors alter the community structure of macroinvertebrates and other autotrophic groups (da Rocha et al., 2016). It has been evidenced that macroinvertebrate assemblages can be affected by anomalies in nutrient dynamics in eutrophic lowland rivers in a transition from a dry to a wet year (Parr and Mason, 2003). An increase in high concentrations of ammonium in low-flow contexts has a negative effect on overall diversity and the relative abundance of shredders (Menéndez et al., 2011). A study found a negative correlation between arthropod and non-arthropod taxa in this context; however, a positive correlation was observed only for the collector-gatherer feeding group (Let et al., 2021). The presence of temperature fluctuations and pesticides in water is associated with negative impacts on Trichoptera, but net-spinning caddisflies are an exception, as it has shown tolerance and a positive response in drought scenarios (Waite et al., 2020). Additionally, the negative correlation between organophosphates and the macroinvertebrate community structure is a result of the damage caused by low flows, worsening the risk of pollutant effects (Bollmohr and Schulz, 2009; Kalogianni et al., 2017). A specific example of this is the aerial application of glyphosate to willow canopies, which affects macroinvertebrates, particularly during intense and severe droughts (Wech et al., 2018).

The concentration of pollutants in urban wastewater increases during dry seasons, exacerbated by droughts, which leads to a homogenization of functional trait composition by the type of river substrate and stream size (Figueroa et al., 2003; Mor et al., 2019). The stream

Table 1
Most recurrent responses of different taxonomic and functional groups of benthic macroinvertebrates associated with increasing drought severity and/or intensity in the literature reviewed here.

Taxonomic or functional feeding groups	Hydrologic or climatic system	Response to increasing drought severity and/or intensity	Possible ecological concerns	Reference
Ephemeroptera, Plecoptera, and Trichoptera	Headwater intermittent streams in temperate climates	Sensible to drought condition due to anomalous rates of low flow	Migration, drift, and emergence can be deteriorated	Storey, 2016
Some Trichoptera families	Lowland temperate streams	Can endure in diminished numbers within modified habitats characterized by reduced flow conditions	Maintained dominance in more altered state from these taxa	Dunbar et al., 2010
Diptera	Semi-arid watersheds	During the extreme drought period, they survive in environments with reduced oxygen concentrations, and colonize diverse habitats	Aridity scenarios can pulse predictable dynamics for intense drought events, with Diptera as bioindicator	Jovem-Azevêdo et al., 2019
Chironomidae	Shallow lake in a wetland area	Various factors linked to drought effects, and others such as ecological succession, dispersal abilities, and lifespan in chironomids contribute to the ambiguity in establishing a common trend	Micro-habitat structure such as algal mat or type of sediments play a key role in the multiple responses from Chironomidae	Cañedo-Argüelles and Rieradevall, 2011
Coleoptera	Temporary rivers	Can prosper in hypoxic conditions when a low-flow scenario results in fragmented habitats	An elevated oxygen deficit, caused by disconnected pools, would determine a decreasing habitat function	Buffagni, 2021
Oligochaeta	Calcareous streams under oceanic climate	Pioneer taxa dominate the community structure following rewetting, although it is presumed that they exhibit lower densities and biomasses compared to those in permanent streams	Hypoxic environment with low organic material processing in post-drought conditions could be evidenced	Martínez et al., 2015
Shredders	Streams of oceanic-temperate climate	If drought event is severe/intense, the recolonization process will depend on the hazards of vegetation in catchment area	Modified flux energy between terrestrial to fluvial ecosystem	Monroy et al., 2017
Collectors	Floodplain wetlands	In experimental settings where coarse organic matter was manipulated during a severe drought, there were significant modifications observed in the trophic dynamics of collector-gatherers	Adaptability times between flood pulses periods may be altered together with food webs	Bush et al., 2017
Scrapers	Riverbed sites	Water flow, temperature, and sedimentation influence organism distribution and density	Likely shift of size and morphology of scrapers, and algal susceptibility to grazing in biofilm dynamics	Fenoglio et al., 2020
Predators	Mediterranean intermittent streams	Discernible alterations in food webs between wet and dry periods can be observed, at the onset of the wet season, only a limited number of predator species are present	Changes in their diet during wet and dry periods	López-Rodríguez et al., 2012

environment downstream from wastewater treatment plant discharges can serve as a stable living habitat for some macroinvertebrates. However, these organisms are still affected by episodic drought perturbations (Canobbio et al., 2009). When examining lotic systems with comparable hydrology, it has been observed that land use significantly influences the variation in biota, but drought has a greater impact on invertebrates than the type of land use (Cowell et al., 2004). The impervious surfaces of channelized urban streams and the crops grown have a homogenizing effect on Odonata specimens. This effect is less frequent in warmer regions but more common in dry summers (Ball-Damerow et al., 2014). Furthermore, streams with an intact catchment area, minimal land use change, and undisturbed riparian vegetation offer more favorable conditions for preserving habitats during drought (Thomson et al., 2012). Ganong et al. (2021) demonstrate that poorly buffered streams experience seasonal acidification and are vulnerable to drought. However, larval midges have a remarkable tolerance for extreme pH levels. During a severe drought, changes in land use within a subtropical catchment resulted in a sudden shift in chemical parameters, including electrical conductivity, which decreased macroinvertebrate richness (Pacheco et al., 2017).

Another significant stressor contributing to shifts in macroinvertebrate communities is the presence of invasive species, which have been shown to resist extreme environmental conditions (Scharler et al., 2020). One of the most extensively researched alien organisms is crayfish, which have a significant impact on native aquatic species, especially during drought. Crayfish are generally larger, longer-lived, and more mobile than most other invertebrates and can dramatically affect the ecosystems they inhabit (Martinez, 2012). In the case of gammarids, most native species are capable of longitudinal migration (Pařil et al., 2019). Aquatic invasive species, however, can overcome specific environmental constraints; for example, they can rapidly migrate to a previously dry area and possess the ability to move both upstream and downstream (Meyer et al., 2004). In arid streams, drought-tolerant species develop a breakdown rate that does not affect that provides drought-tolerant crustaceans, despite the fact that these decrease alpha diversity of colonizing macroinvertebrates (Moody and Sabo, 2013). It is important to conduct long-term surveillance on the dynamics of invasive species, with a focus on controlling their intra- and inter-specific responses. Thus, to determine its distribution and correlation with climate factors, it is important to consider the effects of seasonal drying (Resh et al., 2013), which can be prolonged during intense droughts.

Other directly or indirectly anthropogenic-induced activities can negatively impact on macroinvertebrate diversity and may be exacerbated by drought. Examples of such activities include wildfires (Beganyi and Batzer, 2011), toxic algal blooms (Gérard and Lance, 2019), highway construction (Akay and Dalkıran, 2020), water abstraction (Miller et al., 2007; Skoulikidis et al., 2011), deposition of nutrients (Figueroa et al., 2003; Peralta-Maraver et al., 2018), acidification (Bowman et al., 2006), among others). Climate change affects various levels of ecological structure, associated with changes in temperature and atmospheric conditions, and interacts with the impacts of local or regional disturbances (Ledger et al., 2011). For instance, climate change is related to severe and intense droughts, and its impact leads to extreme events, which in turn lead to long-term disruptions (Nichols et al., 2010). Furthermore, climate change is predicted to increase the frequency and severity of drought events and threats to diversity on a larger spatial scale (Dodemaide et al., 2018). It is expected that species distributions may change or decrease due to future climate change scenarios. For instance, this could impact Gripopterygidae members in neotropical catchments (Silva et al., 2019). The challenges related to the ecological effects of climate change are addressed through the response of species and communities. They may either adapt quickly to environmental variability or face a situation where the severity of the stressor exceeds their capacity to adapt (Parmesan, 2006). Similarly, stress caused by changes in water flow is expected to reduce the effectiveness and success of restoration efforts due to the inadequate recovery period after disturbances (Veríssimo et al., 2013). Numerous studies have concluded that hydrologic changes leading to water scarcity have a greater impact on aquatic communities than chemical pollution (Arenas-Sánchez et al., 2016). Therefore, taking into account all the above-mentioned antecedents, it is reasonable to consider water quantity as a crucial factor when assessing diversity. It is also necessary to consider thermal pollution, which shaped the biomass of detritivores and shredders in harsh drought scenarios (Rivera-Usme et al., 2015). Given the persistent nature of climate change, it is anticipated that drying patterns with erratic weather will significantly shift the bioassessments (de Necker et al., 2022). As already stated, it is recommended that both water quality and quantity considerations be systematically integrated into bioassessments to achieve a comprehensive understanding and effective management.

3.4. *Advanced techniques already or potentially applied*

We describe only three selected advanced techniques already mentioned: molecular techniques, movement-behavioral response setups, and drought simulation methods. Their function has brought or would bring significant shifts in both theoretical and practical knowledge. The advanced/innovative methods discussed in this section are provided in Table 2.

Bioassessments based on "big data" using next-generation sequencing (NGS) can process huge amounts of data, such as metagenomics, to characterize diversity. This technology can also help clarify community structure and functioning in extreme stress situations, such as drought, which can lead to the response analysis (Woodward et al., 2013). The responses of diversity to community-level stressors and the associated functional aspects are not yet fully understood. However, the next generation of biomonitoring programs, known as biomonitoring 2.0, can help achieve these goals. This is due to their ability to generate a more comprehensive range of operational taxonomic units (OTUs) and their respective response to stressors (Leese et al., 2018). In particular, DNA metabarcoding facilitates high-throughput taxonomic identification through automatized processing pipelines, expanding the ability to detect changes in macroinvertebrate communities (Bush et al., 2019). In interpreting diversity patterns in intermittent streams, metabarcoding techniques have been evaluated for taxonomic resolution improvements. These techniques have been shown to provide more accurate information on species-specific habitat preferences due to desiccation events (Laini et al., 2020).

From the same root, omics techniques are innovative evaluations that utilize molecular tools to comprehensively understand ongoing processes at all levels of biological organization in the presence of stressors (Mierzejewska and Urbaniak, 2020). The most commonly used omics approaches include transcriptomics, proteomics, and metabolomics (Mortimer et al., 2022), applied in toxicology to identify biomarkers and clarify mechanisms of toxicity. Metabolomics has been used to diagnose stressors in a multi-stressor environment. However, further research is needed to establish a link between specific combinations of responses and specific stressors (Pomfret et al., 2020). Additionally, multi-omics or omics-based monitoring may be best suited to provide comprehensive linkages between sub-individual biomarker responses and multiple stressor scenarios (Liang et al., 2020). Applications of omics-based monitoring in specific stressors, such as drought, may involve greater complexity than the search for bioindicators. Blackman et al. (2021) suggest that the population size and dynamics of intermittent rivers and related species have not been thoroughly assessed using genomic markers. This approach could help identify specialist species and determine their relative speed of adaptation to desiccation. Another significant contribution of multi-omics is identifying drought-resistant forms of macroinvertebrates, which can be used to estimate the survival rates of specific adaptations (Pařil et al., 2019).

Experimental ecology behavior has expanded its relevance to

Table 2
Innovative techniques condensed here with the main articles containing this information, main findings related to them (innovations are already or potentially applied), and each discipline associated with their research development.

Type of innovation	Articles	Main findings	Disciplines associated
Molecular techniques	Leese et al., 2018; Stubbington et al., 2018; Laini et al., 2020; Blackman et al., 2021.	● Assessment of biomarkers for the recognition of specialist species and their adaptation to desiccation ● Expansion of ecosystem monitoring scope to detect changes in ecological communities ● Gain understanding of the ongoing processes on all levels of biological organization ● Next-generation sequencing (NGS) to characterize diversity in changing environments	Genetics, −omics, Big data management
Behavioral-response assessments	Aspin et al., 2019a; Patel et al., 2021; Gallegos-Sánchez et al., 2022	● Colonization patterns in pre, during and post drought events ● Growth rates in altered conditions by pollution enforced by direct consequences of drought ● Movement traits and other related to determine the resistance and resilience strategies	Engineering, Ecotoxicology, Ethology
Drought simulation	Ledger et al., 2011; Dézerald et al., 2015; Le et al., 2020; Waite et al., 2020	● Environmental flows simulations to identify habitat suitability in groundwater and surface water ● Experimental setups for community structure organization and response ● Measurement of taxonomic compositional turnover across several environmental gradients ● Prediction of total benthic biomass reduction by several orders of magnitude of hydrologic regimes	Engineering, Informatics, Hydrology, Mathematical modelling

multiple aspects of organisms, including intraspecific variability such as fitness, response to seasonality, and body size. This topic has been studied by several authors, including Mancinelli (2010). Nonetheless, progress in this matter should be addressed to deal with the direct consequences of more severe and/or intense drought events. Locomotion, dispersal, and feeding habits are the most commonly analyzed traits in bioassessment schemes and toxicological bioassays (De Castro-Català et al., 2017; Mor et al., 2019). Movement behavior is easily observable in macroinvertebrates, and numerous studies have developed sophisticated methodological procedures using experimental assessments (Longo and Mancinelli, 2014; Shokri et al., 2021). Migration and colonization behavior can create adverse conditions for physiological, morphological, life strategy, or behavioral adaptations aimed at seeking refuge (Durkota et al., 2019). The dispersal of organisms during emergency or submerged migration processes is hindered by drought, particularly in lotic compared to lentic systems (Rosset et al., 2017). A highly saturated substratum influences vertical migration of organisms into deeper sediment layers, as it enhances their survival (Poznańska-Kakareko et al., 2017; Vadher et al., 2017; Loskotová et al., 2019; Pernecker et al., 2020). Survival strategies are directly related to an organism's movement or type of locomotion. In this regard, traits-based bioassessments have been incorporated into Mediterranean streams to evaluate diversity and the effects of drought. This protocol directly indicates how anomalies of ecological integrity are manifested (García-Roger et al., 2011; Elias et al., 2015). Information garnered utilizing movement-behavior setups can enhance comprehension regarding the dynamics of populations across expansive spatial scales. Also, it can clarify the ramifications of various management methodologies shaped by drought on the dispersal capacity of macroinvertebrates (Augusiak and Van den Brink, 2015). Thus, a potential assessment involves the response of dispersal capacity to drought conditions aligned with ecotoxicological procedures in the pursuit of physiological constraints and potential biomarkers. This will aid in recognizing benchmarks and model responses with hydrological atypical patterns linked to specific stressors like pollution.

Cutting-edge methodologies have been developed to simulate physical drought, providing valuable insights. Simulations range from assessing the impact on water temperature to examining community structure and even studying the behavior of species (Ledger et al., 2011; Gallegos-Sánchez et al., 2022). For instance, the trophic behavior of macroinvertebrates has been extensively studied through experimental mesocosms in the field. For example, the predatory behavior of control cages may be affected by intensified droughts (Dorn et al., 2006). In recent decades, innovative methods such as mathematical modeling have been implemented in laboratory or field mesocosm environments (Dézerald et al., 2015) and through hydrological models (Le et al., 2020). The development of models of simulation specifically designed for intermittent Mediterranean river reaches has been reported. These models incorporate environmental flows and baseflows to simulate the habitat suitability of macroinvertebrates (Theodoropoulos et al., 2019). In experimental subtropical wetlands, a physical simulation was carried out on the effects of a drying-to-rewetting sequence on predation pressure responses of dragonflies and crayfish (Knorp and Dorn, 2014). Similarly, Ledger et al. (2011) conducted a controlled experiment using stream mesocosms to examine the impact of repeated drought disturbances on macroinvertebrate assemblages and their functional groups. Through a covariance structure analysis model, it was possible to predict that severe hydrological regimes can reduce the total benthic biomass (Riseng et al., 2004). Furthermore, a "gradient forest" modeling technique has been developed to evaluate potential species-specific thresholds and quantify taxonomic compositional turnover across environmental gradients. This technique considers substrate size, dissolved oxygen levels, and contaminants (Waite et al., 2020). Mathematical modeling has been used in hydrology and engineering to analyze the hydrodynamic interactions between groundwater and surface water. In the field of hyporheic zone ecology, implementing this technique has resulted in significant advancements and progress (Peralta-Maraver et al., 2018). As noted above, the mentioned techniques have facilitated advancements in diversity assessments. In detail, specific improvements in taxonomic determination, movement behavior responses, and interactions between physical variables and ecology of macroinvertebrates.

4. Discussion

Responses of macroinvertebrates should be assessed, taking into account different severities and intensities of drought, although this becomes more complex when combined with the synergistic effects of other stressors. This approach provides a realistic assessment of the likely consequences of drought (White et al., 2022). From numerous climatic regions and hydrological conditions, significant progress has been made in understanding how the responses of macroinvertebrates are due to drought. First and foremost, methods for disentangling responses are focused and more efficient by functional traits. Such a perspective supports the analysis of organisms ranging from rheophilic and lentic tolerances, respiration forms, locomotion, etc. Work on both taxonomic and functional diversity is being organized and integrated using modern techniques for efficient assessment (Skoulikidis et al., 2011). Taxonomic and functional groups respond to drought events with specific trends, each with high variability. However, further research is needed on this matter.

Accordingly, lotic systems are generally the best studied. Conversely, water bodies from arid and semi-arid regions are relatively understudied (see Fig. 2). Further research is also needed in arid and semi-arid regions extending beyond developed countries' borders and encompassing several climatic regions simultaneously. Compared to taxonomic diversity, the literature on functional diversity in unexplored areas can still progress today and seems to receive more attention and consolidation. Agricultural land use, invasive species, and the effects of urbanization are the topics most analyzed in relation to drought hazards. Historical impacts have led to the accumulation of a considerable amount of data on these topics (Fig. 4). It is noteworthy that few studies have investigated these threats using experiments (in the field or other), which can be challenging to conduct at large spatial and temporal scales. The qualitative analysis of innovative techniques aims to determine their consistency using continuously improving methods. Toxicological and monitoring frameworks could serve as examples where bioindicators and biomarkers can be used jointly in standardized methods. This enables the assessment of concurrent stressors that directly contribute to exacerbating drought conditions. For instance, trait-based assessments, increasingly used in different fields (see Fig. 6), could significantly improve by integrating with molecular techniques, such as biomonitoring 2.0 and other related ones. Considering the context of aggravated stressors by drought, bioassessments, management proposals for restoration, mitigation, and other areas on a global scale, it is essential to foster collaboration among multiple countries and organizations.

It is feasible to provide valuable insights for assessing the different variations in the dynamics of drought and extreme dryness under several conditions of perturbations. For example, it may be stated that research conducted in IRES (intermittent rivers and ephemeral streams) take an initial and important role in identifying the factors contributing to severe droughts in macroinvertebrates. It is a useful comparable framework for arid and semi-arid regions to integrate research and resource management with Mediterranean and temperate ecoregions. Moreover, it provides a basis for analysis in experimental contexts conducted in the field. Subsequently, the dynamics of carbon cycling in riparian ecosystems, as an indicator of the trophic capacity of watercourses, are concepts frequently discussed in the articles reviewed. It is important to measure the negative effects of drought on the processing of large organic matter in freshwater systems in different climatic regions. In this way, community structure patterns involved in this ecosystem function, decimated by drought, have been evaluated. Also, water extraction/diversion is a derived stressor that rarely appears in the results of the overall studies examined. This highlights that only 29.4 % of the studies specifically consider the effects of other stressors in combination with drought. This is emphasized because the damage suffered by macroinvertebrates is not solely associated with a single stressor. Therefore, gaining a more detailed understanding of the complexity of freshwater systems in an increasingly anthropogenic context is important.

Experimental analyses are needed to focus on specific species or taxa, as their number is currently limited. It is important to note that integrating community analyses and experimental approaches is still underdeveloped. This is understandable, given the significant resources required to conduct such integrated studies (Vadher et al., 2017). The water quantity factor shows a synergistic interaction with water quality, which amplifies the overall impact. However, existing techniques are insufficient to capture this synergy. Therefore, such techniques should probably be applied using a system of multiple perspectives, including taxonomic, trait-based, and biomonitoring 2.0 methods. Interconnected techniques can shed light on the combined effects, as Aspin et al., (2019b) mentioned. For example, ecotoxicological assessments with molecular techniques to identify biomarkers could be valid where quantity and quality have been altered jointly. The upcoming challenge is to identify biomarkers specifically related to drought impacts. In this sense, only living organisms were sampled to assess the impact dynamics based on the data collected. However, the study of inactive stages (resistant forms) with molecular techniques has hardly been studied.

It is important to understand and recognize that the responses of macroinvertebrates to climate regions vary greatly, as do the potentially unknown effects of extreme conditions. For example, there are marked differences in the combinations of traits observed (Gallardo et al., 2014). Conducting these studies concurrently would improve our ability to predict potentially detrimental effects in these regions. Such predictions could then be extrapolated to other areas, considering the context of fluctuating climate patterns attributed to global change.

As for innovative techniques described, it is clear from the reports and background articles reviewed that including field methods to complement model-based simulations can improve the accuracy of diversity assessments. It would also facilitate the creation of a practical basis for implementing specific measures to protect or mitigate impacts on freshwater systems. This is similar to the extensive use of mathematical models to study, for example, in hyporheic dynamics (Peralta-Maraver et al., 2018). Molecular techniques can potentially uncover hidden information and clarify the characteristics of the biota affected. Non-destructive molecular methods such as eDNA or omics have well-structured methodological protocols for sampling. However, these protocols must be refined for rivers or streams affected by extreme desiccation, such as disturbed ephemeral streams. In such cases, the water may not be the medium through which biological material (e.g., sediments) is recovered (Blackman et al., 2021). This way, we can improve our understanding of the differences between field and experimental methods and develop tools to help organisms withstand challenging drought conditions. Furthermore, integrated strategies at all ecological levels, including ethology (i.e., movement patterns) and biological aspects (i.e., forms of resistance such as cocoons), can help to further address this complexity.

5. Conclusions

To fully understand the impact of extreme drought scenarios and distinguish between regular and abnormal episodes, it is necessary to carry out diversity assessments simultaneously across multiple continents and freshwater systems globally. In addition, simulated droughts, jointly with natural weather anomalies, are expected to be mostly addressed in the long term. This scenario requires introducing new mitigating tools to address altered water flow/volume changes. Therefore, it is necessary to propose diversity assessments with methodological protocols explicitly designed for a scenario with more intense and severe droughts. This includes formulating clear objectives, implementing simple sampling protocols, ensuring optimal specimen fixation or treatment, conducting efficient laboratory investigations, streamlining data extraction, managing databases, and performing *meta*-analysis. All of these steps should inevitably include the most innovative techniques to enhance a realistic understanding of the synergistic effects of drought with other stressors, as described in this review. It is essential to develop manuals, instructions, and practical tools that prioritize assessments during droughts of different intensities, while accounting for the concomitant pressures. For instance, one of the most important challenges is identifying the types of biomarkers that can be used to detect irreversible damage at the physiological level in both the most sensitive and least sensitive species. This involves the basic information already identified, such as morphological and functional traits and life form strategies covered by molecular methods or advanced experimental setup. Based on our results, future studies should focus on these topics (conceptual pillars) separately in more depth. If novel methodologies are utilized to account for the interactions among multiple stressors and reliably bioassessments, potential pathways to future investigations could be revealed, particularly in contexts characterized by progressive climate change and weather anomalies.

Funding

This research was funded by ANID (Agencia Nacional de Investigación y Desarrollo) scholarship, grant number 21210601 and FAPESP-UFRO N°2020/06982-3.

Authors' contributions

J.M-S: idea for the article, literature search, data analysis, original draft preparation, and editing. J.G.F, M.L, P.F: idea for the article, critical revision of the work, supervision, writing, and editing. J.F.B, J-A. N, M.Z, R. P. S. O: critical revision of the work and editing. All authors have read and agreed to the published version of the manuscript.

CRediT authorship contribution statement

Jorge Machuca-Sepúlveda: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Matilde López:** Resources, Investigation, Formal analysis, Conceptualization. **Pablo Fierro:** Writing – review & editing, Supervision, Resources, Formal analysis, Data curation, Conceptualization. **Jorge F. Beltrán:** Supervision, Conceptualization. **Juan-Alejandro Norambuena:** Supervision, Conceptualization. **Ricardo Pinheiro S. Oliveira:** Writing – review & editing, Supervision, Resources. **Mauricio Zamorano:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Conceptualization. **Jorge G. Farias:** Writing – review & editing, Supervision, Project administration, Funding acquisition, 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.

Data availability

Data will be made available on request.

Acknowledgements

Thanks to ANID (Agencia Nacional de Investigación y Desarrollo) scholarship grant 21210601, São Paulo Research Foundation (FAPESP) grant 2018/25511-1, and the National Council of Scientific and Technological Development (CNPq) grants 312923/2020-1 and 408783/2021-4.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.112153.

References

Adámek, Z., Konečná, J., Karásek, P., Všetičková, L., Podhrázská, J., Zajíček, A., 2022. From perennial to intermittent headwater stream: macroinvertebrate community response to climate-induced summer water scarcity. Aquat Ecol 56, 937–950. https://doi.org/10.1007/s10452-022-09964-8.

Adams, S.B., Warren, M.L., 2005. Recolonization by warmwater fishes and crayfishes after severe drought in upper coastal plain hill streams. Trans Am Fish Soc. https://doi.org/10.1577/t04-089.1.

Akay, E., Dalkıran, N., 2020. Assessing biological water quality of Yalakdere stream (Yalova, Turkey) with benthic macroinvertebrate-based metrics. Biologia (bratisl) 75, 1347–1363. https://doi.org/10.2478/s11756-019-00387-9.

Albertson, L.K., Daniels, M.D., 2016. Resilience of aquatic net-spinning caddisfly silk structures to common global stressors. Freshw Biol 61, 670–679. https://doi.org/10.1111/fwb.12737.

Arenas-Sánchez, A., Rico, A., Vighi, M., 2016. Effects of water scarcity and chemical pollution in aquatic ecosystems: State of the art. Sci. Total Environ. 572, 390–403. https://doi.org/10.1016/j.scitotenv.2016.07.211.

Aspin, T.W.H., Hart, K., Khamis, K., Milner, A.M., O'Callaghan, M.J., Trimmer, M., Wang, Z., Williams, G.M.D., Woodward, G., Ledger, M.E., 2019a. Drought intensification alters the composition, body size, and trophic structure of invertebrate assemblages in a stream mesocosm experiment. Freshw Biol. https://doi.org/10.1111/fwb.13259.

Aspin, T.W.H., Khamis, K., Matthews, T.J., Milner, A.M., O'Callaghan, M.J., Trimmer, M., Woodward, G., Ledger, M.E., 2019b. Extreme drought pushes stream invertebrate communities over functional thresholds. Glob Chang Biol 25, 230–244. https://doi.org/10.1111/gcb.14495.

Augusiak, J., Van den Brink, P.J., 2015. Studying the movement behavior of benthic macroinvertebrates with automated video tracking. Ecol Evol 5, 1563–1575. https://doi.org/10.1002/ece3.1425.

Baird, D.J., Hajibabaei, M., 2012. Biomonitoring 2.0: A new paradigm in ecosystem assessment made possible by next-generation DNA sequencing. Mol Ecol 21, 2039–2044. https://doi.org/10.1111/j.1365-294X.2012.05519.x.

Ball-Damerow, J.E., M'Gonigle, L.K., Resh, V.H., 2014. Changes in occurrence, richness, and biological traits of dragonflies and damselflies (Odonata) in California and Nevada over the past century. Biodivers Conserv 23, 2107–2126. https://doi.org/10.1007/s10531-014-0707-5.

Banegas-Medina, A., Montes, I.Y., Tzoraki, O., Brendonck, L., Pinceel, T., Diaz, G., Arriagada, P., Arumi, J.L., Pedreros, P., Figueroa, R., 2021. Hydrological, environmental and taxonomical heterogeneity during the transition from drying to flowing conditions in a mediterranean intermittent river. Biology (basel) 10. https://doi.org/10.3390/biology10040316.

Bazzanti, M., Bella, V.D., Grezzi, F., 2009. Functional characteristics of macroinvertebrate communities in mediterranean ponds (Central Italy): Influence of water permanence and mesohabitat type. Ann Limnol 45, 29–39. https://doi.org/10.1051/limn/09005.

Beganyi, S.R., Batzer, D.P., 2011. Wildfire induced changes in aquatic invertebrate communities and mercury bioaccumulation in the Okefenokee Swamp. Hydrobiologia 669, 237–247. https://doi.org/10.1007/s10750-011-0694-4.

Blackman, R.C., Altermatt, F., Foulquier, A., Lefébure, T., Gauthier, M., Bouchez, A., Stubbington, R., Weigand, A.M., Leese, F., Datry, T., 2021. Unlocking our understanding of intermittent rivers and ephemeral streams with genomic tools. Front Ecol Environ 19, 574–583.

Bogan, M.T., Boersma, K.S., Lytle, D.A., 2013. Flow intermittency alters longitudinal patterns of invertebrate diversity and assemblage composition in an arid-land stream network. Freshw Biol 58, 1016–1028. https://doi.org/10.1111/fwb.12105.

Bollmohr, S., Schulz, R., 2009. Seasonal changes of macroinvertebrate communities in a Western Cape river, South Africa, receiving nonpoint-source insecticide pollution. Environ Toxicol Chem 28, 809–817. https://doi.org/10.1897/08-228R.1.

Bonada, N., Prat, N., Resh, V.H., Statzner, B., 2006. Developments in aquatic insect biomonitoring: a comparative analysis of recent approaches. Annu Rev Entomol 51, 495–523. https://doi.org/10.1146/annurev.ento.51.110104.151124.

Boulton, A.J., 2003. Parallels and contrasts in the effects of drought on stream macroinvertebrate assemblages. Freshw Biol 48, 1173–1185. https://doi.org/10.1046/j.1365-2427.2003.01084.x.

Boulton, A.J., Lake, P.S., 1992. The ecology of two intermittent streams in Victoria, Australia. Freshw Biol 27, 123–138. https://doi.org/10.1111/j.1365-2427.1992.tb00528.x.

Bowman, M.F., Somers, K.M., Reid, R.A., Scott, L.D., 2006. Temporal response of stream benthic macroinvertebrate communities to the synergistic effects of anthropogenic acidification and natural drought events. Freshw Biol 51, 768–782. https://doi.org/10.1111/j.1365-2427.2006.01516.x.

Buffagni, A., 2021. The lentic and lotic characteristics of habitats determine the distribution of benthic macroinvertebrates in Mediterranean rivers. Freshw Biol 66, 13–34. https://doi.org/10.1111/fwb.13596.

Burgazzi, G., Bolpagni, R., Laini, A., Racchetti, E., Viaroli, P., 2020. Algal biomass and macroinvertebrate dynamics in intermittent braided rivers: new perspectives from instream pools. River Res Appl 36, 1682–1689. https://doi.org/10.1002/rra.3675.

Bush, A., Compson, Z.G., Monk, W.A., Porter, T.M., Steeves, R., Emilson, E., Gagne, N., Hajibabaei, M., Roy, M., Baird, D.J., 2019. Studying ecosystems with DNA metabarcoding: lessons from biomonitoring of aquatic macroinvertebrates. Front Ecol Evol. https://doi.org/10.3389/fevo.2019.00434.

Bush, B.M., Hutchens, J.J., Gulis, V., Godwin, K.S., 2017. Impact of macroconsumers on leaf breakdown and detritivores in wetlands on a southeastern US coastal plain floodplain during drought. Wetlands 37, 1169–1179. https://doi.org/10.1007/s13157-017-0949-6.

Cañedo-Argüelles, M., Rieradevall, M., 2011. Early succession of the macroinvertebrate community in a shallow lake: Response to changes in the habitat condition. Limnologica 41, 363–370. https://doi.org/10.1016/j.limno.2011.04.001.

Canobbio, S., Mezzanotte, V., Sanfilippo, U., Benvenuto, F., 2009. Effect of multiple stressors on water quality and macroinvertebrate assemblages in an effluent-

dominated stream. Water Air Soil Pollut 198, 359–371. https://doi.org/10.1007/s11270-008-9851-4.
Carey, N., Chester, E.T., Robson, B.J., 2021. Flow regime change alters shredder identity but not leaf litter decomposition in headwater streams affected by severe, permanent drying. Freshw Biol 66, 1813–1830. https://doi.org/10.1111/fwb.13794.
Cavus, Y., Aksoy, H., 2020. Critical drought severity/intensity-duration-frequency curves based on precipitation deficit. J Hydrol (Amst) 584, 124312. https://doi.org/10.1016/j.jhydrol.2019.124312.
Chadd, R.P., England, J.A., Constable, D., Dunbar, M.J., Extence, C.A., Leeming, D.J., Murray-Bligh, J.A., Wood, P.J., 2017. An index to track the ecological effects of drought development and recovery on riverine invertebrate communities. Ecol Indic 82, 344–356. https://doi.org/10.1016/j.ecolind.2017.06.058.
Chakona, A., Phiri, C., Magadza, C.H.D., Brendonck, L., 2008. The influence of habitat structure and flow permanence on macroinvertebrate assemblages in temporary rivers in northwestern Zimbabwe. Hydrobiologia 607, 199–209. https://doi.org/10.1007/s10750-008-9391-3.
Chase, J.M., Knight, T.M., 2003. Drought-induced mosquito outbreaks in wetlands. Ecol Lett 6, 1017–1024. https://doi.org/10.1046/j.1461-0248.2003.00533.x.
Chessman, B.C., 2015. Relationships between lotic macroinvertebrate traits and responses to extreme drought. Freshw Biol 60, 50–63. https://doi.org/10.1111/fwb.12466.
Cid, N., Bonada, N., Heino, J., Cañedo-Argüelles, M., Crabot, J., Sarremejane, R., Soininen, J., Stubbington, R., Datry, T., 2020. A metacommunity approach to improve biological assessments in highly dynamic freshwater ecosystems. Bioscience 70, 427–438. https://doi.org/10.1093/biosci/biaa033.
Connolly, N.M., Crossland, M.R., Pearson, R.G., 2004. Effect of low dissolved oxygen on survival, emergence, and drift of tropical stream macroinvertebrates. J North Am Benthol Soc 23, 251–270. https://doi.org/10.1899/0887-3593(2004)023<0251:EOLDOO>2.0.CO;2.
Cooper, S.D., Klose, K., Herbst, D.B., White, J., Drenner, S.M., Eliason, E.J., 2021. Wildfire and drying legacies and stream invertebrate assemblages. Freshwater Science 40, 659–680. https://doi.org/10.1086/717416.
Cowell, B.C., Remley, A.H., Lynch, D.M., 2004. Seasonal changes in the distribution and abundance of benthic invertebrates in six headwater streams in central Florida. Hydrobiologia 522, 99–115. https://doi.org/10.1023/B:HYDR.0000029977.94089.b8.
Crabot, J., Dolédec, S., Forcellini, M., Datry, T., 2021. Efficiency of invertebrate-based bioassessment for evaluating the ecological status of streams along a gradient of flow intermittence. Ecol Indic 133, 108440. https://doi.org/10.1016/j.ecolind.2021.108440.
Cunha, A.P.M.A., Zeri, M., Deusdará Leal, K., Costa, L., Cuartas, L.A., Marengo, J.A., Tomasella, J., Vieira, R.M., Barbosa, A.A., Cunningham, C., Cal Garcia, J.V., Broedel, E., Alvalá, R., Ribeiro-Neto, G., 2019. Extreme drought events over Brazil from 2011 to 2019. Atmosphere (basel) 10, 642. https://doi.org/10.3390/atmos10110642.
da Rocha, F.C., de Andrade, E.M., Lopes, F.B., de Paula Filho, F.J., Filho, J.H.C., da Silva, M.D., 2016. Physical-chemical determinant properties of biological communities in continental semi-arid waters. Environ Monit Assess 188. https://doi.org/10.1007/s10661-016-5497-7.
De Castro-Català, N., Muñoz, I., Riera, J.L., Ford, A.T., 2017. Evidence of low dose effects of the antidepressant fluoxetine and the fungicide prochloraz on the behavior of the keystone freshwater invertebrate *Gammarus pulex*. Environ. Pollut. https://doi.org/10.1016/j.envpol.2017.07.088.
De Jong, G.D., Canton, S.P., Lynch, J.S., Murphy, M., 2015. Aquatic invertebrate and vertebrate communities of ephemeral stream ecosystems in the arid southwestern United States. Southwest. Nat. 60, 349–359. https://doi.org/10.1894/0038-4909-60.4.349.
de Necker, L., Gerber, R., van Vuren, J., Wepener, V., Smit, N.J., Brendonck, L., 2022. Temporal dynamics of a subtropical floodplain pool after 2 years of supra-seasonal drought: a mesocosm study. Hydrobiologia 849, 795–815. https://doi.org/10.1007/s10750-021-04743-2.
DeColibus, D.T., Rober, A.R., Sampson, A.M., Shurzinske, A.C., Walls, J.T., Turetsky, M.R., Wyatt, K.H., 2017. Legacy effects of drought alters the aquatic food web of a northern boreal peatland. Freshw Biol 62, 1377–1388. https://doi.org/10.1111/fwb.12950.
Dehedin, A., Maazouzi, C., Puijalon, S., Marmonier, P., Piscart, C., 2013. The combined effects of water level reduction and an increase in ammonia concentration on organic matter processing by key freshwater shredders in alluvial wetlands. Glob Chang Biol 19, 763–774. https://doi.org/10.1111/gcb.12084.
Dézerald, O., Céréghino, R., Corbara, B., Dejean, A., Leroy, C., 2015. Functional trait responses of aquatic macroinvertebrates to simulated drought in a Neotropical bromeliad ecosystem. Freshw Biol 60, 1917–1929. https://doi.org/10.1111/fwb.12621.
Dodemaide, D.T., Matthews, T.G., Iervasi, D., Lester, R.E., 2018. Anthropogenic water bodies as drought refuge for aquatic macroinvertebrates and macrophytes. Sci. Total Environ. 616–617, 543–553. https://doi.org/10.1016/j.scitotenv.2017.10.333.
Doretto, A., Piano, E., Falasco, E., Fenoglio, S., Bruno, M.C., Bona, F., 2018. Investigating the role of refuges and drift on the resilience of macroinvertebrate communities to drying conditions: An experiment in artificial streams. River Res Appl 34, 777–785. https://doi.org/10.1002/rra.3294.
Dorn, N.J., Trexler, J.C., Gaiser, E.E., 2006. Exploring the role of large predators in marsh food webs: Evidence for a behaviorally-mediated trophic cascade. Hydrobiologia 569, 375–386. https://doi.org/10.1007/s10750-006-0143-y.
Dunbar, M.J., Pedersen, M.L., Cadman, D., Extence, C., Waddingham, J., Chadd, R., Larsen, S.E., 2010. River discharge and local-scale physical habitat influence macroinvertebrate LIFE scores. Freshw Biol 55, 226–242. https://doi.org/10.1111/j.1365-2427.2009.02306.x.
Durkota, J.M., Wood, P.J., Johns, T., Thompson, J.R., Flower, R.J., 2019. Distribution of macroinvertebrate communities across surface and groundwater habitats in response to hydrological variability. Fundam. Appl. Limnol. 193, 79–92. https://doi.org/10.1127/fal/2019/1156.
Edwards-Schachter, M., 2018. The nature and variety of innovation. International Journal of Innovation Studies 2, 65–79. https://doi.org/10.1016/j.ijis.2018.08.004.
Elias, C.L., Calapez, A.R., Almeida, S.F.P., Feio, M.J., 2015. From perennial to temporary streams: An extreme drought as a driving force of freshwater communities' traits. Mar Freshw Res 66, 469–480. https://doi.org/10.1071/MF13312.
Fenoglio, S., de Figueroa, J.M.T., Doretto, A., Falasco, E., Bona, F., 2020. Aquatic insects and benthic diatoms: a history of biotic relationships in freshwater ecosystems. Water (basel) 12, 2934.
Fierro, P., Valdovinos, C., Lara, C., Saldías, G., 2021. Influence of intensive agriculture on benthic macroinvertebrate assemblages and water quality in the Aconcagua river basin (Central Chile). Water (basel) 13, 492. https://doi.org/10.3390/w13040492.
Figueroa, R., Valdovinos, C., Araya, E., Parra, O., 2003. Macroinvertebrados bentónicos como indicadores de calidad de agua de ríos del sur de Chile. Rev. Chil. Hist. Nat. 76 https://doi.org/10.4067/S0716-078X2003000200012.
Frouz, J., Matěna, J., Ali, A., 2003. Survival strategies of chironomids (Diptera: Chironomidae) living in temporary habitats: a review. Eur J Entomol 100, 459–465. https://doi.org/10.14411/eje.2003.069.
Gallardo, B., Dolédec, S., Paillex, A., Arscott, D.B., Sheldon, F., Zilli, F., Mérigoux, S., Castella, E., Comín, F.A., 2014. Response of benthic macroinvertebrates to gradients in hydrological connectivity: A comparison of temperate, subtropical, Mediterranean and semiarid river floodplains. Freshw Biol 59, 630–648. https://doi.org/10.1111/fwb.12292.
Gallegos-Sánchez, S., Domínguez, E., Encalada, A.C., Ríos-Touma, B., 2022. Effects of experimental warming on two tropical Andean aquatic insects. PLoS One 17, e0271256.
Ganong, C., Oconitrillo, M.H., Pringle, C., 2021. Thresholds of acidification impacts on macroinvertebrates adapted to seasonally acidified tropical streams: Potential responses to extreme drought-driven pH declines. PeerJ 9. https://doi.org/10.7717/peerj.11955.
García-Roger, E.M., del Sánchez-Montoya, M.M., Gómez, R., Suárez, M.L., Vidal-Abarca, M.R., Latron, J., Rieradevall, M., Prat, N., 2011. Do seasonal changes in habitat features influence aquatic macroinvertebrate assemblages in perennial versus temporary Mediterranean streams? Aquat Sci 73, 567–579. https://doi.org/10.1007/s00027-011-0218-3.
Gérard, C., Lance, E., 2019. Decline of freshwater gastropods exposed to recurrent interacting stressors implying cyanobacterial proliferations and droughts. Aquat Ecol 53, 79–96. https://doi.org/10.1007/s10452-019-09674-8.
Green, M.D., Anderson, K.E., Herbst, D.B., Spasojevic, M.J., 2022. Rethinking biodiversity patterns and processes in stream ecosystems. Ecol Monogr 92. https://doi.org/10.1002/ecm.1520.
Griswold, M.W., Berzinis, R.W., Crisman, T.L., Golladay, S.W., 2008. Impacts of climatic stability on the structural and functional aspects of macroinvertebrate communities after severe drought. Freshw Biol 53, 2465–2483. https://doi.org/10.1111/j.1365-2427.2008.02067.x.
Guo, W., Weiperth, A., Hossain, M.S., Kubec, J., Grabicová, K., Ložek, F., Veselý, L., Bláha, M., Buřič, M., Kouba, A., Velíšek, J., 2021. The effects of the herbicides terbuthylazine and metazachlor at environmental concentration on the burrowing behaviour of red swamp crayfish. Chemosphere. https://doi.org/10.1016/j.chemosphere.2020.128656.
Gutiérrez-Fonseca, P.E., Ramírez, A., Pringle, C.M., Torres, P.J., McDowell, W.H., Covich, A., Crowl, T., Pérez-Reyes, O., 2020. When the rainforest dries: Drought effects on a montane tropical stream ecosystem in Puerto Rico. Freshwater Science 39, 197–212. https://doi.org/10.1086/708808.
Herbst, D.B., Cooper, S.D., Medhurst, R.B., Wiseman, S.W., Hunsaker, C.T., 2019. Drought ecohydrology alters the structure and function of benthic invertebrate communities in mountain streams. Freshw Biol 64, 886–902. https://doi.org/10.1111/fwb.13270.
Hill, M.J., Mathers, K.L., Little, S., Worrall, T., Gunn, J., Wood, P.J., 2019. Ecological effects of a supra-seasonal drought on macroinvertebrate communities differ between near-perennial and ephemeral river reaches. Aquat Sci 81, 1–12. https://doi.org/10.1007/s00027-019-0659-7.
Hille, S., Kristensen, E.A., Graeber, D., Riis, T., Jørgensen, N.K., Baattrup-Pedersen, A., 2014. Fast reaction of macroinvertebrate communities to stagnation and drought in streams with contrasting nutrient availability. Freshwater Science 33, 847–859. https://doi.org/10.1086/677554.
Hilsenhoff, W.L., 1988. Rapid Field Assessment of Organic Pollution with a Family-Level Biotic Index. J North Am Benthol Soc 7, 65–68. https://doi.org/10.2307/1467832.
Humphries, P., Baldwin, D.S., 2003. Drought and aquatic ecosystems. Freshw Biol 48, 1141–1146.
Irfan, S., Alatawi, A.M.M., 2019. Aquatic ecosystem and biodiversity: A review. Open J Ecol 09, 1–13. https://doi.org/10.4236/oje.2019.91001.
Irons III, J.G., Miller, L.K., Oswood, M.W., 1993. Ecological adaptations of aquatic macroinvertebrates to overwintering in interior Alaska (U.S.A.) subarctic streams. Can J Zool 71, 98–108. https://doi.org/10.1139/z93-015.
Jourdan, J., O'Hara, R.B., Bottarin, R., Huttunen, K.-L., Kuemmerlen, M., Monteith, D., Muotka, T., Ozoliņš, D., Paavola, R., Pilotto, F., Springe, G., Skuja, A., Sundermann, A., Tonkin, J.D., Haase, P., 2018. Effects of changing climate on European stream invertebrate communities: A long-term data analysis. Sci. Total Environ. 621, 588–599. https://doi.org/10.1016/j.scitotenv.2017.11.242.

Jovem-Azevêdo, D., Bezerra-Neto, J.F., Azevêdo, E.L., Gomes, W.I.A., Molozzi, J., Feio, M.J., 2019. Dipteran assemblages as functional indicators of extreme droughts. J Arid Environ 164, 12–22. https://doi.org/10.1016/j.jaridenv.2019.01.014.
Kalogianni, E., Vourka, A., Karaouzas, I., Vardakas, L., Laschou, S., Skoulikidis, N.T., 2017. Combined effects of water stress and pollution on macroinvertebrate and fish assemblages in a Mediterranean intermittent river. Sci. Total Environ. 603–604, 639–650. https://doi.org/10.1016/j.scitotenv.2017.06.078.
Karaouzas, I., Skoulikidis, N.T., Giannakou, U., Albanis, T.A., 2011. Spatial and temporal effects of olive mill wastewaters to stream macroinvertebrates and aquatic ecosystems status. Water Res 45, 6334–6346. https://doi.org/10.1016/j.watres.2011.09.014.
Karaouzas, I., Theodoropoulos, C., Vardakas, L., Kalogianni, E., Skoulikidis, Th., N.,, 2018. A review of the effects of pollution and water scarcity on the stream biota of an intermittent Mediterranean basin. River Res Appl 34, 291–299. https://doi.org/10.1002/rra.3254.
King, R.S., Scoggins, M., Porras, A., 2016. Stream biodiversity is disproportionately lost to urbanization when flow permanence declines: Evidence from southwestern North America. Freshwater Science 35, 340–352. https://doi.org/10.1086/684943.
Knorp, N.E., Dorn, N.J., 2014. Dissimilar numerical responses of macroinvertebrates to disturbance from drying and predatory sunfish. Freshw Biol 59, 1378–1388. https://doi.org/10.1111/fwb.12352.
Kouba, A., Tíkal, J., Císař, P., Veselý, L., Fořt, M., Příborský, J., Patoka, J., Buřič, M., 2016. The significance of droughts for hyporheic dwellers: evidence from freshwater crayfish. Sci Rep 6, 26569. https://doi.org/10.1038/srep26569.
Laini, A., Beermann, A.J., Bolpagni, R., Burgazzi, G., Elbrecht, V., Zizka, V.M.A., Leese, F., Viaroli, P., 2020. Exploring the potential of metabarcoding to disentangle macroinvertebrate community dynamics in intermittent streams. Metabarcoding Metagenom 4, 65–79. https://doi.org/10.3897/mbmg.4.51433.
Le, C.T.U., Paul, W.L., Gawne, B., Suter, P.J., 2020. Quantitative flow-ecology relationships using distributed lag nonlinear models: large floods in the Murray River could have delayed effects on aquatic macroinvertebrates lasting more than three decades. Water Resour Res 56, 1–20. https://doi.org/10.1029/2019WR025896.
Leberfinger, K., Bohman, I., Herrmann, J., 2010. Drought impact on stream detritivores: Experimental effects on leaf litter breakdown and life cycles. Hydrobiologia 652, 247–254. https://doi.org/10.1007/s10750-010-0337-1.
Ledger, M.E., Hildrew, A.G., 2001. Recolonization by the benthos of an acid stream following a drought. Fundam. Appl. Limnol. 152, 1–17. https://doi.org/10.1127/archiv-hydrobiol/152/2001/1.
Ledger, M.E., Edwards, F.K., Brown, L.E., Milner, A.M., Woodward, G., 2011. Impact of simulated drought on ecosystem biomass production: An experimental test in stream mesocosms. Glob Chang Biol 17, 2288–2297. https://doi.org/10.1111/j.1365-2486.2011.02420.x.
Leese, F., Bouchez, A., Abarenkov, K., Altermatt, F., Borja, Á., Bruce, K., Ekrem, T., Jr, F.Č., Čiamporová-Zaťovičová, Z., Costa, F.O., 2018. Why we need sustainable networks bridging countries, disciplines, cultures and generations for aquatic biomonitoring 2.0: a perspective derived from the DNAqua-Net COST action. Adv Ecol Res.
Let, M., Špaček, J., Ferenčík, M., Kouba, A., Bláha, M., 2021. Insecticides and drought as a fatal combination for a stream macroinvertebrate assemblage in a catchment area exploited by large-scale agriculture. Water (switzerland) 13. https://doi.org/10.3390/w13101352.
Liang, X., Martyniuk, C.J., Simmons, D.B.D., 2020. Are we forgetting the "proteomics" in multi-omics ecotoxicology? Comp Biochem Physiol Part D Genomics Proteomics 36. https://doi.org/10.1016/j.cbd.2020.100751.
Longo, E., Mancinelli, G., 2014. Size at the onset of maturity (SOM) revealed in length-weight relationships of brackish amphipods and isopods: An information theory approach. Estuar Coast Shelf Sci 136, 119–128. https://doi.org/10.1016/j.ecss.2013.11.013.
López-Rodríguez, M.J., Peralta-Maraver, I., Gaetani, B., Sainz-Cantero, C.E., Fochetti, R., de Figueroa, J.M.T., 2012. Diversity patterns and food web structure in a Mediterranean intermittent stream. Int Rev Hydrobiol 97, 485–496. https://doi.org/10.1002/iroh.201201541.
Loskotová, B., Straka, M., Pařil, P., 2019. Sediment characteristics influence benthic macroinvertebrate vertical migrations and survival under experimental water loss conditions. Fundam. Appl. Limnol. 193, 39–49. https://doi.org/10.1127/fal/2019/1138.
Mancinelli, G., 2010. Intraspecific, size-dependent variation in the movement behaviour of a brackish-water isopod: A resource-free laboratory experiment. Mar Freshw Behav Physiol 43, 321–337. https://doi.org/10.1080/10236244.2010.512728.
Martinez, P.J., 2012. Invasive crayfish in a high desert river: Implications of concurrent invaders and climate change. Aquat Invasions 7, 219–234. https://doi.org/10.3391/ai.2012.7.2.008.
Martínez, A., Pérez, J., Molinero, J., Sagarduy, M., Pozo, J., 2015. Effects of flow scarcity on leaf-litter processing under oceanic climate conditions in calcareous streams. Sci. Total Environ. 503–504, 251–257. https://doi.org/10.1016/j.scitotenv.2014.06.018.
McDaniel, C.H., McHugh, J.V., Batzer, D.P., 2019. Colonization of drying temporary wetlands by Coptotomus loticus (Coleoptera: Dytiscidae): a unique strategy for an aquatic wetland insect. Wetl Ecol Manag 27, 627–634. https://doi.org/10.1007/s11273-019-09681-4.
McDowell, W.G., Sousa, R., 2019. Mass mortality events of invasive freshwater bivalves: current understanding and potential directions for future research. Front Ecol Evol 7, 1–12. https://doi.org/10.3389/fevo.2019.00331.
Menbohan, S.F., Meyer, A., Lepr, A., Usseglio-polatera, P., 2022. Relationships between Physico-Chemical Parameters and Taxonomic Structure of Benthic Macroinvertebrate Assemblages in Streams of West Cameroon.
Menció, A., Boix, D., 2018. Response of macroinvertebrate communities to hydrological and hydrochemical alterations in Mediterranean streams. J Hydrol (Amst) 566, 566–580. https://doi.org/10.1016/j.jhydrol.2018.09.040.
Menéndez, M., Descals, E., Riera, T., Moya, O., 2011. Leaf litter breakdown in Mediterranean streams: Effect of dissolved inorganic nutrients. Hydrobiologia 669, 143–155. https://doi.org/10.1007/s10750-011-0657-9.
Merritt, R.W., Cummins, K.W., Berg, M.B., Novak, J.A., Higgins, M.J., Wessell, K.J., Lessard, J.L., 2002. Development and application of a macroinvertebrate functional-group approach in the bioassessment of remnant river oxbows in southwest Florida. J North Am Benthol Soc 21, 290–310. https://doi.org/10.2307/1468416.
Merritt, R.W., Cummins, K.W., Berg, M.B., 2017. Trophic Relationships of Macroinvertebrates, in: Methods in Stream Ecology, Volume 1. Elsevier, pp. 413–433. https://doi.org/10.1016/B978-0-12-416558-8.00020-2.
Meyer, A., Kaschek, N., Meyer, E.I., 2004. The effect of low flow and stream drying on the distribution and relative abundance of the alien amphipod, Echinogammarus berilloni (Catta, 1878) in a karstic stream system (Westphalia, Germany). Crustaceana 77, 909–922. https://doi.org/10.1163/1568540042781702.
Meyer, C.K., Whiles, M.R., 2008. Macroinvertebrate communities in restored and natural Platte River slough wetlands. J North Am Benthol Soc 27, 626–639. https://doi.org/10.1899/07-086.1.
Mierzejewska, E., Urbaniak, M., 2020. Molecular methods as potential tools in ecohydrological studies on emerging contaminants in freshwater ecosystems. Water (basel) 12, 2962.
Miller, S.W., Wooster, D., Li, J., 2007. Resistance and resilience of macroinvertebrates to irrigation water withdrawals. Freshw Biol 52, 2494–2510. https://doi.org/10.1111/j.1365-2427.2007.01850.x.
Monroy, S., Martínez, A., López-Rojo, N., Pérez-Calpe, A.V., Basaguren, A., Pozo, J., 2017. Structural and functional recovery of macroinvertebrate communities and leaf litter decomposition after a marked drought: Does vegetation type matter? Sci. Total Environ. 599–600, 1241–1250. https://doi.org/10.1016/j.scitotenv.2017.05.093.
Moody, E.K., Sabo, J.L., 2013. Crayfish impact desert river ecosystem function and litter-dwelling invertebrate communities through association with novel detrital resources. PLoS One 8. https://doi.org/10.1371/journal.pone.0063274.
Mor, J.R., Dolédec, S., Acuña, V., Sabater, S., Muñoz, I., 2019. Invertebrate community responses to urban wastewater effluent pollution under different hydro-morphological conditions. Environ. Pollut. 252, 483–492. https://doi.org/10.1016/j.envpol.2019.05.114.
Mormul, R.P., Moi, D.A., Pressinatte-Júnior, S., Perbiche-Neves, G., Takeda, A.M., 2022. Temporal dynamics of Chironomid (Diptera) diversity under flood–drought pulses in a shallow tropical floodplain lake. Limnology (Tokyo) 23, 37–48. https://doi.org/10.1007/s10201-021-00668-w.
Mortimer, M., Fang, W., Zhou, X., Vodovnik, M., Guo, L.-H., 2022. Omics Approaches in Toxicological Studies. Advances in Toxicology and Risk Assessment of Nanomaterials and Emerging Contaminants.
Nichols, S.J., Robinson, W.A., Norris, R.H., 2010. Using the reference condition maintains the integrity of a bioassessment program in a changing climate. J North Am Benthol Soc 29, 1459–1471. https://doi.org/10.1899/09-165.1.
Ormerod, S.J., Dobson, M., Hildrew, A.G., Townsend, C.R., 2010. Multiple stressors in freshwater ecosystems. Freshw Biol 55, 1–4. https://doi.org/10.1111/j.1365-2427.2009.02395.x.
Pacheco, F.S., Miranda, M., Pezzi, L.P., Assireu, A., Marinho, M.M., Malafaia, M., Reis, A., Sales, M., Correia, G., Domingos, P., Iwama, A., Rudorff, C., Oliva, P., Ometto, J.P., 2017. Water quality longitudinal profile of the Paraíba do Sul River, Brazil during an extreme drought event. Limnol Oceanogr 62, S131–S146. https://doi.org/10.1002/lno.10586.
Pardo, I., García, L., 2016. Water abstraction in small lowland streams: Unforeseen hypoxia and anoxia effects. Sci. Total Environ. 568, 226–235. https://doi.org/10.1016/j.scitotenv.2016.05.218.
Pařil, P., Leigh, C., Polášek, M., Sarremejane, R., Řezníčková, P., Dostálová, A., Stubbington, R., 2019. Short-term streambed drying events alter amphipod population structure in a central European stream. Fundam. Appl. Limnol. 193, 51–64. https://doi.org/10.1127/fal/2019/1164.
Parr, L.B., Mason, C.F., 2003. Long-term trends in water quality and their impact on macroinvertebrate assemblages in eutrophic lowland rivers. Water Res 37, 2969–2979. https://doi.org/10.1016/S0043-1354(03)00115-5.
Patel, C., Vadher, A.N., Mathers, K.L., Dwyer, C., Wood, P.J., 2021. Body size affects the vertical movement of benthic amphipods through subsurface sediments in response to drying. Hydrobiologia 848, 1015–1025. https://doi.org/10.1007/s10750-020-04500-x.
Patrick, C.J., Yuan, L.L., 2017. Modeled hydrologic metrics show links between hydrology and the functional composition of stream assemblages. Ecol. Appl. 27, 1605–1617. https://doi.org/10.1002/eap.1554.
Peralta-Maraver, I., Reiss, J., Robertson, A.L., 2018. Interplay of hydrology, community ecology and pollutant attenuation in the hyporheic zone. Sci. Total Environ. 610–611, 267–275. https://doi.org/10.1016/j.scitotenv.2017.08.036.
Pernecker, B., Mauchart, P., Csabai, Z., 2020. What to do if streams go dry? Behaviour of Balkan Goldenring (Cordulegaster heros, Odonata) larvae in a simulated drought experiment in SW Hungary. Ecol Entomol 45, 1457–1465. https://doi.org/10.1111/een.12931.
Peterson, M.G., Lunde, K.B., Chiu, M.C., Resh, V.H., 2017. Seasonal progression of aquatic organisms in a temporary wetland in northern California. West N Am Nat 77, 176–188. https://doi.org/10.3398/064.077.0205.

Piano, E., Doretto, A., Falasco, E., Fenoglio, S., Gruppuso, L., Nizzoli, D., Viaroli, P., Bona, F., 2019. If Alpine streams run dry: the drought memory of benthic communities. Aquat Sci 81, 1–14. https://doi.org/10.1007/s00027-019-0629-0.

Pinna, M., Marini, G., Rosati, I., Neto, J.M., Patrício, J., Marques, J.C., Basset, A., 2013. The usefulness of large body-size macroinvertebrates in the rapid ecological assessment of Mediterranean lagoons. Ecol Indic 29, 48–61. https://doi.org/10.1016/j.ecolind.2012.12.011.

Pomfret, S.M., Brua, R.B., Izral, N.M., Yates, A.G., 2020. Metabolomics for biomonitoring: an evaluation of the metabolome as an indicator of aquatic ecosystem health. Environ. Rev. 28, 89–98.

Popović, N., Marinković, N., Čerba, D., Raković, M., Đuknić, J., Paunović, M., 2022. Diversity patterns and assemblage structure of non-biting midges (diptera: chironomidae) in urban waterbodies. Diversity (basel) 14, 187. https://doi.org/10.3390/d14030187.

Poznańska-Kakareko, M., Budka, M., Zbikowski, J., Czarnecka, M., Kakareko, T., Jermacz, Ł., Kobak, J., 2017. Survival and vertical distribution of macroinvertebrates during emersion of sandy substratum in outdoor mesocosms. Fundam. Appl. Limnol. 190, 29–47. https://doi.org/10.1127/fal/2017/1017.

Resh, V.H., Bêche, L.A., Lawrence, J.E., Mazor, R.D., McElravy, E.P., O'Dowd, A.P., Rudnick, D., Carlson, S.M., 2013. Long-term population and community patterns of benthic macroinvertebrates and fishes in Northern California Mediterranean-climate streams. Hydrobiologia 719, 93–118. https://doi.org/10.1007/s10750-012-1373-9.

Reznickova, P., Pařil, P., Zahrádková, S., 2007. The ecological effect of drought on the macroinvertebrate fauna of a small intermittent stream - An example from the Czech Republic. Int Rev Hydrobiol 92, 514–526. https://doi.org/10.1002/iroh.200610997.

Riseng, C.M., Wiley, M.J., Stevenson, R.J., 2004. Hydrologic disturbance and nutrient effects on benthic community structure in midwestern US streams: A covariance structure analysis. J North Am Benthol Soc 23, 309–326. https://doi.org/10.1899/0887-3593(2004)023<0309:HDANEO>2.0.CO;2.

Rivera-Usme, J.J., Pinilla, G.A., Rangel-Churio, J.O., Castro, M.I., Camacho-Pinzón, D.L., 2015. Biomass of macroinvertebrates and physicochemical characteristics of water in an Andean urban wetland of Colombia. Braz. J. Biol. 75, 180–190. https://doi.org/10.1590/1519-6984.10613.

Roobavannan, M., van Emmerik, T.H.M., Elshafei, Y., Kandasamy, J., Sanderson, M.R., Vigneswaran, S., Pande, S., Sivapalan, M., 2018. Norms and values in sociohydrological models. Hydrol Earth Syst Sci 22, 1337–1349. https://doi.org/10.5194/hess-22-1337-2018.

Rosenberg, D.M., Resh, V.H., 1993. Freshwater biomonitoring and benthic macroinvertebrates. Chapman and Hall, New York.

Rosset, V., Ruhi, A., Bogan, M.T., Datry, T., 2017. Do lentic and lotic communities respond similarly to drying? Ecosphere 8. https://doi.org/10.1002/ecs2.1809.

Ruiz, T., Carrias, J.-F., Bonhomme, C., Farjalla, V.F., Jassey, V.E.J., Leflaive, J., Compin, A., Leroy, C., Corbara, B., Srivastava, D.S., Céréghino, R., 2022. Asynchronous recovery of predators and prey conditions resilience to drought in a neotropical ecosystem. Sci Rep 12, 1–10. https://doi.org/10.1038/s41598-022-12537-2.

Sabater, S., Elosegi, A., Acuña, V., Basaguren, A., Muñoz, I., Pozo, J., 2008. Effect of climate on the trophic structure of temperate forested streams. A comparison of Mediterranean and Atlantic streams. Sci. Total Environ. 390, 475–484. https://doi.org/10.1016/j.scitotenv.2007.10.030.

Sarremejane, R., Messager, M.L., Datry, T., 2021. Drought in intermittent river and ephemeral stream networks. Ecohydrology. https://doi.org/10.1002/eco.2390.

Scharler, U.M., Lechman, K., Radebe, T., Jerling, H.L., 2020. Effects of prolonged mouth closure in a temporarily open/closed estuary: a summary of the responses of invertebrate communities in the uMdloti Estuary, South Africa. Afr J Aquat Sci 45, 121–130. https://doi.org/10.2989/16085914.2019.1689911.

Shokri, M., Cozzoli, F., Ciotti, M., Gjoni, V., Marrocco, V., Vignes, F., Basset, A., 2021. A new approach to assessing the space use behavior of macroinvertebrates by automated video tracking. Ecol Evol 11, 3004–3014. https://doi.org/10.1002/ece3.7129.

Silva, D.P., Dias, A.C., Lecci, L.S., Simião-Ferreira, J., 2019. Potential effects of future climate changes on Brazilian cool-adapted stoneflies (insecta: plecoptera). Neotrop Entomol 48, 57–70. https://doi.org/10.1007/s13744-018-0621-8.

Skoulikidis, N.T., Vardakas, L., Karaouzas, I., Economou, A.N., Dimitriou, E., Zogaris, S., 2011. Assessing water stress in Mediterranean lotic systems: Insights from an artificially intermittent river in Greece. Aquat Sci 73, 581–597. https://doi.org/10.1007/s00027-011-0228-1.

Slette, I.J., Post, A.K., Awad, M., Even, T., Punzalan, A., Williams, S., Smith, M.D., Knapp, A.K., 2019. How ecologists define drought, and why we should do better. Glob Chang Biol 25, 3193–3200. https://doi.org/10.1111/gcb.14747.

Soria, M., Leigh, C., Datry, T., Bini, L.M., Bonada, N., 2017. Biodiversity in perennial and intermittent rivers: a meta-analysis. Oikos 126, 1078–1089. https://doi.org/10.1111/oik.04118.

Storey, R., 2016. Macroinvertebrate community responses to duration, intensity and timing of annual dry events in intermittent forested and pasture streams. Aquat Sci 78, 395–414. https://doi.org/10.1007/s00027-015-0443-2.

Strachan, S.R., Chester, E.T., Robson, B.J., 2015. Freshwater invertebrate life history strategies for surviving desiccation. Springer Sci Rev 3, 57–75. https://doi.org/10.1007/s40362-015-0031-9.

Stubbington, R., Chadd, R., Cid, N., Csabai, Z., Miliša, M., Morais, M., Munné, A., Pařil, P., Pešić, V., Tziortzis, I., Verdonschot, R.C.M., Datry, T., 2018. Biomonitoring of intermittent rivers and ephemeral streams in Europe: Current practice and priorities to enhance ecological status assessments. Sci. Total Environ. 618, 1096–1113. https://doi.org/10.1016/j.scitotenv.2017.09.137.

Theodoropoulos, C., Papadaki, C., Vardakas, L., Dimitriou, E., Kalogianni, E., Skoulikidis, N., 2019. Conceptualization and pilot application of a model-based environmental flow assessment adapted for intermittent rivers. Aquat Sci 81, 1–17. https://doi.org/10.1007/s00027-018-0605-0.

Thomson, J.R., Bond, N.R., Cunningham, S.C., Metzeling, L., Reich, P., Thompson, R.M., Mac Nally, R., 2012. The influences of climatic variation and vegetation on stream biota: Lessons from the Big Dry in southeastern Australia. Glob Chang Biol 18, 1582–1596. https://doi.org/10.1111/j.1365-2486.2011.02609.x.

Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J., 2014. Global warming and changes in drought. Nat Clim Chang 4, 17–22. https://doi.org/10.1038/nclimate2067.

Vadher, A.N., Leigh, C., Millett, J., Stubbington, R., Wood, P.J., 2017. Vertical movements through subsurface stream sediments by benthic macroinvertebrates during experimental drying are influenced by sediment characteristics and species traits. Freshw Biol 62, 1730–1740. https://doi.org/10.1111/fwb.12983.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37, 130–137. https://doi.org/10.1139/f80-017.

Verdonschot, R.C.M., van Oosten-Siedlecka, A.M., ter Braak, C.J.F., Verdonschot, P.F.M., 2015. Macroinvertebrate survival during cessation of flow and streambed drying in a lowland stream. Freshw Biol 60, 282–296. https://doi.org/10.1111/fwb.12479.

Veríssimo, H., Lane, M., Patrício, J., Gamito, S., Marques, J.C., 2013. Trends in water quality and subtidal benthic communities in a temperate estuary: Is the response to restoration efforts hidden by climate variability and the Estuarine Quality Paradox? Ecol Indic 24, 56–67. https://doi.org/10.1016/j.ecolind.2012.05.028.

Verkaik, I., Vila-Escalé, M., Rieradevall, M., Prat, N., 2013. Seasonal drought plays a stronger role than wildfire in shaping macroinvertebrate communities of Mediterranean streams. Int Rev Hydrobiol 98, 271–283. https://doi.org/10.1002/iroh.201201618.

Verkaik, I., Prat, N., Rieradevall, M., Reich, P., Lake, P.S., 2014. Effects of bushfire on macroinvertebrate communities in south-east Australian streams affected by a megadrought. Mar Freshw Res 65, 359–369. https://doi.org/10.1071/MF13039.

Waite, I.R., Pan, Y., Edwards, P.M., 2020. Assessment of multi-stressors on compositional turnover of diatom, invertebrate and fish assemblages along an urban gradient in Pacific Northwest streams (USA). Ecol Indic 112, 106047. https://doi.org/10.1016/j.ecolind.2019.106047.

Wech, J., Suren, A., Brady, M., Kilroy, C., 2018. The effect of willow control using a glyphosate formulation on aquatic invertebrates within a New Zealand wetland. N Z J Mar Freshwater Res 52, 16–41. https://doi.org/10.1080/00288330.2017.1326388.

Wenisch, B., Fernández, D.G., Szöcs, E., Mckie, B.G., Schäfer, R.B., 2017. Does the loss of climate sensitive detritivore species alter leaf decomposition? Aquat Sci 79, 869–879. https://doi.org/10.1007/s00027-017-0538-z.

Wetzel, R.G., Likens, G.E., 2000. Limnological Analyses. Springer New York, New York, NY. https://doi.org/10.1007/978-1-4757-3250-4.

White, J.C., Aspin, T.W.H., Picken, J.L., Ledger, M.E., Wilby, R.L., Wood, P.J., 2022. Extreme low-flow effects on riverine fauna: A perspective on methodological assessments. Ecohydrology 1–24. https://doi.org/10.1002/eco.2422.

White, H.L., Nichols, S.J., Robinson, W.A., Norris, R.H., 2012. More for less: A study of environmental flows during drought in two Australian rivers. Freshw Biol 57, 858–873. https://doi.org/10.1111/j.1365-2427.2011.02732.x.

Wilding, N.A., White, J.C., Chadd, R.P., House, A., Wood, P.J., 2018. The influence of flow permanence and drying pattern on macroinvertebrate biomonitoring tools used in the assessment of riverine ecosystems. Ecol Indic. https://doi.org/10.1016/j.ecolind.2017.10.059.

Woodward, G., Gray, C., Baird, D.J., 2013. Biomonitoring for the 21st Century: new perspectives in an age of globalisation and emerging environmental threats. Limnetica 32, 159–174. https://doi.org/10.23818/limn.32.14.

Wright, J.F., Clarke, R.T., Gunn, R.J.M., Winder, J.M., Kneebone, N.T., Davy-Bowker, J., 2003. Response of the flora and macroinvertebrate fauna of a chalk stream site to changes in management. Freshw Biol 48, 894–911. https://doi.org/10.1046/j.1365-2427.2003.01058.x.

Xu, H., Bai, X., Li, Y., Li, J., Meng, Y., Xu, Z., Tang, J., Lu, Y., Huang, Y., 2022. Changes in the immunity, histopathology, and metabolism of crayfish (*procambarus clarkii*) in response to drought. Animals 12, 890. https://doi.org/10.3390/ani12070890.