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Tracking aquatic non-native macroinvertebrate species in Germany using long-term data

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Abstract

Biological invasions pose a global challenge, threatening both biodiversity and human well-being. Projections suggest that as invasions increase, the financial costs associated with management and the ecological harm they cause will also escalate. Here, we examined whether long-term biomonitoring strategies were adequate to identify and track benthic aquatic non-native macroinvertebrate species by using the German subset (151 time series; 129 of which reported non-native species) of the currently most comprehensive European long-term dataset of 1816 macroinvertebrate community time series from 22 European countries. The detection of aquatic non-native species was directly linked to the availability of long-term sites and thus, monitoring effort, having identified the spatio-temporal occurrence of 32 non-native species. The available long-term monitoring site data were mostly concentrated in the western part of Germany, predominantly covering the Rhine River and its tributaries. The spatially biased network of long-term monitoring sites, therefore, naturally skews the detection and reporting of aquatic non-native species toward this area and underestimates Eastern and Southern regions, impeding the comprehension of invasion dynamics. However, based on the available data, we found that the absolute number of non-native species increased and the proportion of non-native species relative to native species decreased over time. This indicates complex ecological interactions between native and non-native species and underlines the value of long-term data for investigating invasion dynamics. Considering the value of comprehensive monitoring networks, a spatially biased network delays the application of management and mitigation plans, possibly worsening the ecological and economic effects of biological invasions in Germany. The results provided here indicate the disadvantages of biased datasets, but simultaneously underline the enormous potential of a dense network of long-term monitoring. Our results also highlight the urgent need to increase and diversify long-term biomonitoring efforts throughout Germany to cover the main freshwater resources and their connections where the introduction risk of non-native species is the highest. Centrally collating such data would provide a profound basis for the monitoring of spreading aquatic non-native species and could serve the implementation of national biosecurity efforts.

Keywords Freshwater, *Non-native species*, *Biodiversity*, *Species conservation*, *Species introduction*

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Introduction

The phenomenon of biological invasions, caused by direct human actions and propelled by anthropogenic disruptions within natural habitats, presents a global challenge that affects both biodiversity and human well-being [23, 66]. The introduction of non-native species ranks among the principal causes of biodiversity diminution, accounting for the majority of species extinctions [5], numerous ecological disturbances [58], and monetary losses [15]. Mirroring the upward trajectory of invasion rates [24, 62], increasing financial costs and growing ecological threats are expected in the future [3, 24].

Freshwater ecosystems are particularly threatened by non-native species introductions due to their covering nature (i.e. hiding non-native species from detection; [29, 49, 60] as well as substantial human alterations and uses facilitating non-native species introductions [31, 74]. Management strategies in Europe currently aim to tackle biological invasions through a blend of policy initiatives and practical measures. At the national level, individual European countries have increasingly relied on 'black-' or 'deny-lists'—although these lists face valid criticisms [13, 67]—as essential tools for prioritising non-native species for management efforts [6, 17, 19, 55]. Recognizing the benefits from e.g. canalisation for global trade [9, 51], the interconnected nature of river systems extending beyond national borders [18] continues to play a crucial role in the continental (i.e. European) dispersal of non-native species [4, 41]. Both international and regional cooperation are therefore pivotal [38], with significant legislation such as the EU Regulation on Invasive Alien Species (1143/2014) being crucial for safeguarding Europe's biodiversity and reducing economic losses. However, especially for the management or biosecurity measures for aquatic invasions, the basis remains congruent data, stemming from continuously surveying aquatic ecosystems. Despite being a demanding and costly endeavour [73], established long-term monitoring sites remain an indispensable tool for the understanding and mitigation of biological invasions at regional [25] or national levels [33, 34] which are vital not only for preserving biodiversity but also for safeguarding economic interests and public health in the face of ongoing socio-economic challenges [43].

Germany stands out among European countries due to its robust economy, high levels of economic activity, and strategic position at the centre of European trade and travel networks [70]. Particularly in research-intensive Germany [45, 78], the effective identification and management of aquatic non-native species could be facilitated using existing biodiversity long-term monitoring sites [47]. Using data from just the Rhine River, Haubrock and Soto [25] emphasised the value of sustained monitoring efforts in detecting aquatic non-native species over space and time, highlighting the link between increasing non-native and decreasing native biodiversity. Yet, despite the evident threat biological invasions pose to Germany's economy [23], there remains a notable deficiency in the availability of comprehensive data on the presence and ecological as well as economic impacts of non-native species. This knowledge gap is particularly surprising considering (1) the rich scientific history of Germany [40] and (2) the presence of approximately 1080 non-native species in this country, with only about 10.7% being recognised as invasive [26]. Furthermore, the most thorough recent compilations, such as the *Established Alien Species in the European Union* [30] and the *Global Invasive Species Database* (GISD; [56]), indicate that only 8.1% of the non-native species in Germany are considered invasive based on observed impacts as defining criterium [26, 69]. Given these circumstances, it is crucial to evaluate the effectiveness of long-term biodiversity monitoring for the identification and tracking of freshwater invasions in Germany. This evaluation is essential, because it would help to systematically bridge existing data gaps, provide a clearer understanding of the ecological and economic impacts of non-native species, and improve the management and mitigation strategies for these invasions.

Considering how the vast European river networking has facilitated the spread of numerous non-native species [27, 68], the presence of aquatic non-native species is unlikely contained. This, paired with the pervasive knowledge gaps outlined above, hinders the effective management of biological invasion and the implementation of biosecurity measures (including deny-lists [17, 33, 34, 55]). To generate an overview of the efficacy of long-term monitoring sites in Germany for the detection and tracking of aquatic non-native species, we use a recently collated database of European long-term benthic macroinvertebrate time series [22]. We aimed to identify whether available data (1) covers all major German river networks and (2) if available long-term biomonitoring data can comprehensively identify and track the introduction of aquatic non-native species in Germany over space and time. While we acknowledge the probable existence of several shortcomings in every database, including the database collated by Haase et al. [22] (i.e. inadequate sampling information [28]), we hypothesised that while (i) the network of available long-term biomonitoring sites in Germany may not cover the extensive river network exhaustively, opening the door for non-native species spreading undetected, (*ii*) long-term data can effectively identify non-native species in freshwater ecosystems and track freshwater invasion in German rivers, even those dating back decades. This research will contribute to the growing body of studies investigating the temporal dynamics of freshwater invasions and the relationship between invasion dynamics and long-term biodiversity monitoring.

Methods

Data compilation

We investigated the adequacy of long-term biomonitoring approaches for detecting non-native species in Germany (Supplementary Table 1) using the recently collated and to date most comprehensive European long-term database by Haase et al. [22]. This database contains 1816 macroinvertebrate community time series from rivers and streams in 22 European countries. The data were collected for purposes such as research projects or regulatory biomonitoring that meet the following criteria: (*i*) each time series contained the abundance of macroinvertebrate taxa, (*ii*) sampled in a minimum of 8 (not necessarily consecutive) years, and (*iii*) had consistent sampling effort per site (see [22] for further details). Although macroinvertebrate community sampling protocols varied among time series, they were kept consistent over time within each time series. The nativeness of species in Haase et al. [22] was assessed at the country level by consulting two open databases: the *Global Alien Species First Record Database* [62] and the *Invasive Species Compendium* (CABI; www.cabi.org). In case of a mismatch in the species' non-nativeness among country assessments, we followed the *Global Alien Species First Record Database* [62] classification as the most reliable and updated database to date. For a comprehensive explanation of the data used, see Haase et al. [22]. Although data from the Water Framework Directive-compliant freshwater ecosystem monitoring has previously been used to investigate invasion dynamics in Germany [26], the majority of sites were sampled only once based on the available data. Furthermore, the duration and number of samples per site in those that were sampled multiple times are sporadic and highly variable. Consequently, this data would only allow a space-for-time analytical approach and would not be compatible with the data from Haase et al. [22].

Statistical analyses

To evaluate if long-term biodiversity monitoring of aquatic ecosystems covered all major rivers in Germany and could effectively be used for the detection of benthic non-native macroinvertebrate species (henceforth referred to as 'non-native species'), we first investigated the spatio-temporal distribution of long-term sites in Germany and compared these with those that reported non-native species (hypothesis *i*).

We then analysed trends in the reporting of non-native species over space and time with regard to the availability of long-term monitoring sites to evaluate whether long-term data reported in Haase et al. [22] can track non-native species in Germany (hypothesis *ii*). This was achieved using a series of Generalised Additive Models (GAMs) using the `mgcv` library in R [77]. Every model contained the respective response variable (i.e. the raw and the relative non-native species abundance) and the explanatory variables: 'year' to infer temporal trends, 'longitude and latitude' using a spherical spline to correct for spatial autocorrelation, 'site_id' to correct for site-specific effects, and the number of sites sampled per year to account for differences in the intensity or scale of sampling across different locations and times. To assess correlations among predictors [16], we employed the variance inflation factor (VIF) analysis using the vif function from the R package `car` [20]). We retained all predictors as none expressed any collinearity (threshold = 7). Moreover, we analysed the relationship between occurring non-native species over time and monitoring sites as well as the cumulative occurrence of different macroinvertebrate groups over time using a series of Pearson's product-moment correlations using the *cor.test* function of `base` R. In addition, we investigated the occurrences of four prominent Ponto-Caspian non-native species (i.e. the two most frequently reported species *Dreissena polymorpha* and *Corophium curvispinum*, and the two non-native species not as frequently reported over space and time, *Eriocheir sinensis* and *Jaera istri*). Note that one occurrence does not reflect the number of sites, but the number of individual years a species was reported. All analyses were performed in R version 4.2.3 [61].

Results

In total, the database from Haase et al. [22] contained 151 German long-term monitoring sites reporting long-term macroinvertebrate data from 1968 to 2021 (Fig. 1a). From these, 129 sites (81.13%) reported non-native species, covering the period 1971–2019. These sites were predominantly situated along the Rhine River catchment and to some degree the Ems. Several sites were placed in the Weser River catchment, but not in the Weser River itself. Only one site was on the river Elbe (Fig. 1b).

German long-term data reported in Haase et al. [22] contained occurrence information for 32 non-native species (Supplementary Table 1). The most often reported non-native was *Dreissena polymorpha* ($n = 1157$ occurrences), followed by *Corophium curvispinum* ($n = 610$ occurrences), *Dugesia tigrina* ($n = 515$; synonymous to *Girardia tigrina*), *Dikerogammarus villosus* ($n = 439$), *Gammarus tigrinus* ($n = 393$), *Potamopyrgus antipodarum* ($n = 263$), *Jaera istri* ($n = 221$), *Corbicula fluminea* ($n = 217$) and *Echinogammarus ischnus* ($n = 165$). All other species occurred less than one hundred times

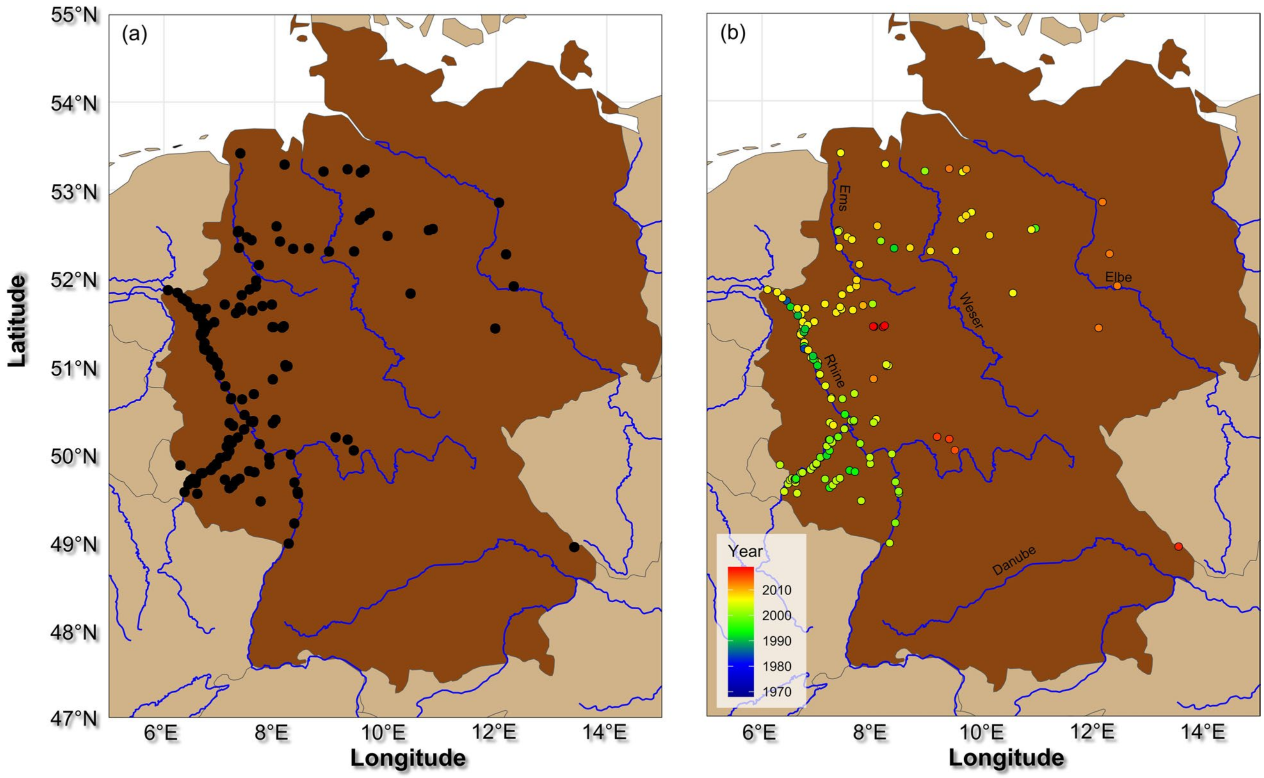

Fig. 1 Distribution of German long-term biodiversity monitoring sites collated in Haase et al. [22] (**a**) and the subset reporting non-native species (**b**). The colour gradient indicates the year a non-native species was first recorded in the respective site

(Supplementary Table 1). Whereas the yearly raw abundance of non-native species reported in German long-term biodiversity monitoring sites increased from on average ~ 30 individuals in 1971 to ~ 305 individuals in 2019 by + 917% (Fig. 2a; Supplementary Table 2), their relative abundance as a fraction of the invaded communities decreased over time by ~ 5% (from ~ 16% in 1971 to ~ 11% in 2019), reflecting a decline of ~ 31% (Fig. 2b; Supplementary Table 3). Both trends over time were found to be significant ($p < 0.05$). Moreover, site ID and coordinates were found to be significant as well ($p < 0.05$), suggesting site-specific and spatial factors affecting the raw and, respectively, the relative abundance over time. The number of unique sites sampled per year, however, only significantly affected the relative abundance of non-native species. It suggests that the increase in the number of unique sites sampled per year is associated specifically with changes in the relative, but not the raw abundance of non-native species (Supplementary Table 2, 3). It should be acknowledged that the adjusted R-squared and the deviance explained of both models was very low (< 0.01; 0.2%), indicating that the predictors were not effective in explaining the variability in the data.

The applied Generalised Additive Model identified a bell-shaped progression in the reporting of non-native species per year over time (despite being corrected for sampling effort), driven by the number of unique sites sampled per year and reaching the highest value in 2002 with 16 reported non-native species (Fig. 3a; Supplementary Table 4). Concomitantly, the number of sites monitoring biodiversity per year increased in a comparably bell-shaped progression (Fig. 3b). The increase in unique sites was significantly correlated with the number of unique non-native species reported per year ($p < 0.001$; $t = 5.09$; df = 46; $R^2 = 0.60$) as well as the cumulative total number of non-native species reported over time ($p < 0.951$; t = -0.06; df = 15; $R^2 = -0.02$).

The cumulative number of reported non-native species (i.e. their first occurrence in long-term biodiversity monitoring over time) increased steadily. The first reported non-native species, *Physella acuta*, occurred in 1971. By 1980, the number of reported non-native species had increased to five, increasing to 12 in 1983 and 17 in 1986. In 2000, the number of non-native species reached 25, totalling 32 reported non-native species in 2012 (Fig. 4).

Using the two most often reported non-native species *D. polymorpha* (Fig. 5a) and *C. curvispinum* (Fig. 5b), we identified their first occurrences in the lower Rhine River close to the Germany–Netherlands border, followed by their spread along the entire Rhine River in the early

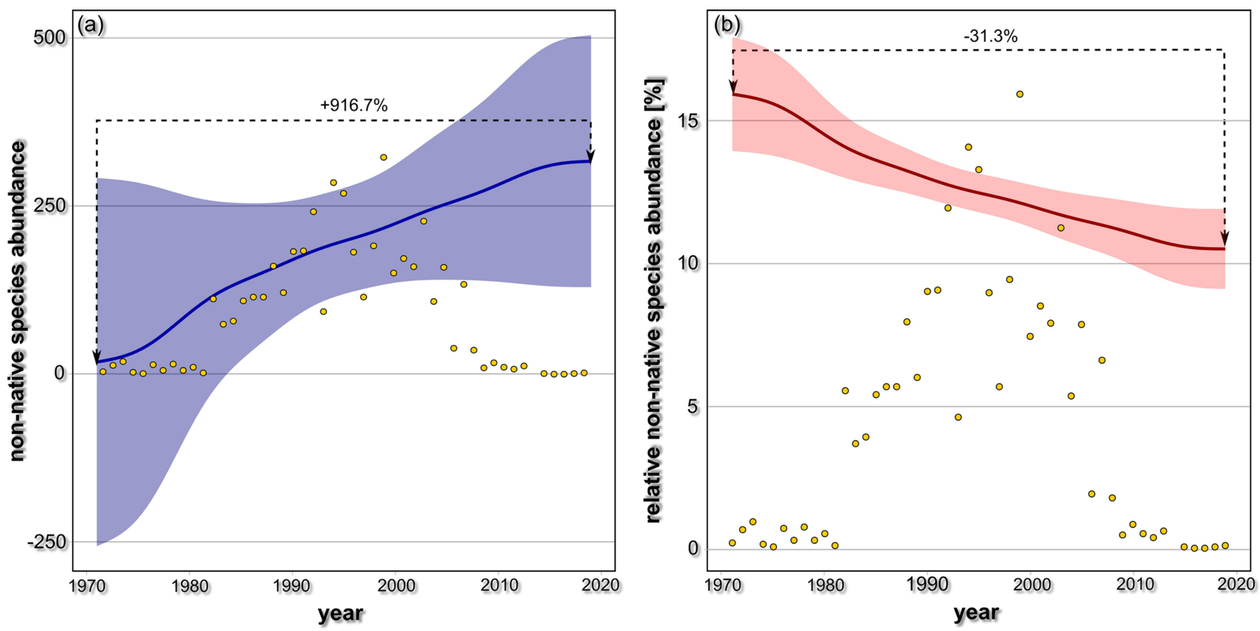

Fig. 2 Trends in the reporting of the raw (**a**) and relative abundances (**b**) of non-native species over time according to the applied Generalised Additive Model. Please see Supplementary Fig. 1 for the distribution of individual data points

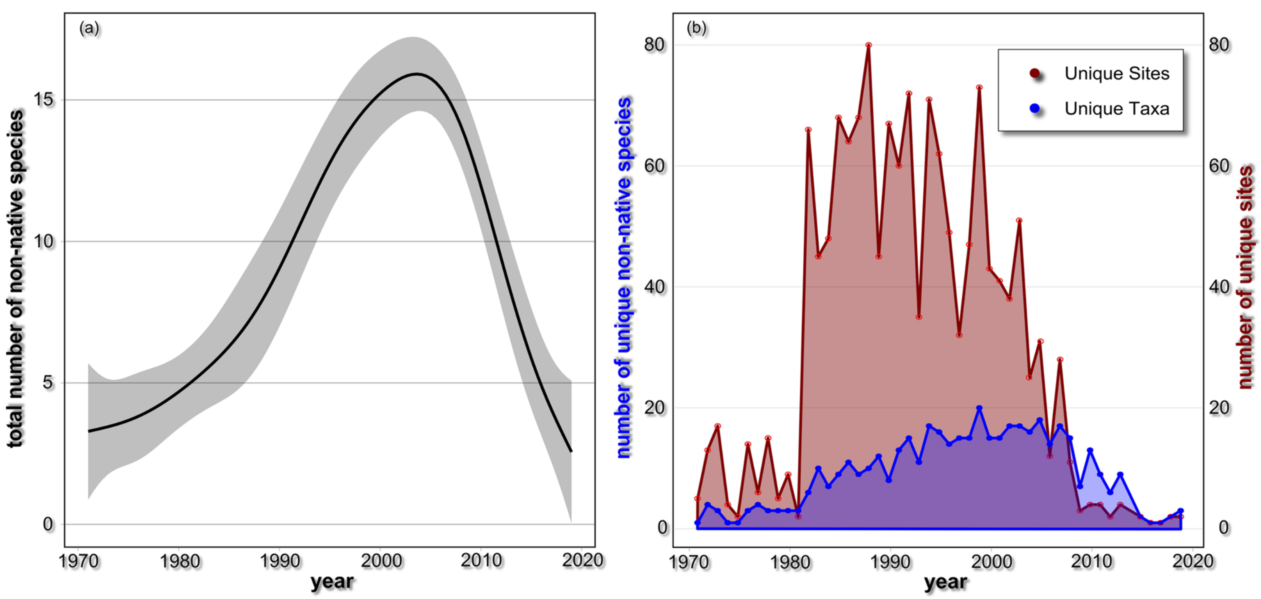

Fig. 3 The trend in the total number of non-native species reported over time but corrected for sampling effort according to the applied Generalised Additive Model (**a**) and the number of unique sites (**b**; red) and unique non-native species reported per year (**b**; blue)

1990s. Following the simultaneous emergence of additional reports along the Rhine River in the 2000s, more appeared westwards towards the Weser River and isolated occurrences in the Elbe River in the 2010s. While *E. sinensis* appeared less frequently, its oldest occurrence in the lower Weser catchment indicates spread going back to the 1990s, with one report in the Elbe and three in the Rhine River, whereas the latest observation was indicated close to the lower Weser catchment in the period 2006–2010 (Fig. 5c). *Jaera istri* was identified predominantly in the Rhine River (aside from one report in the Elbe). Contrasting *D. polymorpha* and *C. curvispinum*, occurrences

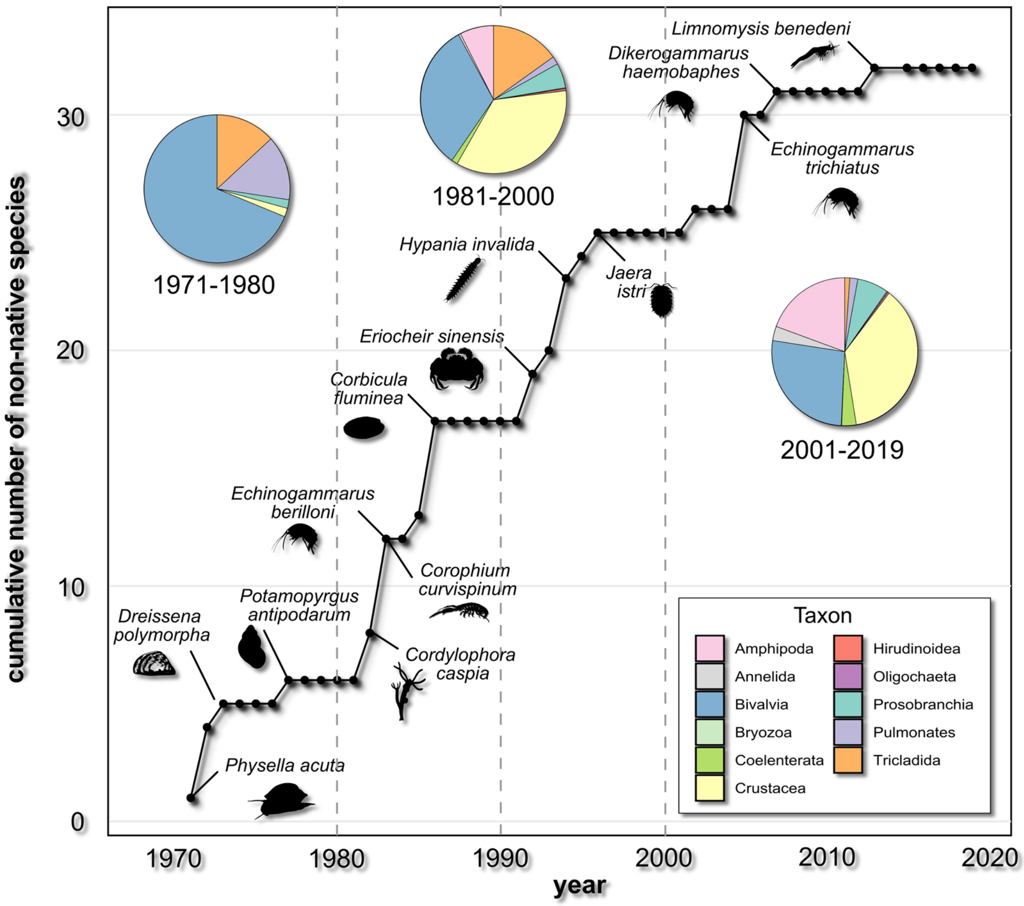

Fig. 4 Cumulative number of non-native species first reporting over time, indicating exemplary key species over time and the composition of non-native species classes over time

of *J. istri* indicated spread outgoing from the upper Rhine River in the period 1991–1995 downwards, with the latest report in the lower Rhine River as early as 2006–2010.

Discussion

This study, leveraging the database collated by Haase et al. [22], provides crucial insights into the efficacy of existing long-term monitoring sites from German rivers and streams for detecting non-native species [25, 39]. We found that while the long-term data successfully captured several introductions of non-native macroinvertebrate species dating back decades, the network of monitoring sites did not comprehensively cover Germany's extensive river network, particularly missing significant rivers such as the Danube. Moreover, the analysis indicated a strong correlation between research efforts and the detection of non-native species (thereby also the detection of native species), highlighting the critical role of continuous and expanded biomonitoring to detect non-native species introductions and understand invasion dynamics in Germany and subsequently manage biological invasions effectively.

We also identified opposing trends in the absolute (raw) and relative abundances of aquatic non-native macroinvertebrates since the 1970s. While the absolute number of non-native specimens increased over time, the relative abundance of these species decreased, suggesting that native specimens proliferated even more. This could be explained by higher productivity of aquatic ecosystems driven by increased temperatures and eutrophication [8], but could also indicate a possible resilience of native species or adaptive responses to changing environmental conditions [48, 50]. Raw and relative abundances are a critical metric for the assessment non-native species and their temporal dynamics (as discussed previously [26, 68], but can also highlight an increase in raw numbers of non-native species, thus reflecting a stable or even thriving native biodiversity [63]. Our findings therefore also indicate that ecosystems may have the capacity to support higher overall biomass and diversity, where native species are not necessarily outcompeted by non-native

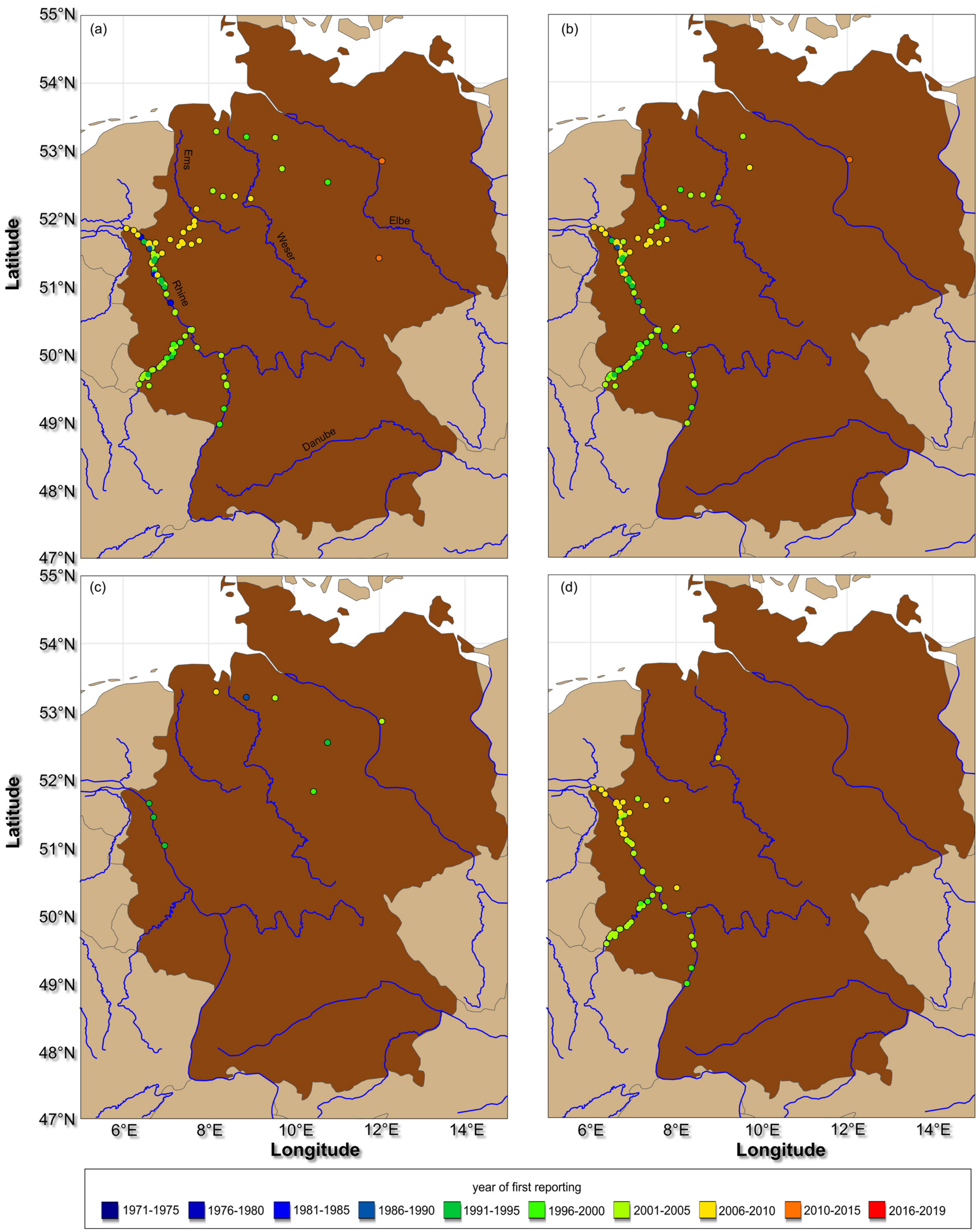

Fig. 5 Spatio-temporal occurrences of *Dreissena polymorpha* (**a**), *Corophium curvispinum* (**b**), *Eriocheir sinensis* (**c**), and *Jaera istri* (**d**) based on their respective occurrences in German long-term biodiversity monitoring data reported in Haase et al. [22]

ones but coexist, possibly due to niche differentiation or other ecological mechanisms [12]. Finally, the inverse nature of the trends in raw and relative abundance identified here also suggests that management strategies focusing solely on the presence of non-native species without considering the overall community structure and function may overlook important aspects of ecosystem health and resilience [7].

Trends in the raw abundance of non-native species differed from those in their richness, with the latter showing a bell-shaped distribution peaking around 2006. This peak could be attributed to the opening of the Rhine-Main-Danube Canal in 1992 [4], which facilitated an influx of non-native species from the Ponto-Caspian region, leading to a temporary surge in non-native species richness as new species were introduced and established. Additionally, other factors such as changes in monitoring intensity, improvements in detection methods, and shifts in regulatory policies might have contributed to this pattern. The subsequent decline in richness after the peak could, however, also indicate a saturation point where the ecosystems reached their carrying capacity for non-native species, thus leading to a 'boom-bust' sigmoidal dynamic [68], while it is unlikely that this bell-shaped distribution reflects successful management and mitigation efforts reducing the establishment of non-native species (see e.g. [2]). Our findings, however, also underscore the dynamic nature of biological invasions and highlight the importance of long-term time series in understanding and managing these events. The early detection and subsequent spread of *D. polymorpha* and *C. curvispinum* along the Rhine River demonstrate the rapid and extensive dispersal capabilities of certain non-native species once they establish in a new environment. The less frequent but notable occurrences of *E. sinensis* (being among the oldest captured in the data from [22]) and *J. istri* further emphasize the variability in invasion success and spread among different species. The historical monitoring data from Germany's freshwater ecosystems, therefore, do provide invaluable insights into the temporal and spatial patterns of these invasions, revealing critical periods and locations of introduction and expansion, despite being limited.

The dataset from Haase et al. [22] provides a comprehensive overview of the long-term macroinvertebrate data from 151 riverine long-term biodiversity monitoring sites, yet primarily focuses on the Rhine River catchment and, to a lesser extent, the Ems and Weser catchments. Notably, major river systems like the Elbe are under-represented or even absent as in the case of the Danube. This is a considerable shortcoming considering that monitoring data from e.g. the River Elbe revealed a poor ecological quality due to high pollution [59, 75, 76]. Ecological disturbances are of critical importance for biological invasions, as they increase the potential for non-native species introductions and their respective outgoing spread through these river systems [21]. However, despite data being scarce before the German reunification, this lack of data [64] could have been exacerbated by the strict criteria for data to be included in Haase et al. [22], e.g. a minimum of 8 sampling years within a period of 15 years. This criterium might have resulted in numerous sites not being included (i.e. from the Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research; eLTER; [46]) or others such as data obtained in the light of the Water Framework Directive-related monitoring activities [52].

The potential for non-native species to spread across the German river network is significantly heightened by the interconnected nature of these waterways, particularly with artificial links such as the Rhine-Main-Danube Canal opened in 1992, facilitating the spread of Ponto-Caspian species into European, and particularly German waters, a phenomenon termed "Ponto-Caspianization" [68]. This man-made canal especially serves as a direct link between several major basins, potentially accelerating the dispersal of non-native species across ecological barriers [4, 68]. The geographical concentration of monitoring sites in West Germany is due to several factors, including the responsibility of the *Bundesanstalt für Gewässerkunde* (BfG), which has focused on the Rhine for decades due to its location in Koblenz and the Rhine's status as the main navigable river in Germany due to its connection to the Rhine-Main-Danube canal. This suggests a regional bias that could lead to an underestimation of non-native species richness in the national context. This spatial bias implies that the reported increase in non-native species, from the initial detection of *Physella acuta* in 1971 to a total of 32 species by 2012, might not fully capture the scope of biological invasions across Germany's riverine ecosystems [53]. Indeed, the *Global Alien Species First Record Database* [62] lists 243 non-native macroinvertebrate species in Germany's freshwater ecosystems, indicating that long-term data (originating from purely riverine ecosystems) used in this work identified only 13.2% of this non-native group. Despite data from Haase et al. [22] encompassing only data from rivers and streams, this percentage is low, but could indeed reflect the lack of lentic ecosystems, regional differences, or sites not coinciding with invasion hotspots [14]. Moreover, the significant trends observed in the raw and relative abundance of non-native species, alongside the bell-shaped progression of reporting and monitoring efforts, indicate a dynamic interplay between human activity, monitoring intensity, and non-native species proliferation [10, 35, 44]. Therefore, while the study sheds light on important trends and patterns, it also emphasizes the need for more comprehensive monitoring efforts [37, 71] that include all major German river systems and account for anthropogenic influences like canal constructions, to better understand and manage the impacts of non-native species on Germany's biodiversity.

Higher research effort generally translates into higher species detection rates, suggesting that the intensity and scope of investigation directly influence the likelihood of identifying non-native species [36, 54]. Despite potential shortcomings in detecting non-native species with the currently employed long-term biomonitoring efforts [28], there exists a clear connection between the number of unique sites reporting non-native species and the total number of reported non-native species. The current distribution of long-term monitoring sites, which predominantly focuses on the western part of Germany, inherently skews the detection and reporting of non-native species towards this region, leaving the Eastern and Southern parts of the country under-monitored. It can, therefore, be assumed that the observed decline in total non-native species richness in recent years may not accurately reflect real trends but rather indicate a monitoring effort-linked lag time in the reporting of non-native species and the nature of our dataset, underscoring (a) the critical need for continuous and expanded surveillance to capture a more accurate picture of species introductions and dynamics over time (b) the value of increasing the number of monitoring sites in the future to monitor their population growth and spread.

Biosecurity and management efforts [1, 42] are needed to mitigate the threat posed by biological invasions, in particular in the face of staggering introduction rates [3, 65] and implemented regulations like EU Regulation No. 1143/2014 "on the prevention and management of the introduction and spread of invasive alien species" or of the EU Biodiversity Strategy for 2030, which contains the commitment to manage established invasive alien species. Highlighting the critical role of sustained research efforts in shedding light on the presence and spread of non-native species within aquatic ecosystems, the findings demonstrate that increased research activity, as evidenced by the number of unique sites and the volume of data collected over time, is fundamentally linked to the enhanced detection and understanding of non-native species richness. Such correlations highlight the importance of comprehensive and continuous biomonitoring programs to accurately assess and mitigate the impacts of non-native species on local biodiversity and ecosystem health [11, 32, 72]. Having identified spatio-temporal patterns in the occurrence of non-native species, this lack of spatially more coherent and comprehensive coverage across the entire German river network risks allowing non-native species to establish and spread largely undetected. Such a scenario not only hinders our understanding of invasion dynamics and ecosystem health across Germany, but also delays the implementation of effective management and mitigation strategies tailored to these underrepresented regions, potentially exacerbating the ecological and economic impacts of biological invasions, thus minimizing the effectiveness and reliability of deny-list approaches [17, 55]. Thus, only with a coherent network of sites monitored consistently over time, changes in biodiversity and drivers of its deterioration (including non-native species), can be adequately assessed. Considering the large research and development expenditure (reaching 112.6 billion € in 2021, 3.13% of the national GDP; www.destatis.de) and the high scientific productivity in Germany [57], it is likely that the observed spatial coverage of long-term sites, and thus the detection rate of non-native species, might be even lower in other countries, underlining the importance of the so-far collected data concomitant to the need to extend the existing long-term monitoring network.

Conclusion

The findings presented here underline the critical need for expanding and diversifying long-term biomonitoring efforts across Germany, especially at the intersections of major rivers and canals where the risk of non-native species introduction and spread is particularly high. Such an expansion is not only crucial for achieving a more comprehensive and representative understanding of the current state and trends of aquatic ecosystems, but also indispensable for the early detection of newly arriving non-native species. Moreover, long-term trend analysis, afforded by extensive monitoring efforts, holds invaluable potential for describing temporal trends in non-native species abundance and distribution, facilitating prompt and well-informed management strategies. Consequently, to safeguard biodiversity and maintain the ecological integrity of Germany's aquatic ecosystems, it is essential to invest in and commit to more geographically extensive and strategically placed long-term biomonitoring sites.

Supplementary Information

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Supplementary material 1.

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Authors contributions
P. J. H. conceived the idea. I. K and P. J. H. visualised the results. All authors contributed equally to the writing of the manuscript.

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Declarations

Ethics approval and consent to participate
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Consent for publication
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Competing interests
The authors have no conflict of interest (financial or non-financial) to declare.

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References

1. Abeysinghe N, Guerrero AM, Rhodes JR, McDonald-Madden E, O'Bryan CJ (2023) How success is evaluated in collaborative invasive species management: a systematic review. J Environ Manage 348:119272. https://doi.org/10.1016/j.jenvman.2023.119272
2. Adams MJ, Pearl CA (2007) Problems and opportunities managing invasive bullfrogs: is there any hope? Biological invaders in inland waters: Profiles, distribution, and threats. Springer, Netherlands, Dordrecht, pp 679–693
3. Ahmed DA, Hudgins EJ, Cuthbert RN, Kourantidou M, Diagne C, Haubrock PJ, Leung B, Liu C, Leroy B, Petrovskii S, Courchamp F (2022) Managing biological invasions: the cost of inaction. Biol Invasions 24(7):1927–1946. https://doi.org/10.1007/s10530-022-02902-9
4. Balzani P, Cuthbert RN, Briski E, Galil B, Castellanos-Galindo G, Kouba A, Kourantidou M, Leung B, Soto I, Haubrock PJ (2022) Knowledge needs in economic costs of invasive species facilitated by canalization. NeoBiota 78:207–223
5. Blackburn TM, Bellard C, Ricciardi A (2019) Alien versus native species as drivers of recent extinctions. Front Ecol Environ 17(4):203–207
6. Carboneras C, Genovesi P, Vilà M, Blackburn TM, Carrete M, Clavero M, D'hondt B, Orueta JF, Gallardo B, Geraldes P, González-Moreno P, Wynde R (2018) A prioritised list of invasive alien species to assist the effective implementation of EU legislation. J Appl Ecol 55(2):539–5471
7. Chambers JC, Allen CR, Cushman SA (2019) Operationalizing ecological resilience concepts for managing species and ecosystems at risk. Front Ecol Evol 7:241
8. Chattopadhyay C, Banerjee TC (2008) Water temperature and primary production in the euphotic zone of a tropical shallow freshwater lake. Asian J Exp Sci 22(1):103–108
9. Chirosca AM, Vazdoaga I, Popa VI, Rusu L (2021) The economic importance of navigation along the danube-black sea channel. Int Multidiscipl Sci GeoConference 21(31):297–305. https://doi.org/10.5593/sgem2021/3.1/s12.45
10. Christy MT, Yackel Adams AA, Rodda GH, Savidge JA, Tyrrell CL (2010) Modelling detection probabilities to evaluate management and control tools for an invasive species. J Appl Ecol 47(1):106–113. https://doi.org/10.1111/j.1365-2664.2009.01753.x
11. Colin N, Villéger S, Wilkes M, De Sostoa A, Maceda-Veiga A (2018) Functional diversity measures revealed impacts of non-native species and habitat degradation on species-poor freshwater fish assemblages. Sci Total Environ 625:861–871. https://doi.org/10.1016/j.scitotenv.2017.12.316
12. Córdova-Tapia F, Contreras M, Zambrano L (2015) Trophic niche overlap between native and non-native fishes. Hydrobiologia 746:291–301
13. Cuthbert RN, Diagne C, Haubrock PJ, Turbelin AJ, Courchamp F (2022) Are the "100 of the world's worst" invasive species also the costliest? Biol Invasions 24(7):1895–1904
14. Devin S, Bollache L, Noël PY, Beisel JN (2005) Patterns of biological invasions in French freshwater systems by non-indigenous macroinvertebrates. Hydrobiologia 551:137–146
15. Diagne C, Leroy B, Vaissière AC, Gozlan RE, Roiz D, Jarić I, Salles JM, Bradshaw CJ, Courchamp F (2021) High and rising economic costs of biological invasions worldwide. Nature 592(7855):571–576. https://doi.org/10.1038/s41586-021-03405-6
16. Dormann CF, Elith J, Bacher S, Buchmann C, Carl G, Carré G, Marquéz JR, Gruber B, Lafourcade B, Leitão PJ, Lautenbach S (2013) Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography 36(1):27–46
17. Essl F, Nehring S, Klingenstein F, Milasowszky N, Nowack C, Rabitsch W (2011) Review of risk assessment systems of IAS in Europe and introducing the German-Austrian Black List Information System (GABLIS). J Nat Conserv 19(6):339–350. https://doi.org/10.1016/j.jnc.2011.08.005
18. Everard M, Powell A (2002) Rivers as living systems. Aquat Conserv Mar Freshwat Ecosyst 12(4):329–337. https://doi.org/10.1002/aqc.533
19. Faulkner KT, Robertson MP, Rouget M, Wilson JR (2014) A simple, rapid methodology for developing invasive species watch lists. Biol Cons 179:25–32
20. Fox J, Weisberg S, Adler D, Bates D, Baud-Bovy G, Ellison S, Firth D, Friendly M, Gorjanc G, Graves S, Heiberger R (2012) Package 'car.' Vienna 16(332):333
21. Gozlan RE, Britton JR, Cowx I, Copp GH (2010) Current knowledge on non-native freshwater fish introductions. J Fish Biol 76(4):751–786. https://doi.org/10.1111/j.1095-8649.2010.02566.x
22. Haase P, Bowler DE, Baker NJ, Bonada N, Domisch S, Garcia Marquez JR, Heino J, Hering D, Jähnig SC, Schmidt-Kloiber A, Stubbington R, Welti EA (2023) The recovery of European freshwater biodiversity has come to a halt. Nature 620(7974):582–588
23. Haubrock PJ, Pilotto F, Innocenti G, Cianfanelli S, Haase P (2021) Two centuries for an almost complete community turnover from native to non-native species in a riverine ecosystem. Glob Change Biol 27(3):606–623. https://doi.org/10.1111/gcb.15442
24. Haubrock PJ, Cuthbert RN, Hudgins EJ, Crystal-Ornelas R, Kourantidou M, Moodley D, Liu C, Turbelin AJ, Leroy B, Courchamp F, Courchamp F (2022) Geographic and taxonomic trends of rising biological invasion costs. Sci Total Environ 817:152948. https://doi.org/10.1016/j.scitotenv.2022.152948
25. Haubrock PJ, Soto I (2023) Valuing the information hidden in true long-term data for invasion science. Biol Invasions 25(8):2385–2394. https://doi.org/10.1007/s10530-023-03091-7
26. Haubrock RN, Cuthbert P, Balzani E, Briski C-B et al (2023) Discrepancies between non-native and invasive species classifications. Biol Invasions 26:371–384. https://doi.org/10.1007/s10530-023-03184-3
27. Haubrock PJ, Soto I, Kourantidou M, Ahmed DA, SerhanTarkan A, Balzani P, Bego K, Kouba A, Aksu S, Briski E, Sylvester F, Cuthbert RN (2024) Understanding the complex dynamics of zebra mussel invasions over several decades in European rivers: drivers, impacts and predictions. Oikos. https://doi.org/10.1111/oik.10283
28. Haubrock PJ, Soto I, Kurtul I, Kouba A (2024) Are long-term biomonitoring efforts overlooking crayfish in European rivers? Environ Sci Eur 867:161537. https://doi.org/10.1016/j.scitotenv.2023.161537

29. Havel JE, Kovalenko KE, Thomaz SM, Amalfitano S, Kats LB (2015) Aquatic invasive species: challenges for the future. Hydrobiologia 750:147–170
30. Henry M, Leung B, Cuthbert RN, Bodey TW, Ahmed DA, Angulo E, Balzani P, Briski E, Courchamp F, Hulme PE, Kouba A, Haubrock PJ (2023) Unveiling the hidden economic toll of biological invasions in the European Union. Environ Sci Eur 35(1):43. https://doi.org/10.1186/s12302-023-00750-3
31. Hermoso V, Clavero M, Blanco-Garrido F, Prenda J (2011) Invasive species and habitat degradation in Iberian streams: an analysis of their role in freshwater fish diversity loss. Ecol Appl 21(1):175–188
32. Hermoso V, Clavero M (2013) Revisiting ecological integrity 30 years later: non-native species and the misdiagnosis of freshwater ecosystem health. Fish Fish 14(3):416–423. https://doi.org/10.1111/j.1467-2979.2012.00471.x
33. Hulme PE (2020) One biosecurity: a unified concept to integrate human, animal, plant, and environmental health. Emerg Top Life Sci 4(5):539–549. https://doi.org/10.1042/ETLS20200067
34. Hulme PE (2020) Plant invasions in New Zealand: global lessons in prevention, eradication and control. Biol Invasions 22(5):1539–1562
35. Koch FH, Yemshanov D, Haight RG, MacQuarrie CJ, Liu N, Venette R, Ryall K (2020) Optimal invasive species surveillance in the real world: practical advances from research. Emerg Top Life Sci 4(5):513–520. https://doi.org/10.1042/ETLS20200305
36. Koen EL, Newton EJ (2021) Outreach increases detections of an invasive species in a crowdsourced monitoring program. Biol Invasions 23(8):2611–2620. https://doi.org/10.1007/s10530-021-02526-3
37. Kühl HS, Bowler DE, Bösch L, Bruelheide H, Dauber J, Eichenberg D, Fernández N, Guerra CA, Henle K, Herbinger I, Bonn A (2020) Effective biodiversity monitoring needs a culture of integration. One Earth 3(4):462–474. https://doi.org/10.1016/j.oneear.2020.09.010
38. Kurtul I, Haubrock PJ (2024) The need of centralized coordination to counter biological invasions in the European Union. Environ Sci Eur 36(1):129
39. Le Hen G, Balzani P, Haase P, Kouba A, Liu C, Nagelkerke LA, Theissen N, Renault D, Soto I, Haubrock PJ (2023) Alien species and climate change drive shifts in a riverine fish community and trait compositions over 35 years. Sci Total Environ 867:161486
40. Leibenath M, Kurth M, Lintz G (2020) Science–policy interfaces related to biodiversity and nature conservation: the case of Natural Capital Germany—TEEB-DE. Sustainability 12(9):3701. https://doi.org/10.3390/su12093701
41. Leuven RS, van der Velde G, Baijens I, Snijders J, van der Zwart C, Lenders HR, bij de Vaate, A. (2009) The river Rhine: a global highway for dispersal of aquatic invasive species. Biol Invasions 11:1989–2008. https://doi.org/10.1007/s10530-009-9491-7
42. Lieurance D, Canavan S, Behringer DC, Kendig AE, Minteer CR, Reisinger LS, Romagosa CM, Flory SL, Lockwood JL, Anderson PJ, Baker SM, Wanamaker C (2023) Identifying invasive species threats, pathways, and impacts to improve biosecurity. Ecosphere 14(12):e4711. https://doi.org/10.1002/ecs2.4711
43. Magurran AE, Baillie SR, Buckland ST, Dick JM, Elston DA., Scott, E M, Smith RI, Somerfield PJ, Watt, AD (2010) Long-term datasets in biodiversity research and monitoring: assessing change in ecological communities through time. Trends Ecol Evol 25(10), 574–582. https://doi.org/10.1016/j.tree.2010.06.016
44. Martinez B, Reaser JK, Dehgan A, Zamft B, Baisch D, McCormick C, Giordano AJ, Aicher R, Selbe S (2020) Technology innovation: advancing capacities for the early detection of and rapid response to invasive species. Biologic Invas 22(1):75–100. https://doi.org/10.1007/s10530-019-02146-y
45. Mayer K, Heger T, Kühn I, Nehring S, Gaertner M (2023) Germany's first Action plan on the pathways of invasive alien species to prevent their unintentional introduction and spread. NeoBiota 89:209–227. https://doi.org/10.3897/neobiota.89.106323
46. Mirtl M (2018) eLTER, european long-term ecosystem and socio-ecological research infrastructure, h2020. Impact 8:30–32
47. Mirtl M, Borer ET, Djukic I, Forsius M, Haubold H, Hugo W, Jourdan J, Lindenmayer D, McDowell WH, Muraoka H, Orenstein DE, Haase P (2018) Genesis, goals and achievements of long-term ecological research at the global scale: a critical review of ILTER and future directions. Sci Total Environ 626:1439–1462. https://doi.org/10.1016/j.scitotenv.2017.12.001
48. Moore JW, Schindler DE (2022) Getting ahead of climate change for ecological adaptation and resilience. Science 376(6600):1421–1426
49. Moorhouse TP, Macdonald DW (2015) Are invasives worse in freshwater than terrestrial ecosystems? Wiley Interdiscip Rev Water 2(1):1–8
50. Mori AS, Furukawa T, Sasaki T (2013) Response diversity determines the resilience of ecosystems to environmental change. Biol Rev 88(2):349–364
51. Mostafa MM (2004) Forecasting the Suez Canal traffic: a neural network analysis. Marit Policy Manag 31(2):139–156. https://doi.org/10.1080/0308883032000174463
52. Müller F, Baessler C, Schubert H, Klotz S (2010) Long-term ecological research. Springer Berlin 10:978–990
53. Nehring S (2002) Biological Invasions into German Waters: An Evaluation of the Importance of Different Human Mediated Vectors for Nonindigenous Macrozoobenthic Species. In: Leppákoski E, Gollasch S, Olenin S (eds) Invasive Aquatic Species of Europe: distribution, Impacts and Management. Academic, Dordrecht, pp 373–383
54. Oswalt S, Oswalt C, Crall A, Rabaglia R, Schwartz MK, Kerns BK (2021) Inventory and monitoring of invasive species. In Invasive Species in Forests and Rangelands of the United States, 231. https://doi.org/10.1007/978-3-030-45367-1_10
55. Pergl J, Sádlo J, Petrusek A, Laštůvka Z, Musil J, Perglová I, Šanda R, Šefrová H, Šíma J, Vohralík V, Pyšek P (2016) Black, grey and watch lists of alien species in the Czech Republic based on environmental impacts and management strategy. NeoBiota 28:1–37. https://doi.org/10.3897/neobiota.28.4824
56. Poorter MD, Browne M (2005) The Global Invasive Species Database (GISD) and international information exchange: using global expertise to help in the fight against invasive alien species. Plant protection and plant health in Europe: introduction and spread of invasive species, held at Humboldt University, Berlin, Germany, 9–11 June 2005, 49–54.
57. Powell JJ, Dusdal J (2017) The European Center of science productivity: research universities and institutes in France, Germany, and the United Kingdom. In The century of science: The global triumph of the research university (pp. 55–83). Emerald Publishing Limited.
58. Pyšek P, Hulme PE, Simberloff D, Bacher S, Blackburn TM, Carlton JT, Dawson W, Essl F, Foxcroft LC, Genovesi P, Jeschke JM, Richardson DM (2020) Scientists' warning on invasive alien species. Biologic Rev 95(6):1511–1534. https://doi.org/10.1111/brv.12627
59. Randak T, Zlabek V, Pulkrabova J, Kolarova J, Kroupova H, Siroka Z, Velisek J, Svobodova Z, Hajslova J (2009) Effects of pollution on chub in the River Elbe, Czech Republic. Ecotoxicol Environ Safety 72(3):737–746
60. Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PT, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Cooke SJ (2019) Emerging threats and persistent conservation challenges for freshwater biodiversity. Biologic Rev 94(3):849–873
61. R Core Team. (2023). R: a language and environment for statistical computing. R foundation for statistical computing, Vienna, Austria. https://www.R-project.org/
62. Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P, Winter M, Arianoutsou M, Bacher S, Essl F (2017) No saturation in the accumulation of alien species worldwide. Nat Communicat 8(1):14435
63. Schlaepfer MA, Sax DF, Olden JD (2011) The potential conservation value of non-native species. Conserv Biol 25(3):428–437
64. Schulz C, Conrad A, Becker K, Kolossa-Gehring M, Seiwert M, Seifert B (2007) Twenty years of the German environmental survey (GerES): human biomonitoring–temporal and spatial (West Germany/East Germany) differences in population exposure. Int J Hyg Environ Health 210(3–4):271–297
65. Seebens H, Bacher S, Blackburn TM, Capinha C, Dawson W, Dullinger S, Genovesi P, Hulme PE, Van Kleunen M, Kühn I, Jeschke JM, Essl F (2021) Projecting the continental accumulation of alien species through to 2050. Global Change Bio 27(5):970–982. https://doi.org/10.1111/gcb.15333
66. Shackleton RT, Shackleton CM, Kull CA (2019) The role of invasive alien species in shaping local livelihoods and human well-being: a review. J Environ Manage 229:145–157. https://doi.org/10.1016/j.jenvman.2018.05.007
67. Simberloff D (2006) Risk assessments, blacklists, and white lists for introduced species: are predictions good enough to be useful? Agric Resour Econ Rev 35(1):1–10

68. Soto I, Cuthbert RN, Ricciardi A, Ahmed DA, Altermatt F, Schafer RB, Archambaud Suard G, Bonada N, Canedo Argüelles M, Csabai Z, Datry T, Dick JTA, Floury M, Forio MAE, Forcellini M, Fruget JF, Goethals P, Haase P, Hudgins EJ, Jones JI, Kouba A, Leitner P, Lizee MH, Maire A, Murphy JF, Ozolins D, Rasmussen JJ, Schmidt Kloiber A, Skuja A, Stubbington R, Lee GHVD, Vannevel R, varbiro G, Verdonschot RCM, Wiberg Larsen P, Haubrock PJ, Briski E (2023) The faunal Ponto-Caspianization of central and western European waterways. Biological Invasions 25(8):2613–2629. https://doi.org/10.1007/s10530-023-03060-0
69. Soto I, Balzani P, Carneiro L, Cuthbert RN, Macêdo R, Serhan Tarkan A, Ahmed DA, Bang A, Bacela-Spychalska A, Bailey SA, Baudry T, Ballesteros-Mejia L, Bortolus A, Briski E, Britton JR, Buric M, Camacho-Cervantes M, Cano-Barbacil C, Copilas-Ciocianu D, Coughlan NE , Courtois P, Csabai Z, Dalu T, Santis VD, Dickey JWE, Dimarco RD, Falk-Andersson J, Fernandez RD, Florencio M, Franco ACS, García-Berthou E, Giannetto D, Glavendekic MM, Grabowski M, Heringer G, Herrera I, Huang W, Kamelamela KL, Kirichenko NI, Kouba A, Kourantidou M, Kurtul I, Laufer G, Liptak B, Liu C, Lopez-Lopez E, Lozano V, Mammola S, Marchini A, Meshkova V, Milardi M, Musolin DL, Nunez MA, Oficialdegui FJ, Patoka J, Pattison Z, Pincheira-Donoso D, Piria M, Probert AF, Rasmussen JJ, Renault D, Ribeiro F, Rilov G, Robinson TB, Sanchez AE, Schwindt E, South J, Stoett P, Verreycken H, Vilizzi L, Wang YJ, Watari Y, Wehi PM, Weiperth A, Wiberg-Larsen A, Yapıcı S, Yogurtçuoglu B, Zenni RD, Galil BS, Dick JTA, Russell JC, Ricciardi A, Simberloff D, Bradshaw CJA, Haubrock PJ (2024) Taming the terminological tempest in invasion science. Biological Reviews.
70. Stehrer R, Stöllinger R (2015) The Central European Manufacturing Core: What is driving regional production sharing? (No. 2014/15–02). FIW-research reports.
71. Stephenson PJ, Stengel C (2020) An inventory of biodiversity data sources for conservation monitoring. PLoS ONE 15(12):e0242923. https://doi.org/10.1371/journal.pone.0242923
72. Takács P, Abonyi A, Bánó B, Erős T (2021) Effect of non-native species on taxonomic and functional diversity of fish communities in different river types. Biodivers Conserv 30(8):2511–2528. https://doi.org/10.1007/s10531-021-02207-6
73. Tam CK, Daniel WM, Campbell E, English JJ, Soileau SC (2021) US Geological Survey invasive species research—Improving detection, awareness, decision support, and control (No. 1485). US Geological Survey. USGS Publications Warehouse
74. Wang Y, Tan W, Li B, Wen L, Lei G (2021) Habitat alteration facilitates the dominance of invasive species through disrupting niche partitioning in floodplain wetlands. Diversity Distribut 27(9):1861–1871
75. Wetzel MA, Von Der Ohe PC, Manz W, Koop JH, Wahrendorf DS (2012) The ecological quality status of the Elbe estuary. A comparative approach on different benthic biotic indices applied to a highly modified estuary. Ecolog Indicat 19:118–129
76. Wilken RD, Wallschläger D (1996) The Elbe River: a special example for a European river contaminated heavily with mercury. Springer, Netherlands, pp 317–328
77. Wood SN (2001) mgcv: GAMs and generalized ridge regression for R. R news 1(2):20–25
78. Zong W, Toseef M (2023) Visual analysis of environmental research progress in Germany linking development anthropology: a sustainable approach based on the web of science. Front Psychol 13:1018183

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