CHEMICAL EXPOSURE

Risks of per- and polyfluoroalkyl substance exposure through marine fish consumption

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Global food trade expansion has enriched diets worldwide but also heightened concerns about contaminant spread. Per- and polyfluoroalkyl substances (PFAS) can persist in the environment for decades, yet their risks through food trade remain unclear. The global median estimated daily intake (EDI) of C8-PFAS (perfluorooctanoic acid and perfluorooctane sulfonate) (0.023 nanograms per kilograms per day) was mapped from 212 marine fish species, which indicated higher EDIs in North America, Oceania, and Europe. Furthermore, European countries play a pivotal role in C8-PFAS trade flows, markedly reshaping exposure pathways and driving increased exposure in many nations. These dynamics highlight the importance of establishing food-safety regulations and international trade standards. Although perfluorooctane sulfonate hazard index decreased by 72% after its 2009 regulations, unregulated long-chain PFAS continue to pose elevated risks.

Per- and polyfluoroalkyl substances (PFAS) are recognized as "forever chemicals" because they can persist in the environment for decades or longer (*1*). PFAS have been widely used in industrial processes and consumer products and are identified as pervasive environmental contaminants (*2*). Their bioaccumulative potential and long-range airborne and oceanic transport have influenced their availability and uptake in food webs (*3*). The frequency of detection of PFAS is as high as 100% in a wide variety of foods, including meats and seafood (*4*, *5*). Consequently, PFAS can accumulate in the human body and pose potential health risks (*6*–*11*).

Although marine fish constitute a key component of global diets, they can be a substantial dietary source of PFAS to humans, with the estimated daily intake (EDI) up to three times that of cereals and 14.5 times that of meat sources (*12*). This is especially critical given the rapid increase in the global trade of marine fish, potentially shaping a regional redistribution of human exposure to these chemicals (*13*). However, the pathways and magnitude of potential PFAS exposure through the international food trade remain unclear, in part because of the absence of well-developed global-scale transport models for PFAS. Recently, the expansion of global PFAS monitoring and the improvement of the United Nations (UN) Comtrade database have enabled the establishment of an up-to-date database that considers relevant factors such as regional environmental characteristics and trade flows.

We present a comprehensive global dataset on PFAS exposure through marine fish by integrating (i) a mechanistic model of bioaccumulation and biomagnification within marine food webs, (ii) global fish catch data at the 0.5° by 0.5° latitude-longitude resolution, and (iii) global marine fish trade data. We developed a marine food web model and analyzed seawater PFAS monitoring data from 3126 sites worldwide over 20 years (*14*), generating a predictive map of PFAS concentrations in 212 edible marine fish species at a 1° by 1° latitude-longitude resolution, contributing to approximately 99% of global fish production in studied countries. Moreover, we quantified PFAS concentrations in 150 marine fish samples from 87 species collected across 14 countries over 3 years (supplementary materials). Additionally, we examined trade pathways by linking global marine fish trade data from the UN Comtrade (https://comtrade.un.org) and global marine fish catch data in exclusive economic zones (EEZs) from The Sea Around Us (http://www.seaaroundus.org). These databases were then used to assess PFAS exposure through marine fish consumption and human health risks in the global fish trade. The methods overview is shown in fig. S1. Our assessment focused on two well-characterized C8-PFAS: perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) (*15*). The findings reveal changes in global PFAS exposure after the 2009 Stockholm Convention and highlight the comparatively higher exposure risks of unregulated long-chain PFAS (perfluorodecanoic acid, perfluorononanoic acid, and perfluoroundecanoic acid) relative to C8-PFAS, offering insights for effective environmental and trade policies that support UN Sustainable Development Goals.

Global C8-PFAS contamination in marine fish species

We estimate that the median global concentration of C8-PFAS (sum of PFOA and PFOS) in 212 marine fish species from 2010 to 2021 was 0.34 ng/g wet weight (ww) (range, 0.004 to 44.45 ng/g ww), with Asia and Oceania exhibiting higher concentrations relative to global levels (Fig. 1A). These findings are consistent with the high PFAS emissions and instances of coastal contamination reported in these regions (fig. S2) (*14*, *16*, *17*). In Asia, the median C8-PFAS concentration in fish reached 1.03 ng/g ww [95% confidence interval (CI): 0.46 to 6.06], which was influenced mainly by high levels in Saudi Arabia (11.72 ng/g ww; 95% CI: 7.07 to 11.80) and Thailand (6.06 ng/g ww; 95% CI: 4.53 to 7.85). In Oceania, the elevated median C8-PFAS concentration was driven primarily by contamination along Australia's east coast. This finding is corroborated by previous reports of elevated concentrations in fish (4.2 to 10 ng/g ww) (*18*) and seawater (0.077 to 19.7 ng/liter) (*19*) from Australia. The C8-PFAS concentrations in South America (0.33 ng/g ww; 95% CI: 0.09 to 0.52) and Europe (0.25 ng/g ww; 95% CI: 0.12 to 0.57) closely matched global levels, whereas in Africa (0.13 ng/g ww; 95% CI: 0.03 to 0.23) and North America (0.11 ng/g ww; 95% CI: 0.05 to 0.24), the levels fell below the global median (0.34 ng/g ww; 95% CI: 0.15 to 0.52). Semienclosed seas with dense populations and advanced economies, such as the Baltic Sea and Bohai Sea, presented elevated levels of PFAS in fish, likely owing to high emission levels and reduced dilution capacity (Fig. 1A) (*20*, *21*). We constructed the distribution of

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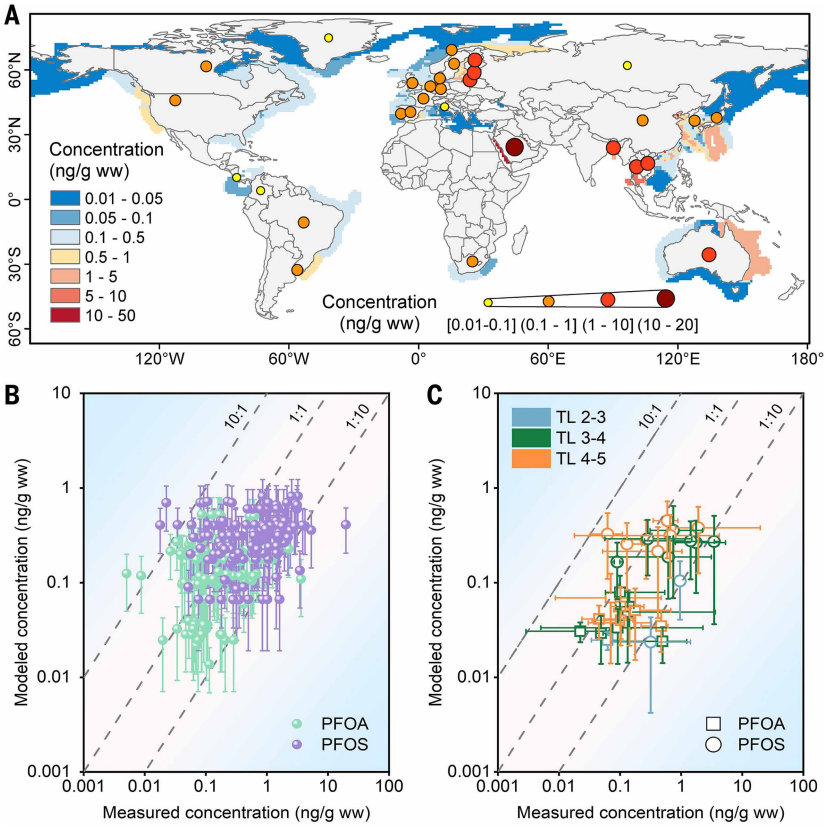

Fig. 1. Predicted concentrations and validation of C8-PFAS in marine fish, 2010 to 2021. C8-PFAS refers to the sum of PFOS and PFOA. Concentrations are in nanograms per gram wet weight. (**A**) Global spatial trends in median concentrations of marine fish species from 2010 to 2021. The colored points indicate median concentrations at the country level; the grids indicate median concentrations within 1° by 1° cells. (**B**) Predicted versus measured concentrations for each fish sample. Vertical error bars indicate the mean absolute deviation of the marine food web model's predicted concentrations in marine fish. (**C**) Predicted versus measured concentrations for fish at the same trophic level (TL) within the same fish category. Horizontal error bars indicate the range of observed data, and vertical error bars indicate the median absolute deviation of predictions. Dashed lines indicate ±10-fold error bounds.

C8-PFAS concentrations across 10 fish categories and found that concentrations were significantly higher in fish at relatively high trophic levels (Dunn's test with Bonferroni correction, $P < 0.05$) (figs. S3 and S4). Moreover, continent-stratified analysis also revealed the same pattern of trophic-level differences (fig. S5).

To validate these predictive concentrations, PFAS levels were measured in 87 fish species across 14 countries (fig. S6). These results were compared against the model's predictions at both the sample and trophic levels (Fig. 1, B and C), with 33% of the data points falling within a twofold error margin and 94% falling within a 10-fold margin at the sample level. Our predictive concentrations also agree with previous measurements in the United States (0.12 to 20 ng/g ww) (*22*) and Baltic states (0.2 to 2.4 ng/g ww) (*23*).

Exposure to C8-PFAS through marine fish consumption globally

Our study revealed the EDI of C8-PFAS through marine fish consumption (Fig. 2A) (*24*). Cod-like and herring-like fish contributed heavily to elevated EDIs because of their high consumption rates (figs. S7 to S9). Exposure to PFOS was greater than that to PFOA by more than an order of magnitude (fig. S10), reflecting the greater stability and bioaccumulation potential of PFOS in fish, which resulted in higher levels of fish residues (*25*).

Furthermore, we found that high-income countries had a median C8-PFAS EDI of 0.068 ng/kg/day (95% CI: 0.051 to 0.144) compared with 0.012 ng/kg/day (95% CI: 0.004 to 0.036) in countries with other income levels, suggesting a strong correlation between economic status and C8-PFAS intake (figs. S11 to S13) (*26*, *27*). Globally, the population-weighted EDI of C8-PFAS was 0.023 ng/kg/day (95% CI: 0.010 to 0.058), with North America exhibiting the highest levels, followed by Oceania and Europe (Fig. 2B). This is consistent with the high PFAS detection in North American, Oceanian, and European populations (*7*, *10*).

We evaluated C8-PFAS mixed-exposure human health risks using the hazard index (HI) (*28*). Regions with high HI generally coincide with areas exhibiting high EDIs, including Greenland, Lithuania, Denmark, Norway, Thailand, and Estonia. By contrast, the values in Colombia, Libya, Costa Rica, Brazil, South Africa, and Cyprus (HI < 0.01) indicated minimal risks (Fig. 2C). The population-weighted HI distributions matched the EDI patterns across continents (Fig. 2D).

Global fish trade alters regional dispersion of PFAS

In Fig. 3, we illustrate the import pathways of C8-PFAS EDI, incorporating data from 581 import transactions across 31 countries. European countries dominated the total import volume, followed by Asian countries. Europe's fish export trade also stands out in terms of both volume and C8-PFAS EDI transfer rate. Sweden and Finland emerge as key exporters within the fish trade network, contributing more than 0.35 ng/kg/day of C8-PFAS EDI to all importing countries, with 76.79 and 82.16% of the EDI in Lithuania and Estonia, respectively, which is driven primarily by exports of salmon and smelts and other herring-like fish (figs. S14 to S17). By contrast, intercontinental fish trade, although prevalent, generally yields limited EDI increases (<0.005 ng/kg/day) (fig. S18).

Comparisons of trade-driven EDIs with hypothetical "no trade" scenarios (fig. S19) highlight how the global fish trade influences C8-PFAS intake (fig. S20). European countries such as Germany, Cyprus, the Netherlands, Portugal, Italy, and Denmark show dramatic trade-related impacts on the C8-PFAS EDI (>90%), predominantly from imported fish within Europe (Fig. 3B). However, the impact of trade outside Europe was relatively limited because the vast majority of countries outside of Europe were less affected by trade (less than 50%), except Vietnam (89.65%), Costa Rica (72.74%), and South Africa (70.59%) (Fig. 3), underscoring the importance of local fish consumption in the global C8-PFAS exposure landscape outside Europe (Fig. 3C).

Our results reveal that in Italy, only 11.71% of the total fish consumed are imported from Sweden, but these fish contribute 35.82% of C8-PFAS exposure to Italians. In comparison, 28.02% of the total fish consumed in Italy were caught locally but contributed to only 5.23% of the C8-PFAS EDI (figs. S16 to S17). Similar patterns appear in the United Kingdom and Colombia, suggesting that imports from regions with elevated C8-PFAS levels can considerably increase exposure levels in the importing countries.

Temporal variations in C8-PFAS exposure risks after the Stockholm Convention

PFOS and PFOA were listed in the Annex to the Stockholm Convention in 2009 and 2019, respectively (*29*, *30*). Consequently, we observed a significant decrease in the global median HI of C8-PFAS between 2002–2009 and 2010–2021 across data from 44 countries, with the PFOS HI decreasing

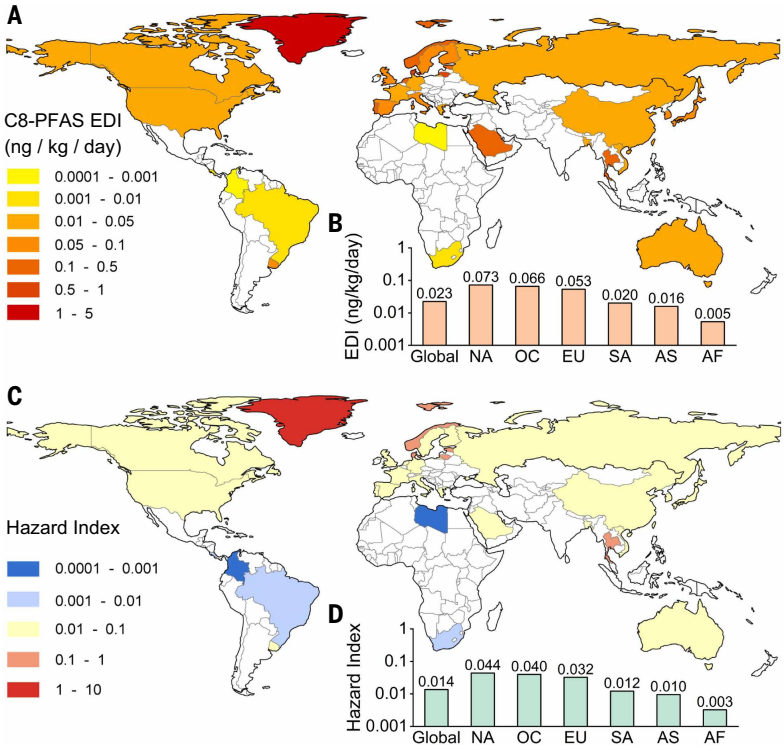

Fig. 2. C8-PFAS EDI distribution and human health risks from marine fish consumption, 2010 to 2021, considering international trade. C8-PFAS refers to the sum of PFOS and PFOA. (**A**) C8-PFAS EDI (nanograms per kilogram per day) from both local and imported fish for an average adult weighing 65 kg. (**B**) Population-weighted EDIs by continent. (**C**) C8-PFAS HI attributable to marine fish consumption. (**D**) Population-weighted HI by continent. NA, North America; OC, Oceania; EU, Europe; SA, South America; AS, Asia; and AF, Africa. Colorless areas on the map indicate that data were not available.

by 72.30% and the PFOA HI decreasing by 40.44% (fig. S21). In the United States and Canada—where PFOS regulations were enforced in 2003 and 2006, respectively (*31*)—the decline in the C8-PFAS HI associated with marine fish is consistent with reduced biomonitoring value (Fig. 4 and fig. S22), reflecting the effectiveness of enacted policies. In Japan and China, regulations related to PFOS were implemented in 2010 and 2014, respectively, resulting in similar improvements (*32*, *33*). The European Union began regulating PFOS in 2006 (*31*), but the effectiveness of the policy appears limited, with modeled PFOS concentrations in marine fish and associated HI values continuing to rise in several EU countries (fig. S23). Countries with more recent regulations, such as Brazil and Australia (*34*, *35*), still show increasing trends in C8-PFAS concentrations in marine fish and associated HI values. Concurrently, an increase in C8-PFAS concentrations in seawater was reported in Australia (*14*).

Temporal variations in C8-PFAS HI do not consistently mirror marine fish concentration trends (fig. S24). For example, in Germany and the Netherlands, a decrease in marine fish C8-PFAS concentrations was observed, but an increase was found in the HI, which was linked to increased per capita intake and large imports of fish with high C8-PFAS levels (such as salmon and smelts and other herring-like fish) from other European countries in 2019 (fig. S16).

Crisis of exposure to unregulated long-chain PFAS

After the phase-outs of PFOA and PFOS, the frequency of detection and concentration of short-chain alternatives to PFAS have steadily increased (*36*). Additionally, certain long-chain PFAS persist at elevated levels (*37*, *38*). We evaluated the exposure risks of these unregulated PFAS by using relative potency factors (*39*) owing to limited reference dose (RfD) information, with PFOS as the reference compound (RfD = 1.8 ng/kg/day) (table S1). Some long-chain PFAS had

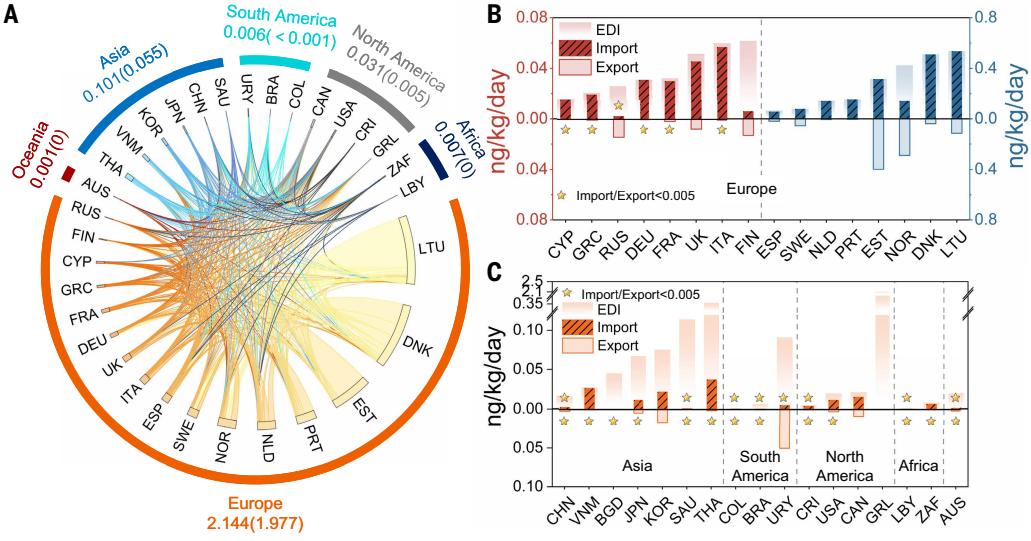

Fig. 3. C8-PFAS EDI import pathways among 31 countries and the EDI composition of each country. (**A**) Pathways of C8-PFAS EDI import through the global marine fish trade among 31 countries as a Circos-type graph. The width of each band indicates the sum of imported EDI (nanograms per kilogram per day), and the band color indicates the net EDI inflow (nanograms per kilogram per day). The outer circle is clustered by continent; numbers outside the circle indicate total intercontinental and intracontinental imported EDI; and numbers in parentheses indicate intracontinental imports. (**B**) Comparative role of imported fish in the total EDI for European countries. Red columns are countries with low EDIs (left *y* axis), and blue columns are for countries with high EDIs (right *y* axis). (**C**) Same comparison for other countries. AUS, Australia; URY, Uruguay; COL, Colombia; BRA, Brazil; ZAF, South Africa; LBY, Libya; SAU, Saudi Arabia; VNM, Vietnam; THA, Thailand; KOR, South Korea; JPN, Japan; CHN, China; BGD, Bangladesh; GRL, Greenland; CRI, Costa Rica; CAN, Canada; USA, United States; RUS, Russia; UK, United Kingdom; SWE, Sweden; ESP, Spain; PRT, Portugal; NOR, Norway; NLD, Netherlands; LTU, Lithuania; ITA, Italy; GRC, Greece; DEU, Germany; FRA, France; FIN, Finland; EST, Estonia; DNK, Denmark; and CYP, Cyprus.

higher HI values than those of PFOS or PFOA, which was driven by their higher relative potency factor due to their high bioaccumulation potential (*40*), posing a substantial but largely overlooked threat to human health (Fig. 5 and fig. S25). The higher toxicity associated with longer carbon chain lengths similarly indicates elevated health risks from long-chain PFAS (*41*). The inclusion of perfluorohexane sulfonic acid in 2022 and long-chain perfluorocarboxylic acids in 2025 under the Stockholm Convention underscores the growing international recognition of their risks (*42*, *43*). By contrast, the exposure risks of short-chain PFAS currently remain within acceptable levels.

Over the geographical scale, results revealed that PFAS HI values exceeding a threshold of 1 occurred in Europe and North America in regions with historically high perfluorocarboxylic acid production and lower mobility of longer-chain PFAS (*44*, *45*), indicating localized potential exposure risks.

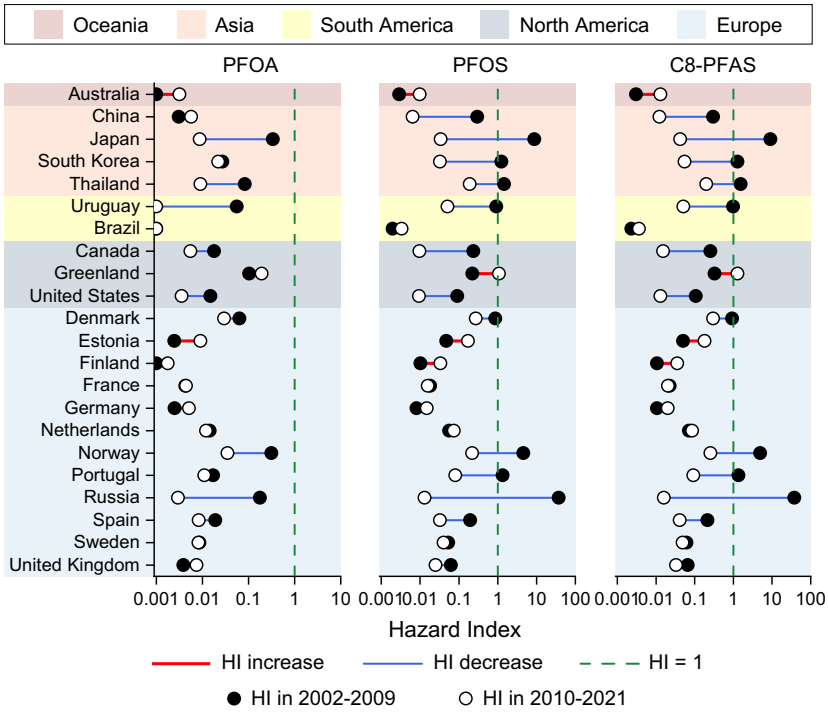

Fig. 4. Temporal variations in the C8-PFAS HI related to marine fish consumption between 2002–2009 and 2010–2021. Only countries with data for both periods are shown. Shaded areas cluster countries by continent; red and blue lines are not shown for countries with minimal changes.

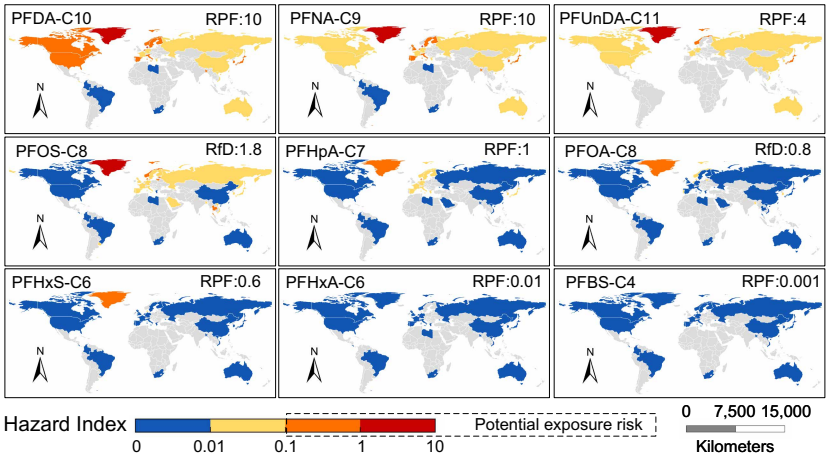

Fig. 5. HI of PFAS (2010 to 2021). Compound names are followed by carbon chain length; RPF (relative potency factor) or RfD (reference dose) values appear in the upper right corners. Images are ordered by decreasing global median HI, arranged from left to right and top to bottom. HI > 1 indicates potential exposure risk to human health; gray indicates no data. PFAS compounds are sorted by their global median of HI. PFDA, perfluorodecanoic acid; PFNA, perfluorononanoic acid; PFUnDA, perfluoroundecanoic acid; PFOS, perfluorooctane sulfonate; PFHpA, perfluoroheptanoic acid; PFOA, perfluorooctanoic acid; PFHxS, perfluorohexane sulfonic acid; PFHxA, perfluorohexanoic acid; and PFBS, perfluorobutane sulfonic acid.

Discussion

By generating a global map of human exposure to PFAS from marine fish and quantifying the resulting health risks, this study offers a new framework that synthesizes environmental concentration data, a marine food web model, bioaccumulation factors, global catch data, trade networks, and health risk assessments. The methodological constraints and high testing costs associated with persistent organic pollutants (POPs) in food have hampered large-scale exposure analyses in the past (*46*).

Our results revealed a trend, with PFAS exposure through marine fish consumption shifting from high-residue regions to low-residue regions along global fish trade pathways, highlighting that the global food trade has the potential to reshape the landscape of PFAS exposure. This is particularly relevant for fish species with high PFAS concentrations at relatively high trophic levels (*47*, *48*). By quantifying the movement and distribution of these substances, our methodology may help guide targeted food inspections (for example, monitoring exports from high-contamination countries or fish species) and inform export standards, ultimately enhancing global food safety measures (*49*). Moreover, consistent with prior research, economic status is strongly correlated with PFAS exposure levels (*50*), suggesting that comprehensive management strategies for these pollutants could integrate environmental data, food web dynamics, trade connections, and economic factors (*51*).

Our spatiotemporal analysis of PFAS risk underlines the importance of strict regulations, reiterating the persistence and far-reaching impact of PFAS. Although many countries have implemented or strengthened international guidelines to manage PFAS exposure, such as setting PFAS concentration limits in edible fish (*52*–*55*), thresholds vary by orders of magnitude worldwide, and some countries lack PFAS regulations. Moreover, although emissions of regulated C8-PFAS have markedly decreased (*56*), unregulated long-chain PFAS remain a concern because of their relatively higher HI. Furthermore, ongoing monitoring and evaluation of emerging PFAS is still essential, particularly of widely used polyether perfluorinated compounds (*57*), to better understand and mitigate their potential risks.

One limitation of this study is the focus on fish caught within EEZs and the exclusion of those from high-seas fisheries and aquaculture, which together may result in an underestimation of PFAS exposure from fish consumption. However, the impact is likely small because high-seas fishing currently accounts for only 4.2% of the total catches (*58*) and contributes approximately 3.98% to C8-PFAS exposure (fig. S26). Because of limited and uncertain data on PFAS concentrations in high-seas fisheries and aquaculture, this component was excluded

from the main analysis in this study. The complexity of differentiating between farmed fish and wild-caught fish in international trade further adds uncertainty. In addition, we assumed that all marine fish caught in a given year were consumed in that same year, neglecting possible carryover. Additionally, cooking can have an impact on dietary exposure risk, but the effect is limited and difficult to assess because of variations in cooking methods across countries and uncertainties in determining influencing factors (*59*–*61*). Aligning database granularity to improve health risk assessments remains a potential goal for enhancing the precision. Furthermore, reducing uncertainties may benefit from broader field sampling, improved data quality, refined modeling, and better toxicity thresholds, as will advanced computational models linked with more extensive pollution distribution data.

Our study highlights an urgency for strengthening global cooperation and policies to facilitate the minimization of human exposure to PFAS from the consumption of marine fishes, particularly through the advancement of relevant guidelines for the international fish trade and tightened control of long-chain PFAS. By modeling and mapping global PFAS exposure and associated health risks while considering fish trade among countries, we provide a useful tool to guide stakeholders and policy-makers in formulating evidence-based approaches to mitigate the human health threats posed by the forever chemicals.

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SUPPLEMENTARY MATERIALS

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Materials and Methods; Figs. S1 to S35; Tables S1 to S10; References (*62*–*109*); MDAR Reproducibility Checklist; Data S1 to S8

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Risks of per- and polyfluoroalkyl substance exposure through marine fish consumption

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Editor's summary

We now live in a world filled, to varying levels, with chemicals that persist in the environment for decades, and it is well known that many of these chemicals impose health risks. Per- and polyfluoroalkyl substances (PFAS) are of particular note because of their persistence and potential for bioaccumulation. Qiu *et al*. looked at concentrations of PFAS in over 200 species of fish harvested for food around the world (see the Perspective by Sun and Sunderland). Exposure risk was high in North America, Oceania, and Europe. Europe, in particular, facilitated movement of exposed fishes to regions that might otherwise have been less exposed. —Sacha Vignieri