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RESEARCH ARTICLE

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How fish populations in Lake Bafa (Western Anatolia) respond to ecological shifts

Irmak Kurtul[1,2] | Cüneyt Kaya[3] | Hakan Kaykaç[1] | Ali Ilhan[1] | F. Ozan Düzbastilar[1] | Zafer Tosunoğlu[1] | Hasan M. Sari[1] | Paride Balzani[4] | Ali Serhan Tarkan[2,5,6] | Phillip J. Haubrock[4,7,8]

[1]Faculty of Fisheries, Ege University, İzmir, Türkiye

[2]Department of Life and Environmental Sciences, Faculty of Science and Technology, Bournemouth University, Poole, Dorset, UK

[3]Faculty of Fisheries, Recep Tayyip Erdogan University, Rize, Türkiye

[4]Faculty of Fisheries and Protection of Waters, South Bohemian Research Centre of Aquaculture and Biodiversity of Hydrocenoses, University of South Bohemia in České Budějovice, Vodňany, Czech Republic

[5]Department of Ecology and Vertebrate Zoology, Faculty of Biology and Environmental Protection, University of Lodz, Lodz, Poland

[6]Department of Basic Sciences, Faculty of Fisheries, Muğla Sıtkı Koçman University, Muğla, Türkiye

[7]Department of River Ecology and Conservation, Senckenberg Research Institute and Natural History Museum Frankfurt, Gelnhausen, Germany

[8]Center for Applied Mathematics and Bioinformatics, Department of Mathematics and Natural Sciences, Gulf University for Science and Technology, Hawally, Kuwait

Correspondence

Irmak Kurtul, Faculty of Fisheries, Ege University, İzmir, Türkiye.
Email: ikurtul@bournemouth.ac.uk

Phillip J. Haubrock, Faculty of Fisheries and Protection of Waters, South Bohemian Research Centre of Aquaculture and Biodiversity of Hydrocenoses, University of South Bohemia in České Budějovice, Zátiší 728/II, 389 25 Vodňany, Czech Republic.
Email: phillip.haubrock@senckenberg.de

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Abstract

1. Long-term biodiversity monitoring is crucial for freshwater ecosystems as it enables the detection of even subtle changes and biodiversity trends, guiding conservation efforts and ensuring the sustainability of these vital habitats. Despite becoming more commonly considered in the field of freshwater ecology and biological invasions, studies using long-term time series from Türkiye's freshwater resources have remained scarce.
2. To assess the availability of data and ultimately present a baseline for future efforts, we combined published museum records and samples from recent field studies from the highly anthropogenically-altered Lake Bafa in Western Anatolia covering the period 1958–2019.
3. Lake Bafa has a very diverse aquatic ecosystem, providing habitat for both freshwater and saltwater species, and is one of the allottees in Türkiye's inland fish production. In the current study, we investigated how fish populations in Lake Bafa were affected by environmental changes and examined changes in taxonomic and functional diversity of non-native species over time.
4. The analyses revealed—concomitant to an increase in native marine and freshwater species richness—an increase in non-native species richness over time. Non-native species did not interfere with native species' niche space, whereas applied models indicate that in this highly altered ecosystem, foremost temperature and salinity shaped the fish community over time, limiting the impacts of non-native species.
5. These results have implications for the fishery of the lake, which includes highly valuable catadromous fish species, highlighting the value and importance of collecting long-term data in Türkiye to better understand both invasion dynamics and changes in the naturality of Turkish ecosystems. These findings further underline the importance of long-term data to create new management strategies for the lake and to start restoration processes, thus improving fisheries management.

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KEYWORDS
anthropogenic impact, coastal ecosystem, data science, ecological changes, fish community, long term monitoring data

1 | INTRODUCTION

The Anthropocene is characterized by the destruction of habitats, environmental pollution, climate change, the introduction of invasive species (Soto et al., 2024), and the overexploitation of natural resources (Corlett, 2015; Pievani, 2014). These combined have led to a rapid loss of biodiversity, with many species facing extinction (Johnson et al., 2017; Turvey & Crees, 2019). In low-resilient fish communities, the effects of anthropogenic disturbances are often more pronounced (Balzani et al., 2021; Daufresne & Boet, 2007). Overfishing and destructive fishing practices had devastating effects on fish populations, causing substantial declines in abundance and diversity (Dudgeon, 2019; Link et al., 2020). Additionally, the introduction of non-native fish species and other aquatic organisms disrupted native communities and led to the displacement or extinction of native species (Bissattini et al., 2021; Haubrock, Balzani, et al., 2020; Haubrock, Pilotto, & Haase, 2020; Roseman et al., 2009). These factors collectively can lead to the collapse of entire fisheries and the loss of important ecosystem services (Gherardi et al., 2011; Morara et al., 2021), underlining the urgent need to investigate how freshwater communities have changed over time.

Among the many impacts of global change, changes in the taxonomic and functional composition of communities are particularly important, having significant consequences for ecosystem functions (Jeppesen et al., 2010) due to the loss of certain traits and the acquisition of others (Haubrock et al., 2021; Le Hen et al., 2023). One such aquatic ecosystem is Lake Bafa in Western Anatolia (Türkiye). Lake Bafa was formed between 50 and 300 AD when alluvium carried by the Büyük Menderes River cut the connection of Latmos Bay with the Aegean Sea, separating it from the sea (Kasparek, 1988; Lahn, 1948; Venice System, 1958). Furthermore, drought periods in the Büyük Menderes River basin resulted in the construction of several dams, which exacerbated severe ecological disturbances in Lake Bafa. Human activities surrounding Lake Bafa, including agricultural runoff, urbanization and the construction of water management infrastructure, have collectively contributed to significant shifts in the lake's fish community. These cumulative impacts, compounded by the introduction of non-native species and fluctuating climate conditions, have led to noticeable changes in species composition and abundance, affecting the lake's biodiversity and the ecological balance critical to local communities (Altınsaçlı, 2014). Lake Bafa's fish community has shown a dynamic composition over time, reflecting changes in climate conditions, human disturbances (i.e. canal building) and the introduction of non-native species (both intentional and accidental), with direct economic and socio-cultural implications on the livelihood of people (Kesici et al., 2013).

Despite some recent works investigating functional changes in aquatic communities and their consequences on ecosystem functioning (Jeppesen et al., 2010; Le Hen et al., 2023), studies investigating drivers of such changes have remained mostly anecdotal—especially in Turkey, a global hotspot for biodiversity (Noroozi et al., 2019). This lack of linking environmental changes to effects on an ecosystem's provisioning to human wellbeing can facilitate ongoing change due to an underlying ignorance towards needed conservation or management interventions, ultimately exacerbating a possible deterioration of fishery production (Arlinghaus et al., 2002). Assessments of any related change in fish communities are however hindered by a lack of baseline study assessing not only the current biodiversity but also past changes. Hence, in this work, we aimed to investigate how the fish community in Lake Bafa responded to environmental changes over time by combining taxonomic information from historical data and recent monitoring with the analysis of species' functional traits to (1) provide a baseline for future studies, (2) assess past changes in Lake Bafa's fish community and (3) present guidance for these future efforts. We hypothesized that (i) community composition has changed substantially over time; (ii) those changes were driven by multiple environmental changes simultaneously; and (iii) they resulted in a complete shift in the occupied functional space and fish community functioning.

2 | MATERIALS AND METHODS

2.1 | Study area

Lake Bafa, also known as Lake Çamiçi, is an alluvial barrier lake located in the southeast delta of the Büyük Menderes River in Western Anatolia which has a rich aquatic habitat diversity due to multiple habitat complexes such as grassy, sandy and stony places, providing a suitable habitat for various catadromous fish and aquatic birds. The lake is located just 2 m above sea level within the borders of Söke (Aydın) and Milas (Muğla). It has a length of 16 km in the east–west direction and a width of 7 km in the north–south direction (Lahn, 1948), and an area of approximately 68 km^2 (Demir, 2007; Kaçar, 2015). The average depth of the lake is 3 m and the maximum depth is 23 m. Livestock, olive cultivation and fishing are carried out in the settlements around the lake and fishing ranks third among these economic activities (Tuna, 2015). Lake Bafa was a part of the Aegean Sea before it was isolated by the alluvium carried by the Büyük Menderes River (Lahn, 1948; Venice System, 1958), which cut the connection of Latmos Bay with the Aegean Sea between 50 and 300 AD (Kasparek, 1988; Lahn, 1948). The waters of Lake Bafa show mesohaline (Venice System, 1958) properties with a salinity of about 13‰ and have an anoxic layer at a depth of 8–10 m due to temperature stratification in the dry period of the year (Sarı et al., 1999). While the eastern part of Lake Bafa remains in regard of unimpaired, the western basin of the lake is largely impacted by human activities, particularly agriculture and husbandry.

2.2 | Sampling

Sampling was carried out two times (dry and wet periods) in 2018 and 2019. Temperature, pH, salinity, electrical conductivity and dissolved oxygen were measured in situ using the WTW Multi 3430 measuring device at a depth of 1–1.5 m (water depth at site 5–6 m). Standard benthic nets, TS-EN 14757 (175 m long with each panel 35 m long and 3 m high, node-to-node mesh width 10, 20, 30, 40 and 50 mm mesh size) were used, aiming to collect all fish species present in the lake. As the lake has a very wide surface area, 28 different localities were investigated (24 on the shore and 4 in the middle of the lake, which did not render any catches and were ultimately discarded for analyses). In addition, we contacted local fishermen to obtain further specimens of species caught in the lake, which we included in the analysis of functional space and ecosystem functioning.

2.3 | Historic data collection

Historical environmental data on temperature, salinity, pH and dissolved oxygen were collected from the available literature (Table S1). Because salinity is the most influential environmental factor, a supporting graph showing its changes over the years is given (Figure S1). To allow for comparability, only data collected during spring were kept (Balık & Ustaoğlu, 1989; Cirik et al., 1989; Demir, 2007; Kazancı et al., 1999; Sarı et al., 1999; Şaşı et al., 2017). Following the same approach, data on fish community composition were retrieved from the literature (Anonymous, 2011; Balık & Ustaoğlu, 1989; Güçlü et al., 2013; Kasparek, 1988; Sarı et al., 1999; Şaşı & Yabanlı, 2015).

2.4 | Species richness and functional analyses

We investigated spatial differences in community composition based on samples obtained in our sampling (in 2018 and 2019) and changes in species richness based on information on the species present over time (from 1989 to 2019) in Lake Bafa. We distinguished changes in native and non-native species richness as well as changes in the richness of marine and freshwater species. We however note that the analyses conducted here are subject to potential biases (i.e. to have favoured different species over time) due to differences in sampling methodologies, but the presented results are meant to form a baseline for future investigations and to provide guidance for future fish biodiversity monitoring in Türkiye.

We used the www.freshwaterecology.info database (Schmidt-Kloiber & Hering, 2015) to collect and summarize the biological and ecological traits of all fishes. When a specific trait information was missing for a species, we supplemented the available information using the www.fishbase.org database (Froese & Pauly, 2024; Data S1) as well as the scientific literature. In total, we collected information on 21 traits (including 67 modalities; Figure S2; Table S2). To infer changes in functional space and ecosystem functioning, we tested for significant correlations (Spearman correlation) between the number of fish species (including catches from fishermen) and the proportions of trait modalities in the fish community across time. We investigated changes in functional metrics to describe changes in the Hutchinsonian niche spaces (i.e. an *n*-dimensional hypervolume with *n* axes equivalent to the species-specific requirements; Blonder, 2018), which is referred to as niche differentiation (Blonder et al., 2018; D'Andrea & Ostling, 2016). In this context, different functional niches reflect different community niches expressed over time and are hereafter referred to as niche spaces.

We quantified changes in the niche space of the fish community in Lake Bafa using five metrics: functional divergence (F_{Div}; a measure of the variance of the species function, whereby clustering extent indicates niche differentiation, as described by Mason et al., 2005), functional dispersion (F_{Dis}; which is the overall convex hull volume occupied by all occurring traits in multidimensional space), functional richness (F_{Ric}; which is a descriptor of how much niche space is occupied by the occurring species, measured as the number of unique trait value combinations in each period; Table S2), functional evenness (F_{Eve}; a measure of the nearest neighbour distance among species, indicating the regular distribution of species in the occupied niche space, as reported by Schleuter et al., 2010 and Villéger et al., 2008) and Rao's Q (RaoQ; a measure of the functional differentiation between multiple groups based on species abundance or presence/absence data). Together, these metrics can depict shifting trends in a community's occupied niche space over time.

Each metric was computed for each year using the *dbFD* function of the R package `FD` (Laliberté et al., 2014), after 'fuzzy coding' standardization (Chevenet et al., 1994) of the traits using the *prep.fuzzy.var.function* of the same package. To display changes in native and non-native species' niche space over time, we used a canonical analysis of principal coordinates (CAPs; R package `vegan`; Oksanen, 2007; Oksanen et al., 2019), which was run using all native and non-native species with their respective traits using Gower dissimilarity distance (Gower, 1971) and Jaccard distance for species abundance and occurrence data, respectively (Anderson & Willis, 2003; Haubrock et al., 2021).

2.5 | Community composition

Finally, to investigate species and trait modalities that were characteristic of changes over time, we performed two separate CAPs, one based on each year's functional trait composition, pooling native and non-native fish species, and then fitted species and trait modalities with non-linear relationships with the principal coordinates, using forward and backward selection to keep only those significantly correlating with the ordination axes until the minimal Akaike's information criterion (AIC) was reached, and another one of each year's community composition (utilized the *vegdist* function of the `vegan` R package, applying Jaccard's index to calculate dissimilarities between years based on presence–absence data). All analyses were performed using the software R (v. 4.2; R Core Team, 2023).

3 | RESULTS

3.1 | Sampling

In the wet period, (between September 2018 and May 2019) mean values of water temperature, salinity, electrical conductivity, pH and dissolved oxygen yielded 24.0°C, 31.7 ppt, 48.6 μS_{25}°C/cm, 7.13 and 6.21 mg/L, respectively (Table S3). The study identified 12 taxa (7 species sampled by our field effort, 5 species sampled from fishermen) belonging to the families Anguillidae, Mugilidae, Atherinidae, Syngnathidae, Cyprinodontidae, Moronidae, Sparidae, Gobiidae and Poeciliidae (Table S4).

In 2018/2019, our sampling across the 24 sites found the most dominant species to be the non-native *Atherina boyeri*, contributing 94.71% of the overall sampled number of individuals, hence being the most caught species in the lake during the two sampling periods (Table S4). This species was very abundant in the western, southern and eastern parts of the lake, both in September and May. The second most abundant species was *Gobius niger*, a non-native species without economic value that entered Lake Bafa in the late 1990s, which also occurred in most sites around Lake Bafa. These species are followed in abundance by members of the family Mugilidae, namely, *Chelon auratus* (constituting 89% of all Mugilidae), *Chelon ramada* (7%) and *Mugil cephalus* (3%), which were the most common native species. They, however only represented 0.80% of the total caught abundance in September 2018 and 0.05% of the total abundance in May 2019, contributing only 0.27% to the total abundance of fish caught in 2018/2019 (Table 1). *Syngnathus abaster* was found only in the Kapıkırı area of Lake Bafa, while *Aphanius fasciatus* was found only in shallow waters with underwater plants near Kapıkırı Village (sites #16–17; Figure 1). The historical and current fish fauna of the studied sites are listed (Table S4).

3.2 | Species richness

Between 1958 and 2018, salinity increased from 3.5 to 23.8 ppt following the establishment of 15 impoundments on its tributary, intense irrigation and seawater inflow. Simultaneously, the number of species increased from 6, known to have occurred in Lake Bafa, to 15 in the years after 2000. From these, non-native contributed four species at their peak in 2017. Concomitant to the incline in native and non-native species (Figure 2a), we found the number of marine species to increase more strongly than the number of freshwater species (Figure 2b).

3.3 | Functional diversity

The computed functional metrics showed no significant change across time ($p > 0.05$ for all). The only identifiable significant change was in the number of species, increasing from 6 species in 1958 to 15 between 2000 and 2015, before declining to 11 in 2018 ($p < 0.05$; Figure 3).

The functional space occupied by the fish community in 1958 was relatively small, limited by the number of present species. In the following years, the number of species and hence, the occupied native niche space increased. The first non-native species, *Gambusia holbrooki* and *A. boyeri*, appeared in 1989 and remained until 2018, occupying a niche space outside that of native species. In 2015, two further non-native species appeared, *Lepomis gibbosus* and *Carassius gibelio*, the latter overlapping with natives' niche space, disappearing again in 2018 (Figure 4).

3.4 | Community composition

Communities changed substantially in their composition over time. However, non-native species were not drivers of compositional changes, but rather the appearance or disappearance of native species was (Figure 5a). Concomitantly, trait modalities that were characteristic of changes in the community composition were numerous but not unique to non-native species (Figure 5b).

4 | DISCUSSION

Anthropogenic activities and global changes have significantly altered freshwater ecosystems and continue doing so, resulting in profound changes in, for example, fish communities (Haubrock et al., 2021). Despite needing further investigation, the observed shift in community composition, paralleled by predominantly an increase in salinization, suggests that salinity changes were the most influential

TABLE 1 Abundance of current fish species in Lake Bafa from sampling in 2018 and 2019 (for both dry and wet seasons).

Fish species	Wet period N	Wet period %N	Dry period N	Dry period %N	Total N	Total %N
Atherina boyeri	4824	82.000	14,440	99.880	19,264	94.705
Gobius niger	1009	17.150	10	0.070	1019	5.010
Chelon auratus	42	0.715	7	0.044	49	0.241
Chelon ramada	3	0.051	1	0.006	4	0.020
Mugil cephalus	2	0.034	0	0	2	0.010
Syngnathus abaster	2	0.030	0	0	2	0.010
Aphanius fasciatus	1	0.020	0	0	1	0.005
Total	5883	100.00	14,458	100.00	20,341	100.00

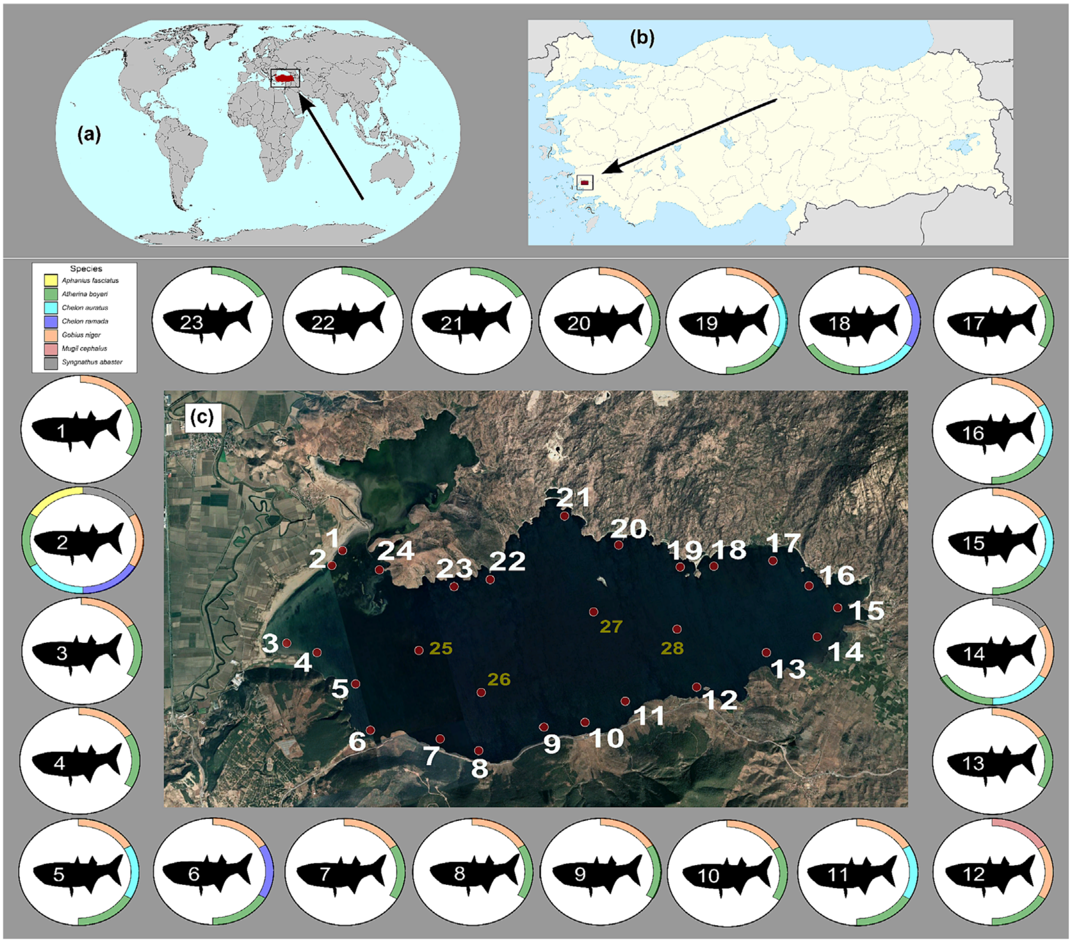

FIGURE 1 Spatial distribution (presence/absence) of fish species sampled in the 24 sampled sites (1–24) that rendered catches and the 4 sites (25–28) that did not render any catches in 2018 and 2019.

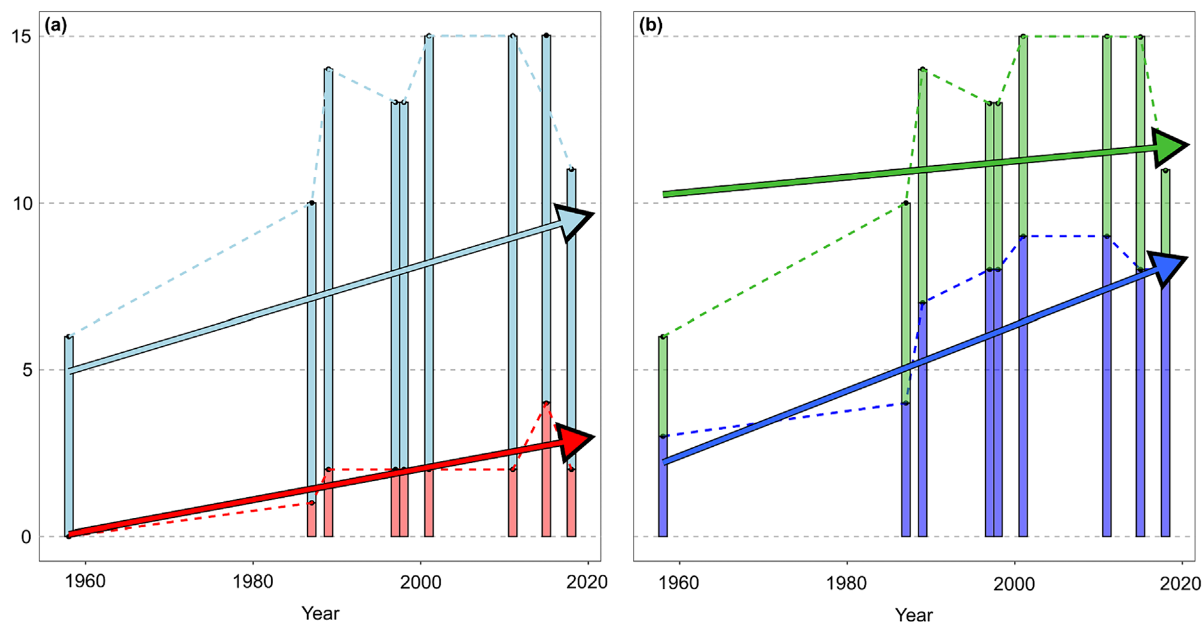

FIGURE 2 Species richness of native (blue) versus non-native (red) species richness over time (a) and freshwater (green) versus marine (blue) species richness over time (b). The respective arrow represents each group's raw incline.

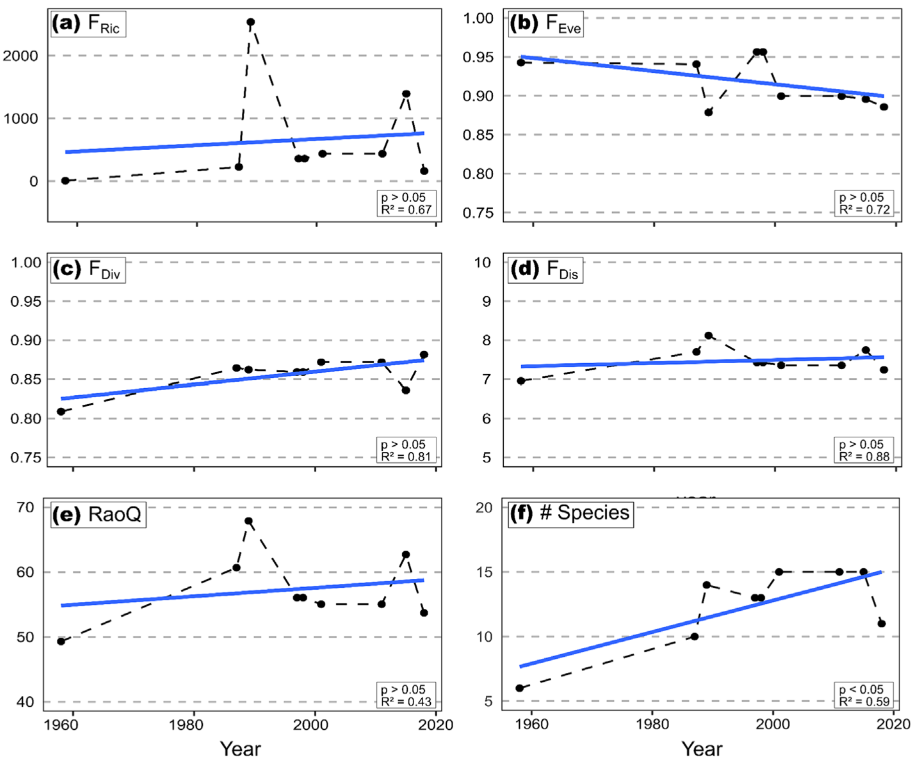

FIGURE 3 Trait metrics (a = functional richness, F_{Ric}; b = functional evenness, F_{Eve}; c = functional divergence, F_{Div}; d = functional dispersion, F_{Dis}; e = Rao's Q, RaoQ; f = number of species, # Species) over time.

factors in restructuring the fish community of Lake Bafa while revealing that the few non-native species played a lesser role, with their arrival probably hindered by environmental filters (i.e. high salinity). Indeed, the analyses confirmed an increase in non-native species richness over time, which however did not interfere with the niche space of native species. Our findings also emphasize potential caveats, but concomitantly underline the possible uses of historical data, signifying the need for considerable improvements for future fish biodiversity assessments in Türkiye.

4.1 | Historical data

Despite the importance of long-term data, including historical data, a limited number of studies on freshwater fisheries management have relied on them (Haubrock, Balzani, et al., 2020; Radinger et al., 2019). This has caused changes in freshwater fish communities to remain hidden, creating ignorance towards drivers of change. Lake Bafa in Türkiye is no exception, with previous studies indicating that native fish communities respond to ecological shifts in the lake, despite providing no information on the effects this may have on ecosystem functioning or local population (Sarı et al., 1999).

Previous studies have been conducted on the fish fauna of Lake Bafa. Artüz (1958) was the first to list six fish species in the area, while an additional 17–20 fish species were reported in the 1980s and 1990s (Balık & Ustaoğlu, 1989; Kasparek, 1988; Sarı et al., 1999). Sampling in 2018/2019 combined with reports from local fishermen, however, detected only 12 of the 25 previously reported species. Thus, it becomes clear that historical data must be approached with caution, recognizing the differences and limitations in field sampling methods over time. Similar to the turnover from a native to an entire non-native species community in the Italian Arno River (Haubrock et al., 2021), technological advancements and refined techniques have led to the discovery of more species, highlighting the importance of understanding the context behind data collection practices.

The observed increase in species counts should however not be confused with the introduction of non-native species. Contemporary, native species richness fluctuated substantially as some of the species occurring over time belong to the lakes` native fauna but could not be recorded continuously or in the last year, with eight species probably being extirpated from the lake. These findings thus underline the potential of using historical data to assess changes in biodiversity. However, it should be noted that *Anguilla anguilla* could not be caught during the sampling studies but was reported as present by local fishermen.

4.2 | Salinity as driver of community change

Environmental change and the concomitantly arising stressors can affect fish communities through a myriad of possible processes (Mueller et al., 2020). The lack of information on the strength of individual stressors can limitate insights into the reasons underlying shifts in community compositions (Le Hen et al., 2023). We however noted a stronger increase in marine than freshwater species (in terms of total numbers), reflecting the lake's gradual salinity increase. Salinity has increased by approximately 280% since the first measurement on the lake's shore until today (Figure S1). There have been many reasons for the increase in salinity in the lake. One of the main reasons is that the delta is deprived of freshwater due to the construction

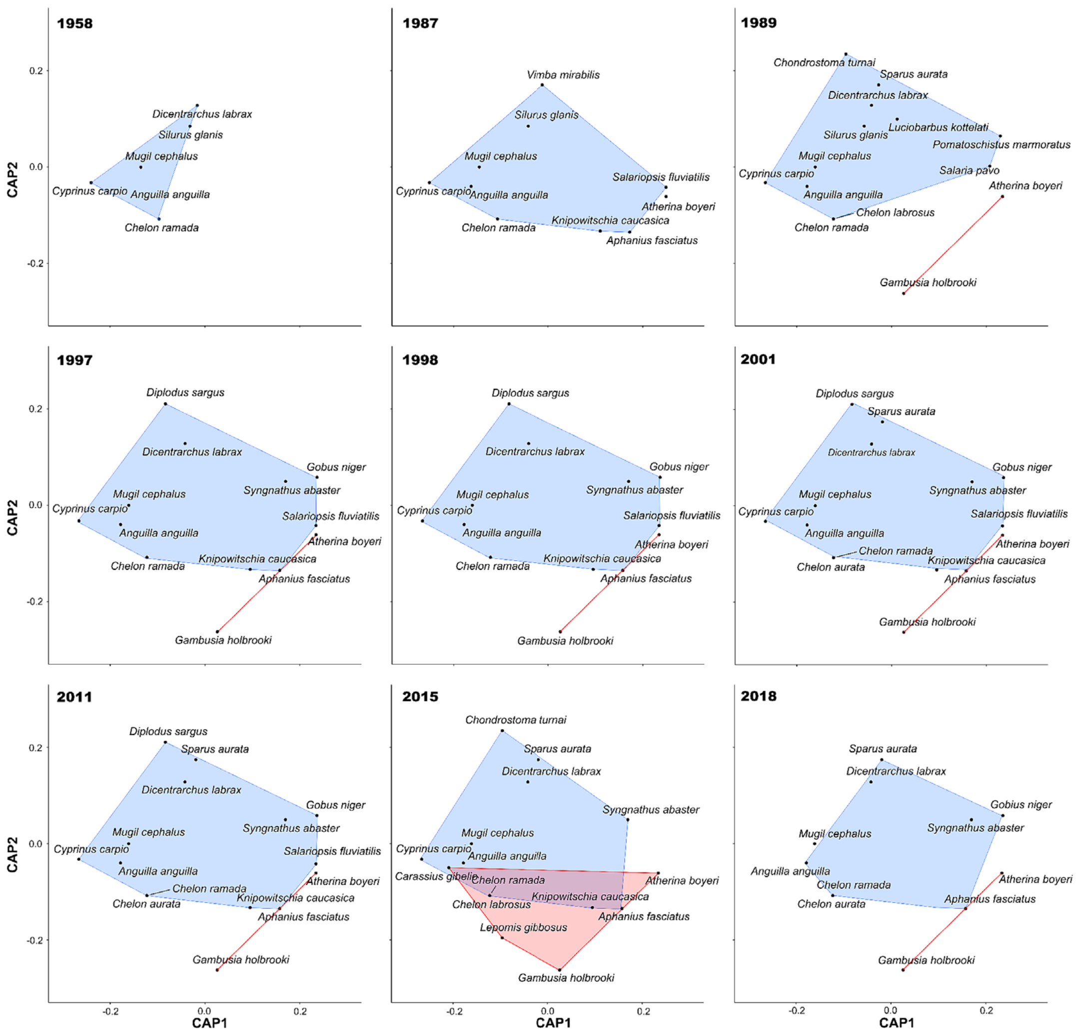

FIGURE 4 Canonical analysis of principal coordinates (CAPs) on fishes' functional traits, indicating their occupied functional space (blue: native species; red: non-native species) over time.

of reservoirs on, for example, the Büyük Menderes River and embankment, which was built with the aim of protecting Serçin Village from floods, resulting in insufficient water supplying the lake from the Serçin water resources. Likely due to the influence of also other environmental variables, *A. boyeri*, which is not a member of the lake's native fauna, has become the dominant fish species, very abundant in the western, southern and eastern parts of the lake. This small zooplanktivorous species is widely distributed around the world and known as invasive for lake habitats in Turkey (Ekmekçi et al., 2013).

It is, however, plausible that the increased salinity of the lake caused significant changes, including the disappearance of native species. Indeed, in an environment of increasing salinity, females of brackish marine species can reproduce earlier, despite lower oocyte numbers, while showing stronger swimming ability (Mück & Heubel, 2018). The large predatory species found in Lake Bafa (e.g. *Dicentrarchus labrax*) are however euryoparous (i.e. without strict spawning habitat preferences). The analyses concomitantly showed that stout species that dominated in 2015 do not protect their eggs, whereas, among the species evaluated within the scope of this study, limnophilic species had moderate buoyancy and continued to breed at the highest ages (Figure 5b). Traits like breeding at older ages and lack of egg protection may simply suggest a more stable community or a lack of species that try to steal eggs, supporting current trait results, but could also be an indicator of dominant lake species that are not under threat.

However, concerns about biodiversity declines after 2015 should consider the impacts of both non-native species and environmental changes, rather than attributing these trends solely to improved detection methods due to a shift from historical to recently collected data. Yet, a lack of measured environmental variables with a high spatial–temporal resolution makes inferences of drivers of compositional changes and those facilitating the success of *A. boyeri* difficult.

4.3 | Changes in functional space

The analysis of functional niche space suggests that the ecological character (i.e. functioning) of Lake Bafa's fish community was stable

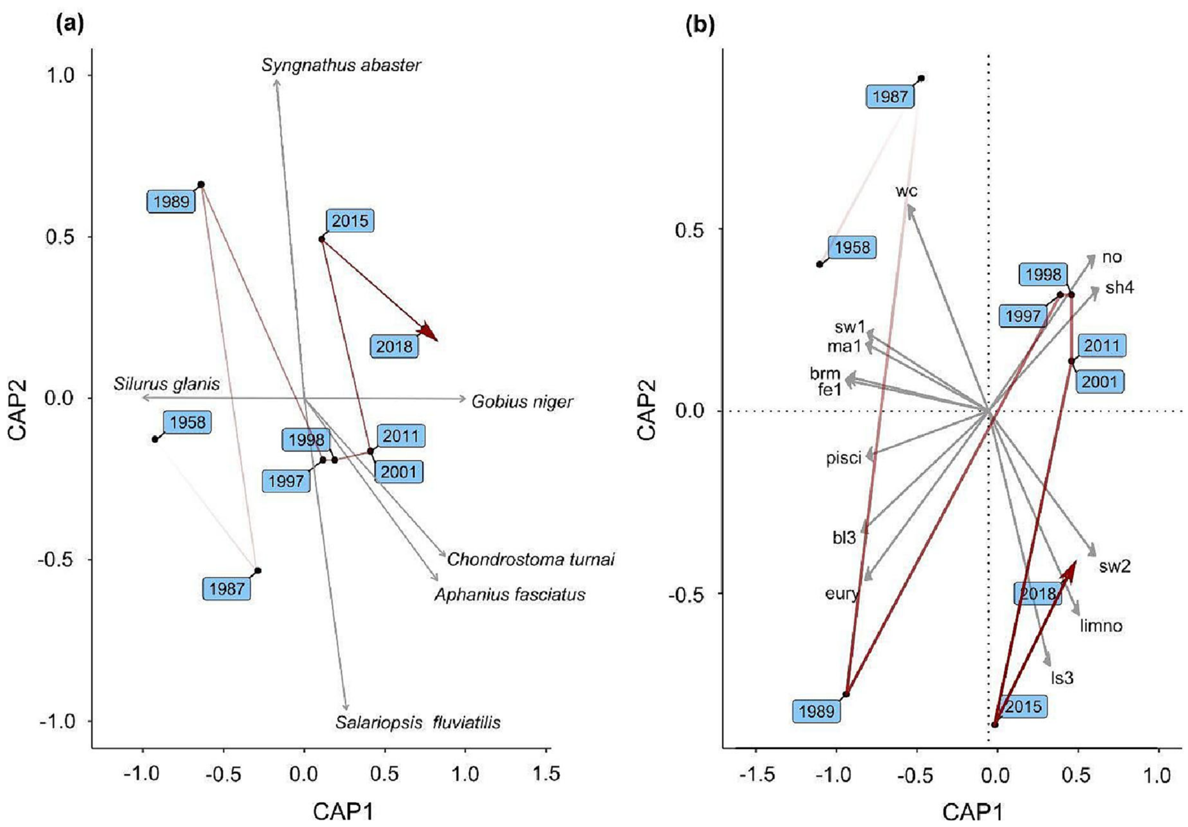

FIGURE 5 Canonical analysis of principal coordinates (CAPs) on the fish community composition, showing changes across time and the significant ($p < 0.05$) features (a) species and (b) trait modalities correlating with them. The abbreviations of trait modalities are as follows: sw1: swimming factor ≤ 0.38; ma1: female maturity ≤ 2 years; brm: brackish marine salinity preference; fe1: absolute fecundity ≤ 55.000 oocytes; bl3: body length ≥ 39 cm; eury: rheophily eurytopic habitat; no: no migration; sh4: shape factor ≥ 5.6; sw2: swimming factor: 0.38–0.43; limno: rheophilic limnophilic habitat; ls2: life span of 8–15 years.

over time, showing no significant change in any regard. This was despite the increase in species richness over the years. We furthermore found that despite the fluctuations of the native fish populations, both *A. boyeri* and *G. holbrooki* occupied positions outside the native niche space. There might be several reasons for this: The main one might be that (i) the resilient niche of native species did not allow any overlap between native and non-native fish species, thereby hindering non-native species in their establishment or the reaching of high abundances (Strayer et al., 2017) due to competitive interactions—as shown in 2015—and (ii) limited resources that could have been shared with native species (Britton et al., 2019). It is however also plausible that (iii) non-native species were subject to a 'boom' phase in between sampled years while being in the 'bust' phase during sampled years (Soto et al., 2023). This however suggests that the introduction of some non-native species, some found to be functionally redundant, reflects a reliance on existing databases for trait information that fail to account for novel traits unique to non-native species. Consequently, such redundancy assessments may overlook the ecological nuances and potential contributions of these newcomers to functional diversity (Dunoyer et al., 2014; Milardi et al., 2020). Moreover, if non-native species are truly functionally redundant, this could lead to direct competition with native species for resources, potentially stressing native populations by duplicating ecological roles rather than diversifying them while maintaining e.g. ecosystem functions (Catford et al., 2009; Rosenfeld, 2002). Another reason (iv) why non-native species tend to disappear is the high salinity. Salinity has often been shown to be a deterrent to species migrations, hindering—to some degree—the influx of several well-known invasive species (Sarı et al., 1999; Zhou et al., 2022). It is, therefore, possible that the salinity also affects the competitiveness of some species (as found by Alcaraz et al., 2008), limiting non-native species establishment. As such, it is no surprise that compositional changes were predominantly characterized by native species and their respective traits.

4.4 | Implications for management and conservation

Lake Bafa has lost its natural ecological condition (especially in terms of salinity parameters), as well as almost all its native fish fauna. This is cumbersome, as Lake Bafa's fishery sustains the livelihood of roughly 6510 people in the lake's surroundings (TUIK, 2019), yet fishery yield of the lake decreased between 2014 and 2018 by 90%

from 312,400 to 31,125 kg/year (Sarı et al., 2021). Aside from members of the family Mugilidae, being arguably the most economically important fishes in Lake Bafa, catadromous fish fauna is also very important for fishing activities of the lake. Yet, catadromous fish species *A. anguilla*, *M. cephalus*, *C. auratus*, *C. ramada* and *Chelon labrosus* entering the lake via the Büyük Menderes River have decreased a lot as a result of the increasing salinity and foremost dam construction.

Our results furthermore suggest that smaller, highly specialized native species, namely, *Sotalia fluviatilis*, *A. fasciatus* and *Knipowitschia caucasica*, are exposed to the greatest risks (see Figure 4). Regarding the fisheries over the past years (see Table S5), *A. anguilla*, *C. ramada* and *M. cephalus* were the most fished species. Due to extensive overfishing, dam construction limiting migration, and invasive species, *A. anguilla* is classified on the IUCN Red List as Critically Endangered, facing substantial local extinction risks (Pike et al., 2020). Indeed, Lake Bafa is frequently used for many human activities and this situation likely served as a stepping-stone for the introduction of invasive species. *A. anguilla* and mullet species (*C. ramada*, *C. labrosus* and *M. cephalus*) have a high tolerance towards high salinities and can presumably withstand stressors to some degree, having sustained environmental pressures until now, including the threat of sporadically appearing non-native species. Yet, although *A. boyeri* was ubiquitously present in Lake Bafa in 2018/2019, other non-native species like *C. gibelio*—and potential pathogens introduced alongside (Innal & Stavrescu-Bedivan, 2022)—can present additional pressure on fishery-relevant species. However, the increasing salinity in Lake Bafa may lower this risk, especially considering the absence of *C. gibelio* in the last sampling year (2018). This should nevertheless be confirmed by subsequent studies.

To mitigate the effects of systematic change in Lake Bafa, but also other aquatic ecosystems facing multiple threats (Giannetto & Innal, 2021), regular biomonitoring should become a requirement. New management strategies need to be implemented, targeting changes over time. In the particular case of Lake Bafa, management should be applied before migration periods, improving the migratory ability of catadromous species, and revert Lake Bafa back to a more natural state. This is because excessive irrigation and droughts in the dry season substantially affect the lake ecosystem. We hence suggest the creation of management strategies, that is, by local research bodies or agencies, to routinely monitor the fish distribution and abundance of Lake Bafa to understand the dispersion and abundance of both saltwater and freshwater fish species to better understand their ecology.

4.5 | Guidance going forward

Aiming to assess the impact of non-native species and environmental changes on fish communities in Lake Bafa, our study faced methodological challenges and discrepancies in study aims from past research from which we obtained data. Previous studies (such as Balık & Ustaoğlu, 1989 or Koçak et al., 2017) varied widely in their methodologies, ranging from differences in sampling techniques to the analytical frameworks used to interpret the data. These variations have undoubtedly influenced the outcomes of our analyses. Hence, our primary aim was to collate and assess the available data to establish a baseline for future studies—not only as a snapshot but also critical reference on past changes—aiming to track and understand future changes in fish community composition in Türkiye, using Lake Bafa as a focal point. Moreover, to disentangle the effects of salinity and different functional spaces between native and non-native species, future 'quantitative' fish monitoring paired with 'quantitative' functional analysis on the basis of spatio-temporally coherently sampled data are required. Such data, advancing our temporal understanding of biological invasions, will help to assess and mitigate the impacts of environmental changes and multiple stressors.

The case of Lake Bafa exemplifies the necessity for improved data collection methodologies to enhance the accuracy and comparability of future fish community assessments in Türkiye. For this, we propose several guidelines: First, there should be a standardization of sampling methodologies for fish (Poesch, 2014), aligning with best practices such as those outlined in the European standard EN 14757 for fish sampling with multi-mesh gillnets. This standard recommends using gillnets composed of 12 different mesh sizes ranging from 5 to 55 mm knot to knot, following a geometric series, which contrasts with the less diverse and arithmetically arranged mesh sizes used in some of the past samplings in Lake Bafa (and possibly across Türkiye). Furthermore, there is a pressing need for persistent spatio-temporal sampling (Leroy et al., 2023). Regular, systematic sampling across different seasons and years would help in understanding temporal trends and the impact of environmental changes (Haubrock et al., 2023; Haubrock & Soto, 2023; Le Hen et al., 2023), such as salinization, climate change and non-native species introductions, on fish communities (Haubrock, Balzani, et al., 2020; Leite et al., 2022; Haubrock & Soto, 2023). Additionally, incorporating environmental DNA (eDNA) sampling could offer insights into species diversity and presence with less impact on the environment and could be particularly useful for detecting rare or elusive species (Sakata et al., 2021). Such genetic approaches could complement traditional sampling methods, providing a more comprehensive overview of biodiversity.

Future sampling efforts could follow the eLTER- (Mirtl, 2018) or Water Framework Directive-scheme (Hering et al., 2010), that is, being unified across Türkiye and expanding the scope of data collection to include both abiotic and biotic factors, such as water quality parameters, habitat characteristics and competitive interactions among species. These recommendations, arguably important for Lake Bafa, should be considered for application in other aquatic environments across Türkiye. Standardizing methodologies and ensuring consistent, detailed data collection across the country would significantly enhance our understanding of biodiversity changes and losses over time. Such efforts would provide invaluable insights for conservation and management strategies, ensuring the sustainability of Türkiye's aquatic ecosystems. This proactive approach towards improved data collection and analysis represents a crucial step towards safeguarding Türkiye's rich aquatic biodiversity for future generations.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

ORCID

Irmak Kurtul https://orcid.org/0000-0002-3566-9172
Cüneyt Kaya https://orcid.org/0000-0002-4531-798X
Hakan Kaykaç https://orcid.org/0000-0002-4807-707X
Ali Ilhan https://orcid.org/0000-0002-7666-1804
F. Ozan Düzbastilar https://orcid.org/0000-0002-5376-7198
Zafer Tosunoğlu https://orcid.org/0000-0002-1168-9611
Hasan M. Sari https://orcid.org/0000-0003-1000-514X
Paride Balzani https://orcid.org/0000-0003-1549-7139
Ali Serhan Tarkan https://orcid.org/0000-0001-8628-0514
Phillip J. Haubrock https://orcid.org/0000-0003-2154-4341

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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