

CLIMATE CHANGE-DRIVEN SHIFTS IN PHYTOBENTHOS ASSEMBLAGES OF THE PANNONIAN ECOREGION: A DECADAL OVERVIEW

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Abstract: This study synthesises research exploring how climate change-induced hydrological extremes influence the structure, species composition, and functional diversity of benthic diatom assemblages in watercourses of varying sizes (from 10 km² to approximately 10,000 km² catchment areas), across multiple temporal (1–15 years) and spatial (Pannonian and Mediterranean) scales. The focus is particularly on intermittent small streams in the Carpathian Basin, encompassing both the Great Hungarian Plain and the Transdanubian region. Rather than treating drying as a separate event, these investigations approach it as a gradual process composed of successive hydrological phases – flowing, standing, and dry – each with distinct impacts on assemblage structure and diversity. The findings contribute to a deeper understanding of how benthic diatom assemblages respond to climatic extremes, offering insight into ecosystem resilience and vulnerability under ongoing environmental change. This work is dedicated to Professor Judit Padišák – as a gesture of gratitude and a tribute to a distant yet ever-supportive mentor, whose early encouragement and continued watchful presence have been invaluable throughout this journey.

Key words: benthic algae, biodiversity, climate change, composition, intermittent streams, large rivers

PROLOGUE

Once upon a time, in a galaxy far, far away, on a planet called Earth, there lived a biologist. From the very beginning of her university studies, she fell in love with microscopic, tiny organisms – algae. So, when, according to the Earth calendar, she was offered a position as an algologist in the early 2010s, the topic was, at least in theory, not unfamiliar to her. Despite her dedication and curiosity, she was filled with fear, for unlike her previous tasks, this position required taxonomic knowledge and field experience – areas where she still felt her knowledge was lacking. Yet the girl did not back down. She saw the task as a challenge, seeking more than simply providing raw data or uncovering simple connections – she had a desire for more. Her aim was to see and understand the ecological patterns – to grasp both local and regional changes. Her first steps were supported by a small group of people who, like her, had limited knowledge about this particular group of organisms: the benthic diatoms. Yet they helped her in every possible way. Thanks to their support, the moment finally came when she completed her first professional work analysing ecological patterns based on benthic diatom data, which was submitted to an international journal. But their initial efforts did not meet the desired outcome. Still, she did not give up the fight. She revised the manuscript again and again, constantly trying to ensure that the international experts – whom she held in the highest regard – would at least consider reviewing her work. Eventually, she submitted it to a journal where she knew there was a good chance that one of the editors would be Judit Padisák, a renowned researcher known and respected both in her home country and internationally. Of course, she too knew – and feared – the researcher she called “Professor”, a woman whose strictness and consistency were the stuff of legend among students, even though she had never taught the young biologist girl directly. However, it was also widely acknowledged that Professor Padisák was always willing to offer a chance to those who demonstrated a genuine desire to learn. And the biologist girl truly did. Because she loved and respected the path she had chosen – one that was no longer just a job, but a calling. Her hands were trembling as she opened the response letter; it was a major revision, accompanied by two thorough and highly professional reviews. Answering them was no easy task. The biologist girl learned a great deal through writing the response letters and revising the manuscript. But in the end – after nearly a year and a half of struggle – it happened: their paper was eventually accepted. This experience motivated the girl to continue her work, and the deep gratitude she felt toward the Professor encouraged her to keep learning. More than ten years have passed since then, but her professional dedication has remained unchanged. Over the years, her relationship with Professor Padisák has gradually deepened.

This study presents the most important results of my/our professional work over the past ten years, and at the same time serves as an expression of gratitude and a tribute to Professor Padisák, who gave me the initial push and has never let me fall since.

INTRODUCTION

Today's ecological and conservation challenges rarely allow for the kind of deep contemplation one experiences when first looking through a microscope and encountering the astonishing morphological diversity of diatoms. The decline in biodiversity has reached a point where many leading researchers no longer speak of a potential future event, but of an ongoing sixth mass extinction (CEBALLOS *et al.* 2015, COWIE *et al.* 2022). Global climate change is identified as one of the main drivers of the biodiversity crisis (COWIE *et al.* 2022, REID *et al.* 2019). The situation is particularly severe in freshwater ecosystems, where ongoing changes are often referred to as a "silent tragedy" (REID *et al.* 2019). Even experts tend to overlook the fact that research has traditionally focused on macroscopic, primarily vertebrate, emblematic or economically significant taxa, while microscopic communities (NASELLI-FLORES and PADISÁK 2022), such as benthic diatoms, are perhaps not given as much attention as they could be (MEA 2003, CALDWELL *et al.* 2024). Over the past decades, diatoms have primarily appeared in scientific studies as bioindicators (for a detailed review, see LOBO *et al.* 2016), largely due to their designation as target organisms and communities under the European Union's Water Framework Directive (EC 2000) and the United States' Clean Water Act (1972). Diatoms can provide a reliable representation of the ecological and biological status of water bodies, as well as the changes occurring within them. In contrast, theoretical ecological and classical conservation-oriented research has only begun to develop significantly in the past decade (SOININEN and TEITTINEN 2019). As a result, our knowledge on this topic could be regarded as somewhat limited in comparison to that related to phytoplankton (for a detailed review, see NASELLI-FLORES *et al.* 2021), despite the undeniable role of benthic diatoms in ecosystem services, including their ecological and conservation significance (B-BÉRES *et al.* 2023).

Due to the species-level uniqueness of their siliceous frustules, recent ecological studies have primarily focused on diatom species, species complexes, or other lower taxonomic units. However, it is important to note that the past 10–15 years have also seen a shift in this approach (for a detailed discussion, see STENGER-KOVÁCS and B-BÉRES 2024). The catalyst for this shift was the diatom guild classification system introduced by PASSY (2007), which opened new perspectives for functional and trait-based studies of diatoms. Initially, alongside

exploratory research, the studies were strongly application-oriented (for more details, see TAPOLCZAI *et al.* 2016), aiming to reduce uncertainties arising from species-level analyses and more reliably integrating the information content of guilds and traits into ecological status assessments. Since then, trait- and guild-based approaches have become an integral part of diatom research (STENGER-KOVÁCS and B-BÉRES 2024), playing an increasingly important role in addressing both theoretical and applied ecological questions. Studies conducted across various spatial and temporal scales offer the opportunity to interpret global environmental challenges – such as climate change, water scarcity, salinization, and eutrophication – not only in local contexts but also at regional, inter-ecoregional, and global levels (for more details, see MAIDANA *et al.* 2024). This approach provides a strong scientific foundation for well-informed and timely interventions necessary for the protection of surface waters.

In this study, we have attempted to summarise and contextualise the results of research that shed light on how climate change-related extremes affect the structure, species diversity, and functional diversity of diatom assemblages in watercourses of varying sizes ($10 \text{ km}^2 \geq \text{catchment area} \approx 10,000 \text{ km}^2$) across different temporal scales (1–15 years) and spatial scales (Pannonian and Mediterranean regions). Particular emphasis is placed on the structural and diversity changes occurring in diatom assemblages of intermittent small streams in the Carpathian Basin (continental region), covering both the Great Hungarian Plain and the Transdanubian region. In these studies, drying is not treated as a discrete event but rather is described and assessed as a process encompassing successive hydrological phases – flowing, standing, and dry – and their impacts on the community.

Perennial, non-intermittent rivers

Regionally, one of the most significant consequences of climate change is the alteration of precipitation patterns, including an increase in the number of dry days, changes in daily maximum precipitation, as well as in the total annual precipitation and its distribution (ITM 2020). These changes can have a significant impact on the hydrological regimes of watercourses, which in some cases may result in changes to water levels, drying events, or flash floods (ITM 2020). Extreme fluctuations in discharge are observed worldwide even in perennial rivers (MESSAGE *et al.* 2021). Although complete drying is less likely in these water bodies – at least in regions such as the Carpathian Basin – low water levels and partially dried riverbeds can induce similar community changes as those observed in intermittent water bodies during the formation of isolated pools (B-BÉRES *et al.* 2014). It is important to emphasise that while planktic algae in larger rivers are

known to respond adversely to changes in environmental conditions (ABONYI *et al.* 2018, HARDENBICKER *et al.* 2014), most studies examining the relationship between climatic extremes and benthic algae focus on communities in smaller watercourses (B-BÉRES *et al.* 2019, NOVAIS *et al.* 2020, SABATER *et al.* 2016, 2017, STUBBINGTON *et al.* 2019).

Sebes-Körös River

Although our research over the past decade has primarily focused on intermittent small watercourses, in our initial study mentioned in the prologue (B-BÉRES *et al.* 2014), we examined the impact of drastic discharge fluctuations on diatom assemblages in a large Hungarian river, the Sebes-Körös. The study was conducted between April and November 2012. Following a prolonged spring and early summer flood, there was a drastic decrease in the discharge of the Sebes-Körös at the end of June, resulting in low-flow conditions that persisted throughout the sampling period. At the same time, it was observed that certain environmental parameters, such as total nitrogen and conductivity, increased to almost double their springtime minima by autumn, showing a close relationship with the passing of time. It is interesting to note that other parameters, such as total phosphorus, did not show a clear trend correlated with discharge or time. However, their extreme values still varied by more than a factor of two. We hypothesized that these extreme environmental changes would significantly alter assemblage structure and reduce biological diversity. Additionally, for the first time in large Hungarian rivers, we investigated changes in diatom guilds associated with discharge fluctuations, a novel approach at the time. Our results, both at the taxonomic and guild levels, clearly demonstrated a significant restructuring of the assemblage. At the same time, our findings also suggested that species within the same guild may respond differently to environmental changes. Furthermore, we demonstrated that changes in the overall relative abundance of certain guilds (e.g. motile or low-profile guilds) do not always positively correlate with changes in guild' taxon richness. With regard to biological diversity, while there was a clear decline in species richness during the study period, other diversity indices did not show a clear relationship with discharge or closely correlated environmental parameters. The drastic decrease in discharge at the end of June unequivocally resulted in reduced biological diversity, which subsequently increased until the autumnal drop in temperature.

These results provided a solid foundation for our subsequent work, which included the proposal and testing of a combination of guilds with other traits (B-BÉRES *et al.* 2016, LUKÁCS *et al.* 2018).

Rába River

Studies addressing composition changes in phytobenthic assemblages of large rivers caused by water level fluctuations are mostly short-term (e.g., B-BÉRES *et al.* 2014, TÖRNÉS *et al.* 2015). As a result, our knowledge of the long-term effects of climatic extremes and climate change-induced precipitation deficits on benthic algal assemblages in large rivers remains very limited.

After the study presented in the previous section, a significant amount of time passed before large rivers once again became the focus of attention. However, in 2021, thanks to our colleague Krisztián Kovács, we were fortunate enough to have the opportunity to analyse a 15-year (2007–2021) diatom dataset from the River Rába (NEMES-KÓKAI *et al.* 2023).

During this period, daily precipitation data were available. Analysis of these data revealed that between 2007 and 2016, drier and wetter years alternated, whereas from 2017 onward, a continuous decline in annual precipitation was observed in the region. We hypothesized that this trend-like decrease in precipitation would lead to a more substantial restructuring of the assemblages than during the preceding fluctuating period, and would also result in a significant decline in diversity. We also examined the extent to which single extreme wet or dry periods affect benthic diatom assemblages compared to average years. Our

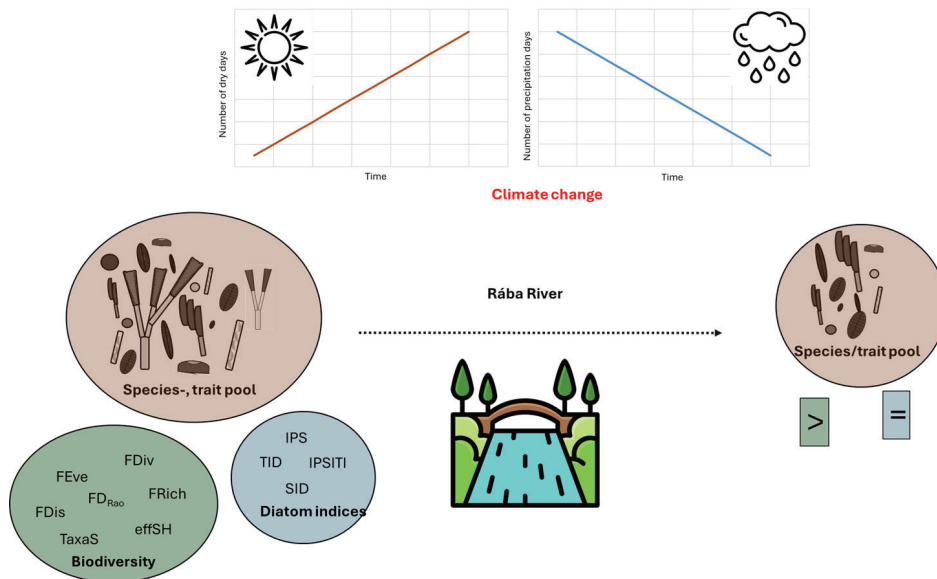


Fig. 1. The impact of climate change on the structure and biodiversity of diatom assemblages, and the ecological status of the Rába River.

results indicated that isolated extreme events had only a minor impact on the composition of benthic diatom assemblages and diversity. In contrast, the prolonged decrease in precipitation significantly reduced both taxonomic and functional diversity. During this period, small-sized species that are strongly attached to the substrate became dominant, while the proportion of larger, tree-like species declined substantially (Fig. 1). This is particularly concerning, as these algae play a key role in riverine food webs. Their absence or population decline may therefore have indirect negative effects on larger organisms inhabiting the river. According to climate model projections, there is a possibility that extreme climatic events, including prolonged periods of low precipitation, could become more frequent in the near future. This suggests that the assemblage-level changes and their impacts, as demonstrated in our study, should be anticipated and may even warrant intervention. One of the most important issues to consider is the possibility of a tipping point, which could potentially lead to long-lasting and difficult-to-reverse changes in biodiversity and community structure.

Intermittent small streams

It is worth noting that in the Carpathian Basin, there has been an increase in the number of drought days over the past century. By the 2000s, the driest period of the year had shifted from the winter months to mid-summer. As a result of these anomalies, a typological shift can be observed in small streams in the region: watercourses that were previously perennial are now drying out more frequently, transitioning into intermittent systems. In Hungary, there are approximately 10,000 watercourses, of which only about 10% are regularly monitored under the National Monitoring Program (STUBBINGTON *et al.* 2018). This is due to the fact that only these watercourses have catchment areas exceeding the 10 km² threshold required by the EU Water Framework Directive (WFD). Current knowledge suggests that more than 30% of these monitored streams now fall into the intermittent category, although this classification currently only applies to small watercourses. The areas most affected by drought and drying are predominantly located in the Great Hungarian Plain (WEB1). For streams with catchments smaller than 10 km², only sporadic data are available, but the proportion of drying watercourses in these systems is presumed to be significantly higher.

It is worth noting that the second half of the 2010s saw the launch of intensive research on stream drying. Some of these studies addressed structural changes in algal communities of such watercourses, with a particular focus on the Mediterranean region. In contrast, processes occurring in temperate regions, where drying have not historically been regular features of flow regimes, and where aquatic organisms and communities have therefore not yet had time to

adapt, are still only sporadically documented. This has led to a significant lack of baseline data and knowledge. Yet, beyond their national natural value, streams affected by desiccation also serve economically important functions such as irrigation, drainage, water storage, and energy production. It is possible that changes in the structure of aquatic communities – particularly periphytic algae – may result in shifts in water quality. These changes have not only ecological and conservation implications, but also serious economic consequences, highlighting the urgent need to develop new conservation biology and, importantly, economic strategies.

Impact of a one-summer drought on benthic diatoms in small perennial lowland streams

We began our work on the drying of small streams in 2012 (KÓKAI *et al.* 2015). At that time, our focus was not yet on drying itself, but rather on the impact of water scarcity on diatom assemblages in 15 lowland streams. We hypothesised that the summer drought period might possibly induce structural changes in the composition of diatom assemblages, which could result in an increase in the proportion of halophilic species within the assemblages. In addition, we also examined how the proportions and relative abundances of taxa with different cell volumes (size) changed within the assemblage. In our study, we found significant correlations between the taxonomic and morphological (cell size) composition of benthic diatom assemblages and the increased conductivity, total nitrogen (TN), and total phosphorus (TP) concentrations induced by summer drought. At the same time, our results also highlighted that among the cell volume groups, only the extremely small and extremely large categories responded clearly to environmental changes. Although the proportion of halophilic taxa increased by more than 50% in the assemblages during the drought period, it was typically the number and relative abundance of large-sized taxa that increased. We observed contrasting trends in different diversity metrics, namely species diversity and evenness: while species richness increased in the assemblages as a result of the drought, evenness declined. This may indicate, on the one hand, that certain opportunistic taxa exploited the disturbed environment and became dominant within the assemblages, and on the other hand, that generalist taxa appeared, contributing to the increase in species richness. At the same time, it may also indicate a lack of stability – that is, a transitional state – suggesting that if the unfavourable conditions persist, the decline in diversity may be reflected in species richness as well. It would seem that the results demonstrate that a small stream does not need to completely dry out for precipitation deficit to induce structural shifts and changes in the diversity of benthic algal assemblages.

Colonisation of benthic algae in a small intermittent stream

Subsequently, in 2014, we conducted a colonisation study on an intermittent lowland stream, Tóció (B-BÉRES *et al.* 2016, LUKÁCS *et al.* 2018, 2021). We investigated how extreme weather events influence the colonisation of benthic algae and the development of mature periphytic assemblages. We studied this through changes in the composition of the assemblage's taxonomic, trait-based, and combined trait-based groups, as well as various diversity metrics. We showed how the Combined Morphological and Functional Grouping (CMFG) system – created by merging morphological and functional characteristics of benthic diatoms – as well as the functional groups developed by combining the traits of the entire phytobenthic assemblage (diatoms and soft algae), are capable of indicating stochastic processes such as colonisation in a lowland, semi-static stream with a resolution equivalent to that of taxonomic classification (B-BÉRES *et al.* 2016, LUKÁCS *et al.* 2018). In addition, based on flow regimes (flow velocity and water depth), the colonisation period could be divided into two distinct hydrological periods – a moderately disturbed period and a highly disturbed period –, during which we examined how assemblage structure and diversity changed (LUKÁCS *et al.* 2021). Our results revealed that the taxonomic and trait-based composition of the communities differed significantly between the two periods. The moderately disturbed period was characterised by large-sized and/or filamentous and/or weakly attached algae, whereas the highly disturbed period was dominated by small-sized and/or unicellular and/or strongly attached and/or fast-moving taxa. Furthermore, we demonstrated that the sensitivity of taxonomic and phylogenetic diversity metrics, as well as trait-based diversity metrics, differed across the periods characterised by varying levels of disturbance – that is, they changed differently between the two periods. Taxonomic and phylogenetic diversity, in accordance with the intermediate disturbance hypothesis, were significantly higher during the moderately disturbed period. In contrast, during the highly disturbed period characterised by extremes, diversity was significantly lower. In contrast, functional diversity metrics – except for functional dispersion, which was higher during the moderately disturbed period – did not differ significantly between the two periods (Fig. 2). This suggests that extreme hydrological conditions (such as drying or flash floods) did not immediately impair the functional integrity of the system. However, it is important to emphasise that in this study, we examined the processes of drying (sampling ended at the beginning of the drying), not the dry phase itself.

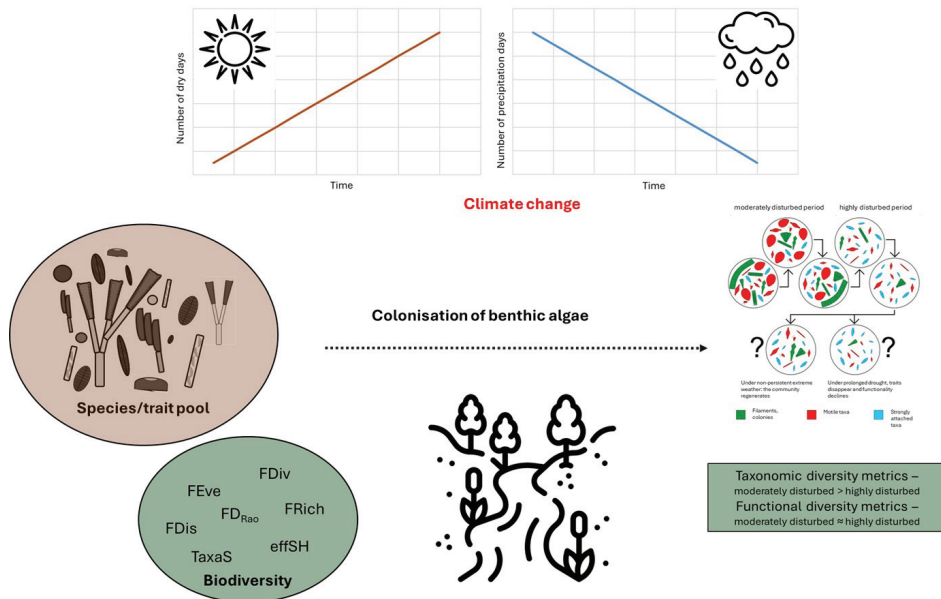


Fig. 2. The impact of climate change on the colonisation dynamics (composition and biodiversity) of benthic algal assemblages during moderately and highly disturbed periods (The figure is based on LUKÁCS (2021), with modifications. <https://dea.lib.unideb.hu/items/94cb4c14-58c8-4e8b-8d59-9efecc733210>).

Perennial and intermittent lowland streams in the Pannonian Ecoregion

As previously discussed, climate change has led to changes in the water supply of small streams, with many that used to be perennial becoming intermittent. We also observed this phenomenon in the 2010s in our lowland small streams. Year by year, it became increasingly common for these watercourses that were previously easy to sample and had flowing water to dry up as early as late spring or early summer. We tested how this affects the trait composition and functional diversity of diatom communities using a dataset from the period 2008–2015 (B-BÉRES *et al.* 2019). Based on the results, we have obtained that the traits characteristic of intermittent small streams have been identified, such as small size, pioneer nature, and aerophile character. In contrast, traits such as motility, high LW (length : width) ratio, or planktic lifeform were typical of perennial waters. The difference in biological diversity between the two water types was evident in functional richness (lower in drying streams) and Berger-Parker trait diversity (higher in drying streams), while functional evenness and divergence did not yet differ significantly (Fig. 3). Our results clearly highlighted that the separation between the two water types had begun, with diatom assemblages in intermittent

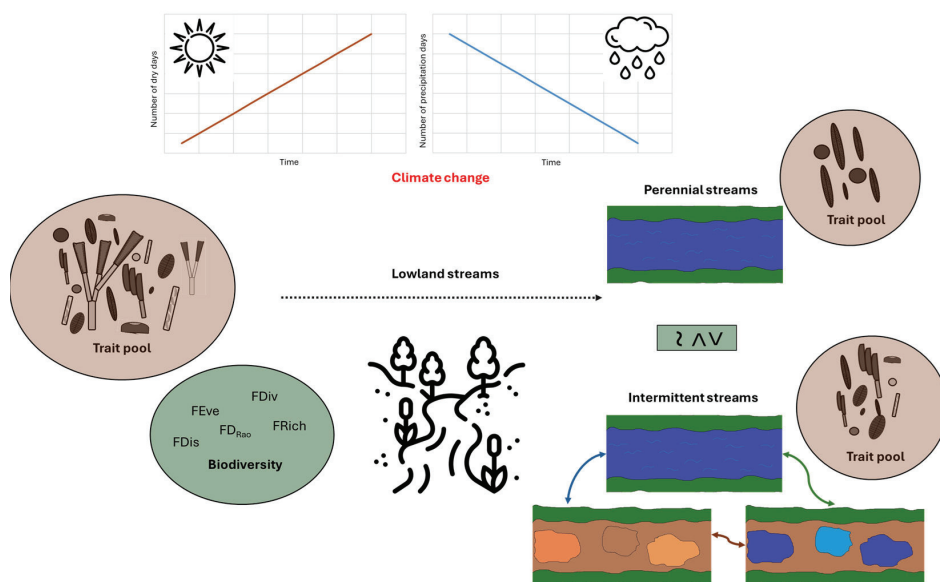


Fig. 3. The impact of climate change on the functional composition and diversity of diatom assemblages in small lowland intermittent streams.

streams potentially being more vulnerable than those in perennial streams. It is therefore important to pay particular attention to these waters, even though they do not dry out every year or for the same duration.

The impact of climate change on benthic diatoms: ecoregional differences

In a subsequent study covering multiple ecoregions (Mediterranean region – Portugal and temperate region – Hungary), we demonstrated that the duration of exposure to drying risk (recent decades *vs.* historic) leads to different structural changes in diatom assemblages in intermittent small streams (VÁRBÍRÓ *et al.* 2020). While certain diatom traits (small size, and/or pioneer, and/or low-profile guild) were clearly definable in intermittent small streams in the temperate region, such traits were not detectable in the Mediterranean region. In contrast, in both regions, colonial life form and high-profile guild were characteristic traits of diatom communities in perennial streams. Furthermore, we showed that community assembly forces (such as environmental filtering and limiting similarity) play different roles in shaping the diatom structure of the studied streams in the two ecoregions. While limiting similarity was the main community assembly force in Hungarian waters, in Portuguese streams environmental filtering played an equally important role as limiting similarity in structuring the assemblages.

Effects of hydrological phases and channel concrete lining on the benthic algal assemblages of an intermittent lowland stream

According to the currently most widely accepted classification, six hydrological states are distinguished in intermittent streams (hyper-, eu-, oligo-, a-, hyporheic, and edaphic; GALLART *et al.* 2012), which can be grouped into three main hydrological phases: flowing, standing, and dry (GALLART *et al.* 2017). Hydrological changes occurring in streams are not necessarily linear; depending on weather conditions during a given period, the process of drying out may be interrupted and may revert to a previous state. Such a reversal can occur, for example, when water becomes confined to isolated pools during a drier period (arheic state; standing water phase). However, a heavy or prolonged rainfall event can cause the system to shift back to an oligo-, eu-, or even hyperheic state (flowing phase), reversing the drying process. The species and trait composition, as well as the diversity of benthic diatom assemblages in the different hydrological phases of intermittent streams (GALLART *et al.* 2017), are strongly influenced by the duration of drought (rain-free) periods and the length of time the streambed remains dry (ACUÑA *et al.* 2017, SABATER *et al.* 2017, TORNÉS *et al.* 2021). However, lowland streams in Hungary are not only exposed to the risk of drying out, but are also subject to various other natural and anthropogenic impacts, which can cause short- or long-term changes in habitat conditions. Artificial interventions can also be observed in stream sections before and after bridges, where the channel has been fully concreted or covered with hollow concrete elements. Such channel modifications can significantly alter hydrological conditions (e.g. water velocity), potentially leading to the accumulation of silt or sand, and ultimately to changes in physical and chemical parameters (GÁL *et al.* 2020), as well as a deterioration in ecological status (WEMPLE *et al.* 2018). To the best of our knowledge, the effects of channel concreting on diatom assemblages have not yet been studied in either perennial or intermittent streams. In our most recent work (KISS *et al.* 2024), we therefore investigated how the drying process (flowing *vs.* standing phase) and channel modification (natural *vs.* concreted) influence the structure and biological diversity of the benthic diatom assemblages in a lowland stream. We found that while the community structure clearly differed between the two phases of drying, the diversity metrics examined did not show significant differences. In the flowing phase, colonial taxa belonging to the high-profile guild and/or moderately attached taxa dominated, whereas in the standing phase, unicellular and/or strongly attached species from the low-profile guild were characteristic (Fig. 4). The seemingly surprising results can be explained by a typical feature

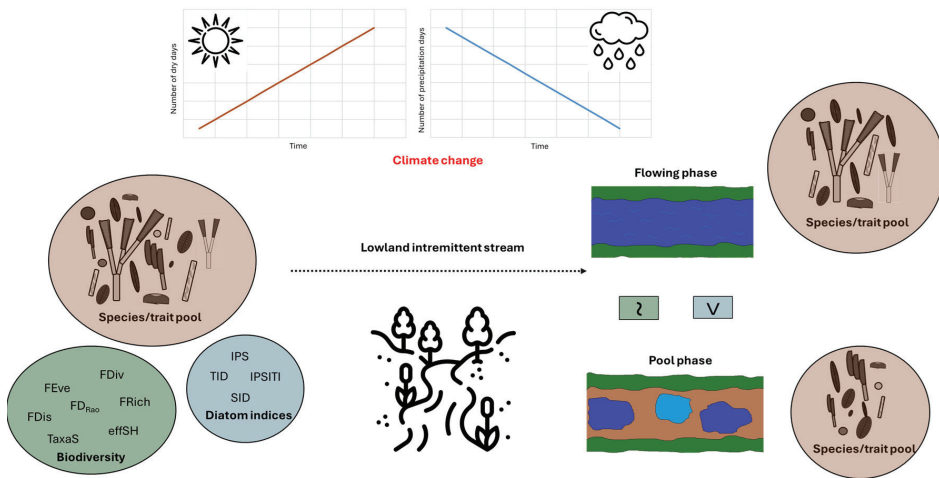


Fig. 4. The impact of climate change on the structure and biodiversity of diatom assemblages, and the ecological status in a small lowland intermittent stream.

of lowland streams: these watercourses are rich in emergent and submerged vegetation, which provide suitable habitats for chain-forming or filamentous algae even during the flowing phase (PASSY 2007). As the water level decreases during the drying process (provided that the suspended sediment content is not high, as was the case in our study), the benthic communities are exposed to high levels of UV radiation. This environment favours species capable of tolerating such conditions (KÓKAI *et al.* 2019, LEIRA *et al.* 2015), or those able to escape into deeper sediment layers (MCKEW *et al.* 2011). Furthermore, our findings demonstrated that channel modification did not impact the taxonomic or trait-based structure of the community. However, we observed higher biological diversity in the concreted section of the stream compared to the natural section. It should be noted that this does not imply that streambeds should be concreted in order to promote biodiversity (see negative correlation: BOUSKA *et al.* 2010, GÁL *et al.* 2020, WELLMAN *et al.* 2000). In this case, mass effect and/or species sorting are likely the main community assembly processes, enabling the presence of taxa even under suboptimal environmental conditions, as well as their spread to any suitable habitat (SOININEN and TEITTINEN 2019). For obvious and understandable reasons, the artificial habitat is a direct continuation of the natural one, thus both assembly processes exert a strong influence. This is particularly evident in the context of mobile taxa, whose distribution may be more strongly affected by the mass effect (JAMONEAU *et al.* 2018).

CONCLUSIONS AND OUTLOOK

The work carried out over the past more than ten years has contributed to a better understanding of the strong and often overriding pressure exerted by climate change-induced hydrological extremes (such as drastic water level changes, desiccation, and flash floods) on benthic diatom assemblages, affecting their structure and biological diversity. At the same time, our results also highlighted that while drawing global conclusions is both possible and necessary in many respects, numerous questions can only be addressed at the ecoregional level. This is particularly evident in Hungary, where the lowland regions are predominantly affected by desertification and subsequent watercourse drying. These waters are typically highly eutrophic and not phosphorus-limited, indicating that their communities are fundamentally different from those found in the low-nutrient Mediterranean or mountainous waters. Their roles in water management also differ, considering the importance of lowland waters for irrigation, water storage, and drainage. Therefore, it is crucial to understand the extent to which and the direction in which drying out will alter community structure and water quality over the long term. It must be emphasized that, in the medium to long term, the development of responsible water management plans (e.g. the need for reservoir construction, water supplementation) can only be undertaken with this knowledge. As our results have also demonstrated, climate change has an impact on both small streams and large rivers. In the near future, it is vital to ascertain the direction in which the community structure of these large rivers is changing, what this indicates, and what it means for water quality. For instance, the replenishment of smaller water bodies is contingent on the availability of larger water bodies. It is imperative that this is also given due consideration when preparing water management plans. It is evident that the problem is far from solved, and many questions remain unanswered. However, over the past 10 years, we have made significant progress in exploring a field with both scientific and practical importance. After all, our surface waters are national treasures, whose protection and preservation are matters of national interest.

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Összefoglaló: Ebben az összefoglaló tanulmányban bemutatjuk, hogyan befolyásolják a klímaváltozás által kiváltott hidrológiai szélsőségek a bentikus kovaalga-közösségek szerkezetét, fajösszetételét és funkcionális diverzitását különböző méretű vízfolyásokban ($10 \text{ km}^2 \leq \text{vízgyűjtő terület} \approx 10\,000 \text{ km}^2$), különböző időskálán (1–15 év), és térbeli léptékben (pannon és mediterrán régiók). Kiemelten foglalkozunk a Kárpát-medence (kontinentális régió) kiszáradó kisvízfolyásaival, mind az Alföld, mind a Dunántúl régióiban. A kiszáradást nem diszkrét eseményként kezeljük, hanem folyamatként, amely olyan egymást követő hidrológiai fázisokból – áramló, álló és száraz – áll, ahol minden fázis jól definiálható és eltérő hatással van a bentikus algaközösség szerkezetére és diverzitására. Az eredmények hozzájárulnak a bentikus kovaalga-közösségek klímaváltozással kapcsolatos szélsőséges hatásokra adott válaszána mélyebb megértéséhez, betekintést nyújtva ezen speciális ökoszisztémák ellenálló képességébe és sebezhetőségébe a folyamatos környezeti változások közepette. A tanulmányt Padisák Judit professzor asszonynak ajánlom – hálaéért és tisztelgéséért egy térben ugyan távoli, ám mindig támogató mentor előtt, akinek biztatása és folyamatos figyelme felbecsülhetetlen segítséget nyújtott szakmai utamon.

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