Science of the Total Environment 1005 (2025) 180872

Contents lists available at ScienceDirect

Science of the Total Environment

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

Global recreational consumption of non-native inland fish: higher economic benefits, but lower nutritional value and climate resilience

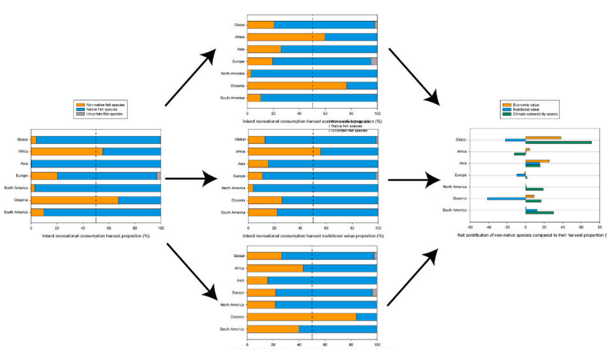
Marco Milardi [a,*], Louisa E. Wood [b], Elizabeth A. Nyboer [c], Holly S. Embke [d], Sui C. Phang [e], Abigail J. Lynch [f]

[a] Southern Indian Ocean Fisheries Agreement (SIOFA), 13 Rue de Marseille, 97420, Le Port, La Réunion
[b] University of Portsmouth, Winston Churchill Ave, Southsea, Portsmouth, PO1 2UP, United Kingdom
[c] Virginia Polytechnic Institute and State University, Blacksburg, VA, 24061, United States
[d] U.S. Geological Survey, Midwest Climate Adaptation Science Center, 1954, Buford Ave St. Paul, MN, 55108, United States
[e] The Nature Conservancy, Fairfax Drive, Suite 100, Arlington, VA 22203-1606, United States
[f] U.S. Geological Survey, National Climate Adaptation Science Center, 12201 Sunrise Valley Drive, MS-300, Reston, VA, 20192, United States

HIGHLIGHTS

- Non-native fish contribute 4 % of global inland harvest but 38.2 % economic value.
- Non-native species reduce nutritional value (−21.9 %) despite economic benefits.
- Non-native fish increase climate vulnerability (+70.9 %) in recreational fisheries.
- Regional complexities reveal socio-ecological trade-offs in fisheries management.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Inland recreational fisheries
Non-native species
Economic value
Nutritional value
Climate vulnerability
Global impacts

ABSTRACT

Inland recreational fisheries are globally significant leisure pursuits, with well-documented benefits to human health and well-being, but also one of the principal drivers of non-native fish introductions to enhance fishing opportunities, whether for sport or sustenance. In this study, we assess the relative reliance of global inland recreational fisheries on non-native versus native species for harvest. We further examine how this reliance varies by economic and nutritional value as well as the climate vulnerability of the species involved. We demonstrate that, of the 1,325,851 t of inland recreational fishes recreationally harvested for consumption worldwide in 2021, non-native fish were a small proportion (4 %; 53,651 t). On a global scale, non-native fish contributed a net positive 38.2 % economic value to inland recreational harvest. However, they also contributed a net negative −21.9 % nutritional value to inland recreational harvest. Non-native fishes were also more climate vulnerable (i.e., higher average climate vulnerability index values) and thus proportionally increased overall estimates of climate vulnerability with a net positive of 70.9 %. Our results quantitatively demonstrate that non-native species play a more important role in inland consumptive recreational fisheries than their mere harvest

* Corresponding author.
E-mail address: marco.milardi@gmail.com (M. Milardi).

https://doi.org/10.1016/j.scitotenv.2025.180872
Received 29 May 2025; Received in revised form 31 October 2025; Accepted 31 October 2025
Available online 6 November 2025

volume would suggest. However, many nuances were seen on the continent and country scale, which reflect the complexity of fisher behavior, fish distribution and socio-economic factors. Our findings help unravel the complex effects of non-native species on human activities and underscore the need to evaluate their global impacts holistically.

1. Introduction

Inland recreational fisheries in rivers, streams, lakes, and other landlocked waters, are globally significant fishing activities, with well-documented benefits to human health and well-being (Cooke et al., 2024). These fisheries hold social and cultural significance, attracting participants of all ages and fostering social cohesion (Villamagna et al., 2014), as well as providing economic value for many communities. For instance, the inland recreational fisheries of the Great Lakes sustain a charter industry valued at $611 million USD (Whitehead et al., 2025). However, while the personal and community benefits of inland recreational fishing are well-recognized, the ecological consequences of recreational fisheries management, particularly the introduction of non-native fish species, remain a critical concern.

Non-native species are species introduced outside of their native range by humans, and recreational fishing is one of the principal drivers of non-native fish introductions into inland waters to enhance fishing opportunities, whether for sport or sustenance (Davis and Darling, 2017). According to Carpio et al. (2019), angling activities have facilitated the establishment of numerous non-native fish species. Iconic species like largemouth bass (*Micropterus salmoides*), common carp (*Cyprinus carpio*), and rainbow trout (*Oncorhynchus mykiss*) have been widely introduced for recreational purposes. As Thomas et al. (2023) highlighted, non-native fish species may substitute native species in angler catches, triggering cascading effects on local ecosystems and complicating management efforts.

The deliberate or accidental introduction of non-native fish species into inland waters can displace native species and alter aquatic ecosystems, with profound implications for biodiversity and ecosystem functioning (e.g., Milardi et al., 2020; Britton, 2023). Furthermore, some non-natives can become invasive, leading to severe ecological and economic disruptions. Effects can range from declines in native biodiversity and ecosystem services to rising management costs associated with population control (Haubrock et al., 2022). These burdens are not only borne by governments and conservation agencies but also by communities reliant on healthy ecosystems for their livelihoods. Despite these risks, some non-native species can also contribute to recreational fisheries in ways that merit careful consideration (Ewel et al., 1999), highlighting the need for balanced evaluations.

While the negative impacts of non-native fish introductions have been extensively studied (e.g., Cambray, 2003; Cucherousset and Olden, 2011; Milardi et al., 2022), less attention has focused on their potential benefits (e.g., Gozlan, 2008; Kleitou et al., 2022), particularly at a global scale. Non-native fishes can support economically valuable recreational fisheries, driving economic activity through tourism, job creation, and food production. For example, activity associated with inland recreational fisheries for non-native trout in New Zealand were estimated to reap around $750 million NZD annually in 1998 (Department of Conservation, 1998). Evaluating where non-native fish populations provide net benefits can help to inform trade-offs and management interventions.

Recent recognition of the need for a more holistic approach to managing the complex issue of non-native species has spurred some studies emphasizing the importance of balanced assessments that consider both their positive and negative contributions (e.g., Schlaepfer et al., 2011; Sax et al., 2022). Although ongoing debates raise concerns over the dangers of this line of thought, increasing studies documenting the use-value of some non-native species make it compelling to at least investigate it (Hickley et al., 2015; Vimercati et al., 2022). The dataset compiled by Embke et al. (2022) offers a valuable resource for assessing the trade-offs between economic and nutritional value and climate risk in global inland recreational fisheries that harvest non-native and native species for consumption. Given the complex and often conflicting effects of non-native fish introductions, these data present a critical opportunity to further investigate their global effects.

In this study, we assess the relative reliance of global inland recreational fisheries on non-native versus native species for food harvest. We further examine how this reliance varies by economic and nutritional value as well as the climate vulnerability of the species involved. Our findings help unravel the complex effects of non-native species on human activities and underscore the need to evaluate their global effects holistically.

2. Materials and methods

2.1. Recreational fisheries data overview

We analyzed a global dataset of recreationally harvested inland fish for consumption (Embke et al., 2022), which included data on harvest volume, economic value, nutritional value (e.g., vitamin B12), and climate vulnerability data from 64 countries and 178 unique harvested taxa. While harvest data covered all 64 countries, economic, nutritional, and climate vulnerability data were available for 58, 59, and 46 countries, respectively (Supplementary Table S.1). Although the dataset broadly represented global inland recreational fisheries, Africa was underrepresented due to gaps in reliable data and potentially low participation rates.

In the Embke et al. (2022) dataset, harvest volumes were estimated using a hierarchical approach. They used direct summation of species-specific harvest (applied when species-specific harvest weight estimates were available), biomass conversion from abundance data (applied when species-specific harvest abundance numbers were known, but not biomass), spatial extrapolation of local harvest rates (applied when harvest data existed only for limited regions within a country), "nearest neighbor" harvest rate borrowing (applied when no national harvest data existed, but species contributions were known), and finally Expert Knowledge Elicitation for all those other countries were no empirical data existed.

We used proxies for non-native fish species relative economic and nutritional values to explore their relevance in recreational fisheries (sensu, Lynch et al. (2024). For a proxy of economic value, we used the total consumptive use value of recreational catch per fisher (Thorpe et al. in Smith, 2018), and standardized it as a share of Gross Domestic Product (GDP) per capita adjusted for purchasing power parity, to allow for global comparisons (Lynch et al., 2024). For a proxy of nutritional value, we focused our main analyses on vitamin B12, as it is an essential micronutrient that is abundant in aquatic species and important for human health. We calculated the vitamin B12 content in the estimated edible portion of fish annually consumed by a recreational fisher, and standardized using the national annual vitamin B12 intake from all sources, to allow for global comparisons (Lynch et al., 2024).

We also used a proxy for the relative contribution of non-native species to the overall country-level climate vulnerability of fishes recreationally harvested for consumption. The climate vulnerability index developed by Nyboer et al. (2021) provides a numerical climate change vulnerability value based on three contributing components: sensitivity and adaptive capacity (based on species ecological and biological traits) and exposure (based on climate projections across a species' range)

(Nyboer et al., 2021; Lynch et al., 2024). We selected the most conservative emission scenario (RCP 4.5) and the longest-term projection (average 2075) to provide a balanced perspective on the range of values available. Various sensitivities of this proxy are discussed in further detail within Nyboer et al. (2021).

2.2. Classification into native and non-native species

We compiled inland fish species occurrence and native/non-native status data from FishBase (Froese and Pauly, 2025) for all countries in the Embke et al. (2022) dataset. After standardizing taxonomic nomenclature to ensure consistency, species were classified as native (naturally occurring within a country's biogeographic range) or non-native (introduced beyond their native range, intentionally or unintentionally). Spatial units followed UN-recognized political country boundaries, aligning with the resolution of the recreational harvest for consumption dataset. We acknowledge that some species are native to parts of a country but non-native in others; thus, our classifications are conservative, potentially underestimating non-native contributions, particularly for larger countries (e.g., in our analysis, trouts are one taxonomic unit for the United States and are considered native even though trout species have been frequently introduced across the country outside their native ranges).

From 18,331 FishBase records, we calculated native-to-non-native species ratios per country as a proxy for non-native availability to recreational fisheries (with the *caveat* that not all non-native species are relevant for recreational fisheries harvest for consumption). We then explored correlations between non-native fish availability and their recreational harvest for consumption.

2.3. Taxonomic Uncertainty

For 57 records in the Embke et al. (2022) dataset lacking species-level resolution (e.g., genus/family-level data), native/non-native status was assigned to 44 records using expert knowledge and the following criteria:

- Native: All species in the taxon occurred natively in at least 1 region of the country.
- Non-native: All species in the taxon were introduced (e.g., trout in Australia).

For the remaining 13 records, the native/non-native status could not be resolved and they were labeled "uncertain" (Supplementary Table S.2) and retained to maintain dataset completeness. These included taxa like the family Cyprinidae (nei), which were too broad to be resolved into either category.

2.4. Data analysis

We calculated the proportion of harvest weight (t), economic value and nutritional value, and climate vulnerability contributed by non-native species in each country (Embke et al., 2022; Lynch et al., 2024).

We quantified non-native contributions by comparing their recreational harvest for consumption proportion to their economic and nutritional value contribution proportion at the national scale:

- Added value: Value contribution > harvest proportion (e.g., non-natives provide disproportionately more economic value than expected based on their harvest proportion).
- Diminished value: Value contribution < harvest proportion (e.g., non-natives proportionally yield less nutritional value than expected based on their harvest proportion).

We similarly quantified non-native contributions to national scale estimates of climate vulnerability of recreational fish.

- Added value: Climate vulnerability contribution proportion > harvest proportion (e.g., non-natives have higher vulnerability index values than natives and thus contribute disproportionately to total climate vulnerability estimates than expected based on their harvest proportion).
- Diminished value: Climate vulnerability contribution proportion < harvest proportion (e.g., non-natives have lower vulnerability index values than natives and thus contribute less than expected based on harvest proportion).

Results were aggregated at the continental scale by summing all the national effects, and at the global scale by summing all the continental effects.

All data handling and presentation were conducted using R software (R Core Team 2025).

3. Results

Global native/non-native fish diversity and non-native fish availability to recreational fisheries.

Total inland fish species diversity was relatively higher in countries extending over large areas and closer to the equator, both in Asia and South America (Supplementary Fig. S.1a). Conversely, the proportion of non-native species was higher in countries in Europe and North Africa, with notable exceptions like New Zealand and Chile (Supplementary Fig. S.1b). No correlations between non-native fish availability and their recreational harvest for consumption were found (Supplementary Fig. S.2).

3.1. Global non-native fish recreational harvest for consumption

With 53,651 t harvested in 2021, non-native fish were a small proportion (4 %) of all estimated inland recreational harvest for consumption worldwide (1,325,851 t) (Fig. 1). Recreational harvest for consumption volumes were highest in Asia (867,602 t), followed by North America (244,650 t), Europe (161,467 t), South America (40,334 t), Oceania (9254 t) and Africa (2543 t).

On a continental scale, non-native fish constituted a significant proportion of estimated inland recreational harvest for consumption in Oceania (67.3 %) and Africa (55.3 %) but were a smaller proportion in Europe (20.5 %). Other continents had even smaller proportions of non-native species recreational harvest for consumption: South America (9.8 %), North America (2.9 %) and Asia (0.2 %) (Fig. 1).

At the country level, the proportion of non-native fish recreational harvest for consumption was significant (≥50 %) in 25 % of the countries for which data was available (14 countries, Supplementary Fig. S.3). Conversely, 17 countries stood out as harvesting exclusively native species in their inland recreational fisheries for consumption (Supplementary Fig. S.3).

3.2. Global value of non-native fish in recreational consumption harvest

Non-native species accounted for 20.6 % of the global extracted consumptive value per annum per inland recreational fisher (Fig. 2). They also accounted for 12.8 % of the global vitamin B12 intake per fisher per annum from inland recreational harvest for consumption, as a share of annual intake from all sources (Fig. 2). Finally, non-native species contributed 26.6 % of global inland recreational harvest for consumption fisheries climate vulnerability (Fig. 2).

On a continental scale, non-native fish constituted a significant proportion of estimated economic value from inland recreational harvest for consumption in Oceania (76.4 %), Africa (59.7 %) and Asia (25.7 %) but were a smaller proportion in Europe (19.4 %) (Table 1). Other continents had even smaller proportions of economic value from non-native species recreational harvest for consumption: South America (10.3 %) and North America (2.8 %) (Table 1). At the country level, non-

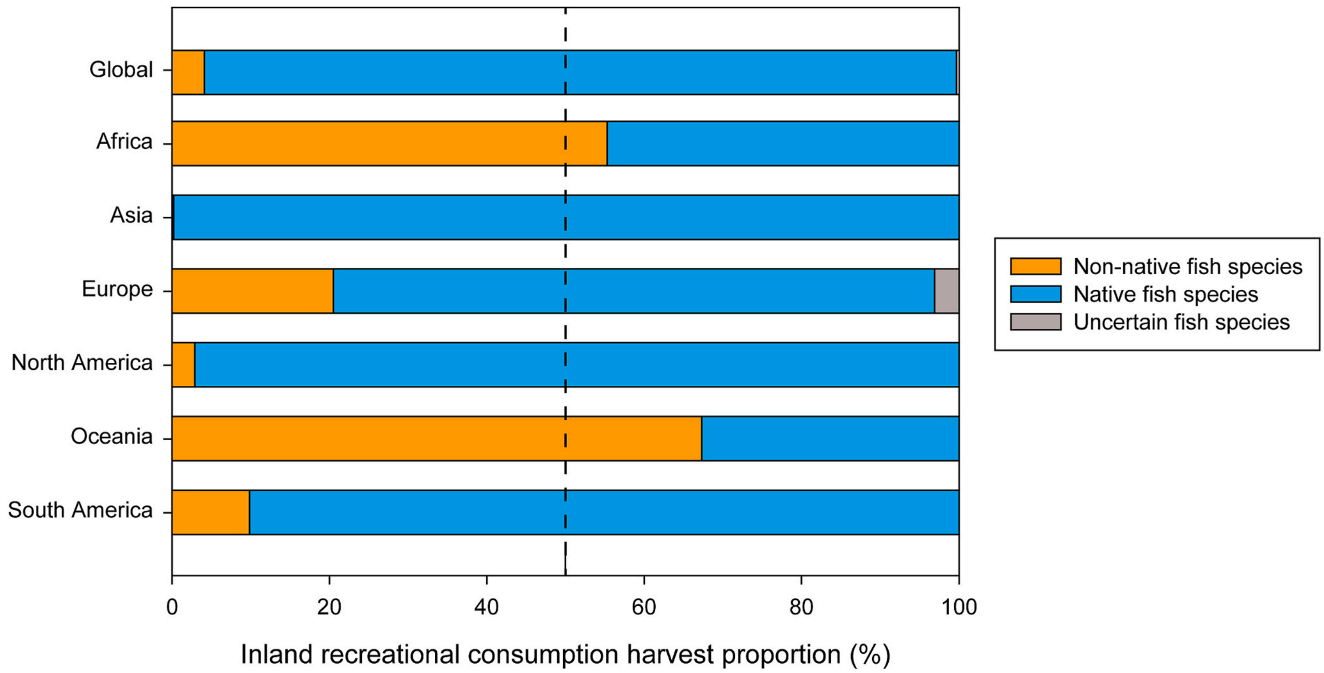


Fig. 1. – Proportion of native and non-native species in inland recreational harvest for consumption by continent and globally. Values in gray represent the harvest of taxa that could not be defined as either native or non-native. Dashed line provides a reference to 50 % proportion. Species were classified as native (naturally occurring within a country's biogeographic range) or non-native (introduced beyond their native range, intentionally or unintentionally).

native species provided a substantial (≥50 %) proportion of economic value in several countries (see Supplementary Fig. S.4).

On a continental scale, non-native fish constituted a significant proportion of estimated nutritional value from inland recreational harvest for consumption in Africa, but were a smaller proportion in Oceania and South America (Table 1). Other continents had even smaller proportions of nutritional value from non-native species recreational harvest for consumption: Asia, Europe and North America (Table 1). At the country level, non-native species provided a substantial (≥50 %) proportion of nutritional value in some countries (see Supplementary Fig. S.4).

On a continental scale, non-native fish constituted a significant proportion of estimated inland recreational harvest for consumption climate vulnerability in Oceania, Africa, and South America, but were a smaller proportion in Europe and North America (Table 1). Asia had even smaller proportions of non-native species recreational harvest for consumption nutritional value (Table 1). At the country level, non-native species provided a substantial (≥50 %) proportion of the climate vulnerability scores of several countries (see Supplementary Fig. S.4).

3.3. Global contribution of non-native fish in recreational harvest for consumption

On a global scale, non-native fish contributed a net positive 38.2 % economic value to inland recreational harvest for consumption (Fig. 3), when compared to their share of the harvest volume. However, they also contributed a net negative −21.9 % nutritional value to inland recreational harvest for consumption and increased the climate vulnerability with a net positive of 70.9 % (Fig. 3).

On a continental scale, non-native fish contributed a net positive inland recreational harvest for consumption economic value in Asia, Africa and Oceania (Table 2), indicating that in these continents non-native species might increase the total economic value of inland recreational fishing harvest for consumption. However, non-native fish contributed a negligible net positive in South America and net negatives in Europe and North America (Table 2). At the country level, non-native species provided significant net benefits in terms of economic value, compared to their harvest proportion, in most countries (Supplementary Fig. S.5).

On a continental scale, non-native fish contributed a net positive inland recreational harvest for consumption nutritional value in Asia and South America (Table 2), indicating that in these continents non-native species might increase the total nutritional value of inland recreational fishing harvest. However, non-native fish contributed a negligible net positive in North America and Africa, and net negatives in Europe and Oceania (Table 2), indicating that in these continents non-native species might decrease the total nutritional value of inland recreational fishing harvest. At the country level, non-native species provided negligible net benefits in terms of nutritional value, compared to their harvest proportion (Supplementary Fig. S.5).

On a continental scale, non-native fish contributed a net positive inland recreational harvest for consumption climate vulnerability in South America, North America, Oceania, Asia and Europe (Table 2), indicating that in these continents non-native species might be proportionally more climate vulnerable than native species, thus increasing the total climate vulnerability of inland recreational fishing harvest. A net decrease in climate vulnerability was found only in Africa (Table 2). At the country level, non-native species provided net increases in terms of climate vulnerability, compared to their harvest proportion (Supplementary Fig. S.5).

4. Discussion

While the role of inland recreational fisheries in global food systems is generally underappreciated, the role of non-native fishes in inland recreational harvest for consumption is complex, and even less considered (Arlinghaus et al., 2019). Our results indicate that non-native fish are a small proportion of all estimated inland recreational harvest for consumption worldwide.

This research takes a more nuanced consideration of the potential economic and nutritional contributions of non-native inland recreational fisheries at different spatial scales while acknowledging the climate vulnerability of these important fisheries. Our results

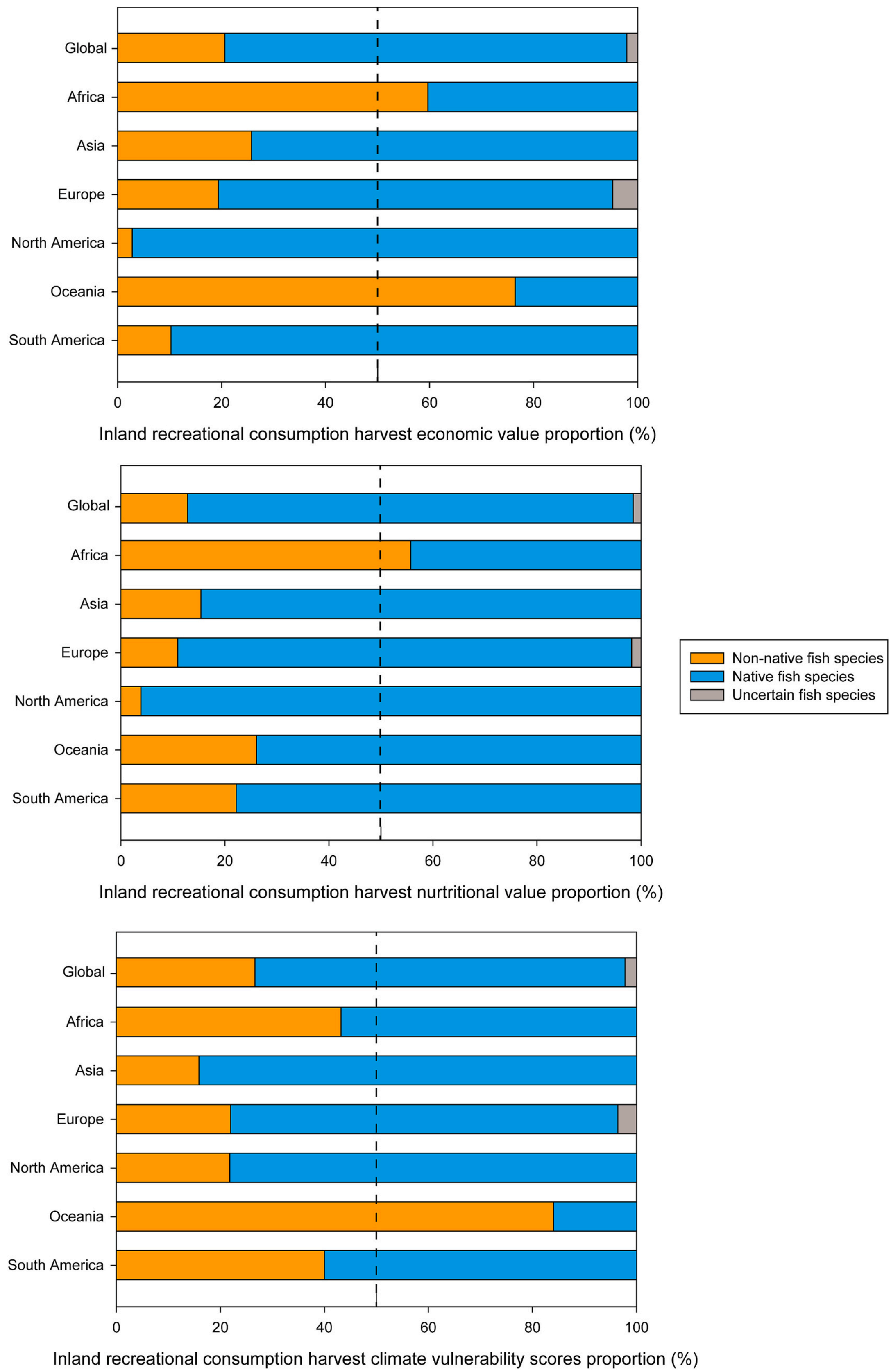


Fig. 2. – Proportion of native and non-native species contribution to economic and nutritional value, and climate vulnerability scores, in inland recreational consumption harvest by continent and globally. Values in gray represent the harvest of taxa that could not be defined as either native or non-native. Dashed lines provide a reference to 50 % proportion. Species were classified as native (naturally occurring within a country's biogeographic range) or non-native (introduced beyond their native range, intentionally or unintentionally).

Table 1
Proportion of non-native species contribution to economic and nutritional value, and climate vulnerability, in inland recreational fisheries harvest for consumption.

Continent	Non-native species harvest (%)	Non-native species economic value (%)	Non-native species nutritional value (%)	Non-native species climate vulnerability (%)
Global	4	20.6	12.8	26.6
Africa	55.3	59.7	55.7	43.2
Asia	0.2	25.7	15.4	15.9
Europe	20.5	19.4	10.9	22.0
North America	2.9	2.8	3.8	21.8
Oceania	67.3	76.4	26.1	84.1
South America	9.8	10.3	22.2	40.0

quantitatively demonstrate that non-native species play a more important role in inland consumptive recreational fisheries than their mere harvest volume would suggest. Despite their low contribution to inland recreational harvest for consumption, non-native species provided added net economic value on the global scale but provided net negative nutritional value and have relatively higher climate vulnerability compared with native species recreational harvest for consumption. However, the proportion of recreational harvest for consumption that comprises non-native fish was spatially heterogeneous, with some countries harvesting only native species. Our results may be explained by a complex interaction between region-specific species preferences for consumption, and geographical trends in the introduction and establishment of non-native fish species.

Fishers target fish species for consumption based on species preferences that are region-specific, and other cultural and economic considerations, among other reasons (Lynch et al., 2024). This study was only limited to consumptive inland recreational fisheries and, therefore, cannot be extrapolated to assess non-native fish contributions to *all* inland fisheries (e.g. commercial or catch-and-release fisheries). This could also contribute to explain the lack of correlation between recreational harvest for consumption of non-native fishes and their availability, which can be affected by fisher target selection criteria as well as the local abundance (not the mere presence) of non-native species.

Non-native fish species, whilst often introduced intentionally to support recreational fisheries (Carpio et al., 2019), may not be primarily introduced to support recreational harvest for consumption. Other motivations for purposeful introductions may include e.g. the establishment of catch-and-release fisheries (da Silva Ladislau et al., 2025). The nature of recreational fisheries may also change over time: for example, non-native fish species that were originally introduced to enhance fisheries harvest, may later become a focus of catch-and-release fisheries. In Italy, rainbow trout (*Oncorhynchus mykiss*) were introduced in 1891 to enhance recreational fisheries (Stanković et al., 2015), which at that time were primarily harvest fisheries. However, today rainbow trout is also a popular species in catch-and-release fisheries (Milardi unpublished data). Similarly, in New Zealand, brown trout (*Salmo trutta*,

Table 2
Non-native species contribution to economic and nutritional value, and climate vulnerability, in inland recreational fisheries harvest for consumption, compared to their harvest volume. Added value: Value contribution > harvest proportion (e.g., non-natives provide disproportionately more economic value than expected based on their harvest proportion). Diminished value: Value contribution < harvest proportion (e.g., non-natives proportionally yield less nutritional value than expected based on their harvest proportion).

Continent	Economic value contribution (%)	Nutritional value contribution (%)	Climate vulnerability contribution (%)
Global	38.2	−21.9	70.9
Africa	4.4	0.4	−12.1
Asia	25.5	15.2	15.7
Europe	−1.1	−9.6	1.5
North America	−0.1	0.9	18.9
Oceania	9.1	−41.2	16.8
South America	0.4	12.3	30.2

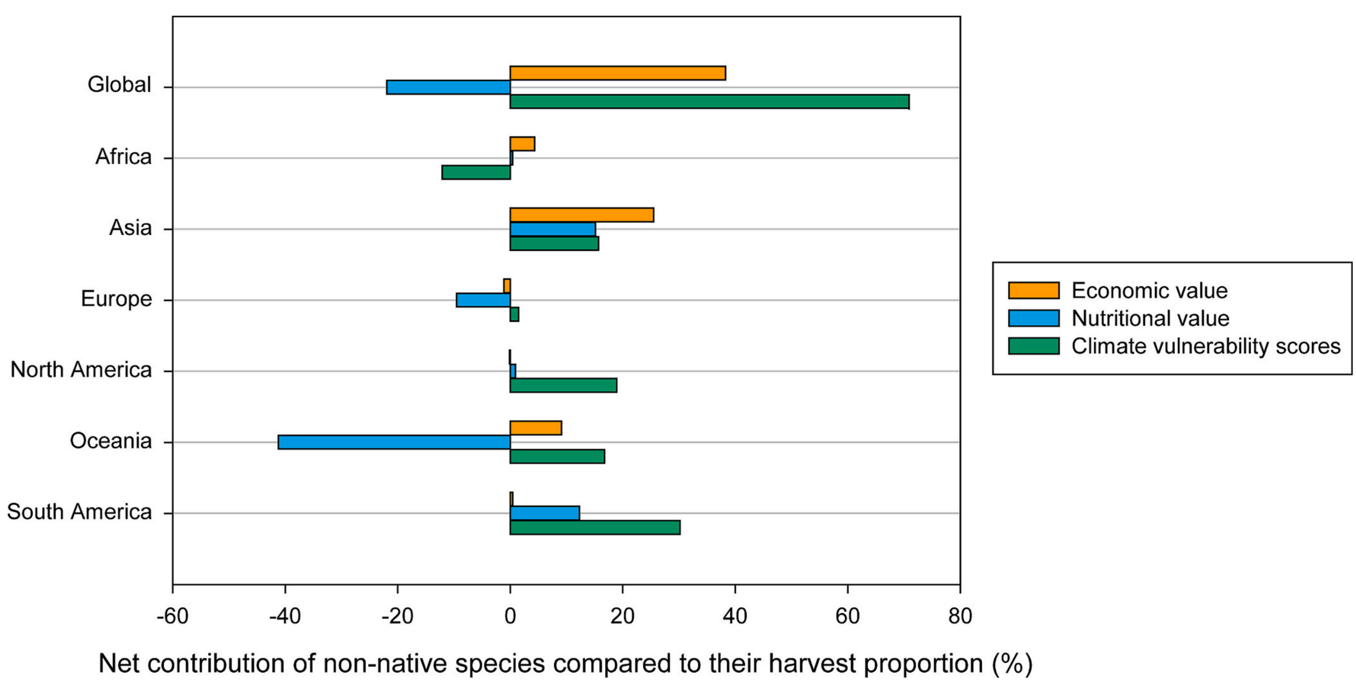


Fig. 3. – Non-native species net contribution to economic and nutritional value, and climate vulnerability scores, in inland recreational consumption harvest by continent and globally. Species were classified as native (naturally occurring within a country's biogeographic range) or non-native (introduced beyond their native range, intentionally or unintentionally).

Salmonidae) and rainbow trout were originally introduced to support harvest fisheries and now are predominantly catch-and-release fisheries (Milardi unpublished data).

4.1. Economic value

While the environmental costs and negative economic externalities of invasive non-native fish species—such as habitat degradation, disease transmission, and native biodiversity loss—have been extensively quantified (e.g., Pimentel et al., 2005; Cuthbert et al., 2021), their potential economic contributions to recreational inland fisheries for consumption remain understudied at a global scale. This analysis represents the first holistic evaluation of non-native fish species' economic value within recreational harvest for consumption systems, revealing a global net economic benefit derived from their utilization. Specifically, non-native species generated a higher net revenue per unit harvest weight (kg) compared to native species (Fig. 2), a disparity driven by their larger average body sizes, higher catchability, and premium market pricing in regions where they are culturally prized (e.g., rainbow trout *Oncorhynchus mykiss* in Chilean Patagonia; Vigliano et al., 2007, Soto et al., 2006).

North America represented a notable exception, with a marginal net loss of economic value attributed exclusively to non-native sunfish (*Lepomis* spp.) and bass (*Micropterus* spp.) harvest in Mexico (Fig. 2). In North America, particularly in the United States, many of the harvested non-native fish species are actually native to certain regions of the continent and were thus assessed to be native according to the criteria and resolution of our assessment. This creates the impression that North American countries harvest fewer non-native fish in their inland recreational fisheries compared to an assessment with higher taxonomic and geographical resolution. Although much harvest for consumption in Canada and the USA is likely to be from non-native fish, causing significant management issues, our analysis missed national non-natives if those fish are native to other parts of the country and/or reported at the Family level. Our data also showed that Europe had a marginal net loss in economic value, driven by countries like Romania, Spain and Belgium, where harvest focuses on less economically valuable non-native cyprinid species (Fig. 2, Supplementary Fig. S.5). This is a good example of national outcomes showing more nuances than can be detected at a continent level analysis, underscoring the interplay of ecological, cultural, and regulatory factors.

Here, the proxy used for economic value was chosen to represent recreational fish contributions to global fish harvest for consumption (Lynch et al., 2024). It is important to note that since recreational consumption is not market based, this valuation is based on 'shadow' prices of the closest comparable (based on expert choice or taxonomic similarity) offering in local market prices (Lynch et al., 2024). These findings assume stable market conditions and static regulatory frameworks, yet emerging factors—such as climate-driven range shifts altering species availability or evolving cultural perceptions of non-native fish—could reshape economic outcomes (Barnes et al., 2022). Additionally, long-term costs of biodiversity loss (e.g., reduced ecosystem resilience), as well as management costs, were excluded from this valuation, potentially overstating net benefits (Diagne et al., 2020). Finally, choosing different metrics for the evaluation of economic value, such as e.g. the total spending on recreational sport fisheries, would emphasize the economic value of sport fisheries in developed countries, while underemphasizing the importance of sustenance fisheries in less developed countries.

4.2. Nutritional value

Globally, inland recreational fisheries harvest reliant on non-native species exhibited a net negative nutritional value relative to systems dominated by native taxa, suggesting that non-native fish often provide less nutrient provisioning capacity than native fish. This result aligns with comparative analyses showing that non-native fish frequently exhibit lower concentrations of essential micronutrients (e.g., omega-3 fatty acids, iron) critical to human health (Byrd et al., 2021). The combination of different selection criteria by which intentional fish introductions are carried out (e.g., for catch-and-release sport fisheries rather than for nutritional purposes) and the nature of unintentional introductions would also align with our results.

Continental-scale patterns revealed marked deviations from global trends. Asia and South America demonstrated net positive nutritional gains, driven by targeted harvests of nutrient-dense non-native species. For example, South American fisheries might have benefited from introduced rainbow trout (*Oncorhynchus mykiss*), which offset declines in native fish (Soto et al., 2006). Conversely, Oceania experienced a net negative gain, attributable to the dominance in harvest of low-nutrient species like European perch (*Perca fluviatilis*) displacing native nutrient-rich staples like golden perch (*Macquaria ambigua*).

These disparities reflect species-specific nutrient profiles, harvest practices, and potentially ecological displacement of native species. While these projections highlight systemic risks, they assume static nutrient compositions and harvest behaviors, and rely on the significance of vitamin B12 as an essential micronutrient important for human health (Golden et al., 2021). Climate-driven shifts in species physiology (e.g., altered lipid synthesis under warming, Yuan et al., 2022) and evolving dietary preferences (e.g., demand for plant-based proteins), as well as the choice of different proxies for nutritional value may modulate the outcomes of future studies. Furthermore, nutrient bioavailability—affected e.g. by cooking practices and gut microbiome interactions—remains poorly quantified in consumption models (Hunt, 2005).

4.3. Climate vulnerability

The introduction of non-native fish species into inland recreational fisheries amplified the overall climate vulnerability of these fisheries. This increased climate vulnerability was consistent across global, continental, and national scales, albeit with notable exceptions (Fig. 3, Supplementary Fig. S.5). For instance, while non-native salmonids (e.g., rainbow trout, *Oncorhynchus mykiss*, brown trout, *Salmo trutta*) enhanced harvest yields in temperate regions, their thermal sensitivity and habitat specificity rendered fisheries disproportionately susceptible to projected warming scenarios (Kovach et al., 2019; Gallagher et al., 2022). Conversely, African fisheries exhibited a moderate net reduction in climate vulnerability, driven by the widespread harvest of thermal and drought-tolerant cyprinids (e.g., common carp, *Cyprinus carpio*) in nations such as Zimbabwe, Kenya, and South Africa. These species demonstrate broader physiological tolerances to fluctuating hydrological regimes which is likely to reduce their sensitivity and increase their adaptive capacity in the face of predicted climate impacts (Matthews, 1998).

In Oceania and South America, the prevalence of non-native salmonids in recreational harvest for consumption exacerbated climate vulnerability due to mismatches between their thermal optima and projected temperature increases (Carlson et al., 2017). For example, salmonid-dominated fisheries in Chile, Australia, and New Zealand exhibited higher vulnerability scores, consistent with the narrow thermal safety margins of the salmonids harvested (Morrongiello et al., 2011). In contrast, African cyprinid fisheries benefited from these species' adaptability to variable flow regimes—a critical trait under climate models predicting intensified droughts and flash floods across the continent (Ahmadalipour et al., 2019).

This suggests that vulnerability is not merely a function of harvest volume but is modulated by species-specific climatic tolerances. For instance, although non-native species constituted 4 % of global recreational harvest for consumption (by biomass), they accounted for 26 % of aggregate vulnerability—a disparity likely largely driven by salmonids' outsized sensitivity to temperature extremes (Jonsson, 2023).

The observed patterns reflect the interplay between current harvest preferences and region-specific climate projections. In regions anticipating greater warming magnitudes (e.g., high-latitude zones) or hydrological instability (e.g., Mediterranean climates) non-native fish are sometimes projected to increase (Bernardo et al., 2003). However, these projections assume static species distributions and harvest practices, whereas anthropogenic adaptation (e.g., shifts in stocking policies, species availability and selection, habitat engineering) and climate-driven range shifts may alter future vulnerability trajectories. Our results suggest that the reliance of recreational harvest for consumption on non-native species would lead to an increased climate vulnerability for these fisheries, potentially decreasing future food security.

4.4. Future research

Although the current dataset reflects a single point in time and does not yet support analysis of temporal trends in non-native fish harvest for consumption, it represents an important foundation for future work. As the dataset continues to evolve through an iterative development process it may enable robust temporal assessments (Embke et al., 2022). Future studies could explore how non-native species contribution changes over time to better understand trends in recreational fishing harvest for consumption. Further, spatial variation in the non-native species contribution to economic and nutritional value, and climate vulnerability highlights a need for in-depth continental and country level assessment, in order to better understand the ecological and socio-economic factors that shape observed trends. Selecting other variables as proxies could also provide a deeper and more nuanced understanding of the contribution of non-native fish species to global food systems.

A notable proportion of countries in Europe (i.e., 11 out of 38) stood out as including a harvest of taxa that could not be unequivocally assigned to either the non-native or native category, a pattern that was not seen in other continents. This was likely due to the low taxonomic resolution of the Embke et al. (2022) data but might be also due to the complexity of European fish taxonomy and its long history of fish introductions which increase the complexity of the task. Future studies could consider improving the taxonomical and spatial resolution of data in order to better understand uncertainties associated with estimates of species status. For example, a higher taxonomical and spatial resolution of data could result in harvest proportions changing due to a more refined accounting of species status (e.g., better accounting for species that are non-native to parts of a country). Related to this, further analyzing and resolving the differences between non-native fish species availability and the subset targeted by recreational fisheries could shed further light on the main selection drivers, allowing for more refined considerations.

4.5. Management implications

Historically, non-native fishes have been introduced into ecosystems with minimal consideration for native biodiversity, resulting in widespread ecological harm (Cambray, 2003). As a leading driver of freshwater biodiversity loss, non-native species threaten aquatic ecosystems globally (Gallardo et al., 2016). Our study argues for evaluating non-native fish impacts not only ecologically but also socioeconomically, including their role in angler nutrition and the economic cost of substituting these catches with alternative food sources. Furthermore, assessing climate change resilience of introduced species is critical to quantifying their long-term costs and sustainability in recreational fisheries.

A holistic framework integrating ecological risks, nutritional contributions (and their replacement costs), and climate vulnerability could improve management decisions. These considerations are particularly urgent in regions where angling-caught fish constitute a large proportion of local diets or total consumption (e.g., in Africa). While non-native species in this study demonstrated higher economic value than natives, they exhibited lower nutritional value and greater susceptibility to climate change (Fig. 3). Such trade-offs necessitate a cultural shift in management paradigms, moving beyond narrow economic metrics to balance ecological, nutritional, and climatic risks.

Recreational harvest fisheries intersect with other fishing sectors, complicating management. Unlike commercial fishers who prioritize income, or recreational fishers who prioritize sport, some recreational fishers are subsistence fishers, and rely on catches for both food and income (Nyboer et al., 2022). This contingent of recreational fishers is, consequently, particularly vulnerable to non-native species impacts and are often excluded from recreational fishery governance. While precautionary management favoring native species (e.g., Zambia's Tiger Fish, *Hydrocynus vittatus*) is ideal, pragmatic compromises may be unavoidable. For example, South Africa's controversial largemouth bass introductions highlight tensions between ecological caution and socio-economic demands (Ellender et al., 2014).

5. Conclusions

Understanding the net contribution of non-native species to global systems is challenging (Sax et al., 2022). Our objective in this paper is simply to demonstrate the often ignored contribution of non-native fish species to inland consumptive recreational fisheries, which are an under-recognized and undervalued food source (Lynch et al., 2024). Our results demonstrate a far more nuanced context for non-native fish species than is given through the classical perspective of them being detrimental to human society and the natural environment (e.g., Pimentel et al., 2005; Jeschke et al., 2014).

Consumptive harvest of non-native fish plays an important, yet often undervalued role in the diets of recreational fishers and their dependents (Figs. 1, 2 and 3). Inland recreational fisheries consumption harvest varies across continents and countries, with some, like Morocco and Chile, primarily harvesting non-native species, while others, such as Nigeria and China, focus exclusively on native species. Non-native species may offer proportionally higher economic value to recreational harvest in some countries, like Ireland or Zimbabwe, but typically provide fewer nutritional benefits and have higher climate vulnerability than native recreational fisheries harvest for consumption. Considering a multi-dimensional approach that includes ecosystem threats, economic and nutritional value, and climate vulnerability can help recreational fisheries managers to make better-informed choices in a changing world.

CRediT authorship contribution statement

Marco Milardi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Louisa E. Wood:** Writing – review & editing, Writing – original draft, Conceptualization. **Elizabeth A. Nyboer:** Writing – review & editing, Visualization, Conceptualization. **Holly S. Embke:** Writing – review & editing, Data curation. **Sui C. Phang:** Writing – review & editing, Conceptualization. **Abigail J. Lynch:** Writing – review & editing, Conceptualization.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

All authors have no competing interest to declare.

Acknowledgements

We thank the coauthors of papers that served as the foundation for this work (Embke et al., 2022; Nyboer et al., 2022; Lynch et al., 2024) and Wesley Daniel for conducting an internal review of this paper for the U.S. Geological Survey. This work received no dedicated funding. Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the US Government.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.180872.

Data availability

The data used is already publicly available

References

Ahmadalipour, A., Moradkhani, H., Castelletti, A., Magliocca, N., 2019. Future drought risk in Africa: integrating vulnerability, climate change, and population growth. Sci. Total Environ. 662, 672–686.

Arlinghaus, R., J. K. Abbott, E. P. Fenichel, S. R. Carpenter, L. M. Hunt, J. Alós, T. Klefoth, S. J. Cooke, R. Hilborn, and O. P. Jensen. 2019. Governing the recreational dimension of global fisheries. Proc. Natl. Acad. Sci. 116:5209–5213, Proc. Natl. Acad. Sci. USA.

Barnes, M. A., A. M. Deines, R. M. Gentile, and L. E. Grieneisen. 2022. Adapting to invasions in a changing world: Invasive species as an economic resource. Pages 327–349 in Ziska L. H. and Dukes J. S. (eds) Invasive Species and Global Climate Change. CABI books, London, UK, 354 pages.

Bernardo, J.M., Ilhéu, M., Matono, P., Costa, A.M., 2003. Interannual variation of fish assemblage structure in a Mediterranean river: implications of streamflow on the dominance of native or exotic species. River Res. Appl. 19, 521–532.

Britton, J.R., 2023. Contemporary perspectives on the ecological impacts of invasive freshwater fishes. J. Fish Biol. 103, 752–764.

Byrd, K.A., Thilsted, S.H., Fiorella, K.J., 2021. Fish nutrient composition: a review of global data from poorly assessed inland and marine species. Public Health Nutr. 24, 476–486.

Cambray, J.A., 2003. Impact on indigenous species biodiversity caused by the globalisation of alien recreational freshwater fisheries. Hydrobiologia 500, 217–230.

Carlson, A.K., Taylor, W.W., Schlee, K.M., Zorn, T.G., Infante, D.M., 2017. Projected impacts of climate change on stream salmonids with implications for resilience-based management. Ecol. Freshw. Fish 26, 190–204.

Carpio, A.J., De Miguel, R., Oteros, J., Hillström, L., Tortosa, F.S., 2019. Angling as a source of non-native freshwater fish: a European review. Biol. Invasions 21, 3233–3248.

Cooke, S.J., Danylchuk, A.J., Zhang, J., Nguyen, V.M., Hunt, L.M., Arlinghaus, R., Fiorella, K.J., Chan, H.M., Goldberg, T.L., 2024. A one health perspective on recreational fisheries. FACETS 9, 1–9.

Cucherousset, J., Olden, J.D., 2011. Ecological impacts of non-native freshwater fishes. Fisheries 36, 215–230.

Cuthbert, R.N., Pattison, Z., Taylor, N.G., Verbrugge, L., Diagne, C., Ahmed, D.A., Leroy, B., Angulo, E., Briski, E., Capinha, C., 2021. Global economic costs of aquatic invasive alien species. Sci. Total Environ. 775, 145238.

da Silva Ladislau, D., de Souza, P.L., Gubiani, É.A., 2025. Recreational fishing in the Neotropical region: a systematic review. Fish. Manag. Ecol. 32, e12753.

Davis, A., Darling, J., 2017. Recreational freshwater fishing drives non-native aquatic species richness patterns at a continental scale. Divers. Distrib. 23, 692–702.

Department of Conservation, 1998. In: Department of Conservation (New Zealand) (Ed.), Target Taupo Page 72.

Diagne, C., Leroy, B., Gozlan, R., Vaissière, A.-C., Assailly, C., Nuninger, L., Roiz, D., Jourdain, F., Jarić, I., Courchamp, F., 2020. InvaCost, a public database of the economic costs of biological invasions worldwide. Sci Data 7, 277.

Ellender, B., Woodford, D., Weyl, O., Cowx, I., 2014. Managing conflicts arising from fisheries enhancements based on non-native fishes in southern Africa. J. Fish Biol. 85, 1890–1906.

Embke, H.S., Nyboer, E.A., Robertson, A.M., Arlinghaus, R., Akintola, S.L., Atessahin, T., Badr, L.M., Baigun, C., Basher, Z., Beard Jr., T.D., 2022. Global dataset of species-specific inland recreational fisheries harvest for consumption. Sci Data 9, 488.

Ewel, J.J., O'Dowd, D.J., Bergelson, J., Daehler, C.C., D'Antonio, C.M., Gómez, L.D., Gordon, D.R., Hobbs, R.J., Holt, A., Hopper, K.R., 1999. Deliberate introductions of species: research needs: benefits can be reaped, but risks are high. BioScience 49, 619–630.

Froese, R., Pauly, D. (Eds.), 2025. FishBase. World Wide Web electronic publication www.fishbase.org (Last accessed April 2025).

Gallagher, B.K., Geargeoura, S., Fraser, D.J., 2022. Effects of climate on salmonid productivity: a global meta-analysis across freshwater ecosystems. Glob. Chang. Biol. 28, 7250–7269.

Gallardo, B., Clavero, M., Sánchez, M.I., Vilà, M., 2016. Global ecological impacts of invasive species in aquatic ecosystems. Glob. Chang. Biol. 22, 151–163.

Golden, C.D., Koehn, J.Z., Shepon, A., Passarelli, S., Free, C.M., Viana, D.F., Matthey, H., Eurich, J.G., Gephart, J.A., Fluet-Chouinard, E., 2021. Aquatic foods to nourish nations. Nature 598, 315–320.

Gozlan, R.E., 2008. Introduction of non-native freshwater fish: is it all bad? Fish Fish. 9, 106–115.

Haubrock, P.J., Bernery, C., Cuthbert, R.N., Liu, C., Kourantidou, M., Leroy, B., Turbelin, A.J., Kramer, A.M., Verbrugge, L.N., Diagne, C., 2022. Knowledge gaps in economic costs of invasive alien fish worldwide. Sci. Total Environ. 803, 149875.

Hickley, P., Britton, J.R., Macharia, S., Muchiri, S., Boar, R.R., 2015. The introduced species fishery of Lake Naivasha, Kenya: ecological impact vs socio-economic benefits. Fish. Manag. Ecol. 22, 326–336.

Hunt, J.R., 2005. Dietary and physiological factors that affect the absorption and bioavailability of iron. Int. J. Vitam. Nutr. Res. 75, 375–384.

Jeschke, J.M., Bacher, S., Blackburn, T.M., Dick, J.T., Essl, F., Evans, T., Gaertner, M., Hulme, P.E., Kühn, I., Mrugała, A., 2014. Defining the impact of non-native species. Conserv. Biol. 28, 1188–1194.

Jonsson, B., 2023. Thermal effects on ecological traits of salmonids. Fishes 8, 337.

Kleitou, P., Moutopoulos, D.K., Giovos, I., Kletou, D., Savva, I., Cai, L.L., Hall-Spencer, J.M., Charitou, A., Elia, M., Katselis, G., 2022. Conflicting interests and growing importance of non-indigenous species in commercial and recreational fisheries of the Mediterranean Sea. Fish. Manag. Ecol. 29, 169–182.

Kovach, R., B. Jonsson, N. Jonsson, I. Arismendi, J. Williams, J. Kershner, R. Al-Chokhachy, B. Letcher, and C. Muhlfeld. 2019. Chapter 20 - climate change and the future of trout and char. Pages 685-716, in Jeffrey L. Kershner, Jack E. Williams, Robert E. Gresswell, and Javier Lobón-Cerviá (eds) trout and char of the world. American fisheries society (publisher), 777 pages.

Lynch, A.J., Embke, H.S., Nyboer, E.A., Wood, L.E., Thorpe, A., Phang, S.C., Viana, D.F., Golden, C.D., Milardi, M., Arlinghaus, R., 2024. Inland recreational fisheries contribute nutritional benefits and economic value but are vulnerable to climate change. Nature Food 5, 433–443.

Matthews, W.J., 1998. Disturbance, Harsh Environments, and Physicochemical Tolerance. In: Patterns in Freshwater Fish Ecology. Springer, pp. 318–379.

Milardi, M., A. J. Green, M. Mancini, P. Trottie, M. Kiljunen, J. Torniainen, and G. Castaldelli. 2022. Invasive catfish in northern Italy and their impacts on waterbirds. NeoBiota, 72, 109–128 [online].

Milardi, M., Soana, E., Chapman, D., Fano, E.A., Castaldelli, G., 2020. Could a freshwater fish be at the root of dystrophic crises in a coastal lagoon? Sci. Total Environ. 711, 135093.

Morrongiello, J.R., Beatty, S.J., Bennett, J.C., Crook, D.A., Ikedife, D.N., Kennard, M.J., Kerezsy, A., Lintermans, M., McNeil, D.G., Pusey, B.J., 2011. Climate change and its implications for Australia's freshwater fish. Mar. Freshw. Res. 62, 1082–1098.

Nyboer, E.A., Embke, H.S., Robertson, A.M., Arlinghaus, R., Bower, S., Baigun, C., Beard, D., Cooke, S.J., Cowx, I.G., Koehn, J.D., 2022. Overturning stereotypes: the fuzzy boundary between recreational and subsistence inland fisheries. Fish Fish. 23, 1282–1298.

Nyboer, E.A., Lin, H.Y., Bennett, J.R., Gabriel, J., Twardek, W., Chhor, A.D., Daly, L., Dolson, S., Guitard, E., Holder, P., 2021. Global assessment of marine and freshwater recreational fish reveals mismatch in climate change vulnerability and conservation effort. Glob. Chang. Biol. 27, 4799–4824.

Pimentel, D., Zuniga, R., Morrison, D., 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecol. Econ. 52, 273–288.

Sax, D.F., Schlaepfer, M.A., Olden, J.D., 2022. Valuing the contributions of non-native species to people and nature. Trends Ecol. Evol. 37, 1058–1066.

Schlaepfer, M.A., Sax, D.F., Olden, J.D., 2011. The potential conservation value of non-native species. Conserv. Biol. 25, 428–437.

Smith, S. F. 2018. *Review of the state of the world fishery resources: inland fisheries.* FAO fisheries and Aquaculture circular no. 942, rev. 3. Food and agricultural organisation (FAO), Rome, Italy. ISBN 978-92-5-130793-9.

Soto, D., Arismendi, I., González, J., Sanzana, J., Jara, F., Jara, C., Guzman, E., Lara, A., 2006. Southern Chile, trout and salmon country: invasion patterns and threats for native species. Rev. Chil. Hist. Nat. 79, 97–117.

Stanković, D., Crivelli, A.J., Snoj, A., 2015. Rainbow trout in Europe: introduction, naturalization, and impacts. Reviews in Fisheries Science & Aquaculture 23, 39–71.

Thomas, K., Brabec, M., Tapkir, S., Gottwald, M., Bartoň, D., Šmejkal, M., 2023. Sampling bias of invasive gibel carp and threatened crucian carp: implications for conservation. Global Ecology and Conservation 48, e02718.

Vigliano, P. H., M. F. Alonso, and M. Aquaculture. 2007. Salmonid introductions in Patagonia: a mixed blessing. Ecological and genetic implications of aquaculture (activities:315-331).

Villamagna, A.M., Mogollón, B., Angermeier, P.L., 2014. A multi-indicator framework for mapping cultural ecosystem services: the case of freshwater recreational fishing. Ecol. Indic. 45, 255–265.

Vimercati, G., Probert, A.F., Volery, L., Bernardo-Madrid, R., Bertolino, S., Céspedes, V., Essl, F., Evans, T., Gallardo, B., Gallien, L., Bacher, S., 2022. The EICAT+ framework enables classification of positive impacts of alien taxa on native biodiversity. PLoS Biol. 20 (8), e3001729.

Whitehead, J. C., L. Cornicelli, L. Bragg, and R. Southwick. 2025. The aggregate economic value of Great Lakes recreational fishing trips. Journal of Great Lakes (Research:102529), J. Great Lakes Res..

Yuan, D., Wang, H., Liu, X., Wang, S., Shi, J., Cheng, X., Gu, H., Xiao, S., Wang, Z., 2022. High temperature induced metabolic reprogramming and lipid remodeling in a high-altitude fish species, *Triplophysa bleekeri*. Front. Mar. Sci. 9, 1017142.