

1 **Recreational fishing drives the global spread of aquatic non-native species**

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1 **Abstract**

2 Recreational fishing provides substantial socio-economic benefits worldwide, yet its role in driving
3 aquatic biological invasions remains insufficiently understood. Here, we assessed global evidence
4 for recreational fisheries-mediated introductions of aquatic non-native species. Using a systematic
5 review of 140 retained studies, we compared temporal trends, geographic coverage, introduction
6 pathways and taxonomic groups to evaluate how angling-related practices contribute to non-native
7 species invasion. We show that research effort is highly uneven, with strong concentrations in North
8 America and Europe, whereas regions with large or rapidly expanding recreational fishing
9 participation, including parts of Asia, Africa, and South America, remain poorly studied. Four major
10 introduction pathways were identified: intentional stocking, live bait use, fishing gear and equipment,
11 and direct release by anglers. Intentional stocking was the dominant pathway, particularly for fish,
12 whereas live bait and contaminated equipment contributed to the movement of invertebrates,
13 aquatic plants, pathogens, and associated organisms. Dominant taxa differed among pathways,
14 with salmonids prevailing in stocking records, whereas live bait and equipment pathways involved
15 more diverse invertebrates, plants, and pathogens. Our synthesis highlights recreational fishing as a
16 globally important but under-governed invasion pathway. Effective prevention will require pathway-
17 based regulation, stronger control of stocking and live bait trade, improved angler biosecurity, and
18 targeted research in underrepresented regions.

19 **Keywords:**

20 *Biological invasion; alien species; angling; invasive species; invasion pathway*

21 **Introduction**

22
23 Recreational fishing, also referred to as sport fishing or angling, continues to increase in popularity,
24 with participants numbers estimated at 220 (World Bank, 2012) to 700 million people (Cooke &
25 Cowx, 2004), catching approximately 47 billion fish annually (Cooke & Cowx, 2004), globally. The
26 average participation rate in recreational fishing from the late 1990s to the early 2010s was
27 estimated at 6.7-10.5% of the total population across the world, concentrated largely in China,
28 United States, Russia, and a number of European countries (Arlinghaus et al., 2015; Funge-Smith,
29 2018). Moreover, recreational fisheries generate substantial social and economic benefits
30 (Brownscombe et al., 2019), accounting for more than US\$190 billion in annual expenditure
31 (Kelleher et al., 2012). For example, in Australia, recreational fisheries contribute AU\$11 billion
32 annually to the national economy and support 100,000s of jobs (Moore et al., 2023).
33

34
35 In Western countries, public values associated with recreational fishing have gradually shifted
36 from anthropocentric to biocentric perspectives. This has involved a move away from traditional

1 extractive fisheries management paradigm centered on enhancing angling experiences to one
2 increasingly recognizing biodiversity conservation as a central objective (Arlinghaus et al., 2021).
3 However, with the rapid expansion of recreational fishing, potential ecological implications of these
4 practices have attracted growing scrutiny. Among the ecological risks arising from human activities,
5 the intentional or accidental introduction of invasive species through anthropogenic pathways has
6 been widely recognized as a major driver of global biodiversity loss, with adverse societal and
7 ecological effects (Haubrock et al., 2026; IPBES, 2023). As important drivers of environmental
8 change, aquatic non-native species often trigger a series of cascading ecological effects during the
9 invasion process (Haubrock et al., 2026; Pyšek & Richardson, 2010), including habitat degradation
10 and competitive exclusion of native species (Blackburn et al., 2011; Gallardo et al., 2016).

11
12 Recreational fishing activities are now recognised as important vectors of the introduction and
13 spread of freshwater non-native species by providing multiple pathways (Cambray, 2003; Smith et
14 al., 2020; Van Zyll De Jong et al., 2004). These include, stocking programs, live bait release,
15 transport on fishing gear and boats, water ballast, and angler release (Johnson et al., 2008). To
16 enhance the angling experience, stocked fish are usually relatively large-bodied and occupy higher
17 trophic levels (Fujitani et al., 2016; Holmlund & Hammer, 2004). Many of these species are also
18 able to survive a wide range of environmental conditions, such as common carp *Cyprinus carpio*
19 (Britton, 2023; Vilizzi et al., 2015), facilitating their ability to establish, spread and cause ecological
20 impacts (Britton et al., 2023). The long-term and widespread stocking of angling fish into inland
21 waters has consequently altered species assemblages and food-web structure in freshwater
22 systems worldwide (Britton et al., 2024; Eby et al., 2006), with catches of recreational anglers in
23 Central Europe now comprising more non-native fish yield than native (Lyach, 2022; Sbragaglia et
24 al., 2023).

25
26 The individual behavior of recreational anglers can also exacerbate the risk of aquatic non-
27 native species spreading (Heck et al., 2015; Pradhananga et al., 2015), as many non-native fish
28 introductions originate from certain anglers themselves (Winfield, 2016), either as target fish, as
29 prey for native fish, or as bait (Gerber et al., 2024; Lewin et al., 2019; Weigle et al., 2005). During
30 movements across water bodies, anglers may also carry invasive organisms on fishing gear and
31 equipment (Kilian et al., 2012; Ready et al., 2018). Thus, from a social-ecological systems
32 perspective, the human decision-making and behavioral processes associated with recreational
33 fisheries constitute an important driving mechanism for the cross-basin and cross-regional spread of
34 aquatic non-native species. Compared with commercial aquaculture and the trade in aquatic
35 species, recreational fisheries have received less attention in management regulations, quarantine
36 systems, and risk assessment frameworks for non-native species, particularly in developing

1 countries and transboundary river basins (Carpio et al., 2019; Lewin et al., 2008; Potts et al., 2020).
2 Although studies on introductions of aquatic non-native species driven by recreational fisheries have
3 increased in recent years, they have generally been dominated by case studies at the single water
4 body, region or country scale, with the research focus often limited to one particular taxonomic
5 group or one specific pathway (Arias et al., 2013; Esposito et al., 2024a; Frischer et al., 2005; Vitule
6 et al., 2006).

7
8 Despite past assessments, of the risks of invasions associated with recreational fishing, a unified
9 analytical framework of the major invasion pathways and their distributional characteristics across
10 different regions and taxonomic groups is lacking. To this end, this study aims to systematically
11 integrate evidence of aquatic biological invasions associated with recreational fisheries at the global
12 scale, with the objectives of: (1) quantifying patterns of change in research attention across
13 temporal and spatial dimensions; (2) synthesizing the major introduction pathways and their
14 transmission mechanisms; (3) comparing the introduction range of species/taxonomic groups and
15 research biases; and (4) proposing implications for prevention and management, thereby offering a
16 scientific basis for the prevention and management of recreational fisheries-mediated biological
17 invasions in China and globally.

18 **Methods**

19 *Bibliometric and Spatial Analysis*

20
21 To systematically review research on the introduction of non-native species and invasion risks
22 caused by recreational fisheries worldwide, we adopted a systematic literature review approach
23 following the PRISMA framework (Supplementary text; Page et al., 2021). The literature search was
24 primarily conducted in the *Web of Science Core Collection* (WoS) and Scopus, covering the period
25 1991 (the earliest eligible study identified) to 2024. In WoS, an initial search string was constructed
26 using the topic field. The search string covered multiple types of recreational fishery activities and
27 concepts related to non-native species invasions. The full search string was as follows:

28
29 TS= ((recreational fish* OR recreational fishing OR lure fishing OR lure angling OR bait fishing
30 OR bait angling OR boat fishing OR boat angling OR fly fishing OR fly angling OR spinning fishing
31 OR leisure fishing OR spinning angling OR leisure angling OR catch-and-release) AND (invasive
32 OR non-native OR alien OR translocated species OR exotic OR introduced species OR non-
33 indigenous OR invasion)).

34
35 To ensure adequate search coverage and refine the search string, a keyword frequency
36 analysis was conducted using the bibliometrix R package (Aria & Cuccurullo, 2017) after the initial

1 search, and then further supplemented the search terms with “species introduction” and “fish
2 introduction”. An equivalent search strategy was applied in the Scopus database. A total of 1,966
3 and 381 records were retrieved from the WoS and Scopus databases, respectively. All retrieved
4 records were first merged, and duplicate records were removed using the ‘dplyr’ R package
5 (Wickham et al., 2024) in combination with manual checking, granting a total of 2040 records. After
6 the exclusion of duplicates, titles and abstracts of the remaining 523 records were screened to
7 exclude studies unrelated to recreational fisheries or not involving species introductions and
8 invasion risks. Studies were included only if they met all following criteria: (1) the study explicitly
9 involved recreational fisheries activities; (2) the study documented species introduction events or
10 biological invasion processes associated with recreational fisheries; (3) the study provided
11 extractable information, including the country or location of the study, the species involved,
12 introduction pathways, ecological impacts, and related dimensions; and (4) the study was a formally
13 published research article in a peer-reviewed, scientific journal. The following types of literature
14 were excluded: (1) grey literature (e.g. reports, conference proceedings); (2) review articles; (3)
15 studies not involving recreational fisheries (e.g., species introduction events caused entirely by
16 commercial aquaculture or commercial stocking) or not involving specific species; and (4) studies
17 for which the full text was unavailable. Studies passing the initial screening were then downloaded
18 in full text for review. Eligibility was assessed according to the predefined inclusion and exclusion
19 criteria, and studies with incomplete information or from which core data could not be extracted
20 were excluded. Ultimately, 140 studies were included for subsequent analyses (Supplementary
21 Table S1), with the detailed screening process provided in Figure S1.

22

23 **Information Extraction and Data Processing**

24 For each included study, the data extracted were the time and location of the study, waterbody type,
25 angling methods applied to the waterbody concerned, the introduction pathway and the species
26 involved. Study time refers to the year in which the research or data collected was implemented, as
27 reported in the paper. If a study did not provide a specific study year, the year of publication was
28 used instead. Where studies were based on multi-year monitoring or long-term datasets and
29 therefore covered relatively long-time spans then multiple years were counted on a year-by-year
30 basis to allow more accurate characterization of changes in research intensity across different
31 periods. To facilitate the presentation of long-term trends, study years were further grouped into
32 decadal intervals, and research records were summarized within each interval. Retrieved
33 geographical information included the country in which the study was conducted, the type of
34 waterbody in the study area (e.g., river, lake, reservoir, pond, estuary, or marine environment), and
35 geographic coordinates. If a study provided a coordinate range, the midpoint was used; if only a

1 place name was provided, the latitude and longitude were identified using tools such as Google
2 Earth; if multiple locations were involved, they were separated into multiple records.

3
4 To identify the potential role of different angling methods in the spread of non-native species,
5 the types of angling methods reported in each paper were extracted and classified into three
6 categories including (1) lure fishing: if the study explicitly mentioned the use of lure equipment or
7 artificial bait; (2) bait fishing: if the study involved bait or live bait use; and (3) N/A: studies that did
8 not specify a particular angling method. For introduction pathway, classification was into four
9 categories: (1) artificial stocking conducted by management authorities or operators to maintain
10 fishery resources (Intentional stocking); (2) personal release behavior by anglers to enhance their
11 own angling experience (Releases by angler); (3) the release of bait into water bodies or the escape
12 of live bait (Live bait); and (4) the spread of attached organisms via fishing gear, boats, or wading
13 equipment (Fishing gear and equipment). Non-native species information then included the
14 scientific name, family, and genus. Non-native species were classified into four broad taxonomic
15 groups: fish, invertebrates, plants, and pathogens. If multiple species were reported in a single
16 study, each species was separated into an independent record.

17
18 After data extraction, temporal analyses were conducted to quantify changes in research
19 intensity over time by summarizing study records annually and across decadal intervals. Spatial
20 analyses were used to examine the geographic distribution of studies, identify countries or regions
21 receiving the greatest research attention, and compare the occurrence of studies among different
22 waterbody types. In addition, descriptive analyses were performed to summarize the frequency of
23 reported angling methods, introduction pathways, and the taxonomic composition of non-native
24 species, thereby identifying the dominant mechanisms and key taxa associated with angling-related
25 introductions.

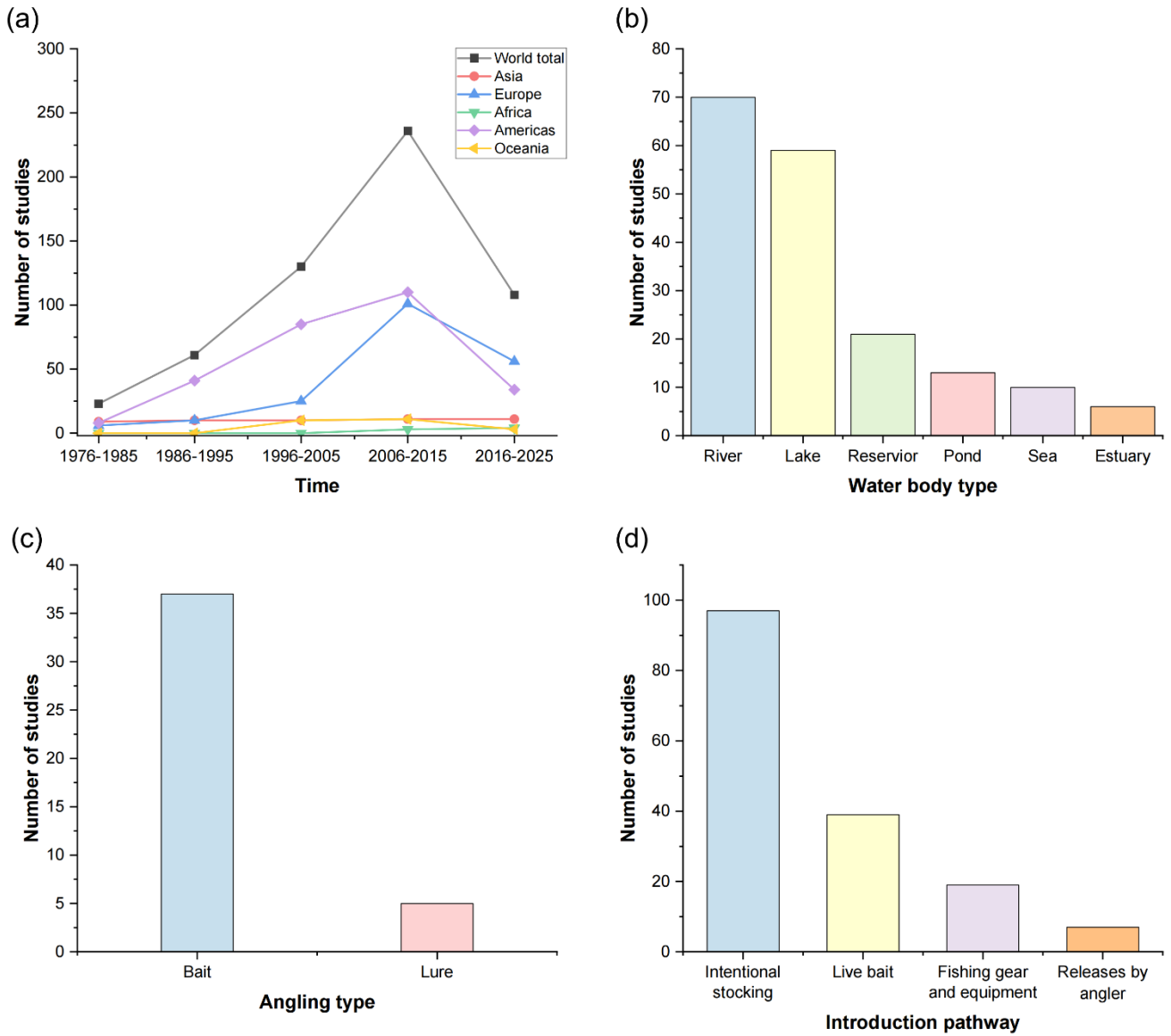
26 27 **Global trends**

28 Across 140 retained studies, 206 non-native fishes were mentioned in a total of 30 countries. The
29 earliest case was from Lake Kawaguchi, Japan, where stocking activities associated with
30 recreational fisheries were traced back to the 1970s, it showed that stocking of carnivorous (e.g.,
31 *Micropterus salmoides* and *Oncorhynchus mykiss*) was associated with marked changes in fish
32 species composition and potential ecological impacts (Hirabayashi & Yoshida, 1998). Earlier
33 stocking or introduction activities may have been recorded in other regions, but many of these
34 records described introductions in general terms without explicitly linking them to recreational
35 fisheries or to subsequent ecological impacts. At the global scale, research on invasion risks
36 associated with recreational fisheries exhibited clear temporal and spatial variation and

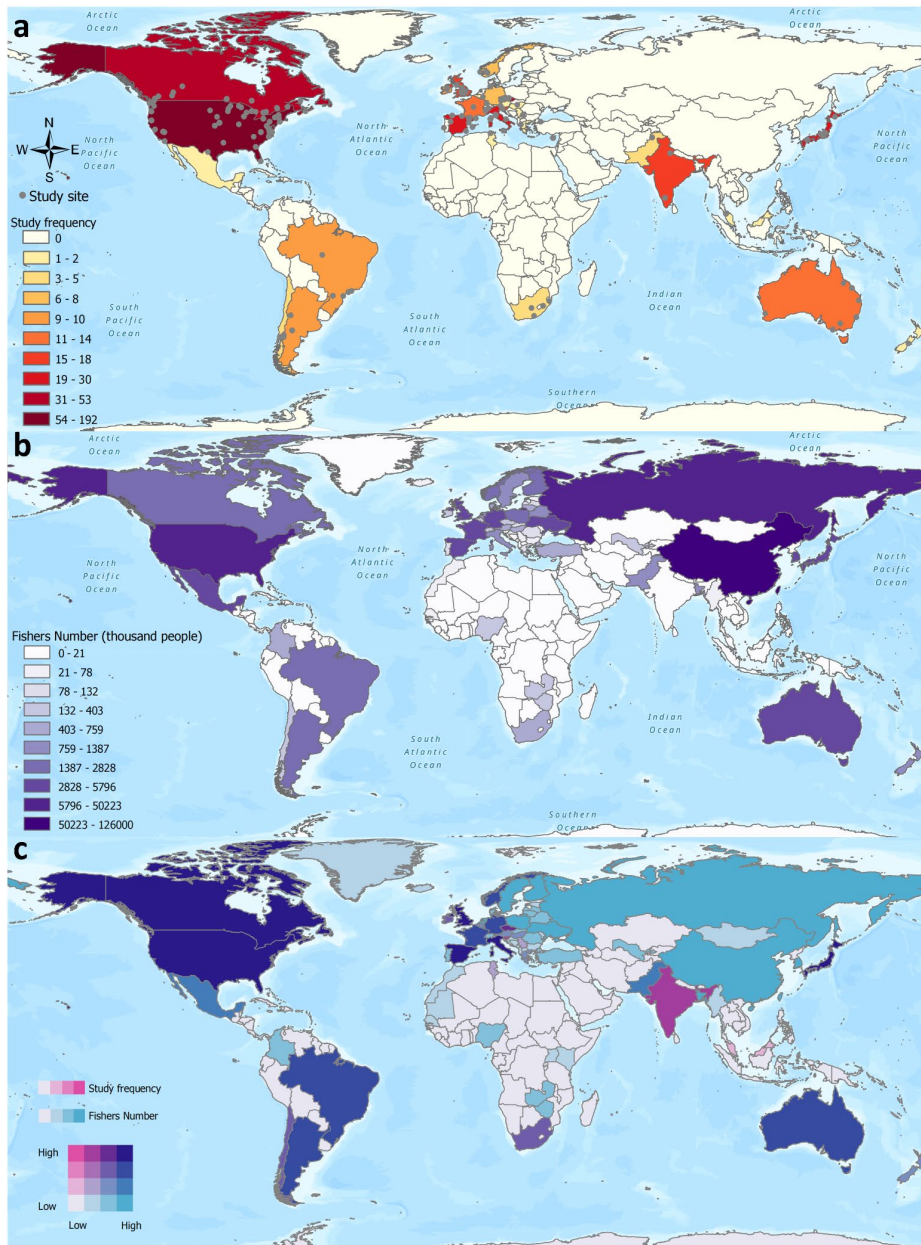
1 unevenness. Invasion risks associated with recreational fisheries exhibited an overall temporal
2 pattern of increase (2006-2015), followed by decline (2016-2025) (Figure 1a). At the continental
3 scale, the Americas and Europe were the main sources of information. The Americas began earlier
4 and showed a relatively steep, early increase, maintaining high record numbers across all periods,
5 whereas Europe increased markedly after 1996-2005 and reached its peak during 2006-2015. In
6 contrast, Asia, Africa, and Oceania consistently showed lower recorded numbers across all periods.
7 Spatially, studies concentrated in North America and Western Europe (Fig. 2a), with the United
8 States contributing the largest number ($n = 46$), followed by Canada ($n = 16$), Italy and Spain (both
9 $n = 10$) and the United Kingdom ($n = 9$). Outside these regions, only a few countries showed a
10 moderate contribution (e.g. Japan/Australia/France, all $n = 6$; Brazil, $n = 5$; Argentina, $n=4$; South
11 Africa, $n = 3$). Most countries had only scattered records, with Africa, Asia, and parts of Latin
12 America lacking systematic research. It should be noted that some countries (e.g., India; Pinder et
13 al., 2020) show relatively high study frequency in the figure, which does not necessarily indicate an
14 equivalent level of research output, but rather suggests that a small number of studies may cover a
15 longer time span.

16
17 Recreational fishing participation was highest in China (126.0 million), followed by Russia
18 (39.8 million), and North America (53.0 million, 50.2 in the United States and 2.8 million in Canada)
19 (Embke et al., 2022). Some European countries (France: 5.6 million; Germany: 5.8 million; United
20 Kingdom: 4.6 million), Australia (4.3 million), and a few South American countries (Argentina:1.8
21 million; Brazil:1.9 million) also had medium to high levels fishing participator, whereas many African
22 countries and some Asian countries were characterized by relatively low estimates (Kenya: 4,800;
23 India:13,000) or lacking data (Fig. 2b) (Embke et al., 2022). Further bivariate mapping analysis of
24 study frequency and angling participation were not consistent on a spatial scale as North America
25 and some European countries showed both relatively high study frequency and large participation
26 scale, whereas countries such as China and Russia were characterized by high participation scale
27 but relatively insufficient related research, with Africa and parts of Asia remaining data deficient (Fig.
28 2c). These results indicate that current research on the risks of aquatic biological invasions driven
29 by recreational fisheries is spatial-biased. Some regions with relatively high recreational fishery
30 activity lack corresponding ecological risk assessments and invasion studies, making the potential
31 risks of species spread and establishment insufficiently recognized, which may lead to a systematic
32 underestimation of invasion risks at the global scale.

33



1
 2 **Figure 1.** (a) Temporal trends in study records worldwide and across continents. (b) Distribution of studies
 3 among different water body types. (c) Comparison of the number of studies among different angling types
 4 (bait and lure fishing). (d) Introduction pathways of biological invasions related to recreational fisheries. The y-
 5 axis in all panels represents the number of studies.
 6



1

2 **Figure 2.** (a) Spatial distribution of studies related to invasion risks associated with recreational fisheries
 3 worldwide. The basemap color indicates study frequency, calculated based on study years rather than
 4 number of articles: for studies spanning multiple years, each study year was counted once, such that this
 5 metric reflects the temporal coverage of research activity rather than publication output. Grey dots indicate
 6 specific study sites. (b) Global spatial distribution of inland recreational fishers. (c) Coupling pattern between
 7 study frequency and inland recreational fishing participation.

8

9 **Angling Practices and Risk Mechanisms**

10 Studies were predominantly conducted in freshwater ecosystems, with rivers ($n = 70$) and lakes ($n =$
 11 59) accounting for the largest proportions, followed by reservoirs ($n = 21$) and ponds ($n=13$). In
 12 contrast, relatively few studies were from marine ecosystems ($n = 10$), and studies on estuarine
 13 ecosystems were even more limited ($n = 6$).

1
2 In terms of angling methods, lure-related records were reported less frequently, with only 28
3 records identified from five studies, indicating that research on introduction risks associated with
4 artificial lure angling remains limited. Existing records were mainly concentrated on fish, including
5 *Sander lucioperca* ($n = 3$), *Micropterus salmoides* ($n = 3$), and *Oncorhynchus mykiss* ($n = 3$),
6 followed by *Ameiurus melas* ($n = 2$), *Cyprinus carpio* ($n = 2$), *Lepomis gibbosus* ($n = 2$), and *Silurus*
7 *glanis* ($n = 2$) (Banha et al., 2024; Britton & Nolan, 2021; Polgar et al., 2023). In contrast, bait
8 fishing-related records were more common, with a total of 139 records from 37 studies, although
9 most of these recorded the use of live bait. Bait fishing generally involved relatively small live bait
10 fish that were easy to obtain and transport, with 48 records in total, among which genus *Phoxinus* (n
11 = 7) was the most common.

12 13 **Introduction Pathways Associated with Angling**

14 By calculating the occurrence frequency and proportion of each pathway in the literature, we found
15 clear structural differences among pathways: Intentional Stocking appeared in 97 studies (Alexiades
16 et al., 2017; Esposito et al., 2024a; Fabrizio et al., 2021), making it the most common pathway; Live
17 bait appeared in 39 studies (McEachran et al., 2022; Shepta et al., 2024), Fishing Gear and
18 Equipment in 19 studies (Coetzee et al., 2009; Frischer et al., 2005), and Releases by angler in only
19 seven studies (Cerri et al., 2017; Yürekli et al., 2024).

20 21 **Intentional stocking**

22 Intentional stocking showed the highest frequency of occurrence in the literature ($n = 97$), and a
23 total of 226 introduction records were documented, involving 96 studies, 75 species, and 25
24 countries. This pathway was overwhelmingly dominated by fish ($n = 222$; 98.2%), with invertebrates
25 and pathogens accounting for only 0.9% ($n = 2$) and no records for aquatic plants were found. The
26 most frequently recorded fish species included the salmonids *Oncorhynchus mykiss* ($n = 41$), *Salmo*
27 *trutta* ($n = 32$), and *Salvelinus fontinalis* ($n = 20$), which are also among the representative target
28 fish in recreational fishing worldwide (Cowx, 2002). For example, in California, United States,
29 salmonids were introduced into naturally fishless lakes to maintain recreational fisheries (Schindler
30 et al., 2001). In Lake Huron, Canada, *Oncorhynchus tshawytscha* and *O. mykiss* had been
31 introduced since the late nineteenth century for the development of recreational fisheries (Hunt et
32 al., 2010; Mills et al., 1993). In Patagonia, Argentina, in the Southern Hemisphere, *Salmo salar* and
33 *S. trutta* were introduced for angling purposes (Valiente et al., 2010). In alpine national parks in
34 Europe and in New Zealand, *S. trutta* was stocked to enhance recreational fisheries (Arlinghaus &
35 Cowx, 2008; Thaulow et al., 2013). Stocking also led to the accidental introduction of non-target
36 species, such as *Phoxinus phoxinus* being released accidentally into new water bodies during

1 intentional stocking of *S. trutta* (Museth et al., 2007). Stocked species may also introduce non-
2 native parasites and pathogens that they carry, thereby promoting the establishment and spread of
3 non-native organisms and their associated pathogenic biota at local and even cross-regional scales
4 (Brynildsrud et al., 2014; Reading et al., 2012).

5 6 **Live bait fishing**

7 Live bait fishing derived non-native species introduction ranked second in frequency of occurrence
8 in the literature ($n = 39$). In studies with extractable records, a total of 136 introduction records were
9 documented, involving 36 studies, 109 species, and 15 countries. Invertebrate and Fish were the
10 main components, accounting for 35.3 % ($n = 48$) and 33.1 % ($n = 45$), respectively, higher than
11 Pathogens (17.6 %, $n = 24$) and Vegetation (14.0 %, $n = 19$). Fish-related records were distributed
12 across 21 studies and 12 countries, mainly involving release and trade as live bait fish. Species
13 such as *Phoxinus phoxinus* repeatedly appeared in multiple studies from Europe (Esposito et al.,
14 2024b; Fernández et al., 2019; Miró & Ventura, 2015; Thaulow et al., 2014), indicating that small
15 bait fish are among the most typical vectors under the Live bait pathway. In contrast, Invertebrates
16 involved 40 species across 15 studies. This group can be used directly as live bait, such as the
17 polychaete *Perinereis linea* (Arias et al., 2013). In the Cap de Creus Marine Protected Area in the
18 northwestern Mediterranean, at least 43 % of the bait used by recreational anglers consisted of live
19 non-native species, mainly polychaetes (Font & Lloret, 2014). In addition, packaging materials used
20 to maintain bait moisture and survival can carry various invertebrates, and if discarded into the
21 water or along the shore after fishing, they may also promote the establishment of non-native
22 species (Font & Lloret, 2014; Haska et al., 2012; Saito, 2017)

23
24 Compared with fish and invertebrates, records related to pathogens and vegetation reported
25 less frequent, involving only 21 and 19 species, respectively. In the northeastern United States,
26 after using the bait worm *Nereis virens*, recreational anglers often discarded the packaging
27 seaweed *Ascophyllum nodosum* ead *scorpioides* together with *Fucus vesiculosus*, *Fucus spiralis*,
28 and residual materials in the box into the water; researchers detected multiple epiphytic algae in
29 some bait box samples, including *Chaetomorpha linum*, *Cladophora ruchingeri*, *Ectocarpus*
30 *siliculosus*, *Percursaria percursa*, and various *Ulva* spp. (Haska et al., 2012). All vegetation records
31 came from the same study, indicating that current research attention to plant spread through the live
32 bait pathway remains limited, and the associated risks may not yet have been fully recognized. In
33 Minnesota, United States, inland recreational anglers released or discarded live bait fish after use,
34 thereby introducing pathogens and parasites carried by the bait fish into public waters (McEachran
35 et al., 2023). The introduced organisms included Viral hemorrhagic septicemia virus (VHSV),
36 *Ovipleistophora ovariae*, and others (McEachran et al., 2021). Holding and transport water in the

1 live bait trade can also serve as reservoirs for pathogenic microorganisms, and potential pathogens
2 may be released into recipient waters when anglers dump leftover bait water (Mahon et al., 2018).

3
4 Overall, the live bait pathway does not merely spread target live bait organisms, but rather
5 functions as a composite pathway involving multiple accompanying taxonomic groups. In addition,
6 the relevant records are highly concentrated in the United States, which also reflects the current
7 geographical unevenness in research distribution. Therefore, future studies should strengthen
8 monitoring and assessment in other regions and of cryptic associated organisms. The reason why
9 live bait release constitutes a significant biological invasion risk is, on the one hand, that anglers
10 have insufficient understanding of the species identity of live bait and its potential ecological
11 consequences, and on the other hand, that they often regard the release of leftover live bait as a
12 harmless or even beneficial disposal practice for the ecosystem, thereby promoting the secondary
13 spread of non-native species and associated pathogens (Akmal et al., 2024; Carvalho et al., 2024;
14 McEachran et al., 2022).

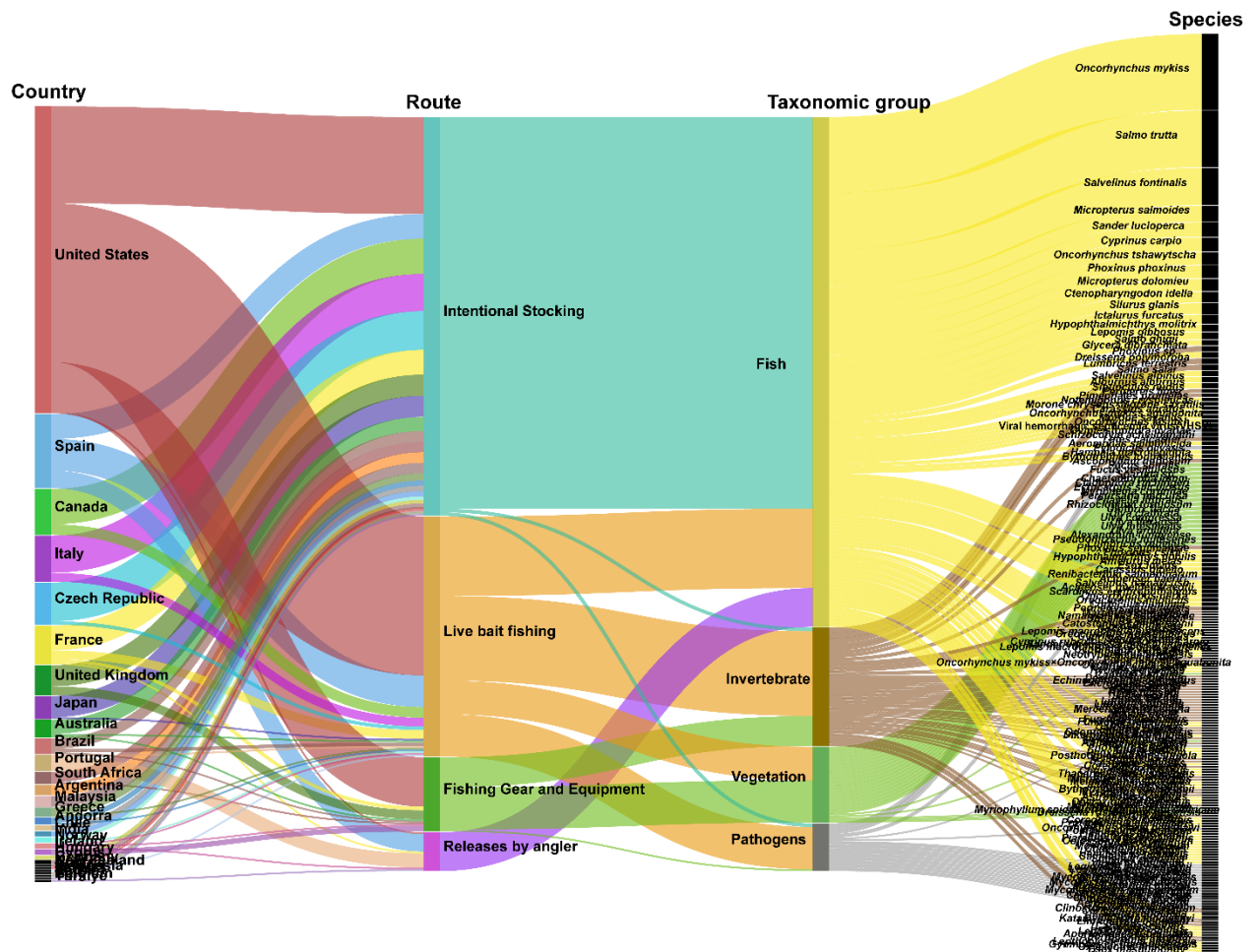
15 16 **Fishing Gear and Equipment**

17 Fishing Gear and Equipment derived non-native introduction were only sporadically reported (n=19).
18 In studies with extractable records, this pathway accounted for 42 introduction records, involving 13
19 studies, 40 species in 8 countries. Vegetation and Invertebrate were the main components,
20 accounting for 57.1 % (n = 24) and 40.5% (n = 17), respectively, followed by Pathogens (2.4%,
21 n=1), and no records of fish were found. Thus, this pathway mainly promotes the spread of plants,
22 invertebrates, and pathogens across water bodies through the repeated use of fishing equipment
23 and boats and inadequate cleaning. Vegetation accounted for the highest proportion, involving 24
24 species, 4 studies, and 3 countries. In Pongolapoort Dam, South Africa, the invasive submerged
25 plant *Hydrilla verticillata* can spread across water bodies via equipment carried by recreational
26 anglers and recreational boats, as its vegetative fragments easily attach to boat hulls and angling-
27 related equipment and be transferred to new water bodies during fishing activities (Coetzee et al.,
28 2009). In contrast, the number of Invertebrate records was slightly lower than that of Vegetation,
29 involving 15 species and 11 studies in 7 countries. *Dreissena polymorpha* repeatedly appeared in
30 multiple studies from the United Kingdom and the United States, mainly spreading through
31 attachment to recreational fishing boats (Frischer et al., 2005; Weir et al., 2022). In the Laurentian
32 Great Lakes and adjacent inland lakes in the United States, individuals and resting eggs of the
33 cladoceran *Bythotrephes longimanus* may be transferred among water bodies in live wells and bait
34 bucket after being ingested by fish, and may also directly attach to angling equipment such as
35 fishing line, anchor ropes, and minnow seine, thereby spreading across water bodies through
36 fishing gear and boat-borne equipment (Kerfoot et al., 2011). Only one pathogen, *Aphanomyces*

1 *astaci*, was recorded under this pathway (Smith et al., 2020). Although it accounted for the lowest
2 proportion, this more likely reflects the current lack of attention to equipment-mediated pathogen
3 spread in the literature rather than suggesting that its actual risk can be ignored. In addition, the
4 relevant records were highly concentrated in the United States (n=28), which also indicates that
5 current research is unevenly distributed across regions. Waders can spread aquatic invasive
6 species between sites by carrying attached water, mud, and viable organisms when not properly
7 cleaned and dried between uses (Anderson et al., 2014).

8 9 **Releases by angler**

10 Releases by angler was the least frequently recorded pathway in the literature ($n = 7$). In studies
11 with extractable records, this pathway accounted for 22 introduction records, involving 6 studies, 15
12 species, and 6 countries. All introduction records under this pathway were Fish, and all were
13 associated with the active release of fish by anglers. The recorded species mainly included
14 *Oncorhynchus mykiss* ($n = 2$), *Ameiurus melas* ($n = 2$), *Cyprinus carpio* ($n = 2$), *Lepomis gibbosus*
15 ($n = 2$), *Micropterus salmoides* ($n = 2$), *Sander lucioperca* ($n = 2$), and *Silurus glanis* ($n = 2$). The
16 relevant records were mainly concentrated in Spain ($n=10$) and Portugal ($n = 8$) (Banha, 2024). In
17 Büyükçekmece Reservoir, Istanbul, Türkiye, *Abramis brama* was transferred from the nearby Lake
18 Durusu and released into the reservoir by recreational anglers to increase angling opportunities
19 (Yürekli et al., 2024). In the Chesapeake Bay region of the United States, researchers inferred that
20 *Ictalurus furcatus* may have entered new water bodies through release by recreational anglers
21 (Fabrizio et al., 2021). The small number of records for this pathway may be related to the difficulty
22 of obtaining evidence and the concealed nature of such events, but this does not necessarily mean
23 that its actual occurrence frequency is low; in regions where recreational fisheries are highly active
24 but monitoring is weak, this pathway may still pose a relatively high invasion risk. Overall, different
25 introduction pathways showed clear differences in country sources, taxonomic composition, and
26 species distribution (Fig. 2).



1
2 **Figure 3.** Sankey diagram of the associations among countries, introduction pathways, taxonomic groups,
3 and species involved in recreational fisheries-related species introductions.

4
5 **Key Species Introduced**

6 **Fish**

7 Fish accounted for a total of 289 introduction records, corresponding to 110 studies and 104
8 species. Overall, fish were the most central and concentrated taxonomic group, and were mainly
9 associated with Intentional Stocking ($n = 222$), accounting for 76.8 % of all fish records and was
10 clearly higher than Live bait ($n = 45$) and Releases by angler ($n = 22$); no fish records were found to
11 be spread through Fishing Gear and Equipment. At the family level, fish records were highly
12 concentrated within a few taxa. Salmonidae was the most prevalent family ($n = 129$), followed by
13 Cyprinidae ($n = 36$), Leuciscidae ($n = 28$), and Centrarchidae ($n = 26$). Percidae ($n = 11$) and
14 Ictaluridae ($n = 10$) were also notably represented. At the genus level, fish records were clearly
15 concentrated to few genera, with salmonids being particularly prominent: *Oncorhynchus* ($n = 60$)
16 ranked highest, followed by *Salmo* ($n = 39$) and *Salvelinus* ($n = 26$), and together these three
17 genera accounted for 43.3 % of all fish records; in addition, *Micropterus* ($n = 17$) and *Phoxinus* ($n =$
18 17) also showed relatively high record frequencies. The most frequently recorded species were

1 *Oncorhynchus mykiss* ($n = 43$), *Salmo trutta* ($n = 32$), and *Salvelinus fontinalis* ($n = 21$), followed by
2 *Micropterus salmoides* ($n = 9$), *Cyprinus carpio* ($n = 8$), and *Oncorhynchus tshawytscha* ($n = 7$).
3 These records were mainly associated with artificial stocking and active introductions by
4 recreational anglers (De Santis et al., 2021; Fernández et al., 2019; Koizumi et al., 2017; Pinter et
5 al., 2019; Thaulow et al., 2013). In contrast, *Phoxinus* spp. were introduced as live bait in multiple
6 parts of Europe (Miró et al., 2018; Thaulow et al., 2014).

7
8 Considering continental distribution, Europe was the region with the highest concentration of
9 fish introduction records ($n = 136$), accounting for 47.1 %, followed by the Americas ($n = 112$),
10 accounting for 38.8 %; together, the two continents accounted for 85.9% of all fish records.
11 However, in terms of species coverage, the Americas involved 57 fish species, which was higher
12 than the 39 species recorded in Europe, indicating that fish introduction records in Europe were
13 more concentrated on a small number of high-frequency species, such as *O. mykiss* ($n = 19$), *S.*
14 *trutta* ($n = 16$), and *Salvelinus fontinalis* ($n = 14$). At the species level, fish research records showed
15 clear continental bias. *Oncorhynchus mykiss* and *S. trutta* were the most widely covered fish
16 species, with records on all five continents, indicating that these two salmonids already have a
17 relatively sufficient cross-regional research basis. By contrast, *Micropterus dolomieu* had records in
18 Asia, Europe, Africa, and the Americas, but remained absent from Oceania; *M. salmoides* was
19 recorded only in Asia, Europe, and Africa, with no records in the Americas or Oceania. It should be
20 noted that FishBase records that both *Micropterus dolomieu* and *Micropterus salmoides* were
21 introduced to Fiji for angling purposes, and that the latter has established a local population (Froese
22 & Pauly, 2026). In addition, although *Cyprinus carpio* is one of the most widely introduced non-
23 native fish species globally (Chen et al., 2024), it was recorded only in Europe; *Salvelinus fontinalis*
24 was recorded only in Asia, Europe, and the Americas; and *Oncorhynchus tshawytscha* was
25 recorded only in the Americas and Oceania.

26
27 Several other common non-native fish species showed an strong pattern of concentration on
28 one or two continents, such as *Carassius auratus* ($n = 2$), which appeared only in the Americas,
29 *Ctenopharyngodon idella* ($n=6$) and *Hypophthalmichthys molitrix* ($n = 4$), which were mainly
30 concentrated in Europe and the Americas, *Perca fluviatilis* ($n = 1$), which appeared only in Europe,
31 and *Abramis brama* ($n = 1$), which appeared only in Asia. These results indicate clear continental
32 bias in species-level research, and gaps in some continents may lead to insufficient regional
33 understanding of the invasion risks posed by relevant species.

34 Invertebrates

1 Invertebrates were the second most frequently recorded taxonomic group after fish ($n = 67$). At the
2 family level, invertebrate records were relatively dispersed across multiple taxa. Lumbricidae was
3 the most frequently recorded family ($n = 8$), followed by Nereididae ($n = 5$) and Dreissenidae ($n = 5$).
4 Families such as Glyceridae, Cercopagididae, Littorinidae, and Mysidae were each recorded three
5 times, while numerous other families appeared only sporadically ($n \leq 2$). At the genus level, they
6 showed an overall pattern of dispersion across multiple genera. The more frequent genera mainly
7 included *Lumbricus* ($n = 5$), *Glycera* ($n = 3$), and *Dreissena* ($n = 3$), whereas most other genera only
8 had 1-2 records. Their introduction records mainly came from Live bait ($n = 48$), which accounted for
9 71.6% of all invertebrate records, followed by Fishing Gear and Equipment ($n = 17$). The most
10 frequently recorded species were *Dreissena polymorpha* ($n = 3$), *Glycera dibranchiata* ($n = 3$), and
11 *Lumbricus terrestris* ($n = 3$), followed by *Lumbricus rubellus* ($n = 2$), *Perinereis linea* ($n = 2$),
12 *Schizocotyle acheilognathi* ($n = 2$), *Sipunculus nudus* ($n = 2$), *Bythotrephes longimanus* ($n = 2$), and
13 *Corbicula fluminea* ($n = 2$).

14
15 Compared with fish, invertebrates were not concentrated to a few core species, but instead
16 showed a more broader dispersed multi-species pattern. The Americas had the highest
17 concentration of reported invertebrate introductions ($n = 41$), accounting for 61.2 %, followed by
18 Europe ($n = 23$), accounting for 34.3 %. Together, the two continents accounted for 95.5 % of all
19 invertebrate records. In terms of species coverage, the Americas included 35 species, clearly higher
20 than the 19 species recorded in Europe. Although some classic invertebrates are common in
21 aquatic invasion research, they did not show broad continental coverage in the present dataset. For
22 example, *Dreissena polymorpha* ($n = 3$) was recorded only in Europe and the Americas; *Corbicula*
23 *fluminea* ($n = 2$) only in Europe; and *Bythotrephes longimanus* ($n = 2$) only in the Americas. Some
24 other species with relatively strong invasion potential or dispersal ability, such as *Carcinus maenas*
25 ($n = 1$) and *Cherax quadricarinatus* ($n = 1$), appeared on only a single continent. In other words,
26 even for invertebrate invasive species that are relatively well known in ecology and management,
27 the evidence in the field of recreational fisheries remains limited to a small number of regional case
28 studies and has not yet formed a truly global comparative basis. The dispersal risk of invertebrates
29 is not necessarily lower; rather, this pattern more likely reflects the current uneven research
30 attention across continents and insufficient recognition of the risks of recreational fisheries-mediated
31 spread of relevant species in some regions.

32 33 **Vegetation**

34 Plants accounted for a total of 43 introduction records, including only 4 studies and 24 species. At
35 the family level, records were predominantly represented by Ulvaceae ($n = 14$), followed by
36 Fucaceae ($n = 6$). A subset of families exhibited intermediate frequencies, most notably

1 Acinetosporaceae and Cladophoraceae ($n = 4$ each). Families less frequently reported were
2 Hydrocharitaceae, Haloragaceae, Ostreopsidaceae, Bacillariaceae, and Poaceae ($n = 2$ each),
3 while the remaining taxa appeared only as single records. At the genus level, dominant genera
4 mainly including *Ulva* spp. ($n = 10$), followed by *Fucus* spp. ($n = 4$) and *Myriophyllum* spp. ($n = 3$).
5 Their introduction records were associated with two pathways, Fishing Gear and Equipment ($n = 24$)
6 and Live bait ($n = 19$), accounting for 55.8 % and 44.2 % of all plant records, respectively. Unlike
7 fish and invertebrates, plants did not show a pattern of dominance by a few high-frequency species,
8 but were characterized by a large number of species being recorded in parallel within a small
9 number of studies. Considering continental distribution, plant introduction records were mainly
10 concentrated in the Americas ($n = 41$), accounting for 95.3 % and involving 22 plant species, while
11 Europe and Africa each reported only one species (*Ludwigia grandiflora* and *Hydrilla verticillata*,
12 respectively). Many typical invasive species that are repeatedly discussed in the management of
13 non-native aquatic plants did, however, not appear in our dataset despite their risk status. For
14 example, *Hydrilla verticillata* ($n = 1$) was recorded only in Africa, *Myriophyllum aquaticum* ($n = 1$)
15 and *Myriophyllum spicatum* ($n = 1$) were recorded only in the Americas, and *Ludwigia grandiflora* (n
16 = 1) was recorded only in Europe; even *Spartina* sp. ($n = 2$) and *Ascophyllum nodosum* ($n = 2$),
17 which are often regarded as taxa with high dispersal potential, were recorded only in the Americas.
18 Many of the current plant records were algae and attached plants detected in a small number of
19 case studies from the Americas, making the plant group appear species-rich. However, this diversity
20 more likely reflects intensive detection of organisms associated with attached materials or
21 packaging media in a few individual studies, rather than sufficiently broad and balanced attention at
22 the global scale. Therefore, the risks of plant spread through recreational fisheries have not yet
23 been fully recognized, especially in continents such as Asia, Oceania, and Africa where records
24 remain clearly limited. The currently low number of records in these regions more likely represents
25 research gaps rather than simply indicating lower risk.

26

27 **Pathogens**

28 Pathogens accounted for a total of 27 introduction records, corresponding to 5 studies and 23
29 species. Pathogens were a taxonomic group with relatively few records but highly concentrated
30 introduction pathways, among which Live bait ($n = 24$) accounted for 88.9 % of all pathogen
31 records, followed by Intentional Stocking ($n = 2$) and Fishing Gear and Equipment ($n = 1$). The
32 recorded pathogens mainly included *Aeromonas salmonicida* ($n = 2$), *Ovipleistophora ovariae* ($n =$
33 2), Viral hemorrhagic septicemia virus (VHSV) ($n = 2$), and *Renibacterium salmoninarum* ($n = 2$),
34 whereas all other pathogens were recorded only once. Considering continental distribution, the
35 Americas were the region with the highest concentration of pathogen introduction records ($n = 4$),
36 involving 21 pathogen species; Europe had only a small number of records ($n = 3$), and no records

1 were found from the other continents. Compared with the taxonomic groups discussed above,
2 pathogens showed a more pronounced pattern of continental bias and insufficient research
3 attention. Judging only from the number of records, pathogens may appear to account for a
4 relatively small proportion of introductions associated with recreational fisheries. However, in terms
5 of species composition, the recorded pathogens already included several pathogen types with clear
6 risk significance in fisheries and invasion ecology (Delghandi et al., 2020; Kim & Faisal, 2010; Park
7 et al., 2020). For example, Viral hemorrhagic septicemia virus (VHSV) ($n = 2$) and *Aeromonas*
8 *salmonicida* ($n = 2$) were recorded only in the Americas, *Renibacterium salmoninarum* ($n = 2$) was
9 recorded only in Europe, and *Aphanomyces astaci* ($n = 1$) was also recorded only in Europe. In
10 other words, even these pathogens, which have clear management significance and are often
11 considered likely to spread through live bait or related fishing gear and equipment, were still
12 recorded only on very few continents and in a small number of case studies in the current literature.

13
14 At the spatial scale, study frequency and record numbers were concentrated in North America
15 and Europe, whereas Asia, Africa, Oceania and parts of South America remained poorly
16 represented. This imbalance was not fully consistent with global recreational fishing participation, as
17 some countries with large numbers of anglers, such as China and Russia, had relatively limited
18 research on angling-related invasion risks. Thus, low numbers of records in some regions more
19 likely indicate gaps in research effort, ecological risk assessment and monitoring capacity, rather
20 than necessarily lower invasion risk. Similar biases were evident at the species and pathway levels.
21 Intentional stocking dominated the documented literature and was mainly associated with large-
22 bodied target fishes, especially salmonids such as *Oncorhynchus mykiss*, *Salmo trutta* and
23 *Salvelinus fontinalis*, partly because stocking for recreational fisheries has a long history in many
24 well-studied regions and is more likely to leave formal management or research records. In contrast,
25 pathways such as live bait use, fishing gear and equipment, and direct release by anglers were less
26 frequently recorded, but they are also more difficult to detect because they involve small-bodied bait
27 species, associated invertebrates, aquatic plants, pathogens, contaminated equipment, or informal
28 human behaviour. Regional histories of angling further affect both introduction processes and the
29 research evidence available for them. In regions where recreational fisheries were historically
30 developed through organized stocking, the literature is more likely to emphasize non-native sport
31 fishes. In regions where recreational angling is expanding more recently, occurs through private
32 fishing venues, relies on informal bait trade, or remains weakly regulated, introductions may be
33 more closely linked to bait disposal, angler release, equipment-mediated transfer, or escape from
34 semi-managed systems, but these processes may not yet be systematically studied. Therefore, the
35 apparent dominance of particular regions, species and pathways in this review reflects not only

1 biological invasion processes, but also uneven research attention, pathway detectability, monitoring
2 capacity and the historical development of recreational angling across regions.

3 4 **Ecological and Socio-economic Impacts**

5 Among fish introduced through recreational fisheries, *O. mykiss*, *S. trutta*, *M. salmoides*, *C. carpio*,
6 and *Oreochromis mossambicus* were all listed by the IUCN among the “100 of the World’s Worst
7 Invasive Alien Species” (Lowe et al., 2000). Introduced fish can impose substantial predation
8 pressure on native fauna, leading to declines or even local extinction of native fish, amphibians,
9 reptiles, and large invertebrates (Pine et al., 2007; Pusey et al., 2006). For example, in Australia,
10 introduced *O. mykiss* heavily preys upon the native freshwater crayfish *Cherax cainii* (Tay et al.,
11 2007). Non-native fish can also directly compete with native species for food resources and habitat
12 space, alter the foraging behavior of native species, and force them to undergo niche shifts
13 (Peterson et al., 2024; Tiberti et al., 2022). Introduced closely related species may hybridize and
14 introgress with native species, resulting in the loss of the unique genetic attributes of native
15 taxa (Pinter et al., 2019; Rueda et al., 2017). For example, in Italy, the long-term stocking of *S. trutta*
16 has caused the critically endangered *S. marmoratus* to face a serious threat of genetic hybridization
17 (Polgar et al., 2023; Righi et al., 2023). The introduction of non-native salmonids can profoundly
18 alter the structure of aquatic ecosystems through trophic cascade effects. Heavy predation by fish
19 on large filter-feeding zooplankton can lead to the proliferation of phytoplankton, especially
20 cyanobacteria, due to reduced grazing pressure, thereby causing declines in water quality and
21 transparency (Reissig et al., 2006). Fish can also accelerate the cycling of nutrients such as
22 phosphorus in the water through predation on benthic animals and through excretion, further
23 promoting algal blooms (Schindler et al., 2001).

24
25 Introduced invertebrates (such as crayfish, earthworms, and polychaete worms) often
26 become invasive, competing with native species for food and habitat, and even directly preying on
27 them (Akmal et al., 2024; Font et al., 2018). In Maryland, United States, the introduction of the non-
28 native crayfish *Orconectes virilis* by anglers led to the decline of native crayfish populations and
29 even their extinction throughout the watershed (Kilian et al., 2012). The burrowing activities of
30 fossorial crustaceans, such as the ghost shrimp *Neotrypaea californiensis*, can significantly affect
31 sediment turnover, sorting, and mixing, thereby altering sediment dynamics and solute exchange
32 between water and sediment (Pernet et al., 2008). The introduction of the live bait earthworm
33 *Lumbricus terrestris* can alter soil dynamics, particularly by significantly increasing the emission of
34 the greenhouse gas N₂O, thereby affecting the normal functioning of forest ecosystems (Fugère et
35 al., 2017). Species such as polychaete worms may overconsume benthic organisms, leading to
36 imbalances in local biological communities and restructuring food-web structure (Çınar, 2013). In

1 addition, invertebrates can also act as vectors of pathogens and parasites (Pernet et al., 2008),
2 which represents a relatively serious component of the risks associated with introductions related to
3 recreational fisheries. After introduction, live polychaete bait may not only establish populations
4 itself, but may also carry non-native ciliates and other potentially pathogen-associated organisms
5 into recipient waters, thereby posing risks to the health of native benthic invertebrates through
6 infection of eggs and larvae (Arias et al., 2013). Some invertebrates may also cause blockage of
7 water intake facilities and increase management costs, thereby generating both ecological and
8 socio-economic impacts (Lucy et al., 2012).

9
10 Non-native aquatic plants introduced through recreational fisheries can enter new water bodies
11 by attaching to boat hulls, engines, and trailers, or through their use as packaging materials for live
12 bait (Font & Lloret, 2011; Smith et al., 2020). These plants can establish in a variety of freshwater
13 habitats and form extensive dense vegetation cover, often shading native plants and benthic algae,
14 altering community composition and spatial heterogeneity, and further interfering with the foraging,
15 settlement, and habitat use of other organisms, thereby causing significant ecological and economic
16 damage (Golebie et al., 2023; Wallentinus & Nyberg, 2007). In addition, the human-mediated
17 connectivity network formed by anglers is much broader than the natural river network, with more
18 connected lakes and denser dispersal pathways, so the spread of these plants may rapidly expand
19 from local areas to larger regions (Weir et al., 2022). For example, *Hydrilla verticillata* has become a
20 serious aquatic weed in the southeastern United States. Its high-density outbreaks can affect
21 irrigation operations and hydropower generation, hinder dock use and propeller-driven boat
22 navigation, and result in very high control costs; in Florida alone, the annual cost of controlling
23 *Hydrilla verticillata* is approximately US\$14.5 million (Coetzee et al., 2009).

24
25 Pathogens themselves can also be regarded as invasive species (Van Helden et al., 2020).
26 Recreational fisheries can spread pathogens through live bait, fish stocking, and contaminated
27 angling equipment, thereby causing disease and mortality in important fish species (Boonthai et al.,
28 2018; McEachran et al., 2023; Smith et al., 2020), and resulting in population declines, local
29 extinctions, and ecosystem-level changes (Crowl et al., 2008; O'Hanlon et al., 2018). The stocking
30 of salmonids is one of the causes of the global spread of bacterial kidney disease (BKD). BKD is a
31 chronic infection that poses a fatal threat to both farmed and wild salmonids. The disease is highly
32 cryptic: infected fish may show no obvious symptoms for a considerable period, yet it can continue
33 to spread within fish populations and trigger costly management measures such as disinfection,
34 fallowing, and culling (Brynildsrud et al., 2014; Mahon et al., 2018). Some pathogens transmitted
35 through the live bait pathway can infect fish reproductive tissues and significantly reduce
36 reproductive capacity (McEachran et al., 2021). In live bait fish from retail bait shops in Michigan,

1 United States, large numbers were found to carry the Asian fish tapeworm *Schyzocotyle*
2 *acheilognathi*, and infected fish may suffer pathological consequences such as abdominal swelling,
3 intestinal wall expansion, intestinal blockage, and hemorrhage (Boonthai et al., 2017).

4 5 ***Management and Policy Implications***

6 At the policy and legislative level of recreational fisheries, practices vary considerably across
7 regions and countries. Because the removal of established non-native populations from large water
8 bodies is difficult, the prevention of aquatic invasive species (AIS) is more cost-effective than post-
9 invasion response, and management efforts therefore usually focus on prevention (Britton et al.,
10 2008; Lovell et al., 2006; Seekamp et al., 2016). When new non-native fish introductions occur, the
11 key to effective management lies in early detection, preferably through identification and monitoring
12 before population establishment, followed by appropriate intervention measures, such as the
13 eradication of high-risk species (Britton et al., 2011; Vander Zanden et al., 2010). Because non-
14 native species richness is usually still low and their spatial distribution remains limited during the
15 early stages of invasion, early detection can often significantly reduce the resources required for
16 eradication (Britton et al., 2011). Many countries and regions have already formulated relevant laws,
17 regulations, and policies to address the biological invasion risks that may be caused by recreational
18 fisheries (Arlinghaus et al., 2002). Importantly, recreational fisheries-mediated introductions should
19 not be viewed simply as the result of deliberately reintroducing non-native species; rather, they arise
20 from a complex set of interacting pathways, including formal and informal stocking, live bait trade
21 and release, contaminated equipment and boats, accidental transport of associated organisms, and
22 behavioural decisions shaped by angling culture, regulation, and enforcement.

23
24 In terms of specific management measures, managers mainly reduce the biological invasion
25 risks associated with recreational fisheries through introduction approval, stocking restrictions, live
26 bait management, and public participation. For example, in the United Kingdom, all fish proposed
27 for introduction must undergo strict risk assessment (Copp, 2013); to protect the genetic purity of
28 wild brown trout, the United Kingdom also requires that brown trout stocked in rivers must be sterile
29 triploids, in order to prevent mating between farmed and wild fish and the resulting degradation of
30 wild populations (Environment Agency, 2009); EIFAC has also proposed that the introduction of
31 non-native species for the purpose of developing fisheries should be avoided, and where
32 introduction is considered necessary, it must comply with relevant regulations, undergo independent
33 expert review, and encourage recreational fishery groups to participate in the reporting, removal,
34 and biosecurity management of non-native invasive species (Council of Europe, 2014); New
35 Zealand stipulates that, without written authorization, sport fish or their eggs may not be transferred
36 from one catchment to another (Department of Conservation, 1983). Scotland, Bavaria in Germany,

1 Ireland, some states in the United States, and some provinces in Canada prohibit or restrict the use
2 of live bait fish (Britton et al., 2008; Mulligan et al., 2025; Winfield & Durie, 2004). Relevant
3 regulations in Illinois, United States, require anglers to hold fishing licenses, require fish stocking to
4 be approved, prohibit the release of unused live bait, and prohibit the transfer of wild-caught live bait
5 to other water bodies (Illinois General Assembly, 2015). In addition to legal restrictions,
6 communication with and participation by recreational anglers are also considered one of the key
7 factors in promoting the effective management and sustainability of recreational fisheries (Cooke et
8 al., 2013; Delle Palme et al., 2016), and educational activities can therefore serve as an important
9 preventive management strategy. The Government of Canada has proposed that one of the keys to
10 preventing future introductions of non-native species is to provide the public with data and
11 information and to involve them directly in invasive species management (Environment Canada,
12 2004). Many developed countries have also established relevant organizations to increase public
13 awareness of invasive species through public participation, demonstration, and educational
14 activities, and to encourage the public to participate in preventing the spread of invasive species
15 through control, monitoring, and prevention programs (Funnell et al., 2009; Winfield & Durie, 2004).

16
17 To address the risk of aquatic invasive species being spread by fishing gear and boats during
18 recreational fisheries activities, an international preventive management framework represented by
19 “Check, Clean, Dry” has gradually been established. This measure originated in New Zealand
20 (Ministry for Primary Industries, 2026) and was later adopted by multiple countries and regions,
21 including the United Kingdom, Ireland, and the European Union (Council of Europe, 2014; Inland
22 Fisheries Ireland, 2013; Smith et al., 2020), reflecting a shared management approach aimed at
23 reducing the risk of cross-waterbody spread through behavioral regulation. The United States
24 launched “Stop Aquatic Hitchhikers! (SAH!)”, encouraging anglers to conduct “Clean, Drain, Dry”
25 procedures each time before leaving a water body (Golebie et al., 2021; U.S. Fish & Wildlife
26 Service, 2021). At the same time, some states have further incorporated relevant requirements into
27 legislation. For example, in Illinois, all equipment (bait bucket, livewell, bilge) must be emptied
28 before leaving a water body (Illinois Department of Natural Resources, 2015), and boats with
29 attached aquatic organisms are not allowed to enter new water bodies (Illinois General Assembly,
30 2013). However, such legal and regulatory frameworks remain absent, incomplete, or weakly
31 enforced in many countries, particularly where recreational fisheries are expanding but have not yet
32 been formally recognized as a distinct management sector. In these contexts, non-native species
33 introductions associated with angling may fall between conventional fisheries management,
34 aquaculture regulation, biodiversity conservation, and biosecurity policy, creating institutional gaps
35 that allow risky practices to persist.

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Conclusion

Recreational fishing is an important but still under-recognized pathway for the global introduction and spread of aquatic non-native species. By synthesizing evidence from existing studies, this review shows that invasion risks associated with recreational fisheries are taxonomically diverse, geographically uneven, and mediated by multiple interacting pathways. These pathways can generate substantial ecological impacts, including predation, competition, hybridization, disease transmission, food-web alteration, and economic costs. However, current research remains strongly biased toward North America and Europe, while regions with large recreational fishing participation, such as Asia and parts of the Global South, remain poorly studied. This mismatch may lead to systematic underestimation of invasion risks. Effective management therefore requires moving beyond species-by-species responses toward pathway-based prevention, stronger regulation of stocking and live bait use, improved biosecurity for fishing equipment and boats, and greater engagement with anglers. Recognizing recreational fishing as a distinct and globally significant invasion pathway is essential for safeguarding aquatic biodiversity while sustaining the social and economic benefits of angling.

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Author contributions

J.S. conceptualized, managed and coordinated the study. H.Y. and J.S. carried out data organization, prepared the figures, and wrote the original draft. H.Y., P.J.H., R.J.B., A.S.T., E.J., S.M.G., H.M., Y.X. and J.S. reviewed and edited the manuscript. All authors approved the final version of the manuscript.

Declaration of interests

The authors declare no competing interests.

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