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Journal of Environmental Management 370 (2024) 122474

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Review

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ARTICLE INFO

Keywords:
Shipping
Navigation infrastructures
Waterway
River management
Freshwater ecosystems
Biodiversity

ABSTRACT

Inland navigation is one of the most sustainable transport alternatives to help decarbonise the world economy. However, the likely impacts of intensifying inland navigation on freshwater ecosystems are difficult to predict. A global map of knowledge that considers both abiotic and biotic responses to increasing shipping traffic and developing infrastructures is lacking. Deriving general evidence-based assessments is challenging, because most studies on inland navigation impacts are merely descriptive and either consist of local case studies, or address single navigation stressors or specific taxa only. We conducted a systematic mapping of the published literature (1908–2021) to provide a global synthesis of the effects of inland navigation on the biotic and abiotic components of freshwater ecosystems. We show that only half of the reported navigation-related impacts were statistically tested. Navigation itself (vessel operation) had mainly negative effects on native taxa (57%), followed by waterway management (40%), and navigation infrastructures (35%). Navigation has direct negative impacts caused by physical disturbances such as vessel-induced waves, and indirect impacts that facilitate the spread of aquatic invasive species, and altering the abiotic habitat conditions. Thirty percent of the tested relationships showed non-significant impacts on the biotic environment, while in 10% of cases impacts were context-dependent. We identified the main gaps of knowledge, namely (i) impacts of waterway management on communities, (ii) underlying processes of navigation impacts on river ecosystems; and (iii) interactions between multiple navigation factors and cascading effects on multi-taxa responses. These future research directions should improve the diagnosis, mitigate the negative impacts of navigation on rivers and provide guidelines for improving navigated river management.

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https://doi.org/10.1016/j.jenvman.2024.122474
Received 8 April 2024; Received in revised form 21 June 2024; Accepted 8 September 2024
Available online 21 September 2024

1. Introduction

Inland freshwater navigation is promoted as one of the most sustainable transport alternatives in the world (Rohács and Simongáti, 2007; Terziev et al., 2023) and a way to achieve carbon neutrality by 2050 (Barros et al., 2022; INE, 2020; Sys et al., 2020). For instance, in Europe, the European Union Green Deal aims to intensify and promote "green shipping" by improving, restoring or creating new Inland Navigation Infrastructures (INIs) such as canals, sluices, dams, locks, and ports (INE, 2019, 2014). Yet, the extent to which intensified inland navigation will impact river integrity and aquatic biodiversity globally is not clear.

Inland navigation can potentially affect all aspects of river integrity as well as the surrounding landscape (Némethy et al., 2022). It has direct and indirect consequences on ecosystem components by triggering secondary mechanisms that affect ecosystems. Indeed, the five major threats for freshwater biodiversity (Dudgeon et al., 2006) can directly or indirectly be driven by inland navigation and the construction and management of inland navigation infrastructures (INIs) - namely, water pollution (Floehr et al., 2013; Maguire, 1991; Weijters et al., 2009), flow modification (Bunn and Arthington, 2002; Tales and Boët, 2005; Wolter et al., 2004; Yang et al., 2023), habitat degradation (Blanton and Marcus, 2013; Wolter, 2001), loss of river connectivity (Belletti et al., 2018; Jones et al., 2020; Poff et al., 2007), and introduction of invasive species (Leprieur et al., 2008; Leuven et al., 2009; Magliozzi et al., 2020). Vessel operation directly disturbs aquatic species, by wake wash (Gabel et al., 2017), draw down (Holland, 1986), return currents (Wolter et al., 2004), propeller wash (Killgore et al., 2011), boat collisions (Miranda and Killgore, 2013), water pollution such as plastics (Climo et al., 2022), hydrocarbons (Gao et al., 2024; González et al., 2024), or salts from ballast water (Duan et al., 2023a), and noise (Duan et al., 2023b; Graham and Cooke, 2008). In addition, infrastructures supporting navigation (e.g., canals, sluices, and boat ramps) as well as waterway management and maintenance (e.g., water level regulation or dredging activities) impact the environment (Cowx and Welcomme, 1998; Lepori et al., 2005; Simons et al., 2001; Staentzel et al., 2020) and facilitate the spread of invasive species (Rodríguez-Rey et al., 2021). For example, while groynes and rip-rap change habitat for aquatic species (Bischoff and Wolter, 2001; Fischer et al., 2018), dams, weirs and sluices will influence their mobility and dispersal (Duarte et al., 2021; Robinson et al., 2019).

On the other hand, INIs can also support selected species and communities, by providing artificial habitats (Harvolk et al., 2015; Horsák et al., 2009), dispersal corridors (Ouédraogo et al., 2020), and preventing the spread of some aquatic exotic species (Favaro and Moore, 2015; Rahel, 2013). Thus, the relative effects of these three main types of navigation-related pressures (namely navigation activity, related-infrastructures and their management), and how they influence both biotic and abiotic components of the river environment are still unclear (but see Wolter et al., 2004) and are difficult to disentangle. Therefore, these effects deserve more attention to better identify and prioritise mitigation actions.

Further intensifying inland navigation will require the creation of new INIs as well as the restoration and upgrading of existing ones (EIWTP, 2021). To minimize impacts on riverine biodiversity a better understanding is needed on how such infrastructures modify water flow, alter habitats, affect river connectivity, and shape species communities by invasions and extirpations. Until now, most studies that addressed navigation impacts focussed on selected INIs, single taxa, or particular components of river integrity (Villemey et al., 2018; Zajicek et al., 2018) which makes it difficult to draw conclusions.

To provide a comprehensive assessment of the global impact of navigation, we carried out a systematic mapping of the scientific literature to provide a global knowledge map of the effects of navigation-related factors on biotic and abiotic components in river ecosystems while considering the robustness of the analysed relationships. The systematic map of knowledge "collates, describes and catalogues available evidence on the topic" and allows addressing open-framed questions (James et al., 2016) such as here, the links between navigation factors and river components. Our specific aims were to: (i) assess and summarise direct and indirect effects of navigation and INIs on river integrity, while explicitly differentiating between evidenced (i.e., statistically tested) vs. asserted (i.e., with no statistical support) results; (ii) comparatively analyse effects of all three navigation-induced pressures – navigation, infrastructures, and waterway management – on abiotic and biotic components of river ecosystems including native and exotic taxa; (iii) identify main gaps in knowledge and propose future research fields to make mitigation actions more effective.

2. Material and methods

2.1. Literature search and articles selection

A systematic literature search was done on the September 16, 2021 in ISI Web of Science Core Collection and Scopus, which are considered the main reference sources (Mongeon and Paul-Hus, 2016). The literature search focused on articles published in English between 1900 (first selected paper in 1908 according to Scopus, and in 1983 according to WOS) and 2021. Following methodological recommendations for systematic mapping (e.g. Foo et al., 2021; James et al., 2016), the literature search was conducted using the PECO strategy for systematic search that is considered to be the most powerful and reproducible approach for formulating research questions (Miller and Forrest, 2001; Sordello et al., 2019). The PECO method (Population Exposure Comparator Outcomes) requires the formulation of the research equation including four main aspects: the ***P***opulation object of the study (here inland freshwater ecosystems), the ***E***xposure (here navigation), a ***C***omparator (here any comparator that can reflect a relationship), and the ***O***utcomes or focus of the effects (here biodiversity in the broad sense). The literature search was applied on titles and abstracts using the search equation shown in Fig. 1a (see also **Appendix S1**).

The initial literature search returned 15,058 published articles in Web of Science (5,696) and Scopus (9,362). To analyse and filter this corpus of articles, we then used the PRISMA approach (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; Page et al., 2021) (Fig. 1b). After removing duplicates, article titles and abstracts were manually screened and articles were included for further analysis if they met the following eligibility criteria: (1) peer-reviewed (journal articles, reviews and book chapters), (2) dealing with inland navigation, i.e. excluding marine and coastal ecosystems, and (3) having mentioned, discussed and/or analysed a relationship between any navigation factor (i.e. inland navigation, navigation-related infrastructures, or their management and maintenance) and any river biotic response (e.g., biodiversity, vegetation, fish) in the abstract. Articles that focused their analyses on the abiotic response of the river were kept as long as they highlighted the implications of their findings for the biotic response of the river. This first screening retained 506 articles. Then, a second screening was carried out excluding (1) articles that did not directly analyse the impacts of inland navigation rather than evaluate the effects of measures to mitigate or rehabilitate navigation effects were excluded from the analyses ($N = 39$ papers); and (2) articles dealing with recreational boating, because its impact on the river environment is not comparable to the impact of commercial navigation (Söhngen et al., 2008) and the topic has already been analysed at large scale by Zajicek and Wolter (2019) as well as synthesized by Schafft et al. (2021). All the manual screening was carried out by a team of 18 researchers, experts in freshwater ecology (NAVIDIV consortium). A final cross random screening procedure was carried out by two of the experts to check the inclusion consistency (i.e. each member was assigned two papers initially screened by another member and had to check the inclusion validity – in case of conflict, the member initially in charge of this paper had to verify again their list of papers and revise it following the inclusion rules of the group). The final number of articles included in the systematic review after full-text analysis was 243 (Fig. 1b).

2.2. Information extraction

2.2.1. Geographic and sampling context

The final 243 articles retained were full-text analysed for information synthesis. We recorded geographic origin and sampling context, including: (1) country and catchment, (2) type of hydrosystems (river, canal, lake, reservoir, floodplain, and pond as the most frequent options) and, its name, (3) spatial extent of the study, and geographic coordinates when available, (4) number of sampling observations, (5) length of river stretch that was sampled and/or analysed by the papers (based on maps and/or protocols provided within the original papers, when applicable), and (6) duration and frequency of sampling.

2.2.2. Navigation-related factors

We then identified the navigation-related pressures analysed and found 22 navigation-related factors. These were further classified into three main groups: navigation itself, navigation-related infrastructures and waterway management (Table 1). Navigation itself, hereafter navigation, refers to vessel operation and its direct physical consequences, such as wake wash, draw down, return currents, or noise generation. Navigation-related infrastructures, hereafter inland navigation infrastructures (INIs), refer to those pressures caused by the constructed infrastructures needed to enable or facilitate the navigation, such as locks, canals, channelised rivers, or ports. Finally, waterway management refers to those actions needed to maintain the adequate conditions for navigation such as dredging activities, regular vegetation cutting or water level management. Because some articles analysed combined navigation-related factors, such as the ensemble of shipping activity in canals, or of lock existence plus lock operations, a fourth category was created as the mix of multiple navigation-related factors (Table 1).

2.2.3. Biotic and abiotic responses

Biotic and abiotic responses analysed in the articles were identified. For biotic responses, we extracted information such as the taxonomic group (e.g., fish, macrophyte, or invertebrates); the level of organisation at which the analysis was carried out (e.g., individuals, populations, or communities); and the response metric analysed in the navigation-response relationship (e.g., mortality, abundance, or species richness;

Table 1
Classification of the 22 navigation-related factors into four main groups: navigation itself and its direct physical consequences (NAVI), navigation infrastructures (INI), waterway management and maintenance (MANAG), and the mix of multiple navigation-related factors (MULTI).

Group/navigation-related factor	Definition
Inland Navigation (NAVI)	
SHIP	Shipping activity as a general factor, presence of ships
TRAF	Traffic as a quantitative measure of navigation activity, number of ships per time unit
WAVE	Waves, propeller wash and drawdown due to boat passage (WAVE + PROP + DRAW)
STRIK	Strikes by boats or boat propellers
POLL	Chemical pollution
AC.POLL	Acoustic pollution
BALL	Ballast water and solid ballast (BALL + SOLID.BALL)
MULTI_NAVI	Mix of multiple navigation-related factors
Inland Navigation Infrastructures (INI)	
CAN	Canals - as new river connections
CHA	Channelised river - as modified river stretch to allow for navigation
MODIF	Large-scale river bed modification to allow for navigation, including both channelisation, floodplain modifications and infrastructure development
LOC	Locks and sluices (LOC + SLU)
DAM	Navigation dams, weirs and bridges (DAM + WEI + BRI)
EMB	Embankment
IMP	Impoundment
PORT	Ports
YARD	Shipyards
MULTI_INI	Mix of multiple INIs
Waterway Management and Maintenance (MANAG)	
DRE	Dredging for building or maintaining waterway navigability
LEV	Water level regulation
FLOW	Flow regulation
BWTS	Ballast water treatment
VEGCUT	Vegetation cutting
LOCOP	Lock operations for ship passage
MULTI_MANAG	Mix of multiple waterway management or maintenance factors
Multiple Navigation-related Factors (MULTI)	
MULTI	Mix of multiple navigation-related factors across NAVI, INI and MANAG (e.g. SHIP + CAN, LOC + LOCOP, etc.)

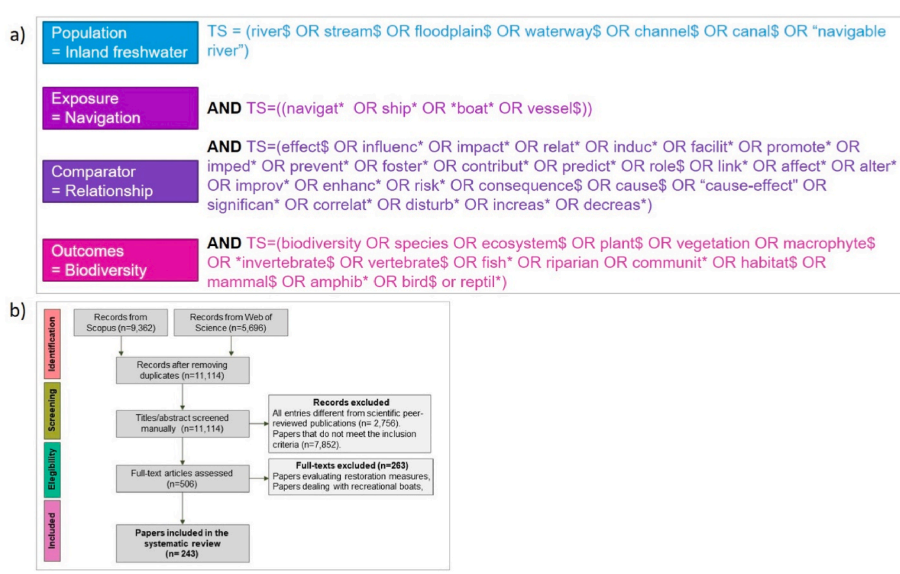

Fig. 1. Literature search and analysis. *a) Literature search equation used for Web Of Science following the PECO search strategy. Note that $ should be replaced by * when search is performed in SCOPUS database (see **Appendix S1**). b) PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram* (Page et al., 2021) *showing the procedure of article selection applied after the literature search.*

full table available here: https://doi.org/10.57745/N6Y6QR; Jeliazkov, 2024).

In particular, we carefully considered the status of the taxa analysed, namely either (1) natives, (2) exotics (including invasives), (3) both (for communities mixing both natives and exotics), and (4) unknown.

For abiotic responses, we noted the variables of interest (e.g., salinity, water temperature, conductivity) and their units. Given the high diversity of variables studied, we grouped them for synthesis into eight broad categories: 1) acoustic environment or noise, 2) flow conditions, 3) geomorphological conditions, 4) habitat characteristics, 5) soil characteristics, 6) water conditions, 7) bank characteristics, and 8) mixed (a mix of several responses) (Table 2).

2.2.4. Characteristics and testedness of the relationships analysed

Each individual relationship between a navigation-related factor and a river component analysed was listed along with the particular response metric analysed (fish species richness, vegetation composition, dissolved oxygen, etc.). In addition, evidence of impact was assessed based on statistical testing procedures reported in the paper. An effect was considered evidenced if it was statistically tested; otherwise, the purported effect was considered asserted (i.e., without statistical support). All statistically tested relationships were coded as “negative” (NEG), “positive” (POS), “non-significant” (NS), “change” (CHANGE) when the relationship significance or sign varied depending on a third factor, e.g. location, river, level of alteration, species considered, nonlinear behaviour, etc., or “unclear” (UNK) when the sign of the relationship was ambiguous, not reported or inappropriately interpreted (e.g., a discussion affirming an effect that is not supported by the raw figures). All asserted relationships were similarly coded as “negative” (NEG), “positive” (POS), “no effect” (NS) when authors explicitly discuss neutral effect/absence of effect, “change” (CHANGE) when authors explicitly mention that the relationship depends on other factors, or “unclear” (UNK) when the authors remain elusive about the effect discussed.

Each individual relationship was the statistical unit of observation in the present study, and the main focus of the following analyses.

Table 2
The eight categories of abiotic responses considered in the synthesis and examples of response variables included in these categories.

Category of abiotic response (label)	Examples of responses studied
Acoustic environment/noise (Acoustic)	Sound duration; sound frequency; mean number of sounds per day; spectral density
Flow conditions (Flow)	Wave energy; wave height; flow velocity; water level fluctuation; Indicators of Hydrologic Alteration; bed shear stress
Geomorphological conditions (Geomorpho)	Water depth; river width; geomorphological dynamics; river bed erosion; morphology; fluvial forms
Soil characteristics (Soil)	Organic matter content; sediment size; silt-clay fraction; contaminant concentrations; sedimentation rate
Water conditions (Water)	Water turbidity; water quality indices; pH; dissolved oxygen; temperature; conductivity; ionic concentrations
Bank characteristics (Bank)	Bank erosion rate, retreat, stability; riverine habitats; sand bar size (excluding in-water habitats and mainly taxon-unspecific environmental characteristics)
Habitat characteristics (Habitat)	Habitat availability; habitat structure; habitat suitability; environmental change; floodplain area; spawning area (including both riverine and in-water habitats and mainly taxon-specific environmental characteristics)
Mix of several responses (Mix)	Habitat and substrate; water and river bed conditions; soil, topographical, flooding dynamics, biotic and abiotic parameters (Note: Usually, these fuzzy responses are not tested but mainly discussed.)

Although some papers analysed and presented multiple relationships, 75% of the papers analysed less than five relationships (Fig. S1). All information was extracted and compiled into a single data table (see original data available in Jeliazkov, 2024).

2.3. Data analysis and synthesis

The final corpus of 243 articles included 89% empirical research articles (including 10% experimental articles), 8% review/synthesis/opinion articles, and 3% simulation/analytical modelling articles. These articles reported in total 1103 navigation-river ecosystem relationships, which constituted our dataset for assessing and synthesising the current knowledge on the effect of navigation-related factors on river ecosystems.

First, to assess the knowns and the unknowns about navigation effects on river ecosystem, i.e. the potential imbalance in actual evidences, we counted and graphically compared the proportions of relationships evidenced vs. asserted across the different types of navigation-related factors, response types (biotic vs. abiotic), biotic compartment (non-natives, natives, or both), and taxa (fish, invertebrates, etc.).

Second, to quantitatively synthesize the evidence of navigation-**biotic** relationships, we focused only on the statistically tested relationships ($N = 564$ relationships) for each biotic compartment (natives, exotics, and both) and calculated the proportion of relationships reported as negative, positive, non-significant, unknown, and changing across the four categories of navigation-related factors INI, NAVI, MANAG, and MULTI. All data analyses were performed in R (R4.3.0, R Core Team, 2023). To assess whether there is significant imbalance of effect signs across navigation factors, we statistically compared these proportions using Pearson’s goodness-of-fit Chi-squared tests for count data (function ‘chisq.test’ in package {stats}) with a threshold p-value of 0.05. We further tested the relative dominance of the effect signs (negative [NEG] vs. positive [POS] vs. changing [CHANGE] vs. non-significant [NS]) with separate Chi-squared tests on each combination of navigation factor by biotic response when the sample characteristics allowed it (i.e., expected counts for each factor combination≥5, which excluded all UNK effects). Given the limited sample size for the evidenced **abiotic** responses (77 evidenced relationships for 8 categories), we only explored the number and signs of the relationships graphically for each combination of navigation factors and abiotic responses.

Finally, to draw the map of knowledge, that is, the schematic representation of the hypothesised causal relationships between navigation factors and biotic components, we used the proportions of relationships calculated above and kept the two most supported ones for each factor-response couple to facilitate figure reading. For instance, 40%, 21%, 19%, 15%, and 5% of NAVI-Exotics relationships were reported as POS, NS, NEG, CHANGE, and UNK, respectively. Then we included the two most frequently observed links on the map, i.e. POS and NS.

It is worthy of note that first, we are creating a systematic map of knowledge and not a meta-analysis. To synthesize data that are mainly textual and/or categorical, and to more deeply review the broad topic of navigation effects on rivers, the principle of systematic mapping was the best compromise between a fully narrative, qualitative literature review, and a quantitative analysis fulfilling the strict constraints of a meta-analysis (Haddaway et al., 2016; Miake-Lye et al., 2016). Especially as we already know there are too few papers fulfilling these constraints on our topic (Ouédraogo et al., 2020; Villemey et al., 2018). The systematic map allows us to use our evidence collection to address an open-framed question (Haddaway et al., 2016; James et al., 2016) - namely the impacts of navigation on river ecosystems - and does not target effect sizes analysis. Therefore, our analyses are contingent on the categories (or ‘knowledge clusters’ (James et al., 2016)) that emerged from our evidence collection, such as the three main types of navigation factors, or the eight types of abiotic responses of the river environment. Second, we used a ‘vote counting’ approach (Koricheva and Gurevitch, 2013;

Siddaway et al., 2019), where we synthesized the counts of positive, negative, and non-significant navigation-environment relationships. This can be problematic when one does not account for potential differences across studies in statistical power nor reliability of the methods used to test these relationships (Haddaway et al., 2020). In our case, the differentiation we made between evidenced vs. asserted relationships allowed us at least to distinguish two levels of reliability among the examined studies. In addition, we did not detect many papers with noticeably low statistical power; the rare ones that aroused severe doubts were classified as "unknown/unclear" (UNK). Thus, the positive and negative counts – focus of the map – should not be severely biased by the 'vote counting' approach. The count of non-significant effects is interpreted with caution (see *Discussion*), that is not necessarily as an evidence of absence of effect, but rather as insights on the knowledge gaps and study limitations. Questioning further the validity of the studies would equate discrediting the peer-review process that these studies underwent, which seemed rather counter-productive given our objective of first attempt of comprehensive, qualitative knowledge mapping. Furthermore, the extensive metadata information provided in the synthesis table, such as sample size, methods of analysis and comments we made (see original data in Jeliazkov, 2024) will allow the readers to easily check the studies and make their own critical appraisal about those. Finally, another limit classically criticised in any literature syntheses (including meta-analyses) is the reporting bias, where non-significant results would be under-reported, resulting in biased conclusions about the importance of the effect studied (e.g., Kotiaho and Tomkins, 2002). Our approach of dissecting each study and extracting each individual relationship evidenced vs. asserted precisely allowed us to detect the many instances of non-significant results, and even the unexpected ones, which are reported in the figures but not necessarily put in the front by the authors. Therefore, we can be confident that our literature synthesis has managed to detect a substantial and representative part of the complexity and depth of the topic. Due to this relatively good representativeness, our focus on the academic evidences, and the difficulty to access and process non-academic evidences without any country/language bias, we did not add grey literature to our systematic map (Livoreil et al., 2017).

Data accessibility statement:

The data and code supporting the results have been archived on the public repository recherche.data.gouv and are available at: https://doi.org/10.57745/N6Y6QR.

3. Results

3.1. General overview of navigation-environment studies

Studies of navigation-environment interactions were published across the globe with highest numbers from North America, Europe, and China (Fig. 2). Still, we noted four inter-continental studies that covered mainly Europe and North America (Audzijonyte et al., 2008; Czerniejewski et al., 2012; Marescaux et al., 2016; Nagrodski et al., 2012).

The total river length studied varied from several metres to 100,000 km (Fig. 3a). The temporal extent in terms of monitoring years varies from "snapshots" (single observation in time) to more than 100 years with historical data (Fig. 3c). Most relationships involved a biotic response (85%), while 14% evaluated an abiotic response, and 1% a mixed response (Fig. 3d). The majority of navigation-biotic relationships concerned fish and invertebrates (Fig. 3e), mainly native species (Fig. 3f). A wide range of responses were used to assess the biotic responses to navigation, across all levels of biological organisation (from individuals to populations to communities to ecosystems), including DNA damage, organism's metabolism, behaviour, movement, abundance, area or percentage of cover, mortality, distribution, presence/absence, taxonomic and functional diversity and composition (alpha and beta diversities). The majority of the navigation-abiotic relationships were about water quality (32% of the relationships) and hydrological/flow conditions (21%) (Fig. S2).

The studied navigation-environment relationships, including both biotic and abiotic responses, investigated effects of navigation itself (47%), navigation infrastructures (35%), waterway management (10%), or a mixture of two (9%) (Fig. 3b). Three quarters of the navigation was represented by shipping activity, traffic, and waves; slightly more than half of the infrastructures were represented by canals, locks and dams; and more than half of the waterway management was represented by dredging, and flow regulation (Fig. S3).

3.2. Navigation effects on river ecosystems

Half (52%) of the 1103 navigation-environment relationships were statistically tested, the other 48% were asserted or only narratively discussed without any statistical test. We observed the highest proportions of tested relationships from studies that analyse the effects of navigation (Fig. S4a), and the responses of mixed communities pooling both exotics and natives (Fig. S4c). We observed the smallest proportions of tested relationships from studies that analyse the effects of

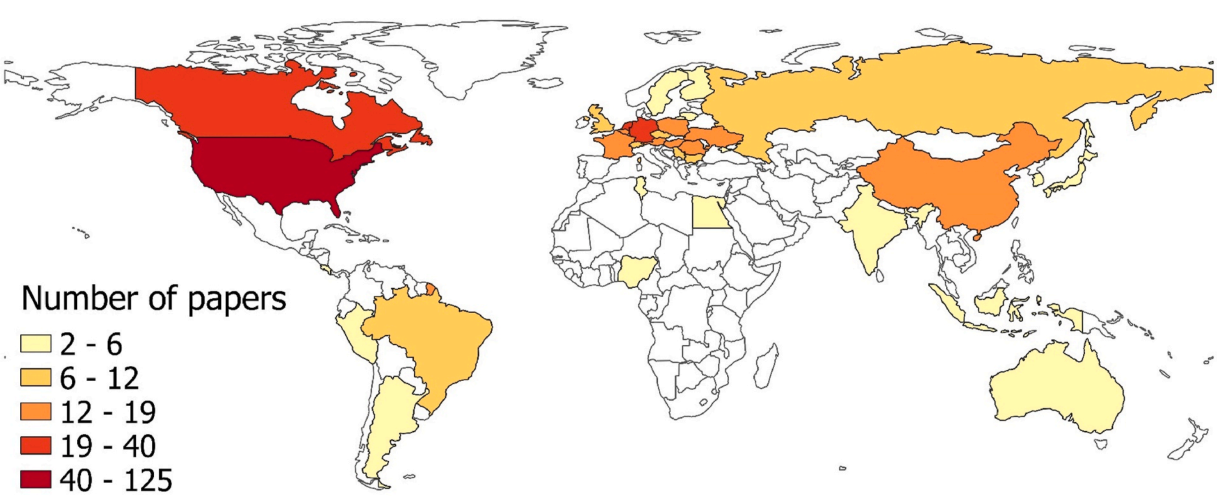

Fig. 2. Global distribution of navigation effects studies. Geographical map of the number of papers per country that study navigation effects on the river environment (country of the study area, not of the author's affiliation). Uncoloured countries are countries with no paper on navigation according to our literature search. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

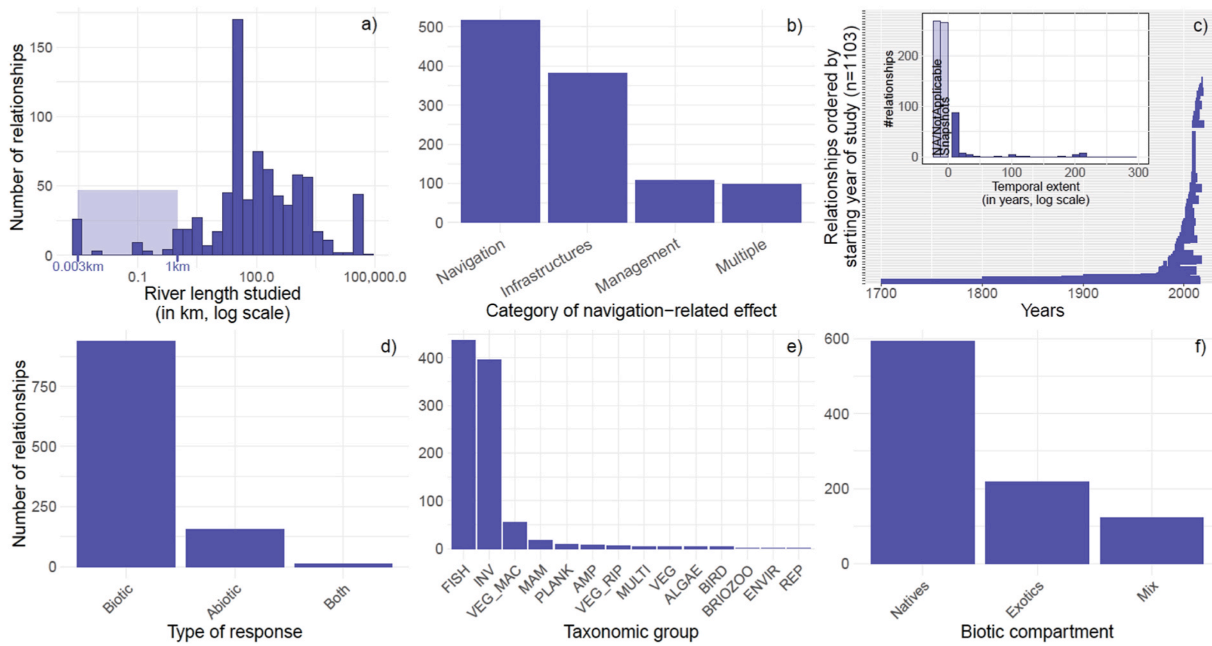

Fig. 3. Metadata of the navigation-river environment relationships studied. Distribution of the number of studied navigation-river environment relationships across: a) the river length studied (the blue transparent box represent the number of relationships that are local studies, i.e. single site studies of less than 1 km length); b) the four categories of navigation-related factors (navigation, infrastructures, waterway management, and multiple factors); c) the time span of the studies in years with starting and ending years of study (on Y-axis, relationships are represented by ticks, only every 10 are shown to facilitate visualization); the insert represents the distribution of the study durations; d) the type of river response (biotic, abiotic, and both); e) the taxonomic group (FISH = fish, INV = invertebrates, VEG_MAC = macrophytes, MAM = mammals, PLANK = plankton, AMP = amphibians, VEG_RIP = riparian vegetation, MULTI = multiple taxa, VEG = multiple vegetation strata, ALGAE = algae, BIRD = birds, BRIOZOO = bryozoans, ENVIR = general biotic environment, REP = reptiles), and f) the biotic compartment (natives, exotics or mix of both). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

infrastructures (Fig. S4a), the responses of exotic taxa (Fig. S4c), and the responses of macrophyte and riparian vegetation (Fig. S4d). We also noticed that integrative influences such as multiple navigation effects (Fig. S4a) and integrative responses such as multiple taxa (Fig. S4d) or whole ecosystems (represented by the mix of biotic and abiotic responses in Fig. S4b) are less statistically investigated than their individual components. Finally, most of the statistically tested navigation effects were evidenced negative or non-significant, while most of the asserted effects were considered negative or positive (Fig. S6).

3.2.1. Navigation effects on the biotic components of the river

Focussing on the tested effects of navigation on the biotic components, separate analyses were carried out for native, exotic and mixed compartments. In case of native taxa, most effects were negative, with highest proportions of negative relationships found for navigation itself (55%) and the combination of multiple pressures (52%) (Fig. 4a). In addition, positive relationships between native taxa and navigation-related factors were also found, in particular with infrastructures and waterway management.

For exotic taxa most navigation-related effects were positive, with

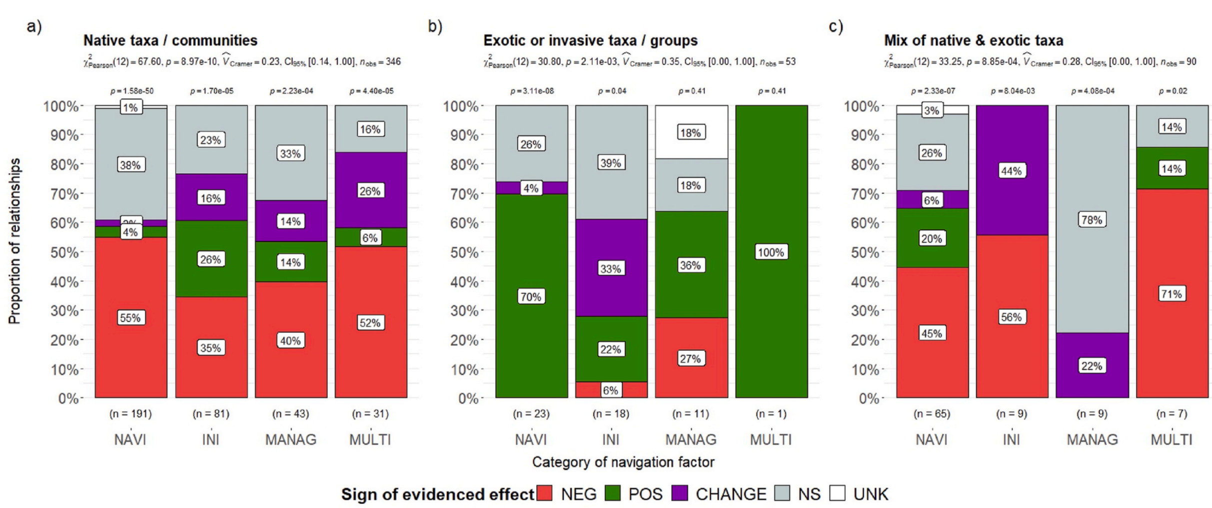

Fig. 4. Tested effects of navigation on biota. Chi-square analyses of the tested effects of navigation-related factors on the different biotic compartments of the river, namely a) native taxa/communities, b) exotic or invasive taxa/groups, and c) mix of both native and exotic taxa. For the association degree and significance between relationship sign and navigation factor, see Fig. S7.

the highest interpretable proportion of positive relationships from navigation itself (70%) (Fig. 4b). Effects from infrastructures and waterway management were harder to discern. Infrastructures effects were mostly non-significant or contingent on other factors. Waterway management effects were statistically balanced between negative, positive, non-significant and unknown (Fig. 4b).

Finally, regarding the navigation-related effects on the mix of both native and exotic taxa, most of the effects were negative, except from waterway management where relationships were either non-significant or contingent on other factors (Fig. 4c).

Overall, we observed the highest amount of unknown effects between the waterway management and the exotic taxa (Fig. 4b); the highest amount of non-significant effects between the waterway management and the mix of native and exotic taxa (Fig. 4c); and the highest amount of contingent/changing effects between the infrastructures and the mix of native and exotic taxa (Fig. 4c).

3.2.2. Navigation effects on the abiotic components of the river

Given the small amount of statistically tested relationships between navigation factors and abiotic components (only 77 out of the 160 when including combined responses such as “habitat”, “environment”, “nature”, etc.) and the diversity of abiotic responses studied (8 categories; Table 2), we only could explore the results graphically. In general, more categories of abiotic responses were asserted rather than actually tested, with acoustic environment, water quality and hydrological conditions being most often statistically tested (Fig. 5). Negative effects of navigation were reported on almost all responses, and contrasting effects (both positive and negative) for the response of water quality and hydrological conditions to infrastructures (Fig. 5).

3.2.3. Map of knowledge

Based on the synthesis of statistically tested relationships and selecting only the significant associations obtained from individual Chi-squared tests of navigation-biota relationships (Table S8), we created a map of knowledge that draws and compares causal links supported by the scientific literature. These causal links relate the four types of navigation pressure Navigation, Infrastructures, Management and Multiple with the native, exotic and abiotic ecosystem components (Fig. 6). Navigation has the strongest positive relationship with the exotic taxa that are mainly represented by invertebrates. Both navigation, management and combination of multiple navigation pressures have the strongest negative relationship with the native taxa that are mainly represented by invertebrates and fish. The prevalent signs of the other relationships are less distinct according to our analyses (Fig. 6; Table S8).

4. Discussion

Inland navigation has a long and rich history, from the Lingqu Canal (China), one of the oldest canals of the world (2300 years ago, Qian, 2023), to nowadays. Here, our synthesis had to start at the 18th century, following two centuries of major development of canal construction to connect interior countries to sea, or sea to sea (e.g. in Europe, Ketelaars, 2004; Rijkswaterstaat, 2011). Water transport has prospered through the 18th-19th centuries, as being the cheapest mode of transport for people, materials and goods. It then temporarily declined due to the advent of the railway freight and was finally revived in the 20th century (Crompton, 2004). The replacement of steam ships with first motorised vessels and push barges, the invention of radars, the popularization of containers and bow thrusters, all contributed to the improvement and expansion of inland navigation over the last decades (Crompton, 2004; Rijkswaterstaat, 2011). This has led to the change of vessel fleets towards larger (lowest cost per freight) and more powerful ships (better manoeuvrability and safety of operation). As a result, and in parallel of navigation development, the regulation and legislation of inland navigation on rivers had to evolve from localized, rudimentary controls to sophisticated, internationally coordinated frameworks. Several commissions have born with the role of setting the rules for inland navigation regulation and ensuring its durability in a context of international cooperation, e.g. the CCNR (Central Commission for the Navigation of the Rhine, created in 1815), the European waterway network, and the International Joint Commission (between Canada and the USA). This evolution reflects broader societal changes, technological advancements, and a growing recognition of the need for sustainable and environmentally responsible navigation practices (Wiegmans and Konings, 2016). Indeed, navigation development came with adverse effects from the ecological point of view, including physical impacts of vessel operation, and the need to enlarge, deepen and reinforce bank protections of the fairways (Söhngen et al., 2008). To guide further activities and development of inland navigation, our synthesis provides a knowledge-based assessment of the impacts that inland navigation has exerted on river ecosystems globally over the last decades and proposes

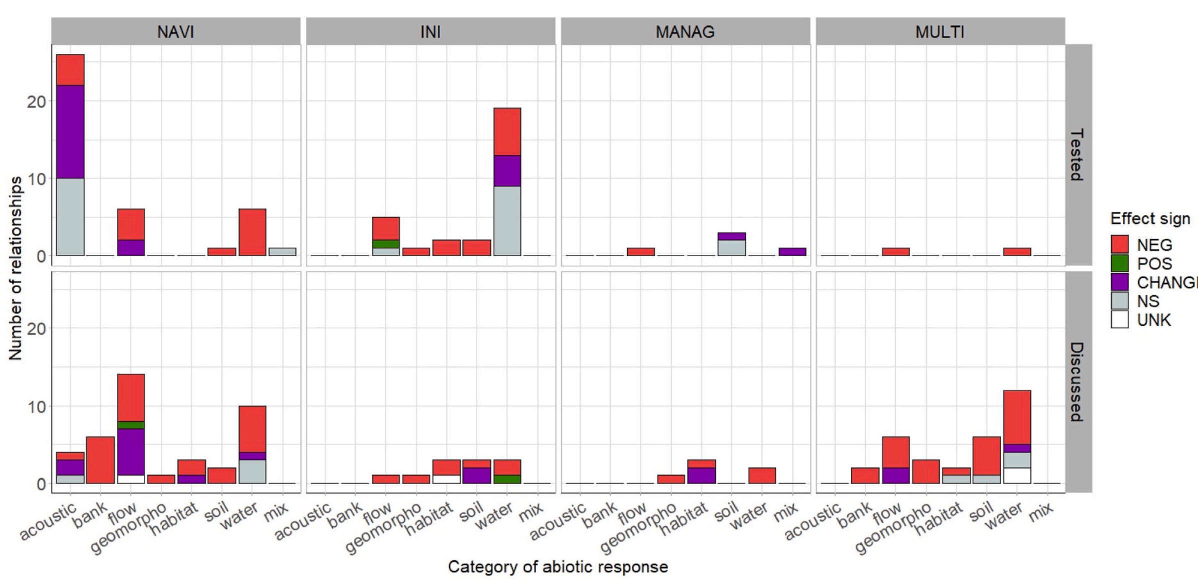

Fig. 5. Abiotic effects of navigation. Distribution of tested (evidenced) vs. narratively discussed (asserted) effects of navigation factors on the abiotic responses of river environment.

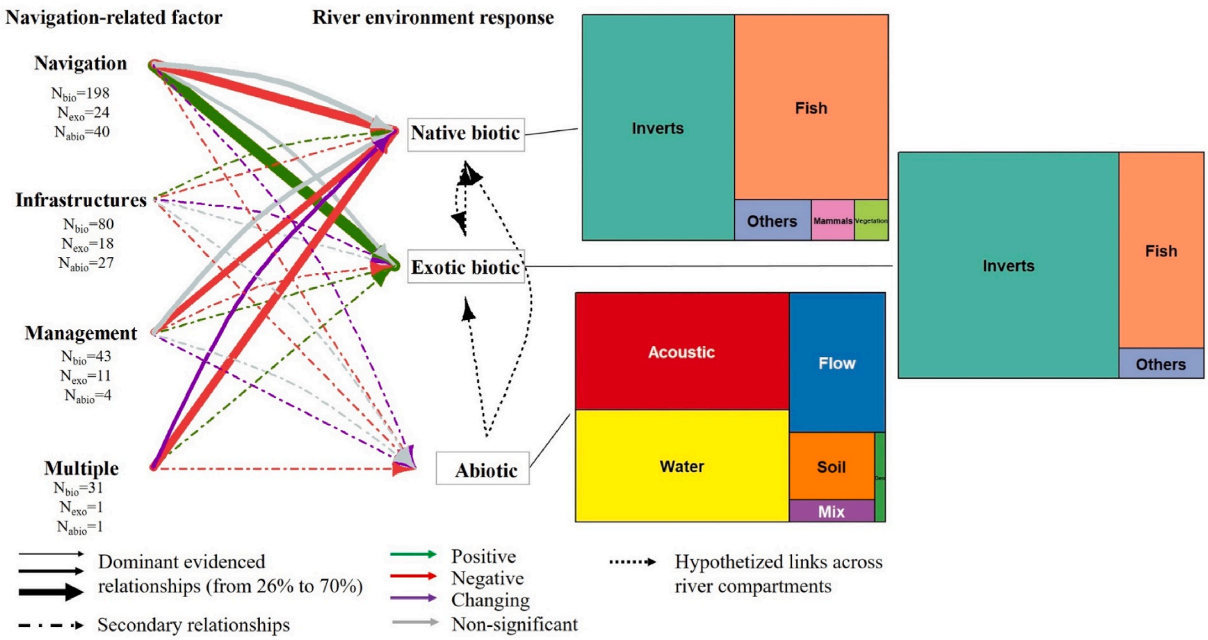

Fig. 6. Map of knowledge of navigation effects on river ecosystem. Evidence-based causal map of knowledge of navigation-related factors effects on river environment. Left panel: The dominant relationships (i.e. the ones showing significant imbalance from proportion analyses) are represented with plain arrows. The secondary relationships (i.e. the ones showing no significant imbalance from proportions analyses for the biotic component, and not testable for the abiotic component) are represented with dot-dashed arrows. Thickness of the arrows is proportional to the percentages revealed by the proportion analysis and colour of the arrows indicate the sign of the relationship. Right panel: treemaps showing the relative representativeness of the main taxa and the types of abiotic responses into the map of knowledge. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

future research directions for sustainable inland navigation.

4.1. Effects of navigation-related factors on the river environment

Our literature synthesis shows that, on average, half of the evidenced relationships between commercial inland navigation-related factors and riverine biota were negative for native taxa and positive for exotic taxa and highlights the generalisation of these impacts at the global scale. This assessment confirms impacts of navigation stressors on native biota reported by many empirical, local-scale studies from all over the globe (e.g., Dey et al., 2019; Huckstorf et al., 2011; Killgore et al., 2011; Leclere et al., 2012; Luttenton et al., 1986; Luttenton and Rada, 1986; Moog et al., 2018; Peng et al., 2020; Rivero et al., 2013) or by continental-scale studies mainly from Europe (e.g., Leitner et al., 2021; Zajicek and Wolter, 2019). The general assessment of positive effects of navigation-related stressors on exotic biota results from the synthesis of previous studies reporting significant effects of shipping intensity, ballast water and inland navigation infrastructures on the spread or diversity of exotic and regularly becoming invasive species, such as Ponto-Caspian gobies in Germany (Tavares et al., 2020), zebra and quagga mussels (Allen and Ramcharan, 2001; Rodríguez-Rey et al., 2021), Silver carp (Fritts et al., 2021) and fishhook waterflea (Maxson et al., 2023) in the USA, and several exotic invertebrate species all over Europe (Bij de Vaate et al., 2002; Leitner et al., 2021; Leuven et al., 2009).

In particular, our study supports that navigation impacts native river biodiversity directly and indirectly. Direct impacts include shipping disturbance (e.g., otter, Gomez et al., 2014), propeller wash/wake wash/waves produced by boat passage leading to fish drift and stranding (Gabel et al., 2011; Kucera-Hirzinger et al., 2009; Schludermann et al., 2014), invertebrate dislodgment from preferred habitats (Gabel et al., 2008, 2012), injuries resulting from boat collisions including dolphins (Bechdel et al., 2009), sturgeons (Hondorp et al., 2017), and other fish species (Killgore et al., 2001). Navigation activities further impact native biodiversity indirectly. It does so first through facilitating the spread of invasive species via the transport of macrophytes, fish and invertebrates propagules by boats themselves (Jacobs and Keller, 2017) or by their ballast water (Adebayo et al., 2014 for invertebrates; Tavares et al., 2020 for fish) that might in turn affect native species (Gallardo et al., 2016; Gaye-Siessegger et al., 2022). Second, navigation activities lead to the changes in the abiotic conditions of the river, such as the alteration of acoustic environment (Putland et al., 2021; Rountree et al., 2020) potentially affecting mammals (Dey et al., 2019; Duan et al., 2023b) and fish (Graham and Cooke, 2008; Wysocki et al., 2006), the decrease of water quality (Henry Ogbuagu et al., 2013; Wehr et al., 1997) potentially affecting benthic invertebrates (Arbačiauskas et al., 2008; Xu et al., 2014), and disturbance of hydrological conditions potentially affecting all groups (Habersack et al., 2016). However, only 37 out of the 243 studies actually analysed both the abiotic and biotic responses of the river ecosystem to navigation stressors. Among those, even fewer explicitly analysed the links between the two components in a context of navigation pressures, although they are expected to influence many groups (Niimi, 1982). In particular, vessel traffic and waves influence water turbidity, hydrological conditions, and habitat suitability that in turn affect fish diversity (Gutreuter et al., 2006; Hanafiah et al., 2013; Kano et al., 2013; Koel and Stevenson, 2002), and invertebrates' attachment to their substrate (Fleit et al., 2016). Similarly, vessel traffic results in short-term flow velocity changes and draw down, bed shear stress, bank erosion, sediment alteration and water quality alteration that in turn affect both macrophyte and riparian vegetation (Ali et al., 1999; Karle et al., 2005; Racine et al., 1998; Thunnissen et al., 2019). However, the rarity of comprehensive studies plus limitations of study designs (e.g., difficulty to cross multiple effects *in situ*) challenge drawing general causal conclusions on underlying processes of direct and indirect effects of navigation on biodiversity (see next section *Gaps of knowledge & future research avenues*).

Although navigation itself was the main factor influencing both native and exotic taxa, we showed that inland navigation infrastructures certainly indirectly add to this impact. In particular, navigation dams negatively influence fish, invertebrates and phytoplankton communities and populations via habitat modification and connectivity loss (Arai et al., 2019; Argent et al., 2016; Brewer et al., 1995; Wehr and Thorp, 1997; Yi et al., 2010), and channelization and embankment negatively influence riparian vegetation and fish diversity mainly due to habitat loss (Harvolk et al., 2015; Kano et al., 2013; Valová et al., 2014). Most of the effects of inland navigation infrastructures on river biota are potentially mediated by their primary effects on different abiotic aspects of the river environment, such as water quality (Wehr et al., 1997), flow conditions (Mirza, 1997; Rivero et al., 2013), and geomorphological and sediment characteristics (Brewer et al., 1995). However, considering both direct and indirect effects, infrastructures and waterway management may not be more impactful than navigation alone. This is also supported by studies reporting successful mitigation of navigation-induced impacts, such as by regulating boat traffic (Bradbury et al., 1995; Grant; Lewis, 2010; Rüdel et al., 2007) and ballast water (Ricciardi and MacIsaac, 2022), or by restoring more natural flow conditions (Collas et al., 2018; Schorg and Romano, 2018; Theiling et al., 1996). However, it must be noted that most INIs were constructed, and impacted riverine communities decades before the first studies of navigation-induced environmental impacts. One example being the documented historical extinction of diadromous fish as a result of earlier dam construction (e.g., Le Pichon et al., 2020; Merg et al., 2020). The rarity of evidence-based studies at this time scale probably resulted in an underestimation of the impacts of INIs on aquatic biota in the present synthesis.

More surprisingly, INIs and waterway management sometimes showed positive effects on native taxa (26% and 14% of the tested relationships, respectively). This could be observed for instance when studies analysed the abundance of generalist or highly-tolerant native species, or the diversity of communities that shifted from small, highly-specialised communities to bigger, more generalist communities, reflecting an overall homogenisation of the river ecosystem (Angradi et al., 2009). In addition, INIs such as groynes or dams could tend to favour some invertebrate and phytoplankton taxa through the creation of impounded habitats (Buczyński et al., 2017; Wehr and Thorp, 1997) and waterway management such as specific lock operations could favour fish passage (Fritts et al., 2021; Turney et al., 2022).

Notwithstanding, 30% of the statistically tested relationships between navigation stressors and river ecosystems were not statistically significant. This may be due to lack of power of some of the studies on the topic (e.g., difficulty in obtaining high enough sample sizes, or in defining proper baselines (Moog et al., 2018; Xiong et al., 2021). However, in fact, it is more likely that this number comes from rather well-designed studies that test multiple relationships among which only some turned out significant (see large-scale studies with numerous spatio-temporal replicates such as (Leitner et al., 2021; Rountree et al., 2020; Zajicek et al., 2018); for more information, see the synthesis table in Jeliazkov, 2024). Detecting effects of navigation-related pressures also seems more difficult in naturally highly variable environments (e.g., in a delta, Liashenko et al., 2022) or under the influences of complex hydrological connectivity (e.g., river-lake connectivity, Xiong et al., 2023). This leaves open the question of navigation impacts, especially for the quantitative effects of shipping intensity (Leitner et al., 2021; Xiong et al., 2021, 2023) but see (Sexton et al., 2024), shear stress (Gabel et al., 2012), lock operations (Fritts et al., 2021), and embankments (Brabender et al., 2016) on a number of fish and invertebrates species or communities.

Finally, around 10% of the relationships depended on one or more covariates, i.e., where the sign of the effect depended on the effect of a third variable. This figure is likely underestimated given that in the present synthesis, we consider each relationship separately while the articles analysing several relationships are likely to find different responses for each depending on a third factor, such as the type of response analysed, the study design used, etc. We here highlight the context-dependent nature of some navigation effects on biodiversity, particularly in relation to river (Harnish et al., 2012), mesohabitat of the river (Rountree et al., 2020; Scharf and Brunke, 2013), taxa or functional groups (Munawar et al., 1991; Zajicek and Wolter, 2019), season (Zadnik et al., 2009), or river uses and climate change (Templeton et al., 2024). We further noticed that this context-dependency might play a stronger role in the study of INIs effects on exotic taxa (33%), and of the combination of multiple stressors on native taxa (26%). Therefore, we advocate that context-dependency likely shapes the impacts of inland navigation on river integrity and deserves further attention (Sexton et al., 2024).

Our literature synthesis approach provides a comprehensive literature review on the topic of navigation effects on river ecosystems (243 papers), a certain accuracy in the information extracted, a substantial amount of data collected (1103 navigation-environment relationships), a relatively fine degree of interpretation and generalisation (see the Results), a good degree of repeatability (data and R codes available at https://doi.org/10.57745/N6Y6QR) and has been successfully used in other synthesis works in freshwater ecology (Jackson et al., 2016; Lange et al., 2018). While it does not have the strength of a strict meta-analysis (neither its weaknesses, Kotiaho and Tomkins, 2002) and is limited by the 'vote counting' perspective (Koricheva and Gurevitch, 2013; Siddaway et al., 2019), our approach was appropriate and more performant than a traditional narrative review to achieve our objectives, that were to summarise and reinterpret the knowledge on the topic, and to identify potential gaps in this knowledge.

4.2. Gaps of knowledge and future research avenues

When considering the total number of relationships studied between navigation-related factors and river components, we showed that waterway management - e.g., ballast water treatment and vegetation cutting - is the least studied effect of navigation (but see Ricciardi and MacIsaac, 2022). The lack of evidence on waterway management effects is a result of the fine classification we proposed between different drivers of navigation impacts. This driver is less investigated than the others, maybe because this requires an elaborative monitoring design such as before-after intervention (e.g., dredging, cutting, McCabe et al., 1998; Moog et al., 2018), developing holistic frameworks to account for other stressors (Suedel et al., 2024), and interviewing navigators or operators on their practices (e.g., ballast water treatment, Locke et al., 1993), which can be more complicated, long and costly than measuring navigation intensity or infrastructure density, for instance.

Thanks to the separation of asserted vs. evidenced effects of navigation, and to the report of unknown effects from tested relationships, we have been able to further characterise the gaps of knowledge in the topic of navigation-environment relationships. For instance, we have three times less evidence (in both absolute and relative terms) on exotic taxa responses to navigation factors than on native taxa, despite the widely advertised influence of the former on the latter (Byers, 2002; Havel et al., 2015; Leppäkoski et al., 2013). To better understand the effect of navigation on native communities and isolate the indirect effect precisely due to the navigation-induced spread of invasive taxa, it would be worthwhile to systematically analyse both parts of the communities' responses and check the links between those responses instead of pooling those. This could be done for example by analysing species association matrices from joint species distribution modelling (Ovaskainen et al., 2019; Pollock et al., 2014; Zurell et al., 2020). In addition, although infrastructure effects are relatively well studied, they are almost twice less strictly tested. This may be due to the high number of studies that describe local biotic responses (e.g., number of fish passage) around one particular infrastructure (e.g., one weir or one lock system), which allows addressing the question descriptively but not statistically. Many studies lack control and historical baseline information, especially in multiple-pressure contexts (e.g., Christie et al., 2019). Such underpowered assessments result in a certain difficulty to clarify the role of navigation infrastructures in river ecosystems, which is reflected in our synthesis where positive and negative effects come out as balanced.

Although our search equation was mainly centred on the response of the biotic component of the river environment to navigation factors, we detected a certain amount of evidence about the effects on the abiotic component, as long as these were addressed in relation with any biotic response. However, this amount remained quite low (15%). This suggests that among studies addressing the effects of navigation on biodiversity, relatively few of them actually investigate the potential processes underlying these effects, including the modification of the abiotic conditions that allow species to persist (but see Fischer and Claflin, 1995; Flinn et al., 2008; Kano et al., 2013; Peng et al., 2020; Wolter et al., 2004). Although many studies analyse the links between biotic and abiotic conditions in the context of navigated rivers (47 papers), the main driver as traffic intensity, dam or channelisation is often assumed and not systematically measured neither actually linked with the abiotic response (e.g., Ali et al., 1999; Best et al., 2001; Freund and Hartman, 2005). A couple of recent works make the exception that strive to apprehend this causality chain from navigation pressure to abiotic response to biotic response. They deduce these chains empirically, such as the effect of waterway construction and ship traffic on water quality that in turn affects benthic invertebrates (Dou et al., 2022), the effect of ballast water on water salinity that in turn affects freshwater phytoplankton (Duan et al., 2023a), or the effects of boat traffic on acoustic pollution that in turn affects porpoise survival (Duan et al., 2023b). The low amount of investigation of the abiotic component in relation with the biotic response to navigation may also be due to a historical legacy effect where the abiotic components drastically changed immediately after river regulation (Mossa and Chen, 2022) and thus, already formed baseline conditions for later navigation impact studies ("shifting baselines"; Humphries and Winemiller, 2009; Soga and Gaston, 2018). We thus need further investigation and evidence-based assessment to understand direct and indirect effects of navigation on the river environment, including the role of historical river modifications. Here, we explore hypothetical causal relationships, which opens new questions of research and methodological challenges such as: how to assess directness of the navigation effect; how to disentangle biotic and abiotic processes involved in river environment response to navigation pressures; and how to design sampling schemes to address these questions.

We generally lack knowledge about the influence of combined navigation pressures as well as the mix of responses (abiotic and biotic, exotics with native, and mixed taxa) and more than 75% of the current knowledge relies only on fish and invertebrates. This suggests a need for more integrative studies where interaction effects of multiple navigation factors could be analysed on biotic responses that may be representative of the whole river ecosystem, e.g., metacommunities with several trophic levels (e.g., Borthagaray et al., 2015). The potential feedback loops between, for instance, the navigation and riparian vegetation that in turn may affect aquatic communities through habitat changes or trophic interactions modifications are not studied (Hohensinner et al., 2018). We need to scale up to metacommunities and metaecosystems (Cid et al., 2021; Gounand et al., 2018; Heino, 2013; Schiesari et al., 2019) in order to better account for the spatialized and functional effects of navigation on river biodiversity and ecosystems. Such studies allow important progress, such as showing, for instance, that more natural waterway management practices can enhance trophic functioning of freshwater communities (Brauns et al., 2022). We need these more integrative studies, also because the river functions as a continuum with lateral and longitudinal connectivities (Boulton et al., 2017; Manfrin et al., 2020; Ward, 1989). Very few studies address the effects of navigation on river connectivities, except local specific ones tagging fishes and monitoring their movement and behaviour around and through a given sluice-lock system (Fritts et al., 2021; Garrone Neto et al., 2014; Vergeynst et al., 2019). We do not know for instance the cumulative effects of navigation locks and dams on biodiversity at the watershed scale, although this scale is considered as relevant for river restoration (Fausch et al., 2002; Friberg et al., 2017). In the context of future inland navigation development, we need approaches to better anticipate collateral damages and avoid adverse effects of waterway construction on freshwater ecosystems (Dou et al., 2022), such as prospective work (Wantzen et al., 2024) and simulation modelling (Yin et al., 2022).

New technologies play a crucial role in enhancing the tracking and monitoring of river navigation (Bandini et al., 2023). The implementation of advanced Global Positioning Systems (GPS), remote sensors, and real-time data management platforms has revolutionized the way river routes are supervised. These tools enable continuous and precise surveillance of maritime traffic, improving the safety and efficiency of transportation. The integration of these technologies also supports environmental protection by enabling more stringent control over activities that could negatively impact river ecosystems. The combination of high spatiotemporal resolution satellite imagery and deep learning methods offers great opportunities for the monitoring of human footprint in inland waterways, which can improve local and regional assessment of environmental impacts of anthropogenic activities on riverine ecosystems (Guan et al., 2023; Smigaj et al., 2023).

We have also noticed a strong geographical bias in the knowledge available in the English-speaking, white scientific literature, with an overrepresentation of China, Europe, and North America. Complementing this work with a synthesis of the grey literature in national languages would help fill this gap. It remains nonetheless that increasing navigation is a global phenomenon. While for some rivers there are international conventions and committees dealing with conservation aspects (e.g., International Commission for the Protection of the Rhine), for others, there are transboundary treaties that mostly focus on navigation and water use for damming and irrigation (e.g., Niger), while many rivers are increasingly used for navigation but lack any consideration for the potential impact of both INIs and shipping on the riverine ecosystem services (e.g., the Paraguay River in Brazil, Wantzen, 2023; see also Jähnig et al., 2022). If we are to plan future inland navigation management in coherence with other environmental policies (Convention on Biodiversity, Aïchi targets, European Framework Directives), we have to develop a more sustainable navigation (Plotnikova et al., 2022) and to adapt the management strategies to functional scales for a better resilience of the ecosystems in the face of global change.

5. Conclusions

Our literature synthesis organises, summarizes and reinterprets the great but scattered amount of knowledge on the topic of navigation effects on river ecosystems by proposing an original classification of navigation-related pressures – namely navigation itself, infrastructures and waterway management – and by analysing the literature through this novel prism.

Our synthesis shows the generalised negative impacts of inland navigation on native biodiversity and its positive effects on exotic taxa. The strongest impacts are due to navigation itself (such as shipping intensity and wave drawing) and to the combination of multiple navigation factors (i.e. navigation, infrastructures, and waterway management or maintenance). This suggests that inland navigation policies will need to reinforce regulation on boat traffic to limit erosion and nuisances, e.g., by limiting boat speed and/or access (Bradbury et al., 1995; Kuhajda and Rider, 2016), on lock operations to improve connectivity, e.g., by increasing the frequency of opening (Arai et al., 2019; Simcox et al., 2015), and on ballast water to avoid contamination, e.g., by water treatment (Elskus et al., 2015) (and see more recommendations in PIANC, 2003). Waterway management will need to minimize or conceive environment-friendly dredging activities (Mossa et al., 2020; Pledger et al., 2021; Suedel et al., 2022) and to apply creative suites of restoration actions to mitigate the impacts of navigation (Flores et al., 2022; Schmitt et al., 2018; Söhngen et al., 2018; Weber et al., 2012). Waterway policies will have to account for the importance of interactions between multiple navigation impacts by adopting a more integrative view of the river ecosystems (Cid et al., 2021; Friberg et al., 2017). The future inland navigation regulation will further need to adapt to the context of global change where some rivers are and will be increasingly exposed to flow modifications (Olsen et al., 2012), and species invasions (Rahel and Olden, 2008).

Our synthesis nevertheless reveals that in half of the cases, some impacts of navigation-related pressures remain unclear, either due to lack of evidence/proper testing or contradicting responses. This reflects the current absence of consensus and hence, the remaining gaps of knowledge in the topic that need to be addressed in order to better guide river management planning. The main research priorities we identified are to investigate (i) the effects of waterway management on communities, (ii) the indirect effects of navigation pressures on biodiversity through the analysis of abiotic responses that condition the biotic responses to gain deeper understanding of the underlying processes of navigation impacts on river ecosystems; and (iii) the interaction between multiple navigation factors and their effects on multi-taxa responses.

This and future research provide policy makers and waterway managers with more evidence-based and large-scale guidance that will help build and coordinate inland navigation management policies and fulfil the objectives of transboundary consistency of inland navigation.

CRediT authorship contribution statement

Alienor Jeliazkov: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Vanesa Martínez-Fernández:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Vassil Y. Altanov:** Writing – review & editing, Visualization, Validation, Methodology, Data curation. **Jean-Nicolas Beisel:** Writing – review & editing, Validation, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Anthonie Dirk Buijse:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization. **Sofia Consuegra:** Writing – review & editing, Data curation. **Swann Felin:** Data curation. **Carlos Garcia de Leaniz:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Wolfram Graf:** Data curation. **Fengzhi He:** Writing – review & editing, Data curation. **Sonja C. Jähnig:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Patrick Leitner:** Data curation. **Astrid Schmidt-Kloiber:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Aaron N. Sexton:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization. **Cybill Staentzel:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization. **Evelyne Tales:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization. **Karl M. Wantzen:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization. **Christian Wolter:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data and R codes are publicly available at: https://doi.org/10.57745/N6Y6QR.

Acknowledgements

This research is a product of the NAVIDIV group funded by the synthesis centre CESAB of the French Foundation for Research on Biodiversity (FRB; www.fondationbiodiversite.fr) and by the French National Research Program on Transport Infrastructure, Territories, Ecosystems and Landscapes (ITTECOP; https://www.ittecop.fr/en/) of the French Ministry of Ecological Transition (MTE). S.C.J. acknowledges funding by the Leibniz Competition project Freshwater Megafauna Futures. We thank Nicolas Casajus and Joseph Langridge for their advice on early stages of this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122474.

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