Title

A meta-analysis reveals PFAS concentrations double with each trophic level across aquatic and terrestrial food webs

Short title

PFAS biomagnification in food webs.

Authors

Lorenzo Ricolfi,[a,*] Yefeng Yang,[a,*] Patrice Pottier,[a,b] Kyle Morrison,[a] Coralie Williams,[a,c] Pietro Pollo,[a] Daniel Hesselson,[d] G. Gregory Neely,[e] Matthew D. Taylor,[a,f,g] Shinichi Nakagawa,[a,h,i,†] Malgorzata Lagisz,[a,i,†]

Affiliations

[a] Evolution and Ecology Research Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales Sydney, Sydney, Australia

[b] Division of Ecology and Evolution, Research School of Biology, The Australian National University, Canberra, Australian Capital Territory, Australia

[c] School of Mathematics and Statistics, University of New South Wales, Sydney, Australia

[d] Centenary Institute and Faculty of Medicine and Health, The University of Sydney, Sydney, Australia

[e] Dr. John and Anne Chong Lab for Functional Genomics, Charles Perkins Centre, School of Life and Environmental Sciences, University of Sydney, Sydney, Australia

[f] Port Stephens Fisheries Institute, New South Wales Department of Primary Industries, Nelson Bay, Australia

[g] Queensland Alliance for Environmental Health Sciences, Faculty of Health and Behavioural Sciences, The University of Queensland, Brisbane, Australia

[h] Theoretical Sciences Visiting Program, Okinawa Institute of Science and Technology Graduate University, Onna, Japan

[i] Department of Biological Sciences, Faculty of Science, The University of Alberta, Edmonton, Canada

[*] Corresponding authors

[†] Equal supervision

ORCIDs and EMAILs

Lorenzo Ricolfi: 0000-0001-7101-3309; l.ricolfi@unsw.edu.au. Yefeng Yang: 0000-0002-8610-4016; yefeng.yang1@unsw.edu.au. Kyle Morrison: 0000-0002-3700-2398; kyle.morrison@unsw.edu.au. Patrice Pottier: 0000-0003-2106-6597; p.pottier@unsw.edu.au. Coralie Williams: 0000-0003-1312-4953; coralie.williams@unsw.edu.au. Pietro Pollo: 0000-0001-6555-5400; pietro_pollo@hotmail.com. Daniel Hesselson: 0000-0002-8675-9426; d.hesselson@centenary.org.au. G. Gregory Neely: 0000-0002-1957-9732; greg.neely@sydney.edu.au. Matthew D. Taylor: 0000-0002-1519-9521; matt.taylor@dpi.nsw.gov.au. Shinichi Nakagawa: 0000-0002-7765-5182; s.nakagawa@unsw.edu.au. Malgorzata Lagisz: 0000-0002-3993-6127; m.lagisz@unsw.edu.au.

Abstract

Per- and polyfluoroalkyl substances (PFAS) threaten ecosystems worldwide due to their persistence, bioaccumulation, and toxicity. Through a global-scale meta-analysis of 122 aquatic and terrestrial food webs from 64 studies, we analyse 1,009 trophic magnification factors (TMFs) for 72 PFAS and identify key variability drivers. PFAS concentrations systematically doubled with each trophic level increase (mean TMF=2.00, 95% CI:1.64-2.45), confirming widespread biomagnification across ecosystems. Methodological disparities across studies emerged as the dominant source of TMF variability. Our models explained 84% of the variation in TMFs, underscoring predictive capacity. Notably, the industrial alternative F-53B exhibited the highest magnification (TMF=3.07, 95% CI:2.41-3.92), a critical finding given its expanding use and minimal regulatory scrutiny. This synthesis establishes PFAS as persistent trophic multipliers and provides a framework to prioritise high-risk compounds and harmonise biomagnification assessments. Our results call for consideration of stricter PFAS regulation to curb cascading ecological and health impacts.

Teaser

A global analysis reveals “forever chemicals” levels double with each food chain step, threatening ecosystems and human health.

MAIN TEXT

Introduction

Human activities increasingly destabilise ecological networks, eroding the integrity of food webs and their capacity to withstand environmental shifts (*1*). This degradation accelerates biodiversity decline and amplifies vulnerabilities across ecosystems, with contamination by persistent toxic chemicals representing a pervasive and escalating threat (*2*). Per- and polyfluoroalkyl substances (PFAS) are synthetic chemicals specifically engineered for durability. PFAS are currently used across more than 200 categories of products (*3*), and their resistance to degradation has led to global environmental infiltration, permeating ecosystems from industrial zones to remote habitats (*4*, *5*). A portion of this contamination transfers from the geosphere to the biosphere (*6*, *7*) and moves from prey to predator (*8*). Once introduced into food webs, PFAS can traverse trophic levels if organisms absorb these compounds faster than they can metabolise or excrete them. Such dynamics drive trophic magnification, concentrating PFAS in apex predators, including humans, at levels exponentially exceeding environmental background concentrations (*9*). Such type of bioaccumulation, coupled with PFAS' known toxicity (*10*), risks destabilising ecological hierarchies and exacerbating health crises across species, underscoring an urgent need to quantify and mitigate their cascading impacts.

Efforts to quantify PFAS' impacts face the critical barrier of stark inconsistencies in reported trophic magnification (*11*, *12*). Conflicting evidence ranges from reports of negligible accumulation or even biodilution in select food webs (*13*, *14*) to extreme biomagnification in others (*9*, *15*, *16*), with magnitudes varying over tenfold. This unresolved variability hinders predictive models and regulatory decisions as explanations remain contested. Competing hypotheses attribute discrepancies to inherent ecological complexity (e.g., food web structure, compound-specific traits) or methodological artifacts that artificially inflate variability. Resolving this ambiguity is essential to isolate true ecological risks from study design biases, a prerequisite for evidence-based policy.

To quantify PFAS biomagnification and resolve persistent ambiguities, we conducted the first global meta-analysis integrating standardised trophic magnification factors (TMFs) from 64 studies spanning 122 food webs. TMFs, calculated as the antilog of

log-concentration versus trophic-level regression slopes, provided a unified metric to quantify cross-ecosystem trends. Our analysis systematically addressed four objectives: [1] estimating PFAS and compound-specific TMFs, [2] dissecting within- and between-study variability, [3] ranking drivers of variability (e.g., methodological, ecological; Tab. 1), and [4] discussing critical data gaps. By synthesising fragmented evidence into predictive models, this meta-analysis delivers definitive trophic magnification values for PFAS as a class and individual compounds. Doing so establishes a benchmark for harmonising future research and policy, bridging the divide between ecological theory and actionable chemical regulation.

Tab. 1. **Factors expected to have an impact on the trophic magnification estimate.** The table provides the list of potential moderators (i.e., potential predictors of influence) alongside the prediction of the expected influence of each moderator, an explanation of the predictions, and references supporting the predictions. Moderators were chosen *a priori* and pre-registered in the research protocol (see *(*17*)*). The moderator "chemicals' regulation status" variable was added post-hoc; thus, it was not pre-registered in the research protocol.

Moderator	Prediction	Explanation	References
		Research methodological factors	
Whole-organism or organ/tissue-specific analysis	PFAS biomagnification estimates based exclusively on whole-organism samples may differ from those on a mix of whole-organism and organ-specific.	Whole-organism concentrations are usually measured at the base of food webs (plankton, invertebrates, and other small organisms). For animals of higher trophic levels (seals, bears, and other large organisms) practical and ethical reasons mean sampling is done on specific organs or fluids instead. The sampling strategy also pertains to whether the data was initially gathered due to a study's focus on ecological risk (whole animals) or human health risk (emphasizing edible parts such as fillets, eggs, muscle tissue, etc.).	(*11*, *12*, *18*)
PFAS concentrations normalised to lipid or protein levels	The biomagnification estimates of TMFs based on protein- or lipid-normalized PFAS concentrations may differ from those based on non-normalised concentrations.	Evaluation of biomagnification using TMFs based on protein- or lipid-normalized concentrations in food web organisms has been rarely suggested. However, it should be considered a source of variability in biomagnification estimates.	(*11*, *19*)

Treatment of concentrations below analytical quantification or reporting limits	A substitution of undetected compound values by one-half of the limit value decreases the TMF compared with other approaches.	Using one-half of the limit value as a substitution for undetected compounds may inflate baseline compound concentrations.	(*12*, *18*)
N-isotope trophic enrichment factor (TEF)	Different TEF choices can result in under- or overestimation of PFAS biomagnification.	Different studies use different N-isotope TEF to calculate the trophic level of species. The choice of TEF can affect the resulting TMF.	(*12*, *20*, *21*)
		Biological and environmental factors	
Sampling Latitude	PFAS biomagnification estimates for food webs closer to the equator may be lower than those at higher latitudes.	Tropical food webs are more intricate due to higher biodiversity, enabling more diverse consumer diets. Greater biomass and tissue turnover may dilute pollutants across networks. The latitude may be linked to the synergic effect of several factors, such as food web length and nature of top predator and food web baseline organism.	(*12*, *18*, *22–24*)
Type of breathing	PFAS biomagnification estimates tend to be higher in food webs that include solely air-breathing organisms or a combination of air breathing and water breathing organisms, compared to those consisting exclusively of water-breathing organisms.	Biomagnification of PFAS in food webs dominated by water breathing organisms is lower than in food webs dominated by air breathers because of the differences in metabolic rates and lipid content between these two types of organisms.	(*12*, *18*, *22*)
The lowest trophic level measured	Analysing lower trophic level organisms is likely to affect biomagnification estimates.	Studies where a primary producer was used as the base of the food web are likely to have different biomagnification estimates compared to those with a primary consumer. Extending the food web to include lower trophic levels increases the baseline variability in contaminant concentrations, which can dilute or amplify	(*12*, *22*)

		biomagnification estimates depending on the specific bioaccumulation dynamics at the base of the food web.	
The highest trophic level measured	The trophic position of the top predator will likely affect the biomagnification estimates.	Higher trophic-level organisms typically have higher lipid contents and longer lifespans. These allow more bioaccumulation over time, leading to higher concentrations in the top predators.	(*18*, *22*)
Food web length	A broader range in studied trophic levels will likely increase the biomagnification estimate.	Bioaccumulation occurs at each trophic transfer. With more trophic levels, contaminants accumulate to higher concentrations at the top predators.	(*12*, *18*, *23*)
		Compounds' physicochemical properties	
Carbon chain length	Biomagnification estimates tend to increase with the carbon chain length of PFAS.	Laboratory studies in which fish were exposed to contaminants solely through diet observed a direct positive relation between biomagnification factors and the number of carbon atoms.	(*25–27*)
Chemical functional group	Perfluoroalkyl sulfonates (PFSA) are more bioaccumulative in food webs than perfluoroalkyl carboxylic acids (PFCAs) of the same fluorinated carbon chain length.	There is no clear mechanistic explanation for the greater bioaccumulation potential of acids containing a sulfonyl functional group. Nevertheless, Jones et al. (2003) showed that sulfonic acids bind strongly to proteins and thus could show higher bioaccumulative potential.	(*25–27*)
		Others	
Chemicals' regulation status (added post-hoc)	PFAS listed in major international regulations have larger trophic magnification factors.	Chemicals, whose production and use are strongly regulated by global treaties such as the Stockholm Convention on Persistent Organic Pollutants, have higher trophic magnification potentials.	NA

Results

Systematic review and dataset overview

Our meta-analysis synthesised 64 studies reporting the TMF of PFAS (Tab. S1; Data S1), yielding 1,009 TMFs from 122 global food webs and 72 PFAS. Most food webs (72%) were aquatic, with a pronounced geographic bias toward the northern hemisphere (East Asia, Europe, North America; Fig. 1). Trophic levels of food webs ranged from 0.9 to 5.9, averaging 11.8 species per food web. Legacy compounds, including perfluorooctanesulfonic acid (PFOS), perfluoroundecanoic acid (PFUnDA), and perfluorodecanoic acid (PFDA) were the most studied (56, 45, and 42 studies, respectively). Perfluoroalkyl carboxylic acids (PFCA) and sulfonates (PFSA) comprised most TMFs (61% and 25%, respectively). Only 1% of the TMFs were from emerging PFAS.

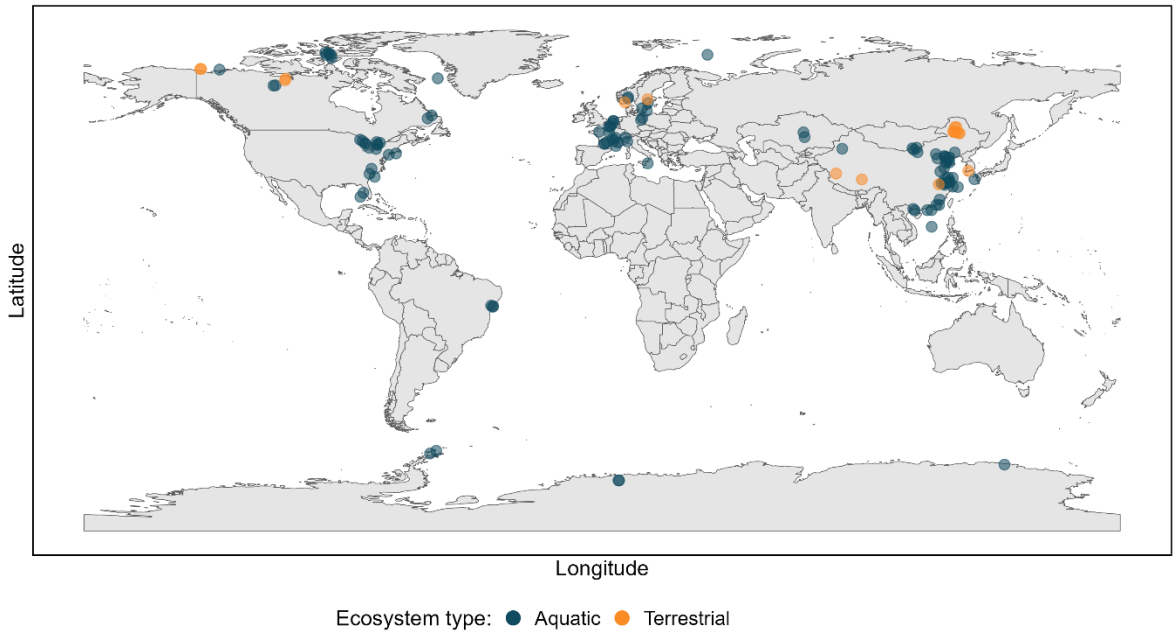

Fig. 1. World map showing the geographical distribution of the 122 food webs included in the meta-analysis. *Each point represents a food web, with colours indicating the corresponding ecosystem type. A slight jitter was applied to minimise overlap between points for clearer visualisation (for exact geographical locations, see Data S2).*

PFAS trophic magnification

Our multilevel meta-analytic model revealed an overall positive and statistically significant TMF of 2 (TMF = 2.00, 95% confidence interval (hereafter CI) = (1.64, 2.45); Fig. 2A). This indicates that, on average, the concentration of PFAS doubles

with each increase in trophic level when combining all studies, food webs, and chemicals included in the analysis.

We observed a high level of relative heterogeneity (*28*) (i.e., the percentage of variance between effect sizes that cannot be attributed to sampling error) across our dataset (I^2_{total} = 97.55%), with the majority of the variation attributed to differences at the effect size, study, and chemical levels (I^2_{PFAS} = 29.84%; I^2_{study} = 27.64%; I^2_{es} = 27.18%). A smaller proportion of the heterogeneity was associated with the food web level (I^2_{fw} = 12.89%). To explain this heterogeneity and explore potential sources of variability (Tab. 1), we conducted single- and multi-moderator meta-regression analyses.

Meta-regression analysis with PFAS identity as moderator identified PFAS type as a statistically significant predictor of TMF ($F_{(df1 = 52, df2 = 935)}$ = 19.3, $p < 0.0001$). Twelve PFAS exhibited results significantly greater than 1, with F-53B, PFOS, and PFDA having the highest TMFs (F-53B: TMF = 3.07, CI = (2.41, 3.92); PFOS: TMF = 3.02, CI = (2.64, 3.46); PFDA: TMF = 2.80, CI = (2.35, 3.33); PFUnDA: TMF = 2.41, CI = (2.04, 2.86); PFNA: TMF = 2.21, CI = (1.85, 2.65); PFTrDA: TMF = 2.04, CI = (1.58, 2.64); PFDoDA: TMF = 2.01, CI = (1.75, 2.32); FOSA: TMF = 1.89, CI = (1.38, 2.59); PFHxS: TMF = 1.76, CI = (1.33, 2.32); PFTeDA: TMF = 1.42, CI = (1.15, 1.75); Fig. 2B; for a glossary of PFAS acronyms, see Data S3). Ten additional compounds also showed TMFs significantly above 1 (Fig. S1), although these results were based on fewer than ten effect sizes. We found no statistical evidence of biodilution for any PFAS (i.e., TMF < 1; Fig. S1). Notably, all TMFs for the substance F-53B were derived from food webs located in East Asia (Tab. S2), and we observed a significant effect of geographic regions (i.e., North America, Europe, East Asia, and polar regions) on the TMF ($F_{(df1 = 5, df2 = 966)}$ = 9.3, $p < 0.0001$; Fig. S2). Stratifying by ecosystem type (terrestrial *vs* aquatic), we did not find statistically significant differences in the results between these two ecosystem types ($F_{(df1 = 1, df2 = 1007)}$ = 0, p = 0.8428; Fig. S3).

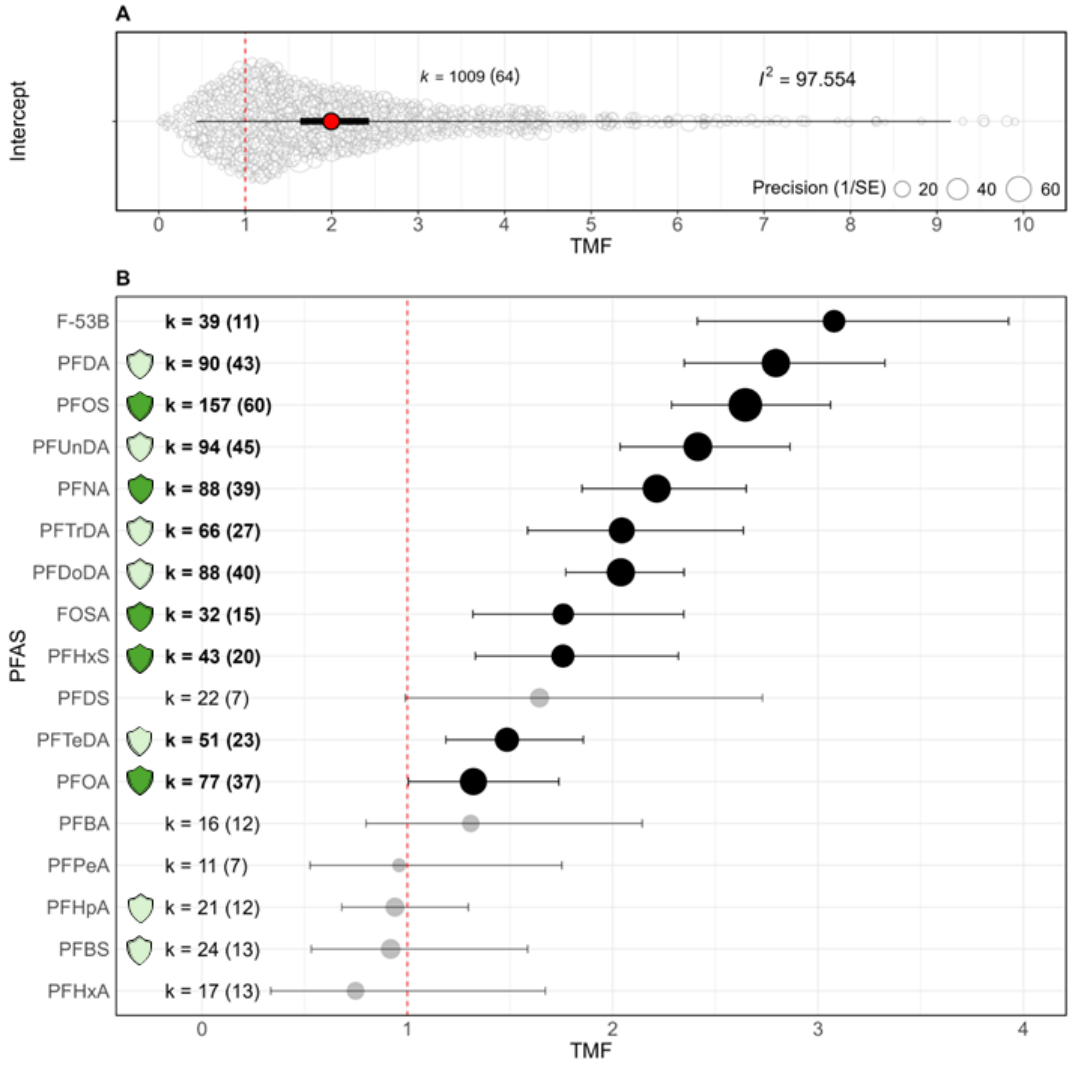

Fig. 2. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS) in food webs*. (A) Overall TMF based on a meta-analysis of 1,009 effect sizes from 117 aquatic and terrestrial food webs. The mean meta-analytic estimate is represented by a black circle filled with red. The thicker bars indicate the 95% confidence interval, while the thinner bars represent the 95% prediction interval. Light grey circles depict individual effect sizes scaled by precision (inverse of the standard error, as shown in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line highlights a TMF of 1 (biomagnification above 1 and biodilution below 1). The x-axis was capped at 10 for improved visual readability and does not show 15 effect sizes (for the full version of the plot, see Fig. S4). (**B**) Compound-specific TMFs for individual PFAS. A black bubble represents the mean TMF for individual chemicals, and the bars indicate the 95% confidence interval. Bubble size represents the number of effect sizes contributing to the estimate. Bubbles and k values in black represent estimates significantly different from 1 (i.e., $p < 0.05$). Dark and light green shields identify compounds listed in the global treaty the Stockholm Convention on Persistent Organic Pollutants and the European regulatory framework REACH regulation, respectively (for more information on PFAS regulation classification, see the 'Statistical modelling overview' paragraph in the Methods section and Tab. S3). Only the results for compounds with at least ten effect sizes are shown in panel B (for the full version of the plot, see Fig. S1).*

Sources of variability

Research methodological factors

A single-moderator meta-regression analysis revealed that the type of sample analyzed (whole-organism, tissue-specific, or a combination of both) was a statistically significant predictor of TMF ($F_{(df1 = 3, df2 = 1006)} = 20.9$, $p < 0.001$; Fig. 3A). On average, TMFs calculated using tissue-specific samples (e.g., liver, muscle, blood plasma) or whole-organism homogenates were 50% higher than those based solely on whole-organism samples ($TMF_{contrast} = 1.50$, CI = (1.21, 1.84)). However, only 10% of studies (n = 6) applied a biomass conversion to adjust tissue-specific concentrations to whole-organism equivalents.

We also found significant differences between TMFs derived from non-normalized PFAS concentrations and those adjusted for protein or lipid content ($F_{(df1 = 1, df2 = 943)} = 17.5$, $p < 0.0001$; Fig. 3B). TMFs based on non-normalized concentrations were, on average, 44% higher than those using normalized values ($TMF_{contrast} = 1.44$, CI = (1.21, 1.70), $p < 0.0001$). Additionally, the nitrogen isotope trophic enrichment factor (TEF) ($F_{(df1 = 4, df2 = 735)} = 12.1$, $p < 0.0001$; Fig. 3C) and the method used to handle undetected data ($F_{(df1 = 1, df2 = 5)} = 4$, $p = 0.0014$; Fig. 3D) were also significant predictors of TMF. We observed high variability in how undetected data were treated across studies (Tab. S4).

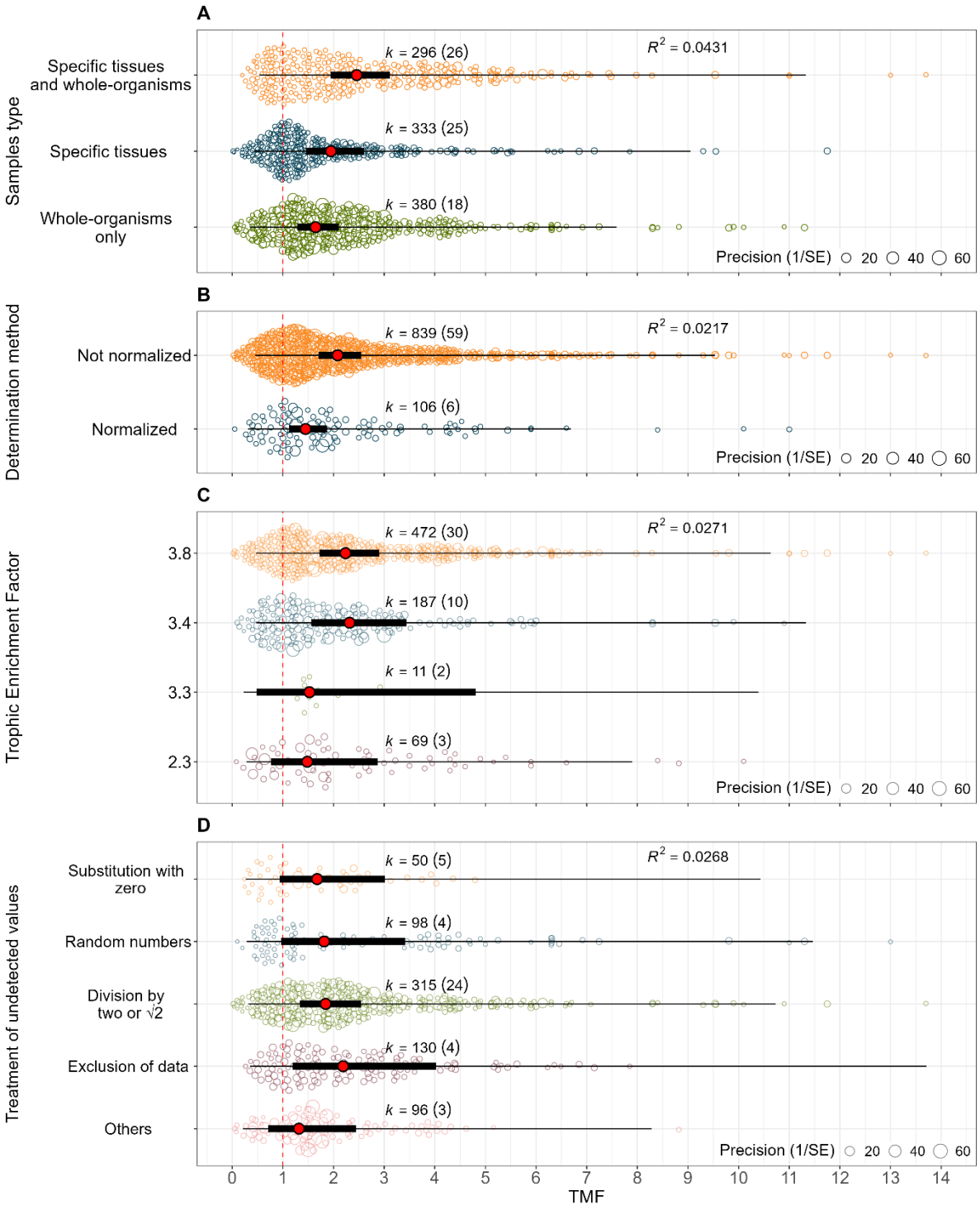

Fig. 3. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS), stratified by sample type (A), concentration determination method (B), trophic enrichment factor (C), and treatment strategy of undetected values (D). *The meta-analytic mean estimate for each stratification is represented by a red-filled circle with a black outline. Thicker bars denote the 95% confidence interval, while thinner bars represent the 95% prediction interval. Light grey circles show individual effect sizes, scaled by precision (inverse of the standard error, as indicated in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line marks a TMF of 1, with values above 1 indicating biomagnification and those below 1 indicating biodilution. TMF values are capped at 14 for improved visual*

clarity (refer to Fig. S5-S8 for full versions). In panel A, "mixed" refers to a combination of specific tissue and whole-organism samples. R^2 values represent the proportion of variance explained only by the fixed effects in the model (marginal R^2).

Biological, environmental, and chemical factors

We observed statistically significant differences in TMFs between food webs composed exclusively of water-breathing organisms and those that included both water- and air-breathing organisms ($F_{(df1 = 1, df2 = 1007)} = 6.2$, $p = 0.0128$; Fig. 4A). Specifically, TMFs in food webs consisting only of water-breathing organisms were 52% lower ($TMF_{contrast} = 0.52$, CI = (0.31, 0.87)), on average, than those in mixed food webs. Similarly, food webs with a water-breathing top predator had TMFs that were 60% lower than those with an air-breathing top predator ($F_{(df1 = 1, df2 = 856)} = 6.6$, $p = 0.0104$; $TMF_{contrast} = 0.60$, CI = (0.41, 0.88); Fig. 4B).

Our meta-regression analysis also identified PFAS chemical class as a moderator of TMF ($F_{(df1 = 4, df2 = 973)} = 1.4$, $p < 0.0001$; Fig. 4C). In contrast, latitude showed no effect on TMFs ($F_{(df1 = 1, df2 = 1007)} = 0$, $p = 0.9722$; Fig. 5A).

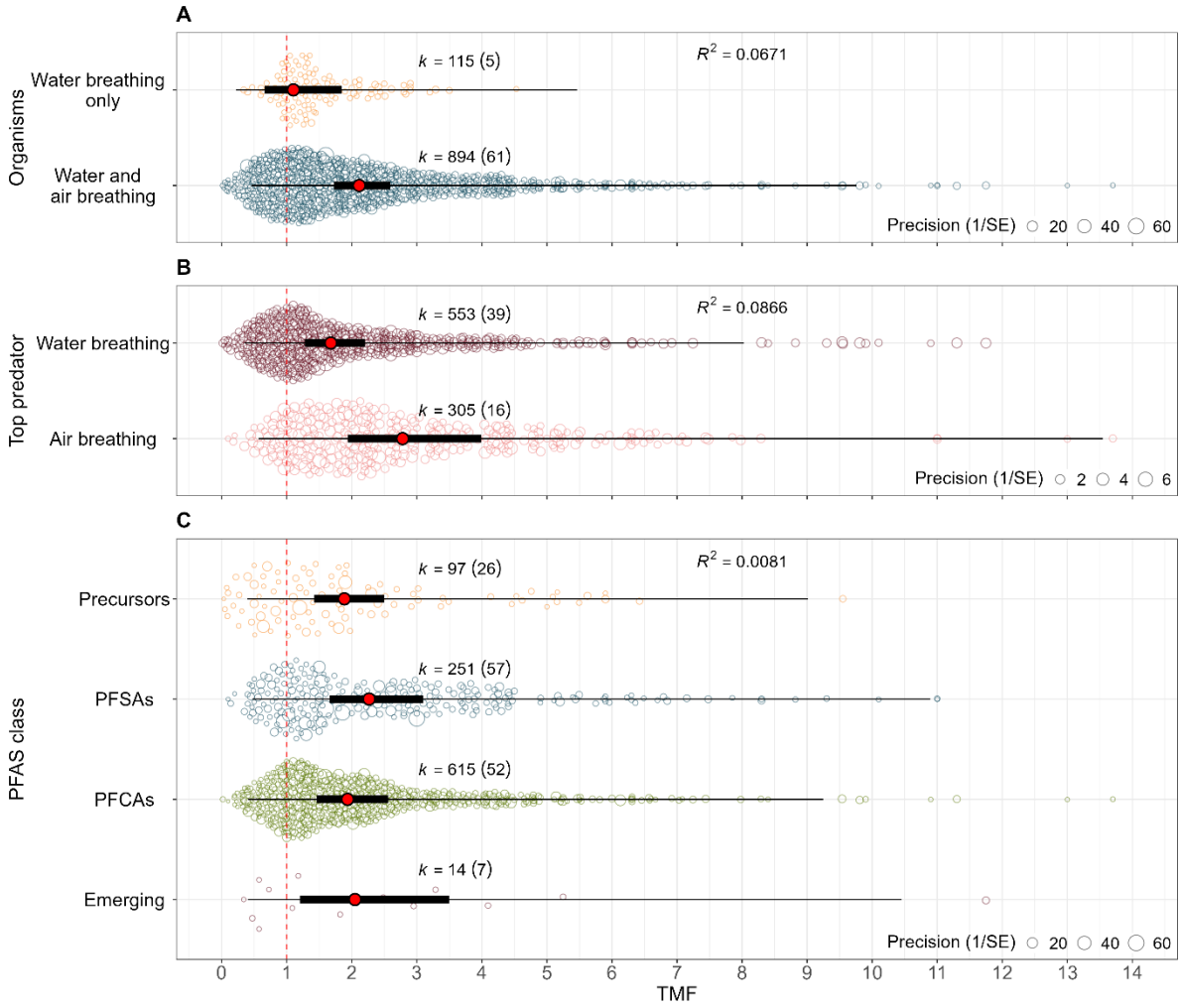

Fig. 4. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS), stratified by food webs of exclusively water breathing organisms versus mixed breathing types (A), food webs with either air breathing or water breathing top predators (B), and PFAS chemical class (C). *The meta-analytic mean estimate for each stratification is represented by a red-filled circle with a black outline. Thicker bars denote the 95% confidence interval, while thinner bars represent the 95% prediction interval. Light grey circles show individual effect sizes, scaled by precision (inverse of the standard error, as indicated in the legend). The number of studies is indicated in parentheses, with "k" representing the number of effect sizes. The red dotted line marks a trophic magnification factor (TMF) of 1, with values above 1 indicating biomagnification and those below 1 indicating biodilution. TMF values are capped at 14 for improved visual clarity (refer to Fig. S9-S11 for full versions). R^2 values represent the proportion of variance explained only by the fixed effects in the model (marginal R^2).*

We found no direct association between TMF and the trophic positions of either the baseline organism ($F_{(df1 = 1, df2 = 839)} = 1.8$, $p = 0.1826$; Fig. 5B) or the top predator ($F_{(df1 = 1, df2 = 839)} = 0.1$, $p = 0.7030$; Fig. 5C). Similarly, the number of trophic levels in a food web was not related to TMF values ($F_{(df1 = 1, df2 = 839)} = 0.5745$, $p = 0.4487$; Fig. 5D), nor was the PFAS carbon chain length ($F_{(df1 = 1, df2 = 984)} = 0.5561$, $p = 0.4560$; Fig. 5E).

When we tested the regulation status of chemicals (i.e., whether they are listed under the Stockholm Convention on Persistent Organic Pollutants, the REACH regulation, or remain internationally unregulated) as a post-hoc moderator (i.e., not pre-registered; see Tab. S3 for details) we found an effect on TMF ($F_{(df1 = 3, df2 = 841)} = 11$, $p < 0.0001$; Fig. S12). However, TMFs did not differ between internationally unregulated compounds and those listed under REACH ($TMF_{contrast} = 0.67$, CI = (0.39, 1.13)) or the Stockholm Convention ($TMF_{contrast} = 0.88$, CI = (0.52, 1.49)).

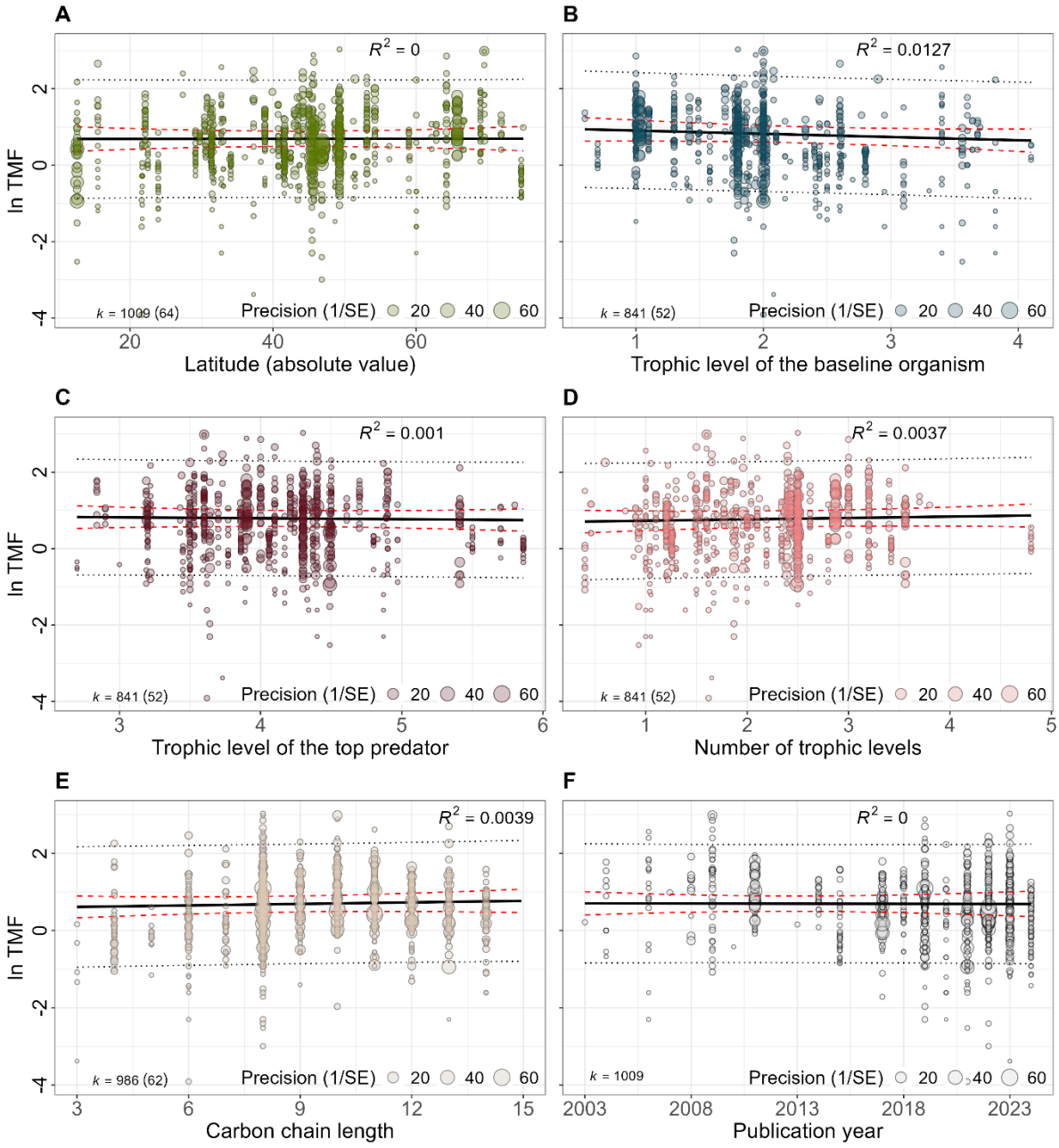

Fig. 5. The relationship between trophic magnification of per- and polyfluoroalkyl substances (PFAS) and food webs' latitude (A), trophic position of the food web's baseline organism (B), trophic position of the food web's

top predator (C), the number of trophic levels in the food web (D), PFAS carbon chain length (E), and publication year of the included studies in the meta-analysis (F). *The uni-moderator fitted models are depicted as thick black lines, with their 95% confidence intervals shown as red dashed lines and 95% prediction intervals represented by dotted black lines. Light grey circles represent the individual effect sizes (k), and the size of each circle reflects its precision (inverse of standard error). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The TMF is on the natural logarithm scale to enhance visual readability of results. R^2 values represent the proportion of variance explained only by the fixed effects in the model (marginal R^2).*

The full model and multi-model inference

The results from the multi-moderator meta-regression model (hereafter the "full model"), which accounts for potential confounding correlations among moderators, corroborated the findings of the univariate models, identifying sample type (i.e., whole-body, tissue-specific, or mixed) and concentration determination method (normalisation) as predictors of variability in TMF ($p < 0.0001$ for both). However, unlike the univariate models, the full model revealed a borderline non-significant effect of breathing type at both the food web and top predator levels ($p = 0.051$ and $p = 0.057$, respectively). PFAS chemical class, carbon chain length, and food webs' latitude did not emerge as predictors of change from the full model. We excluded five moderators with moderate to high levels of missing data from the full model, including the strategy for handling undetected values (n = 281), trophic enrichment factor (n = 83), trophic levels of the baseline organism (n = 119) and top predator (n = 119), and food web length (n = 119) to preserve statistical power. A correlation analysis, aided by visual inspection of an alluvial plot of categorical variables, confirmed that the included moderators were not highly correlated (i.e., no evidence of excessive collinearity; Fig. S13). Notably, the full model accounted for 84% of the variation in the dataset ($R^2 = 0.837$).

We used multi-model inference to generate models with all possible combinations of moderators from the full model. Two "best models" were identified based on the lowest Akaike Information Criterion (AIC). Sample type, concentration determination method, breathing type of top predator and whole food web, and PFAS carbon chain length and chemical class appear in both models. Food webs' latitude did not appear in the second-ranked model but appeared in the first-ranked. Relative importance analysis with Akaike weights identified (1) the type of sample, concentration determination method, and carbon chain length as the most important predictors of

change, (2) the breathing type of top predator and whole food web and PFAS chemical class as secondary predictors, and (3) food webs' latitude as the least important predictor (Fig. S14).

Publication bias and sensitivity analysis

A visual assessment of study precision (inverse of standard error, Fig. S15) and a meta-regression of time-lag ($F_{(df1 = 1, df2 = 1007)} = 0$, $p = 0.9490$; Fig. 5F) provided little evidence of publication bias. However, the meta-regression with standard error as a moderator indicated a potential publication bias ($F_{(df1 = 1, df2 = 1007)} = 22$, $p < 0.001$; Fig. S16). Applying a two-step robust point and variance estimation (*29*) reduced the effect magnitude by a factor of 3.46, but the direction and statistical significance remained unchanged (TMF = 1.65, CI = (1.28, 2.13)). The leave-one-out analysis showed that no individual study had a substantial impact on the overall results (Fig. S17). A validation test of the meta-regression model, using PFAS identity as a moderator, found no evidence of overparameterisation, supporting the model's reliability (Method S1; Fig. S18). A study validity assessment was performed using a modified version of SYRCLE's risk of bias tool (*30*) (Method S2; Data S5). Excluding studies with at least one high-risk-of-bias item did not change the overall direction of the meta-analytic result (Fig. S19). It only slightly affected its magnitude, providing evidence of no significant impact of the removal of potentially biased studies on the robustness of the findings.

Discussion

We found strong evidence for the amplification of PFAS contamination as it moves up the food chain. Notably, when aggregating results from different chemicals (n = 75) and ecosystems (n = 122), we found that, on average, PFAS concentrations doubled with each increase in trophic level. Our data showed high heterogeneity, with nearly 30% of TMF variability attributed to compound-specific differences. The rest was evenly divided between within- and between-study factors. Methodological differences across studies emerged as the primary drivers of TMF variation. Although some differences reflect genuine biological variability, much of the observed variation arises from inconsistent methodological decisions. Two earlier literature reviews (*11*, *12*) hypothesised that multiple factors influence PFAS TMFs. Our analysis ranks the contribution of these factors for the first time, using a quantitative approach and a model that explained 84% of the total variability in the data.

Sample type was one of the most important predictors of change in TMF estimates. Specifically, TMFs measured in food webs where lower trophic level organisms were analysed as whole organisms and upper trophic level ones using a tissue-specific sample had a 50% higher TMF than those with all organisms analysed as whole organisms. This effect arises because some tissues and organs, such as the liver, muscle, and lung, accumulate the highest PFAS concentrations (*31*, *32*), resulting in an overestimation of the TMF. Conversely, using tissues not prioritised by PFAS bioaccumulation (e.g., non-target organs) in top predators risks underestimating TMFs, obscuring true magnification trends. Our finding quantitatively supports concerns previously raised by a literature review (*18*) and emphasises the impact of sampling strategies on TMF outcomes. Concentration determination methods also contributed to variability, as normalising PFAS concentrations for lipid or protein content consistently resulted in lower TMFs. While a previous study (*19*) first proposed accounting for these factors, our analysis reinforces the importance of recognising lipid- and protein-normalization as critical sources of variation in TMF calculations. Furthermore, the observed influence of nitrogen isotope enrichment factors (TEF) on TMF reflects the significance of accurately quantifying $\Delta^{15}N$ dynamics. While the widely applied average $\Delta^{15}N$ of 3.4‰ per trophic level offers practical utility, its oversimplification risks misrepresenting food web structure by masking taxon-specific variability and the dynamic nature of isotopic discrimination

(*20*). However, our model revealed that the specific contribution of TEF to TMF variability was relatively little when accounting for the influence of other moderators included in this meta-analysis. We also observed an effect of the strategy used to deal with undetected values (e.g., the instrument limit divided by two) on the TMF. However, the high variability of strategies and missing information hindered our ability to test its effect while controlling for other moderators.

Beyond methodological drivers, true biological variability associated with ecological and environmental differences exerts limited influence. While TMFs were significantly higher in food webs containing both water and air breathing organisms, particularly those culminating in air-breathing apex predators, this pattern is likely attributable to confounding factors inherent to the samples. Notably, when accounting for potential confounders, biological variability did not emerge as a robust predictor of observed differences. A plausible explanation for this confounding lies in the structural composition of such food webs: systems integrating both water and air breathing organisms predominantly terminate in air breathing predators, where PFAS concentrations are measured in specific tissues or organs. This measurement focus may inadvertently conflate biological processes with methodological artifacts tied to tissue-specific PFAS bioaccumulation dynamics. Furthermore, we observed no significant differences in TMFs between terrestrial and aquatic food webs, corroborating the hypothesis of the aforementioned confounding effect.

Building on these general patterns, our analysis revealed significant trophic magnification for twelve individual compounds. Among these, F-53B (including 6:2 and 8:2 Cl-PFESA), PFOS (including linear and branched isomers), and PFDA exhibited the highest magnification factors (F-53B: TMF = 3.07, CI = (2.41, 3.92); PFOS: TMF = 3.02, CI = (2.64, 3.46); PFDA: TMF = 2.80, CI = (2.35, 3.33)). Of these twelve compounds, six are currently regulated under a global treaty, the Stockholm Convention on Persistent Organic Pollutants, eight are listed in the European REACH regulation, and one (F-53B) remains unregulated at the international level (*33*). We observed significant variation in TMF across compounds, with some exhibiting particularly high magnification patterns, warranting closer examination. Notably, our findings reveal that F-53B, a trade name for a complex mixture of chlorinated polyfluoroalkyl ether sulfonic acids (primarily 6:2 and 8:2 Cl-PFESA), exhibits a higher trophic magnification factor than PFOS, the compound it was designed to

replace (*34*). This finding raises concerns about the environmental safety of F-53B and suggests it may qualify for classification as a very bioaccumulative (vB) substance under the REACH regulation. Originally synthesized in the 1970s, chlorinated polyfluoroalkyl ether sulfonic acids have been used predominantly as mist suppressants in China's electroplating industry (*35*). Mist suppressants reduce the formation of airborne droplets or fumes during industrial processes. Production of F-53B increased after 2000, following the phase-out of PFOS by major manufacturers from 2000 to 2002 (*36*). However, some industries ceased F-53B production in 2020 due to more stringent environmental regulations (*37*). Like PFOS, F-53B is resistant to degradation and poses a risk to aquatic ecosystems (*35*). It has been widely detected in the blood of the Chinese population, with several health disorders linked to its exposure (*33*, *38*). Although F-53B use remains largely confined to China, environmental monitoring has detected its presence in wildlife and ecosystems there (*14*, *34*, *39*), and, to a lesser extent, in South Korea (*40*), Greenland (*41*), the United States, and Europe (*42*). Our results reiterate prior concerns (*43*) about F-53B's extreme bio-persistence, highlighting its potential risks as one of the most enduring PFAS compounds studied to date.

We acknowledge that our meta-analysis rests on key assumptions inherent to the use of the TMF. First, the TMF assumes steady-state conditions (*11*), where the intake and elimination of PFAS are balanced. If the included studies in our meta-analysis violate this assumption, our findings may capture short-term fluctuations rather than long-term trends in PFAS TMF, potentially affecting its accuracy. Second, the TMF assumes that dietary intake is the primary pathway of contaminant exposure, and that trophic level largely determines contaminant buildup in organisms and food webs (*18*). However, the relationship between chemical concentration and trophic level may be distorted due to variability within and between species if different exposure pathways (e.g., inhalation, dermal exposure, direct uptake from water or sediments) significantly influence contaminant levels in upper-trophic level organisms.

In addition to these foundational assumptions, our meta-analysis has minor limitations worth mentioning. Our dataset is skewed towards aquatic food webs, with terrestrial food webs being underrepresented. As a result, our findings are likely more applicable to aquatic ecosystems. Although we did not observe significant differences between the two types of food webs, we consider our results for terrestrial food webs to be

preliminary. Furthermore, the geographic distribution of available studies, with a disproportionate concentration in North America, Europe, and China, limits the global applicability of our findings, particularly for understudied regions like the southern hemisphere. Finally, our results provided some evidence of publication bias, suggesting that smaller studies in our dataset tend to report larger effect sizes. However, after statistically accounting for this correlation, the direction and significance of the effect remained unchanged, demonstrating the robustness of our findings. This pattern may therefore be driven by unexplained heterogeneity rather than a small-study effect (*44*). Despite these limitations, our meta-analysis provides the most comprehensive quantitative synthesis of PFAS TMFs to date, though its conclusions should be interpreted with these caveats in mind.

Considering our findings, we propose two recommendations for future research on TMF estimation for chemicals in general, including but not limited to PFAS. First, researchers could convert biomass to tissue-specific concentrations into whole-body concentrations (see (*45*)) to improve the comparability of lower and higher trophic levels. If a biomass conversion cannot be used, multiple tissues or organs should be used for higher trophic level organisms. Small organisms like plankton and invertebrates are typically analysed whole due to their size. In contrast, contaminants in larger species (e.g., fish, birds, or mammals) are usually quantified via specific tissues due to ethical and practical reasons, ignoring uneven accumulation in the body (*31*, *46*). Biomass-based conversion to whole-body concentrations or multi-tissue analysis would improve TMF accuracy by accounting for relative heterogeneity. Second, future studies should report TMFs using both protein-normalized and non-normalized concentrations. Unlike many persistent organic pollutants, PFAS preferentially bind to proteins (*47*, *48*), making dual reporting helpful for cross-chemical comparisons and standardised estimates across species with diverse tissue compositions. Finally, studies should evaluate the sensitivity of their results to variations in the chosen TEF. In ecological food web models, TEF values are often selected arbitrarily and may not accurately reflect the true isotopic enrichment per trophic level (*20*). Such discrepancies can influence the results, potentially leading to overestimating or underestimating trophic position and biomagnification patterns. Our recommendations aim to enhance methodological consistency, reduce bias, and ensure that observed TMF variability reflects true biological, chemical, or ecological

differences rather than methodological artifacts. For further guidance on measuring the TMF, see (*49*).

In summary, our analysis provides compelling evidence of PFAS trophic magnification in both aquatic and terrestrial food webs by an average factor of 2, identifies F-53B and several other chemicals as highly biomagnifying, and highlights methodological choices as key drivers of variability in TMF estimates. A TMF of 2 indicates that PFAS concentrations double at each trophic level, threatening apex predators and humans and potentially destabilising biodiversity and food web resilience. This quantifiable risk may demand urgent policy action: stricter regulation of PFAS discharges, expanded monitoring of high-trophic species, and global treaties to curb bio-accumulative chemical production. Furthermore, our results reveal widespread methodological disparities that obscure true ecological drivers of PFAS biomagnification, undermining risk assessments and delaying targeted regulations. Addressing these inconsistencies must precede policy. Standardised protocols are essential to isolate real-world trends from study artifacts, ensuring regulatory decisions reflect ecological reality.

Materials and Methods

Our methodology consisted of five key procedural steps. First, we registered the project plan (*17*), which detailed the research questions, hypotheses, and methods. Minor revisions were made to the original plan, and these changes were documented, explained, and justified (Tab. S5). Second, we identified the research question components (Method S3) and conducted a systematic literature search of primary studies relevant to the research topic. Third, we extracted specific data items from the literature and stored them in a relational database. Fourth, we tested our research questions by extracting or estimating effect sizes and using statistical modelling techniques. Fifth, we tested the robustness of our analysis through a publication bias assessment and sensitivity analysis. The methods are presented in accordance with the Method Reporting with Initials for Transparency (MeRIT) system (*50*), while data and analysis reporting adhere to the PRISMA-EcoEvo guidelines (*51*) (Tab. S6). We used an adapted version of the SYRCLE's risk of bias tool for study validity assessment (*30*) (see the Publication Bias and Sensitivity Analysis section for more details). The raw data and code are publicly available in our GitHub repository (https://github.com/ThisIsLorenzo/PFAS_Trophic_Magnification).

Systematic review and dataset structure

LR conducted a systematic literature search across six academic databases (PubMed, Web of Science Core Collection, Scopus, GreenFile via EBSCO, Bielefeld Academic Search Engine, and ProQuest Theses & Dissertations) to identify studies on the trophic magnification of PFAS. The Scopus search string was validated by cross-referencing 25 previously identified records from an earlier literature review (*12*), retrieving all entries, thereby confirming the string's comprehensiveness (Tab. S7). The initial search yielded 3,744 bibliographic records. Comprehensive details regarding search dates, query syntaxes, and the number of hits per database are provided in the Tab. S8.

Duplicated records were systematically identified and removed using a two-step process: first, through string-matching algorithms implemented in the R package *synthesisr* (*52*), which detected 1,385 duplicates; then, additional deduplication using Rayyan's proprietary function (https://www.rayyan.ai/), which identified 14 remaining duplicates. This resulted in a final corpus of 2,345 unique records.

Six independent reviewers (LR, ML, CW, PPottier, KM, PPollo) screened titles and abstracts of 2,345 records against predefined eligibility criteria (Method S4). LR and ML performed a pilot assessment on a 10% subset of records to ensure consistency in full-text screening, after which LR completed the remaining full-text evaluations (Fig. S20). Studies excluded during full-text screening were documented with rationale (Tab. S9). LR extracted the data and organised it into five structured tables summarising study characteristics, study validity assessment results, food web parameters, PFAS analytes, and quantitative datasets used for effect size calculations (Fig. S21).

The trophic magnification factor

In this meta-analysis, we used the Trophic Magnification Factor (TMF) as the effect size, along with its standard error (SE), calculated as the square root of the sampling variance. The TMF is commonly used to assess the trophic magnification potential of pollutants and represents the increase in the concentration of a chemical compound per trophic level. The TMF is derived from the antilog of the slope (b in Equation 1) of the relationship between log-transformed (to the base of 10 or Euler's number) PFAS concentration and the trophic levels of organisms belonging to the same food web (Equation 2).

$$TMF = 10^{b} \text{ or } TMF = e^{b}$$

Equation 1

$$log_{10}[PFAS] = TL(b) + a \text{ or } ln[PFAS] = TL(b) + a$$

Equation 2

where TL represents the trophic level (also known as trophic position) of organisms in a food web and a is the intercept of the regression. The trophic level of an organism is commonly calculated using nitrogen isotope analysis (Equation 3).

$$TL_c = \frac{(\delta^{15}N_c - \delta^{15}N_b)}{\Delta^{15}N + \lambda}$$

Equation 3

where TL_c refers to the trophic level of a consumer, $(\delta^{15}N_c - \delta^{15}N_b)$ is the difference between the ratios of stable isotopes of nitrogen (i.e., ^{15}N to ^{14}N) in the

consumer and a baseline organism, $\Delta^{15}N$ represents the trophic discrimination factor for $\delta^{15}N$ and λ is the trophic level of the baseline organism. The TMF is a reliable and comparable method for evaluating PFAS transfer within food webs (*12*). It is currently adopted under the REACH regulation as a metric of chemicals' environmental persistence and long-term ecological impact (*53*).

In this meta-analysis, we directly extracted the TMF and its associated standard error from the included studies. When the TMF or its standard error were not reported directly, but necessary data were available, we calculated the TMF using the calculation scenarios described in Method S5. When trophic levels were not reported, but nitrogen isotope analysis data were available (i.e., $\delta^{15}N$) (Equation 4), we employed these isotope results as a proxy for the trophic positions of organisms (*54–57*).

$$log_{10}[PFAS] = \delta^{15}N(b) + a \text{ or } ln[PFAS] = \delta^{15}N(b) + a$$

Equation 4

where terms are as mentioned before.

Statistical modelling overview

To estimate the overall TMF for PFAS, LR employed a multilevel meta-analytic model using the *rma.mv* function from the *metafor* R package (version 4.4.0) (*58*). This approach allowed for the incorporation of multiple sources of variability, as our model accounted for random effects at four levels: between studies, between food webs, between types of PFAS, and within studies. LR used the natural logarithm of the TMF as the response variable and specified a variance-covariance matrix clustered over food webs to account for dependence among effect sizes (*59*). The variance-covariance matrix was constructed using the squared standard error of the natural logarithm of the TMF as the variance of the effect sizes. Additionally, a constant within-study correlation coefficient of 0.5 was assumed.

To assess and compare trophic magnification factors (TMFs) across individual PFAS while controlling for covariates, we applied a subgroup-correlated effects meta-regression model (*60*). This approach avoids assuming uniform biomagnification and heterogeneity rates across all PFAS, enabling direct statistical comparison of TMFs between compounds. By isolating compound-specific differences, we quantified their

relative biomagnification risks. LR built the model on a variance-covariance matrix for each PFAS identity, incorporating the clustering effects from food webs and the individual TMF identifiers. LR specified a random effects structure that allowed for variability among food webs while treating the correlations among observations as diagonal. We validated our models' overall quality and robustness to over-parametrisation using their AICc value and profile likelihood of individual variance components (Method S1; Fig. S18).

LR used uni-moderator meta-regression models to explore the moderating effect of individual predictors on PFAS TMF. The models had each predictor as a fixed effect (moderator) and the same random effect structure and variance-covariance matrix as the primary meta-analytic model. The multi-moderator meta-regression model (i.e., full model) tested the combined effect of all moderators together. We assessed the moderators for missingness and correlation before fitting them into the full model (Fig. S13). We also categorised chemicals according to their regulatory status. This classification was determined by evaluating whether the substances were included in Annexes A, B, and C of the Stockholm Convention on Persistent Organic Pollutants, listed in the European regulatory framework REACH regulation, or not listed in any of these two international regulations (details provided in Tab. S3). The categorization reflects the most accurate and comprehensive information available during the analysis. We fitted the groups as moderators using the unregulated group as a reference to see if unregulated compounds had a statistically different mean than regulated ones.

Finally, to identify the most informative predictors of trophic magnification in our meta-analysis, LR employed model selection and multi-model inference using the dredge function (*MuMIn* package, version 1.48.4) (*61*) on the full model. The dredge function systematically generated a set of candidate models by exploring all possible combinations of predictor variables. These models were ranked based on Akaike Information Criterion corrected for small sample sizes (AICc), allowing us to assess the relative support for each candidate model. We selected the top models with a delta AICc value of ≤ 4 for further analysis and interpretation and calculated the sum of model weights for each predictor variable to estimate their relative importance.

All analyses were performed in the R computational environment (version 4.4.0) (*62*). Confidence intervals (CIs) were estimated at the 95% level, and statistical significance was determined at a p-value threshold of 0.05.

Publication bias and sensitivity analysis

LR assessed the risk of publication bias (*63*) by conducting the following two analyses: 1) Visual inspection of the full model's residuals against their standard error (*44*) and regression analysis of the effect size against its variance; 2) Regression analysis with publication year as moderator to test for time-lag bias (*64*). The robustness of the meta-analytic results was assessed through the following three sensitivity analyses: 1) A 'Leave-one-out' analysis; 2) Exclusion of high-risk studies according to a study validity assessment (*30*) (adapted SYRCLE's risk of bias tool; Method S2); 3) Validation of the subgroup correlated effects model (Method S1).

Acknowledgements

Funding: This project was financially supported by the National Health and Medical Research Council (NHMRC) Targeted Research Grant (APP1185002) awarded to Neely, Nakagawa and Hesselson. Ricolfi was supported by an Australian Government Research Training Program (RTP) Scholarship and the NHMRC Targeted Research Grant. Nakagawa also was supported by a Canada Excellence Research Chair (ERC-2022-00074). Our funders and institutions had no role in developing the study.

Author contributions: Lorenzo Ricolfi: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yefeng Yang**: Writing – review & editing, Methodology, Formal analysis. **Patrice Pottier**: Writing – review & editing, Visualization, Literature search. **Kyle Morrison**: Writing – review & editing, Literature search. **Coralie Williams**: Writing – review & editing, Literature search. **Pietro Pollo**: Writing – review & editing, Literature search. **Daniel Hesselson**: Writing – review & editing, Funding acquisition. **G. Gregory Neely**: Writing – review & editing, Funding acquisition. **Matthew D. Taylor**: Writing – review & editing, Supervision. **Shinichi Nakagawa**: Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Malgorzata Lagisz**: Conceptualization, Methodology, Writing – review & editing, Supervision.

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

Data and materials availability: Raw data and analysis code are available at the provided GitHub link.

References

1. D. Pauly, V. Christensen, J. Dalsgaard, R. Froese, F. Torres, Fishing Down Marine Food Webs. *Science* **279**, 860–863 (1998).

2. E. L. Johnston, M. Mayer-Pinto, T. P. Crowe, REVIEW: Chemical contaminant effects on marine ecosystem functioning. *Journal of Applied Ecology* **52**, 140–149 (2015).

3. J. Glüge, M. Scheringer, I. T. Cousins, J. C. DeWitt, G. Goldenman, D. Herzke, R. Lohmann, C. A. Ng, X. Trier, Z. Wang, An overview of the uses of per- and polyfluoroalkyl substances (PFAS). *Environ. Sci.: Processes Impacts* **22**, 2345–2373 (2020).

4. S. Kurwadkar, J. Dane, S. R. Kanel, M. N. Nadagouda, R. W. Cawdrey, B. Ambade, G. C. Struckhoff, R. Wilkin, Per- and polyfluoroalkyl substances in water and wastewater: A critical review of their global occurrence and distribution. *Science of the Total Environment* **809** (2022).

5. K. R. Miner, H. Clifford, T. Taruscio, M. Potocki, G. Solomon, M. Ritari, I. E. Napper, A. P. Gajurel, P. A. Mayewski, Deposition of PFAS 'forever chemicals' on Mt. Everest. *Science of the Total Environment* **759**, 144421 (2021).

6. M. Lechner, H. Knapp, Carryover of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) from soil to plant and distribution to the different plant compartments studied in cultures of carrots (Daucus carota ssp. Sativus), potatoes (Solanum tuberosum), and cucumbers (Cucumis Sativus). *Journal of agricultural and food chemistry* **59**, 11011–11018 (2011).

7. S. Zhao, S. Fang, L. Zhu, L. Liu, Z. Liu, Y. Zhang, Mutual impacts of wheat (Triticum aestivum L.) and earthworms (Eisenia fetida) on the bioavailability of perfluoroalkyl substances (PFASs) in soil. *Environmental pollution* **184**, 495–501 (2014).

8. M. Haukås, U. Berger, H. Hop, B. Gulliksen, G. W. Gabrielsen, Bioaccumulation of per- and polyfluorinated alkyl substances (PFAS) in selected species from the Barents Sea food web. *Environmental Pollution* **148**, 360–371 (2007).

9. K. M. Fremlin, J. E. Elliott, R. J. Letcher, T. Harner, F. A. P. C. Gobas, Developing Methods for Assessing Trophic Magnification of Perfluoroalkyl Substances within an Urban Terrestrial Avian Food Web. *Environ. Sci. Technol.* **57**, 12806–12818 (2023).

10. S. E. Fenton, A. Ducatman, A. Boobis, J. C. DeWitt, C. Lau, C. Ng, J. S. Smith, S. M. Roberts, Per- and Polyfluoroalkyl Substance Toxicity and Human Health Review: Current State of Knowledge and Strategies for Informing Future Research. *ENVIRONMENTAL TOXICOLOGY AND CHEMISTRY* **40**, 606–630 (2021).

11. J. Franklin, How reliable are field-derived biomagnification factors and trophic magnification factors as indicators of bioaccumulation potential? Conclusions from a case study on per- and polyfluoroalkyl substances. *Integrated Environmental Assessment and Management* **12**, 6–20 (2015).

12. D. de A. Miranda, G. F. Peaslee, A. M. Zachritz, G. A. Lamberti, A worldwide evaluation of trophic magnification of per-and polyfluoroalkyl substances in aquatic ecosystems. *Integrated Environmental Assessment and Management* **18**, 1500–1512 (2022).

13. J. Diao, Z. Chen, T. Wang, C. Su, Q. Sun, Y. Guo, Z. Zheng, L. Wang, P. Li, W. Liu, S. Hong, J. S. Khim, Perfluoroalkyl substances in marine food webs from South China Sea: Trophic transfer and human exposure implication. *JOURNAL OF HAZARDOUS MATERIALS* **431** (2022).

14. C.-G. Pan, S.-K. Xiao, K.-F. Yu, Q. Wu, Y.-H. Wang, Legacy and alternative per-and polyfluoroalkyl substances in a subtropical marine food web from the Beibu Gulf, South China: Fate, trophic transfer and health risk assessment. *Journal of Hazardous Materials* **403**, 123618 (2021).

15. C. Simmonet-Laprade, H. Budzinski, M. Babut, K. Le Menach, G. Munoz, M. Lauzent, B. J. D. Ferrari, P. Labadie, Investigation of the spatial variability of poly- and perfluoroalkyl substance trophic magnification in selected riverine ecosystems. *Science of The Total Environment* **686**, 393–401 (2019).

16. G. T. Tomy, K. Pleskach, S. H. Ferguson, J. Hare, G. Stern, G. MacInnis, C. H. Marvin, L. Loseto, Trophodynamics of Some PFCs and BFRs in a Western Canadian Arctic Marine Food Web. *Environ. Sci. Technol.* **43**, 4076–4081 (2009).

17. L. Ricolfi, K. Morrison, C. Williams, Y. Yang, P. Pottier, P. Pollo, M. D. Taylor, M. Lagisz, S. Nakagawa, "What is the overall PFAS trophic magnification estimate and the key drivers of variability?: a Other aggregative reviews (e.g. Meta-analyses, Critical reviews) Protocol" (Collaboration for Environmental Evidence (CEE), 2024); https://doi.org/10.57808/PROCEED.2024.8.

18. K. Borgå, K. A. Kidd, D. C. Muir, O. Berglund, J. M. Conder, F. A. Gobas, J. Kucklick, O. Malm, D. E. Powell, Trophic magnification factors: Considerations of ecology, ecosystems, and study design. *Integrated Environmental Assessment and Management* **8**, 64–84 (2012).

19. B. C. Kelly, M. G. Ikonomou, J. D. Blair, B. Surridge, D. Hoover, R. Grace, F. A. P. C. Gobas, Perfluoroalkyl Contaminants in an Arctic Marine Food Web: Trophic Magnification and Wildlife Exposure. *Environ. Sci. Technol.* **43**, 4037–4043 (2009).

20. Y. Letourneur, P. Fey, J. Dierking, R. Galzin, V. Parravicini, Challenging trophic position assessments in complex ecosystems: Calculation method, choice of baseline, trophic enrichment factors, season and feeding guild do matter: A case study from Marquesas Islands coral reefs. *Ecology and Evolution* **14**, e11620 (2024).

21. R. B. B. Stephens, O. N. N. Shipley, R. J. J. Moll, Meta-analysis and critical review of trophic discrimination factors (Δ¹³C and Δ¹⁵N): Importance of tissue, trophic level and diet source. *FUNCTIONAL ECOLOGY* **37**, 2535–2548 (2023).

22. J. M. Conder, F. A. P. C. Gobas, K. Borgå, D. C. G. Muir, D. E. Powell, Use of trophic magnification factors and related measures to characterize bioaccumulation potential of chemicals. *Integrated Environmental Assessment and Management* **8**, 85–97 (2012).

23. M. Houde, A. O. De Silva, D. C. G. Muir, R. J. Letcher, Monitoring of perfluorinated compounds in aquatic biota: An updated review. *Environmental Science and Technology* **45**, 7962–7973 (2011).

24. R. T. Paine, Food web complexity and species diversity. *The American Naturalist* **100**, 65–75 (1966).

25. J. M. Conder, R. A. Hoke, W. De Wolf, M. H. Russell, R. C. Buck, Are PFCAs bioaccumulative? A critical review and comparison with regulatory criteria and persistent lipophilic compounds. *Environmental Science and Technology* **42**, 995–1003 (2008).

26. P. D. Jones, W. Hu, W. De Coen, J. L. Newsted, J. P. Giesy, Binding of perfluorinated fatty acids to serum proteins. *Environmental Toxicology and Chemistry* **22**, 2639–2649 (2003).

691 27. J. W. Martin, S. A. Mabury, K. R. Solomon, D. C. Muir, Bioconcentration and tissue
692 distribution of perfluorinated acids in rainbow trout (Oncorhynchus mykiss). *Environmental*
693 *Toxicology and Chemistry: An International Journal* **22**, 196–204 (2003).

694 28. J. P. T. Higgins, Measuring inconsistency in meta-analyses. *BMJ* **327**, 557–560 (2003).

695 29. Y. Yang, M. Lagisz, C. Williams, D. W. Noble, J. Pan, S. Nakagawa, Robust point and
696 variance estimation for meta-analyses with selective reporting and dependent effect sizes. *Methods in*
697 *Ecology and Evolution* **15**, 1593–1610 (2024).

698 30. C. R. Hooijmans, M. M. Rovers, R. B. De Vries, M. Leenaars, M. Ritskes-Hoitinga, M. W.
699 Langendam, SYRCLE's risk of bias tool for animal studies. *BMC Med Res Methodol* **14**, 43 (2014).

700 31. A. Robuck, J. McCord, M. Strynar, M. Cantwell, D. Wiley, R. Lohmann, Tissue-Specific
701 Distribution of Legacy and Novel Per- and Polyfluoroalkyl Substances in Juvenile Seabirds.
702 *ENVIRONMENTAL SCIENCE & TECHNOLOGY LETTERS* **8**, 457–462 (2021).

703 32. F. Pérez, M. Nadal, A. Navarro-Ortega, F. Fàbrega, J. L. Domingo, D. Barceló, M. Farré,
704 Accumulation of perfluoroalkyl substances in human tissues. *Environment international* **59**, 354–362
705 (2013).

706 33. Y. He, D. Lv, C. Li, X. Liu, W. Liu, W. Han, Human exposure to F-53B in China and the
707 evaluation of its potential toxicity: An overview. *Environment International* **161**, 107108 (2022).

708 34. W. Liu, H. Qin, J. Li, Q. Zhang, H. Zhang, Z. Wang, X. He, Atmospheric chlorinated
709 polyfluorinated ether sulfonate and ionic perfluoroalkyl acids in 2006 to 2014 in Dalian, China.
710 *Environmental toxicology and chemistry* **36**, 2581–2586 (2017).

711 35. S. Wang, J. Huang, Y. Yang, Y. Hui, Y. Ge, T. Larssen, G. Yu, S. Deng, B. Wang, C. Harman,
712 First report of a Chinese PFOS alternative overlooked for 30 years: its toxicity, persistence, and
713 presence in the environment. *Environmental science & technology* **47**, 10163–10170 (2013).

714 36. N. Briels, T. Ciesielski, D. Herzke, V. Jaspers, Developmental Toxicity of
715 Perfluorooctanesulfonate (PFOS) and Its Chlorinated Polyfluoroalkyl Ether Sulfonate Alternative F-
716 53B in the Domestic Chicken. *ENVIRONMENTAL SCIENCE & TECHNOLOGY* **52**, 12859–12867
717 (2018).

718 37. Environment Agency, Environmental risk evaluation report. Potassium
719 9chlorohexadecafluoro-3-oxanonane-1sulfonate [F-53B] (CAS no. 73606-19-6). 8 (2023).

720 38. S.-H. Hong, S. H. Lee, J.-Y. Yang, J. H. Lee, K. K. Jung, J. H. Seok, S.-H. Kim, K. T. Nam, J.
721 Jeong, J. K. Lee, J.-H. Oh, Orally Administered 6:2 Chlorinated Polyfluorinated Ether Sulfonate (F-
722 53B) Causes Thyroid Dysfunction in Rats. *Toxics* **8**, 54 (2020).

723 39. X. Feng, M. Ye, Y. Li, J. Zhou, B. Sun, Y. Zhu, L. Zhu, Potential sources and sediment-pore
724 water partitioning behaviors of emerging per/polyfluoroalkyl substances in the South Yellow Sea.
725 *Journal of Hazardous Materials* **389**, 122124 (2020).

726 40. W. Wang, J. Lee, J.-K. Oh, S.-J. Lee, S.-D. Choi, J.-E. Oh, Per- and polyfluoroalkyl
727 substances and their alternatives in black-tailed gull (Larus crassirostris) eggs from South Korea
728 islands during 2012–2018. *J. Hazard. Mater.* **411** (2021).

729 41. W. A. Gebbink, R. Bossi, F. F. Rigét, A. Rosing-Asvid, C. Sonne, R. Dietz, Observation of
730 emerging per- and polyfluoroalkyl substances (PFASs) in Greenland marine mammals. *Chemosphere*
731 **144**, 2384–2391 (2016).

42. Y. Pan, H. Zhang, Q. Cui, N. Sheng, L. W. Yeung, Y. Sun, Y. Guo, J. Dai, Worldwide distribution of novel perfluoroether carboxylic and sulfonic acids in surface water. *Environmental science & technology* **52**, 7621–7629 (2018).

43. Y. Shi, R. Vestergren, L. Xu, Z. Zhou, C. Li, Y. Liang, Y. Cai, Human exposure and elimination kinetics of chlorinated polyfluoroalkyl ether sulfonic acids (Cl-PFESAs). *Environmental science & technology* **50**, 2396–2404 (2016).

44. S. Nakagawa, M. Lagisz, M. D. Jennions, J. Koricheva, D. W. Noble, T. H. Parker, A. Sánchez-Tójar, Y. Yang, R. E. O'Dea, Methods for testing publication bias in ecological and evolutionary meta-analyses. *Methods in Ecology and Evolution* **13**, 4–21 (2022).

45. K. A. Kidd, L. P. Burkhard, M. Babut, K. Borgå, D. C. Muir, O. Perceval, H. Ruedel, K. Woodburn, M. R. Embry, Practical advice for selecting or determining trophic magnification factors for application under the European Union Water Framework Directive. *Integrated Environmental Assessment and Management* **15**, 266–277 (2019).

46. L. Ricolfi, M. D. Taylor, Y. Yang, M. Lagisz, S. Nakagawa, Maternal transfer of per-and polyfluoroalkyl substances (PFAS) in wild birds: a systematic review and meta-analysis. *Chemosphere*, 142346 (2024).

47. X. Han, P. M. Hinderliter, T. A. Snow, G. W. Jepson, Binding of Perfluorooctanoic Acid to Rat Liver-form and Kidney-form α2u-Globulins. *Drug and Chemical Toxicology* **27**, 341–360 (2004).

48. L. Zhao, M. Teng, X. Zhao, Y. Li, J. Sun, W. Zhao, Y. Ruan, K. M. Leung, F. Wu, Insight into the binding model of per-and polyfluoroalkyl substances to proteins and membranes. *Environment international* **175**, 107951 (2023).

49. K. M. Fremlin, J. E. Elliott, F. A. P. C. Gobas, Guidance for measuring and evaluating biomagnification factors and trophic magnification factors of difficult substances: application to decabromodiphenylethane. *Integrated Environmental Assessment and Management*, vjae025 (2025).

50. S. Nakagawa, E. R. Ivimey-Cook, M. J. Grainger, R. E. O'Dea, S. Burke, S. M. Drobniak, E. Gould, E. L. Macartney, A. R. Martinig, K. Morrison, Method Reporting with Initials for Transparency (MeRIT) promotes more granularity and accountability for author contributions. *nature communications* **14**, 1788 (2023).

51. R. E. O'Dea, M. Lagisz, M. D. Jennions, J. Koricheva, D. W. Noble, T. H. Parker, J. Gurevitch, M. J. Page, G. Stewart, D. Moher, Preferred reporting items for systematic reviews and meta-analyses in ecology and evolutionary biology: a PRISMA extension. *Biological Reviews* **96**, 1695–1722 (2021).

52. M. Westgate, E. Grames, synthesisr: Import, Assemble, and Deduplicate Bibliographic Datasets, version 0.3.0 R package (2022); https://cran.r-project.org/web/packages/synthesisr/synthesisr.pdf.

53. European Chemicals Agency, Guidance on Information Requirements and Chemical Safety Assessment Chapter R.11: PBT/vPvB Assessment. *ECHA-23-H-10-EN*, 116 (2023).

54. Y. Cherel, K. Hobson, Geographical variation in carbon stable isotope signatures of marine predators: a tool to investigate their foraging areas in the Southern Ocean. *Mar. Ecol. Prog. Ser.* **329**, 281–287 (2007).

55. S. D. Newsome, C. Martinez del Rio, S. Bearhop, D. L. Phillips, A niche for isotopic ecology. *Frontiers in Ecology and the Environment* **5**, 429–436 (2007).

56. Y. Cherel, C. Barbraud, M. Lahournat, A. Jaeger, S. Jaquemet, R. M. Wanless, R. A. Phillips, D. R. Thompson, P. Bustamante, Accumulate or eliminate? Seasonal mercury dynamics in albatrosses, the most contaminated family of birds. *Environmental Pollution* **241**, 124–135 (2018).

57. B. J. Peterson, B. Fry, Stable isotopes in ecosystem studies. *Annual review of ecology and systematics*, 293–320 (1987).

58. W. Viechtbauer, Conducting meta-analyses in R with the metafor package., version 4.8-0 (2010).

59. S. Nakagawa, Y. Yang, E. L. Macartney, R. Spake, M. Lagisz, Quantitative evidence synthesis: a practical guide on meta-analysis, meta-regression, and publication bias tests for environmental sciences. *Environmental Evidence* **12**, 8 (2023).

60. J. E. Pustejovsky, E. Tipton, Meta-analysis with robust variance estimation: Expanding the range of working models. *Prevention Science* **23**, 425–438 (2022).

61. K. Bartoń, MuMIn: Multi-Model Inference, version 1.48.4 R package; https://cran.r-project.org/package=MuMIn.

62. R Core Team, *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, Vienna, Austria, 2021; https://www.R-project.org/).

63. K. Dickersin, The Existence of Publication Bias and Risk Factors for Its Occurrence. doi: 10.1001/jama.1990.03440100097014.

64. L. Costello, J. W. Fox, Decline effects are rare in ecology. *Ecology* **103**, e3680 (2022).

65. S. Fang, X. Chen, S. Zhao, Y. Zhang, W. Jiang, L. Yang, L. Zhu, Trophic Magnification and Isomer Fractionation of Perfluoroalkyl Substances in the Food Web of Taihu Lake, China. *Environ. Sci. Technol.* **48**, 2173–2182 (2014).

66. M. Mazzoni, C. Ferrario, R. Bettinetti, R. Piscia, D. Cicala, P. Volta, K. Borgå, S. Valsecchi, S. Polesello, Trophic magnification of legacy (PCB, DDT and Hg) and emerging pollutants (PFAS) in the fish community of a small protected southern alpine lake (Lake Mergozzo, Northern Italy), *Water (Switzerland)*. **12** (2020). https://doi.org/10.3390/W12061591.

67. M. Houde, T. A. D. Bujas, J. Small, R. S. Wells, P. A. Fair, G. D. Bossart, K. R. Solomon, D. C. G. Muir, Biomagnification of perfluoroalkyl compounds in the bottlenose dolphin (Tursiops truncatus) food web, *Environmental Science and Technology*. **40** (2006)pp. 4138–4144.

68. M. Houde, G. Czub, J. M. Small, S. Backus, X. Wang, M. Alaee, D. C. G. Muir, Fractionation and bioaccumulation of perfluorooctane sulfonate (PFOS) isomers in a lake ontario food web, *Environmental Science and Technology*. **42** (2008)pp. 9397–9403.

69. G. T. Tomy, W. Budakowski, T. Halldorson, P. A. Helm, G. A. Stern, K. Friesen, K. Pepper, S. A. Tittlemier, A. T. Fisk, Fluorinated organic compounds in an Eastern arctic marine food web, *Environmental Science and Technology*. **38** (2004)pp. 6475–6481.

70. E. I. H. Loi, L. W. Y. Yeung, S. Taniyasu, P. K. S. Lam, K. Kannan, N. Yamashita, Trophic magnification of poly- and perfluorinated compounds in a subtropical food web. *Environmental Science and Technology* **45**, 5506–5513 (2011).

71. G. Munoz, H. Budzinski, M. Babut, H. Drouineau, M. Lauzent, K. L. Menach, J. Lobry, J. Selleslagh, C. Simonnet-Laprade, P. Labadie, Evidence for the Trophic Transfer of Perfluoroalkylated Substances in a Temperate Macrotidal Estuary, *Environmental Science and Technology*. **51** (2017)pp. 8450–8459.

816 72. C. Simonnet-Laprade, H. Budzinski, K. Maciejewski, K. Le Menach, R. Santos, F. Alliot, A.
817 Goutte, P. Labadie, Biomagnification of perfluoroalkyl acids (PFAAs) in the food web of an urban
818 river: assessment of the trophic transfer of targeted and unknown precursors and implications,
819 *Environmental Science: Processes and Impacts*. **21** (2019)pp. 1864–1874.

820 73. D. A. Miranda, J. P. Benskin, R. Awad, G. Lepoint, J. Leonel, V. Hatje, Bioaccumulation of
821 Per- and polyfluoroalkyl substances (PFASs) in a tropical estuarine food web, *Science of the Total*
822 *Environment*. **754** (2021). https://doi.org/10.1016/j.scitotenv.2020.142146.

823 74. J. W. Martin, D. M. Whittle, D. C. G. Muir, S. A. Mabury, Perfluoroalkyl contaminants in a
824 food web from Lake Ontario, *Environmental Science and Technology*. **38** (2004)pp. 5379–5385.

825 75. J. Xu, C.-S. Guo, Y. Zhang, W. Meng, Bioaccumulation and trophic transfer of perfluorinated
826 compounds in a eutrophic freshwater food web, *Environmental Pollution*. **184** (2014)pp. 254–261.

827 76. Z. Zhang, H. Peng, Y. Wan, J. Hu, Isomer-specific trophic transfer of perfluorocarboxylic
828 acids in the marine food web of liaodong bay, North China, *Environmental Science and Technology*.
829 **49** (2015)pp. 1453–1461.

830 77. H. Chen, J. Han, J. Cheng, R. Sun, X. Wang, G. Han, W. Yang, X. He, Distribution,
831 bioaccumulation and trophic transfer of chlorinated polyfluoroalkyl ether sulfonic acids in the marine
832 food web of Bohai, China, *Environmental Pollution*. **241** (2018)pp. 504–510.

833 78. W. Liu, W. He, J. Wu, N. Qin, Q. He, F. Xu, Residues, bioaccumulations and
834 biomagnification of perfluoroalkyl acids (PFAAs) in aquatic animals from Lake Chaohu, China,
835 *Environmental Pollution*. **240** (2018)pp. 607–614.

836 79. K. Gao, X. Miao, J. Fu, Y. Chen, H. Li, W. Pan, J. Fu, Q. Zhang, A. Zhang, G. Jiang,
837 Occurrence and trophic transfer of per- and polyfluoroalkyl substances in an Antarctic ecosystem,
838 *Environmental Pollution*. **257** (2020). https://doi.org/10.1016/j.envpol.2019.113383.

839 80. H. A. Langberg, G. D. Breedveld, G. Aa. Slinde, H. M. Grønning, Å. Høisæter, M. Jartun, T.
840 Rundberget, B. M. Jenssen, S. E. Hale, Fluorinated Precursor Compounds in Sediments as a Source of
841 Perfluorinated Alkyl Acids (PFAA) to Biota, *Environmental Science and Technology*. **54** (2020)pp.
842 13077–13089.

843 81. M. Chen, Q. Wang, G. Shan, L. Zhu, L. Yang, M. Liu, Occurrence, partitioning and
844 bioaccumulation of emerging and legacy per- and polyfluoroalkyl substances in Taihu Lake, China,
845 *Science of the Total Environment*. **634** (2018)pp. 251–259.

846 82. P. Wang, Y. Lu, H. Su, C. Su, A. C. Johnson, L. Yu, A. Jenkins, Managing health risks of
847 perfluoroalkyl acids in aquatic food from a river-estuary-sea environment affected by fluorochemical
848 industry, *Environment International*. **138** (2020). https://doi.org/10.1016/j.envint.2020.105621.

849 83. D. Du, Y. Lu, Y. Zhou, Q. Li, M. Zhang, G. Han, H. Cui, E. Jeppesen, Bioaccumulation,
850 trophic transfer and biomagnification of perfluoroalkyl acids (PFAAs) in the marine food web of the
851 South China Sea, *Journal of Hazardous Materials*. **405** (2021).
852 https://doi.org/10.1016/j.jhazmat.2020.124681.

853 84. Y. Li, J. Yao, J. Zhang, Y. Pan, J. Dai, C. Ji, J. Tang, First Report on the Bioaccumulation and
854 Trophic Transfer of Perfluoroalkyl Ether Carboxylic Acids in Estuarine Food Web, *Environmental*
855 *Science and Technology*. **56** (2022)pp. 6046–6055.

856 85. D. Du, Y. Lu, S. Yang, R. Wang, C. Wang, M. Yu, C. Chen, M. Zhang, Biomagnification and
857 health risks of perflfluoroalkyl acids (PFAAs) in seafood from the Yangtze river estuary of China,
858 *Environmental Pollution*. **341** (2024). https://doi.org/10.1016/j.envpol.2023.122930.

86. Y. Liu, T. Ruan, Y. Lin, A. Liu, M. Yu, R. Liu, M. Meng, Y. Wang, J. Liu, G. Jiang, Chlorinated Polyfluoroalkyl Ether Sulfonic Acids in Marine Organisms from Bohai Sea, China: Occurrence, Temporal Variations, and Trophic Transfer Behavior, *Environmental Science and Technology*. **51** (2017)pp. 4407–4414.

87. K. Huang, Y. Li, D. Bu, J. Fu, M. Wang, W. Zhou, L. Gu, Y. Fu, Z. Cong, B. Hu, J. Fu, A. Zhang, G. Jiang, Trophic Magnification of Short-Chain Per- and Polyfluoroalkyl Substances in a Terrestrial Food Chain from the Tibetan Plateau, *Environmental Science and Technology Letters*. **9** (2022)pp. 147–152.

88. C. E. Müller, A. O. De Silva, J. Small, M. Williamson, X. Wang, A. Morris, S. Katz, M. Gamberg, D. C. G. Muir, Biomagnification of perfluorinated compounds in a remote terrestrial food chain: Lichen-Caribou-Wolf, *Environmental Science and Technology*. **45** (2011)pp. 8665–8673.

89. Q. Fu, C. Meyer, M. Patrick, V. Kosfeld, H. Rüdel, J. Koschorreck, J. Hollender, Comprehensive screening of polar emerging organic contaminants including PFASs and evaluation of the trophic transfer behavior in a freshwater food web, *Water Research*. **218** (2022). https://doi.org/10.1016/j.watres.2022.118514.

90. D. Xiong, "Bioaccumulation and Biomagnification of Perfluoroalkyl Substances (PFAS) in a Subarctic Ringed Seal Food Web in Lake Melville, Northern Labrador, Canada," thesis, University of Toronto (Canada) (2021).

91. M. L. Hedgespeth, D. L. Taylor, S. Balint, M. Schwartz, M. G. Cantwell, Ecological characteristics impact PFAS concentrations in a U.S. North Atlantic food web, *Science of the Total Environment*. **880** (2023). https://doi.org/10.1016/j.scitotenv.2023.163302.

92. C. Wang, Y. Lu, B. Sun, M. Zhang, R. Mao, X. Li, S. Song, J. Zhao, M. Yu, Y. Shi, P. Wang, Biomanipulation impacts on per-and polyfluoroalkyl substances accumulation and trophic transfer in an eutrophic lake, *Environment International*. **160** (2022). https://doi.org/10.1016/j.envint.2021.107057.

93. V. Kosfeld, H. Rüdel, C. Schlechtriem, C. Rauert, J. Koschorreck, Food web on ice: a pragmatic approach to investigate the trophic magnification of chemicals of concern, *Environmental Sciences Europe*. **33** (2021). https://doi.org/10.1186/s12302-021-00530-x.

94. J. Ren, A. D. Point, S. F. Baygi, S. Fernando, P. K. Hopke, T. M. Holsen, B. S. Crimmins, Bioaccumulation of polyfluoroalkyl substances in the Lake Huron aquatic food web, *Science of the Total Environment*. **819** (2022). https://doi.org/10.1016/j.scitotenv.2022.152974.

95. G. Munoz, L. Mercier, S. V. Duy, J. Liu, S. Sauvé, M. Houde, Bioaccumulation and trophic magnification of emerging and legacy per- and polyfluoroalkyl substances (PFAS) in a St. Lawrence River food web, *Environmental Pollution*. **309** (2022). https://doi.org/10.1016/j.envpol.2022.119739.

96. W. Zhu, W. Liu, H. Jin, Sediment-seawater partitioning, bioaccumulation, and biomagnification of perfluorobutane sulfonamide in marine environment, *Water Research*. **255** (2024). https://doi.org/10.1016/j.watres.2024.121466.

97. H. Cheng, C. Lv, J. Li, D. Wu, X. Zhan, Y. Song, N. Zhao, H. Jin, Bioaccumulation and biomagnification of emerging poly- and perfluoroalkyl substances in marine organisms, *Science of the Total Environment*. **851** (2022). https://doi.org/10.1016/j.scitotenv.2022.158117.

98. Q. Wang, Y. Ruan, L. Jin, L. S. R. Tao, H. Lai, G. Li, L. W. Y. Yeung, K. M. Y. Leung, P. K. S. Lam, Legacy and Emerging Per- and Polyfluoroalkyl Substances in a Subtropical Marine Food Web: Suspect Screening, Isomer Profile, and Identification of Analytical Interference, *Environmental Science and Technology*. **57** (2023)pp. 8355–8364.

903 99. L. A. Alfaro Garcia, “PFAS bioaccumulation in Antarctic breeding south polar skua
904 (Catharacta maccormicki) and its prey items,” thesis, University of Oslo (2018).

905 100. K. Chu, Y. Lu, Z. Hua, Y. Liu, Y. Ma, L. Gu, C. Gao, L. Yu, Y. Wang, Perfluoroalkyl acids
906 (PFAAs) in the aquatic food web of a temperate urban lake in East China: Bioaccumulation,
907 biomagnification, and probabilistic human health risk, *Environmental Pollution*. **296** (2022).
908 https://doi.org/10.1016/j.envpol.2021.118748.

909 101. G. L. Lescord, K. A. Kidd, A. O. De Silva, M. Williamson, C. Spencer, X. Wang, D. C. G.
910 Muir, Perfluorinated and polyfluorinated compounds in lake food webs from the Canadian High
911 Arctic, *Environmental Science and Technology*. **49** (2015)pp. 2694–2702.

912 102. L. Teunen, L. Bervoets, C. Belpaire, M. De Jonge, T. Groffen, PFAS accumulation in
913 indigenous and translocated aquatic organisms from Belgium, with translation to human and
914 ecological health risk, *Environmental Sciences Europe*. **33** (2021). https://doi.org/10.1186/s12302-
915 021-00477-z.

916 103. X. Xie, Y. Lu, H. Lei, J. Cheng, X. An, W. Wang, X. Jiang, J. Xie, Y. Xiong, T. Wu,
917 Bioaccumulation and trophic transfer of per- and polyfluoroalkyl substances in a subtropical
918 mangrove estuary food web, *Science of the Total Environment*. **927** (2024).
919 https://doi.org/10.1016/j.scitotenv.2024.172094.

920 104. J. Ren, A. D. Point, S. F. Baygi, S. Fernando, P. K. Hopke, T. M. Holsen, B. S. Crimmins,
921 Bioaccumulation of perfluoroalkyl substances in the lake Erie food web, *Environmental Pollution*.
922 **317** (2023). https://doi.org/10.1016/j.envpol.2022.120677.

923 105. E. S. Heimstad, T. Nygård, B. Moe, D. Herzke, New insights from an eight-year study on per-
924 and polyfluoroalkyl substances in an urban terrestrial ecosystem, *Environmental Pollution*. **347**
925 (2024). https://doi.org/10.1016/j.envpol.2024.123735.

926 106. M. A. Khairy, G. O. Noonan, R. Lohmann, Uptake of hydrophobic organic compounds,
927 including organochlorine pesticides, polybrominated diphenyl ethers, and perfluoroalkyl acids in fish
928 and blue crabs of the lower Passaic River, New Jersey, USA, *Environmental Toxicology and*
929 *Chemistry*. **38** (2019)pp. 872–882.

930 107. Y. Li, J. Yao, Y. Pan, J. Dai, J. Tang, Trophic behaviors of PFOA and its alternatives
931 perfluoroalkyl ether carboxylic acids (PFECAs) in a coastal food web, *Journal of Hazardous*
932 *Materials*. **452** (2023). https://doi.org/10.1016/j.jhazmat.2023.131353.

933 108. X. Liang, J. Zhou, X. Yang, W. Jiao, T. Wang, L. Zhu, Disclosing the bioaccumulation and
934 biomagnification behaviors of emerging per/polyfluoroalkyl substances in aquatic food web based on
935 field investigation and model simulation, *Journal of Hazardous Materials*. **445** (2023).
936 https://doi.org/10.1016/j.jhazmat.2022.130566.

937 109. M. Gallien, “Etude comparative de l’écodynamique de micropolluants organohalogénés
938 historiques et d’intérêt émergent dans l’estuaire de Seine,” thesis, University of Bordeaux (2021).

939 110. B. Cara, T. Lies, G. Thimo, L. Robin, B. Lieven, Bioaccumulation and trophic transfer of
940 perfluorinated alkyl substances (PFAS) in marine biota from the Belgian North Sea: Distribution and
941 human health risk implications, *Environmental Pollution*. **311** (2022).
942 https://doi.org/10.1016/j.envpol.2022.119907.

943 111. A. Koch, M. Jonsson, L. W. Y. Yeung, A. Kärrman, L. Ahrens, A. Ekblad, T. Wang, Per- and
944 Polyfluoroalkyl-Contaminated Freshwater Impacts Adjacent Riparian Food Webs, *Environmental*
945 *Science and Technology*. **54** (2020)pp. 11951–11960.

946 112. A. Koch, T. Wang, M. Jonsson, L. W. Y. Yeung, A. Kärrman, L. Ahrens, A. Ekblad,
947 Quantification of biodriven transfer of per- And polyfluoroalkyl substances from the aquatic to the
948 terrestrial environment via emergent insects, *Environmental Science and Technology*. **55** (2021)pp.
949 7900–7909.

950 113. X. Li, L. W. Yin Yeung, M. Xu, S. Taniyasu, P. K. S. Lam, N. Yamashita, J. Dai,
951 Perfluorooctane sulfonate (PFOS) and other fluorochemicals in fish blood collected near the outfall of
952 wastewater treatment plant (WWTP) in Beijing, *Environmental Pollution*. **156** (2008)pp. 1298–1303.

953 114. Y. Pan, Y. Shi, Y. Wang, Y. Cai, G. Jiang, Investigation of perfluorinated compounds (PFCs)
954 in mollusks from coastal waters in the Bohai Sea of China, *Journal of Environmental Monitoring*. **12**
955 (2010)pp. 508–513.

956 115. K. I. Van De Vijver, P. T. Hoff, K. Das, W. Van Dongen, E. L. Esmans, T. Jauniaux, J.-M.
957 Bouquegneau, R. Blust, W. De Coen, Perfluorinated Chemicals Infiltrate Ocean Waters: Link between
958 Exposure Levels and Stable Isotope Ratios in Marine Mammals, *Environmental Science and*
959 *Technology*. **37** (2003)pp. 5545–5550.

960 116. Z. Jiao, N. Yu, J. Mao, Q. Yang, L. Jiao, X. Wang, W. Shi, H. Yu, S. Wei, The occurrence,
961 tissue distribution, and PBT potential of per- and polyfluoroalkyl substances in the freshwater
962 organisms from the Yangtze river via nontarget analysis, *Journal of Hazardous Materials*. **458** (2023).
963 https://doi.org/10.1016/j.jhazmat.2023.131868.

964 117. J. Kobayashi, Y. Maeda, Y. Imuta, F. Ishihara, N. Nakashima, T. Komorita, T. Sakurai,
965 Bioaccumulation Patterns of Perfluoroalkyl Acids in an Estuary of the Ariake Sea, Japan, *Bulletin of*
966 *Environmental Contamination and Toxicology*. **100** (2018)pp. 536–540.

967 118. R. Miniero, V. Abate, G. Brambilla, E. Davoli, E. De Felip, S. P. De Filippis, E. Dellatte, S.
968 De Luca, R. Fanelli, E. Fattore, F. Ferri, I. Fochi, A. Rita Fulgenzi, N. Iacovella, A. L. Iamiceli, D.
969 Lucchetti, P. Melotti, I. Moret, R. Piazza, A. Roncarati, A. Ubaldi, S. Zambon, A. di Domenico,
970 Persistent toxic substances in Mediterranean aquatic species, *Science of the Total Environment*. **494–**
971 **495** (2014)pp. 18–27.

972 119. Z. Chen, X. zhan, J. Zhang, J. Diao, C. Su, Q. Sun, Y. Zhou, L. Zhang, R. Bi, M. Ye, T. Wang,
973 Bioaccumulation and risk mitigation of legacy and novel perfluoroalkyl substances in seafood:
974 Insights from trophic transfer and cooking method, *Environment International*. **177** (2023).
975 https://doi.org/10.1016/j.envint.2023.108023.

976 120. M. Barghi, X. Jin, S. Lee, Y. Jeong, J.-P. Yu, W.-K. Paek, H.-B. Moon, Accumulation and
977 exposure assessment of persistent chlorinated and fluorinated contaminants in Korean birds, *Science*
978 *of the Total Environment*. **645** (2018)pp. 220–228.

979 121. J. E. Yordy, S. Rossman, P. H. Ostrom, J. L. Reiner, K. Bargnesi, S. Hughes, J. D. Elliot,
980 Levels of chlorinated, brominated, and perfluorinated contaminants in birds of prey spanning multiple
981 trophic levels, *Journal of Wildlife Diseases*. **49** (2013)pp. 347–354.

982 122. L. Mo, N. Wan, B. Zhou, M. Shao, X. Zhang, M. Li, Y. Liu, B. Mai, Per- and polyfluoroalkyl
983 substances in waterbird feathers around Poyang Lake, China: Compound and species-specific
984 bioaccumulation, *Ecotoxicology and Environmental Safety*. **273** (2024).
985 https://doi.org/10.1016/j.ecoenv.2024.116141.

986 123. T. Thomas, A. Malek, J. Arokianathar, E. Haddad, Global Regulations Around PFAS: The
987 Past, the Present and the Future.

988

989

Supplementary Materials for

A meta-analysis reveals PFAS concentrations double with each trophic level across aquatic and terrestrial food webs

Ricolfi *et al.*

Corresponding authors: Lorenzo Ricolfi (l.ricolfi@unsw.edu.au) & Yefeng Yang (yefeng.yang1@unsw.edu.au)

The PDF file includes:

- Supplementary Figures from Fig. S1 to S21
- Supplementary Text from Method S1 to S5
- Supplementary Tables from Tab. S1 to S9
- Legends for Data S1 to S5

Other Supplementary Material for this manuscript includes the following:

- Data S1 to S5.

Supplementary Figures

Supplementary Figure 1

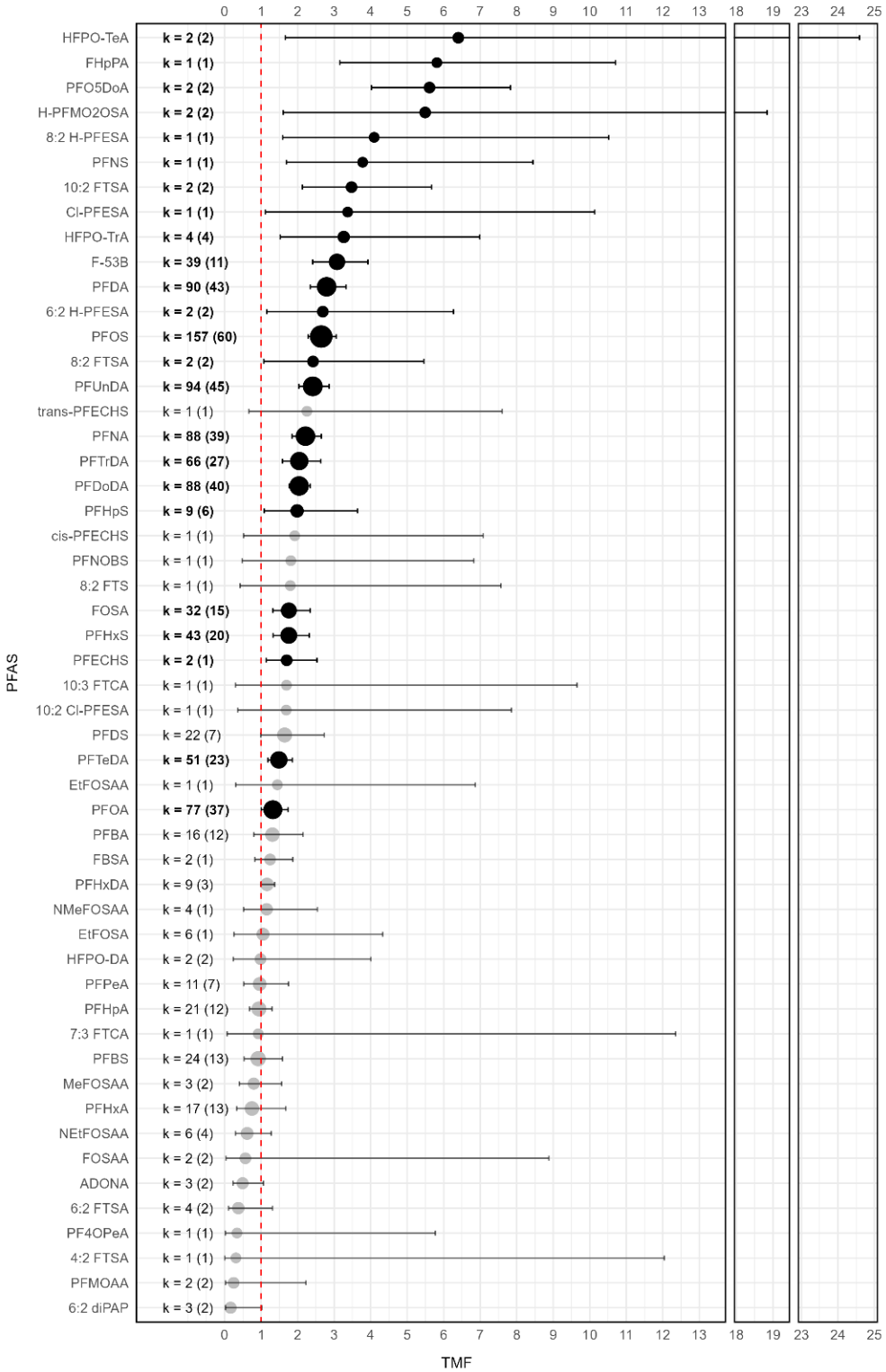

Fig. S1. Trophic magnification of per- and polyfluoroalkyl substances (PFAS) in aquatic and terrestrial food webs*. The plot is the full version of Figure 2 in the main text, showing the subgroup correlated effects model results for each PFAS regardless of their number of effect sizes.*

Supplementary Figure 2

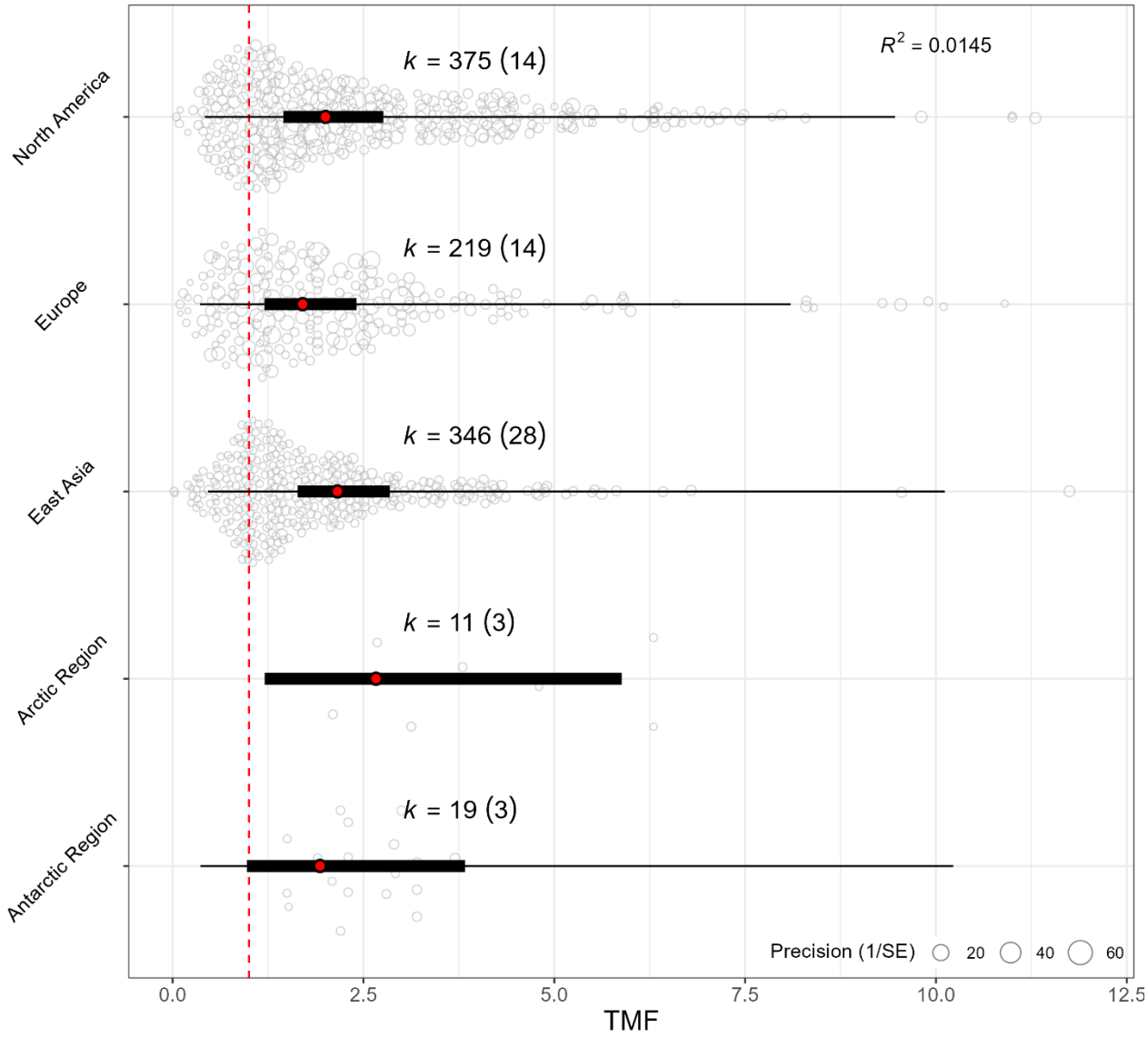

Fig. S2. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS), stratified by geographic location of food webs. *The meta-analytic mean estimate for each stratification is represented by a red-filled circle with a black outline. Thicker bars denote the 95% confidence interval, while thinner bars represent the 95% prediction interval. Light grey circles show individual effect sizes, scaled by precision (inverse of the standard error, as indicated in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line marks a trophic magnification factor (TMF) of 1, with values above 1 indicating biomagnification and those below 1 indicating biodilution. TMF values are capped at 12.5 for improved visual readability. The R^2 value represents the proportion of variance explained only by the fixed effect in the model (marginal R^2).*

Supplementary Figure 3

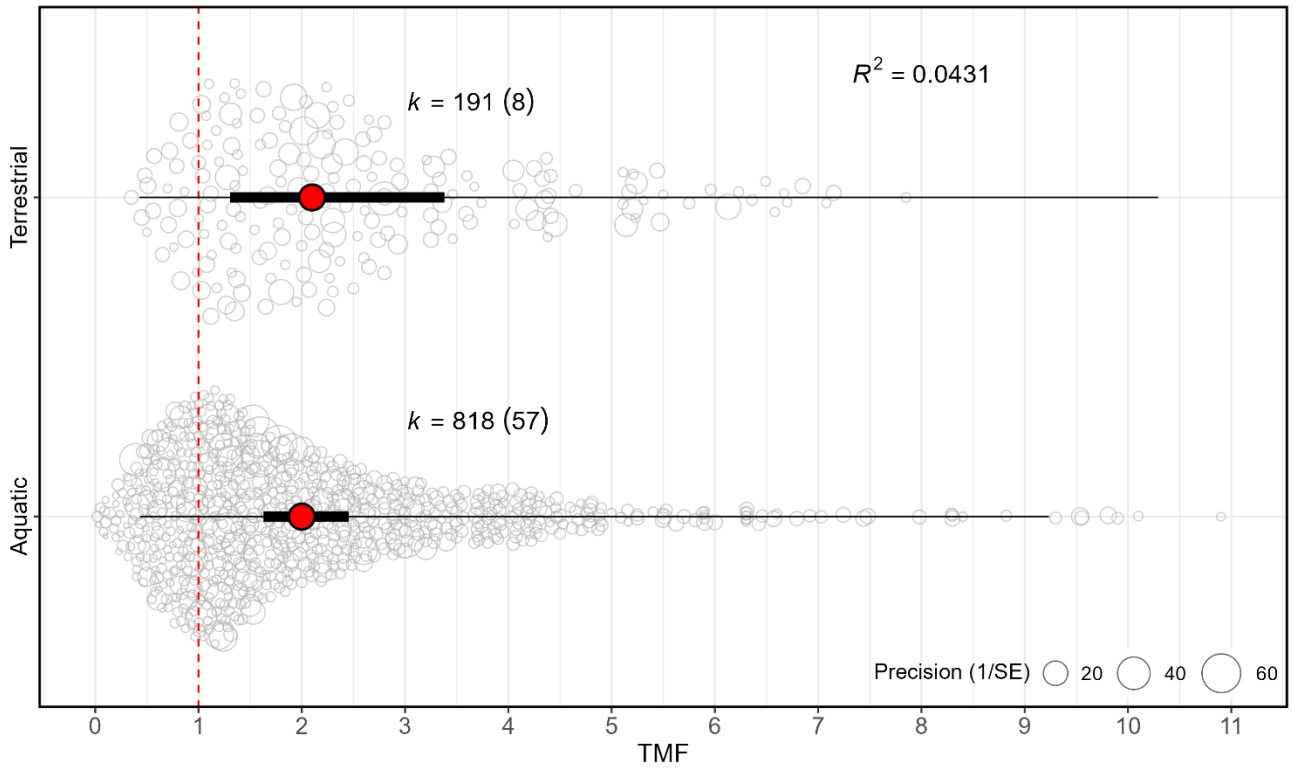

Fig. S3. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS), stratified by ecosystem type. *The meta-analytic mean estimate for each stratification is represented by a red-filled circle with a black outline. Thicker bars denote the 95% confidence interval, while thinner bars represent the 95% prediction interval. Light grey circles show individual effect sizes, scaled by precision (inverse of the standard error, as indicated in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line marks a trophic magnification factor (TMF) of 1, with values above 1 indicating biomagnification and those below 1 indicating biodilution. TMF values are capped at 11 for improved visual readability. The R2 value represents the proportion of variance explained only by the fixed effect in the model (marginal R2).*

Supplementary Figure 4

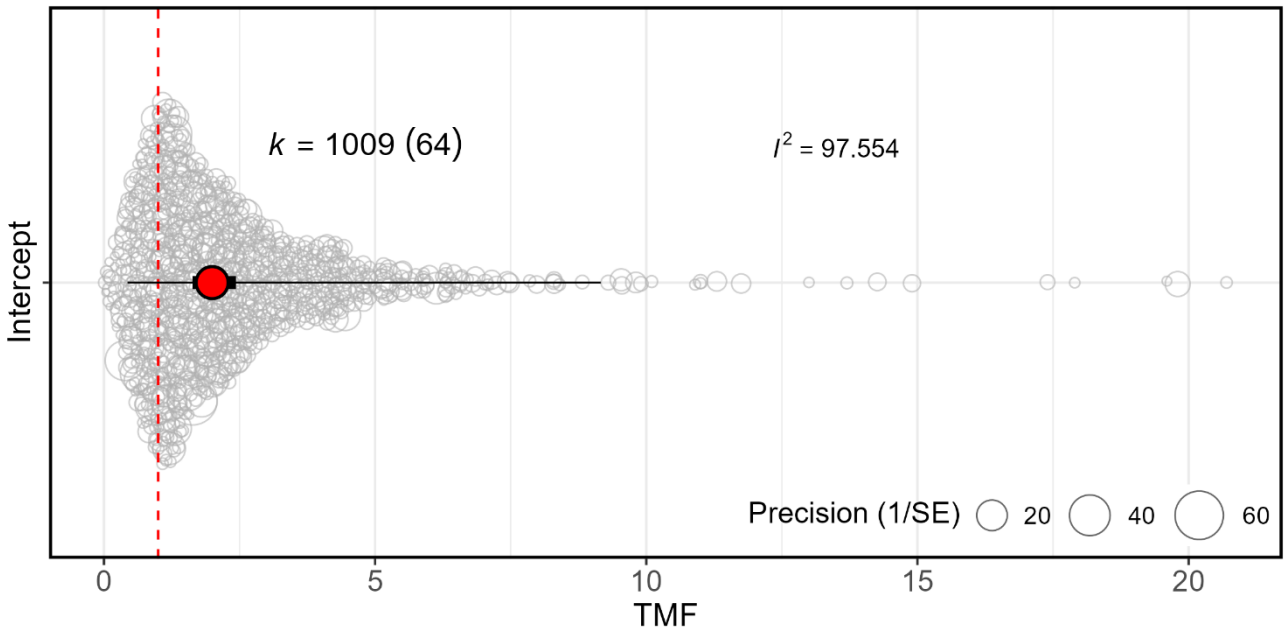

Fig. S4. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS) in food webs. *Overall TMF based on a meta-analysis of 1,009 effect sizes from 117 aquatic and terrestrial food webs. The mean meta-analytic estimate is represented by a black circle filled with red. The thicker bars indicate the 95% confidence interval, while the thinner bars represent the 95% prediction interval. Light grey circles depict individual effect sizes scaled by precision (inverse of the standard error, as shown in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line highlights a TMF of 1 (biomagnification above 1 and biodilution below 1).*

Supplementary Figure 5

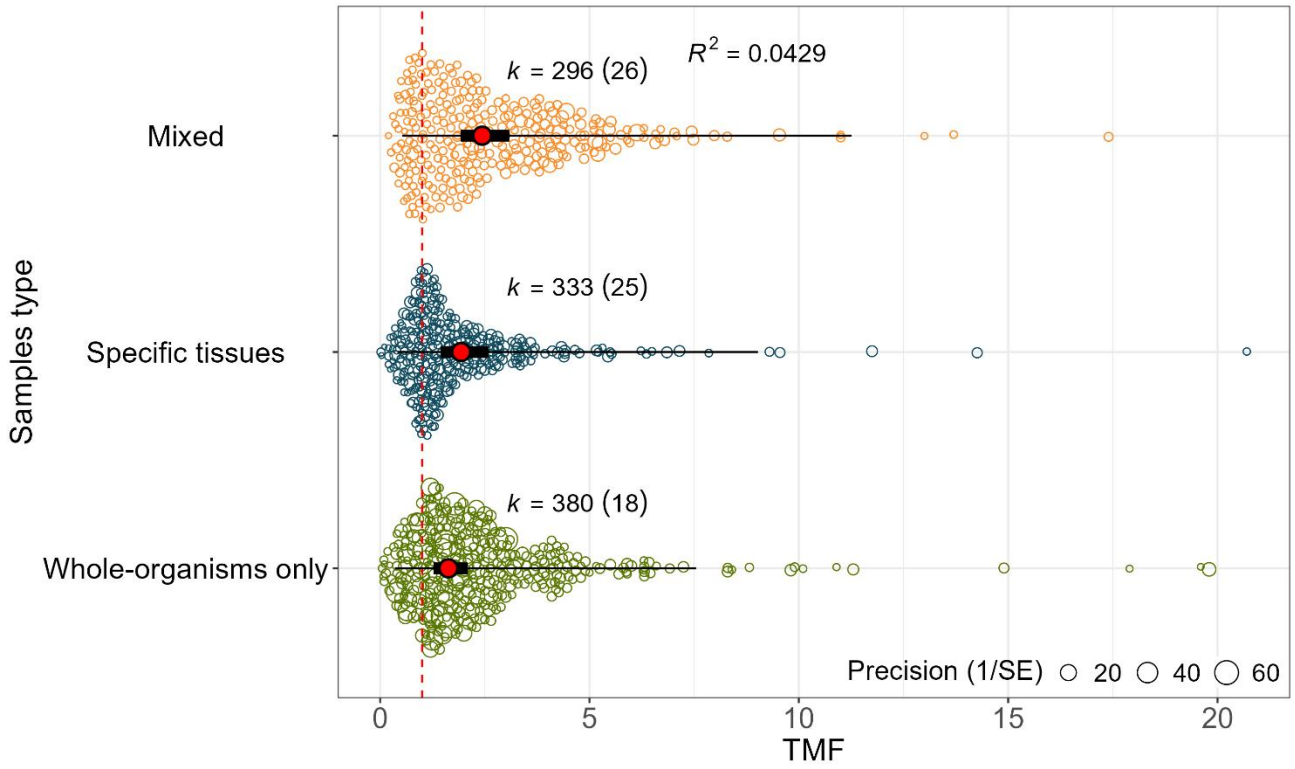

Fig. S5. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS), stratified by sample type. *The meta-analytic mean estimate for each stratification is represented by a red-filled circle with a black outline. Thicker bars denote the 95% confidence interval, while thinner bars represent the 95% prediction interval. Light grey circles show individual effect sizes, scaled by precision (inverse of the standard error, as indicated in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line marks a TMF of 1, with values above 1 indicating biomagnification and those below 1 indicating biodilution. "Mixed" refers to a combination of specific tissue and whole-organism samples. The R^2 value represents the proportion of variance explained only by the fixed effect in the model (marginal R^2).*

Supplementary Figure 6

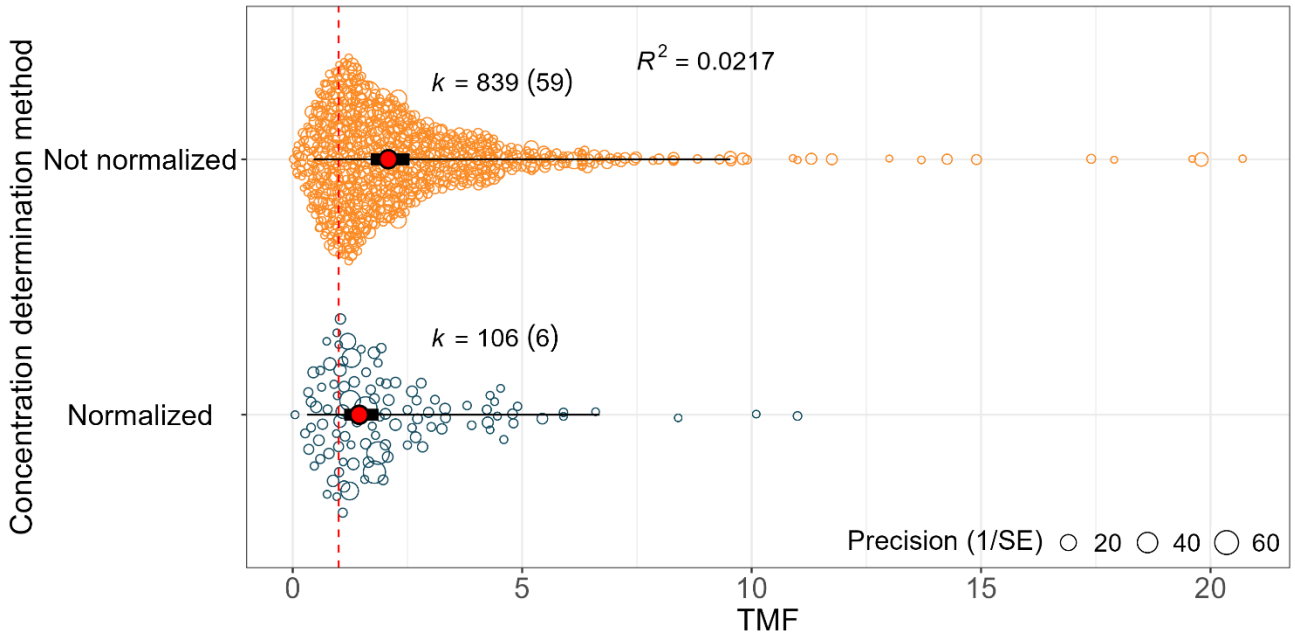

Fig. S6. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS), stratified by concentration determination method. *The meta-analytic mean estimate for each stratification is represented by a red-filled circle with a black outline. Thicker bars denote the 95% confidence interval, while thinner bars represent the 95% prediction interval. Light grey circles show individual effect sizes, scaled by precision (inverse of the standard error, as indicated in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line marks a TMF of 1, with values above 1 indicating biomagnification and those below 1 indicating biodilution. The R^2 value represents the proportion of variance explained only by the fixed effect in the model (marginal R^2).*

Supplementary Figure 7

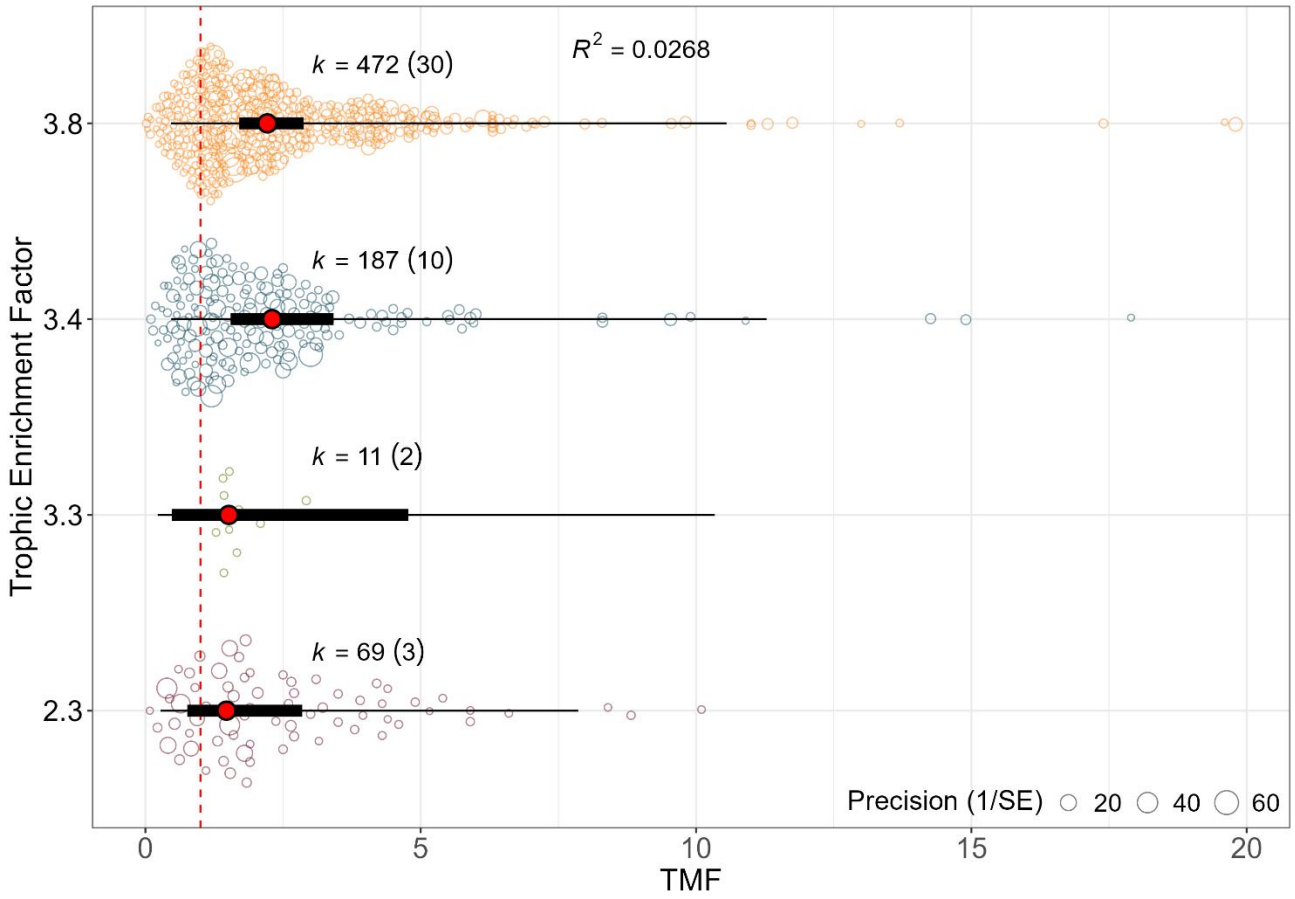

Fig. S7. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS), stratified by trophic enrichment factor. *The meta-analytic mean estimate for each stratification is represented by a red-filled circle with a black outline. Thicker bars denote the 95% confidence interval, while thinner bars represent the 95% prediction interval. Light grey circles show individual effect sizes, scaled by precision (inverse of the standard error, as indicated in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line marks a TMF of 1, with values above 1 indicating biomagnification and those below 1 indicating biodilution. The R^2 value represents the proportion of variance explained only by the fixed effect in the model (marginal R^2).*

Supplementary Figure 8

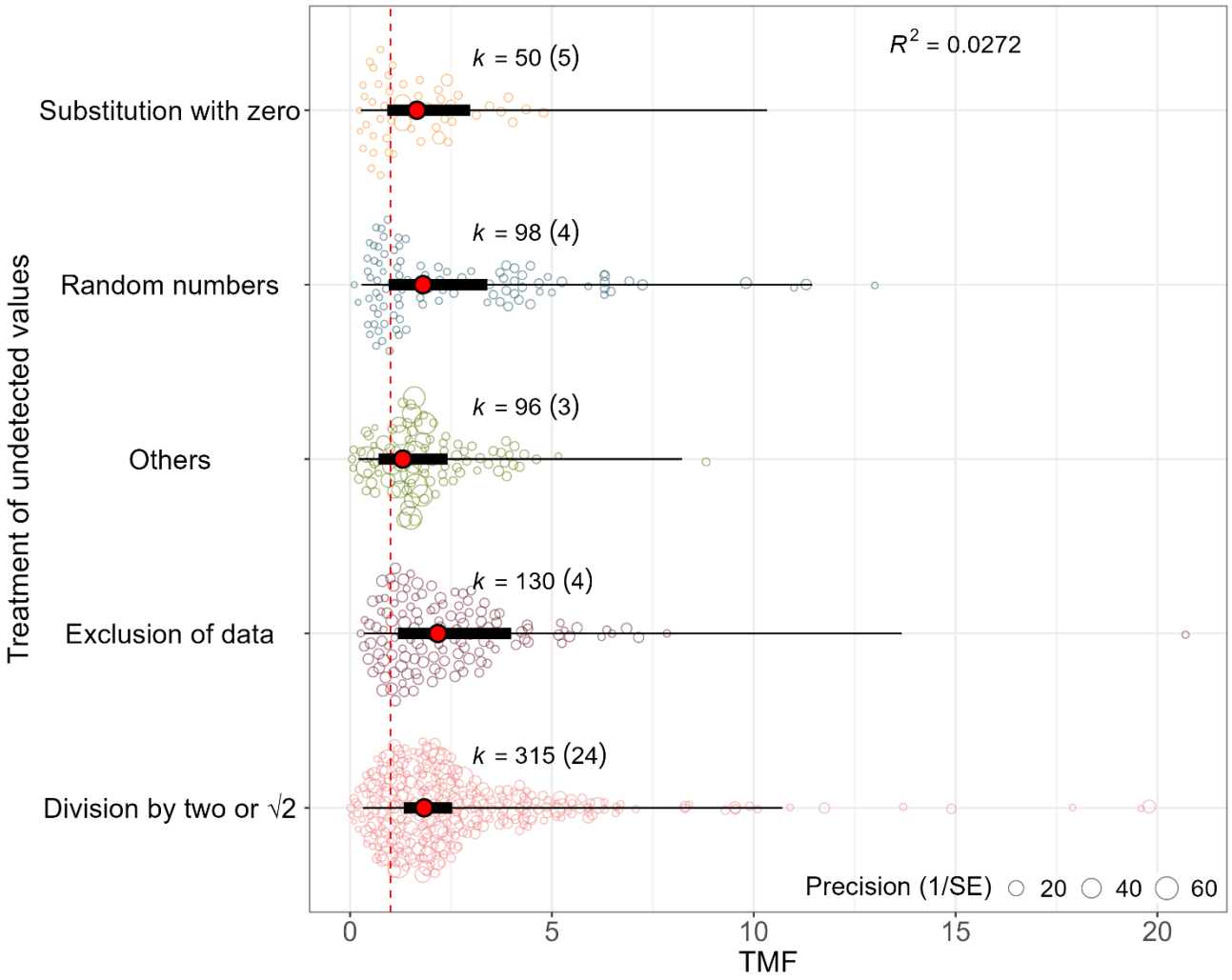

Fig. S8. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS), stratified by treatment stretgy of undetected values. *The meta-analytic mean estimate for each stratification is represented by a red-filled circle with a black outline. Thicker bars denote the 95% confidence interval, while thinner bars represent the 95% prediction interval. Light grey circles show individual effect sizes, scaled by precision (inverse of the standard error, as indicated in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line marks a TMF of 1, with values above 1 indicating biomagnification and those below 1 indicating biodilution. The R^2 value represents the proportion of variance explained only by the fixed effect in the model (marginal R^2).*

Supplementary Figure 9

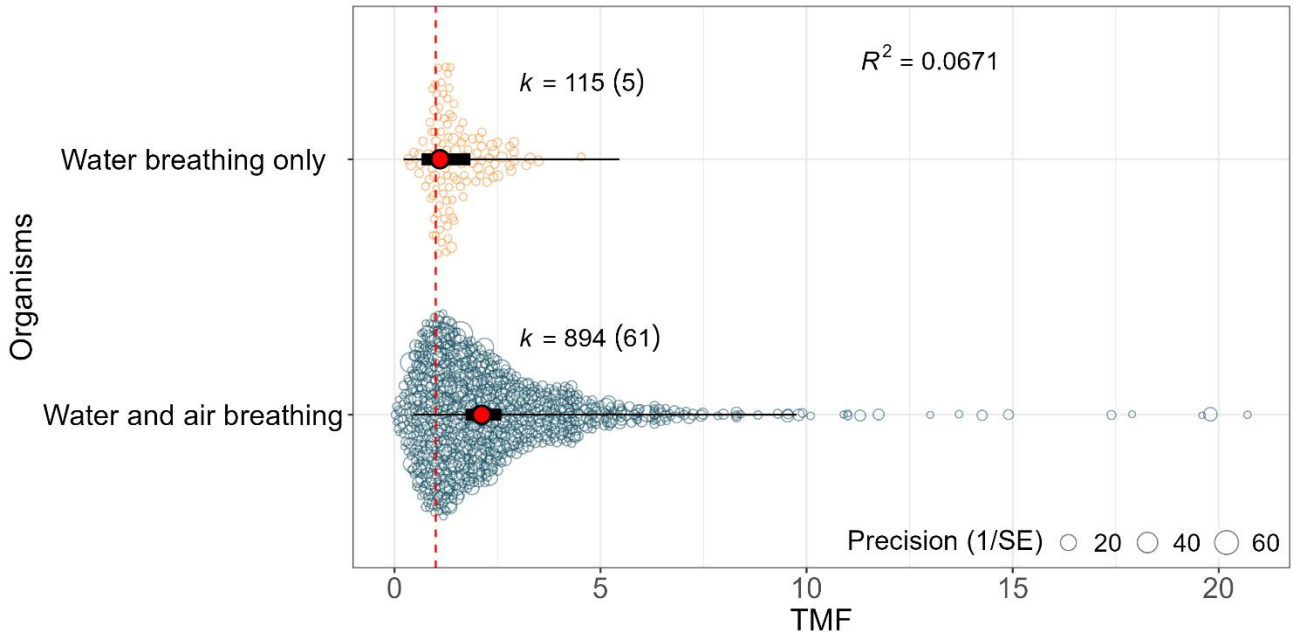

Fig. S9. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS), stratified by food webs of exclusively water breathing organisms versus mixed breathing types. *The meta-analytic mean estimate for each stratification is represented by a red-filled circle with a black outline. Thicker bars denote the 95% confidence interval, while thinner bars represent the 95% prediction interval. Light grey circles show individual effect sizes, scaled by precision (inverse of the standard error, as indicated in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line marks a TMF of 1, with values above 1 indicating biomagnification and those below 1 indicating biodilution. The R^2 value represents the proportion of variance explained only by the fixed effect in the model (marginal R^2).*

Supplementary Figure 10

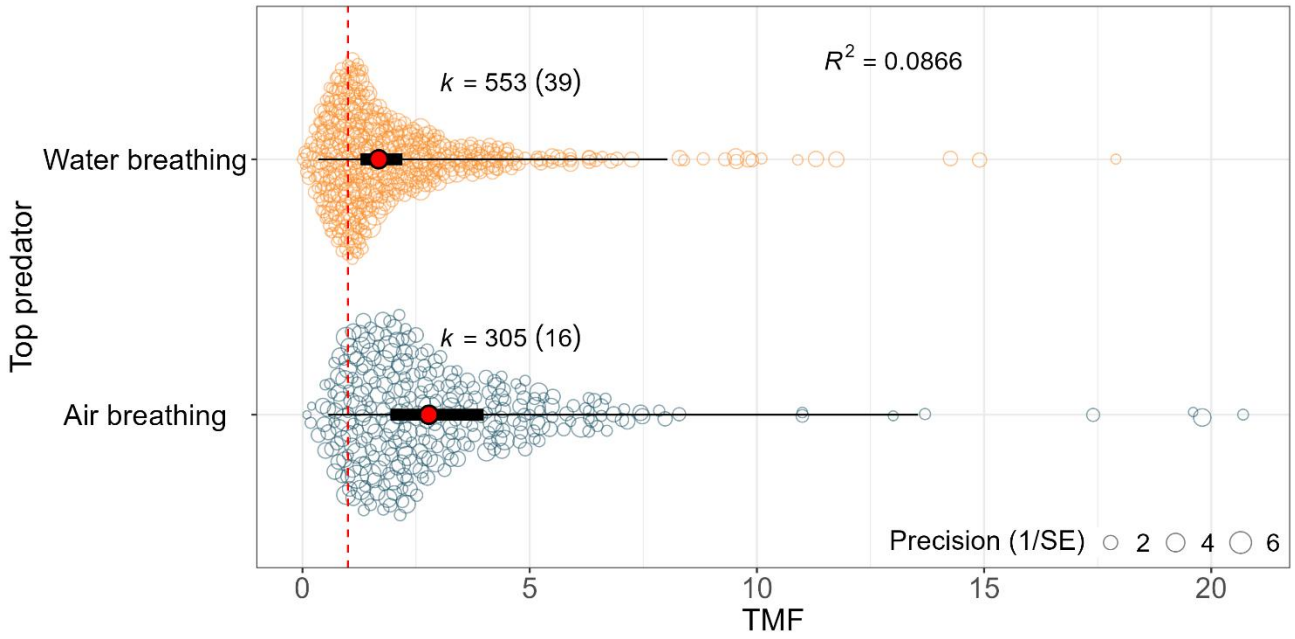

Fig. S10. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS), stratified by food webs with either air breathing or water breathing top predators. *The meta-analytic mean estimate for each stratification is represented by a red-filled circle with a black outline. Thicker bars denote the 95% confidence interval, while thinner bars represent the 95% prediction interval. Light grey circles show individual effect sizes, scaled by precision (inverse of the standard error, as indicated in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line marks a TMF of 1, with values above 1 indicating biomagnification and those below 1 indicating biodilution. The R^2 value represents the proportion of variance explained only by the fixed effect in the model (marginal R^2).*

Supplementary Figure 11

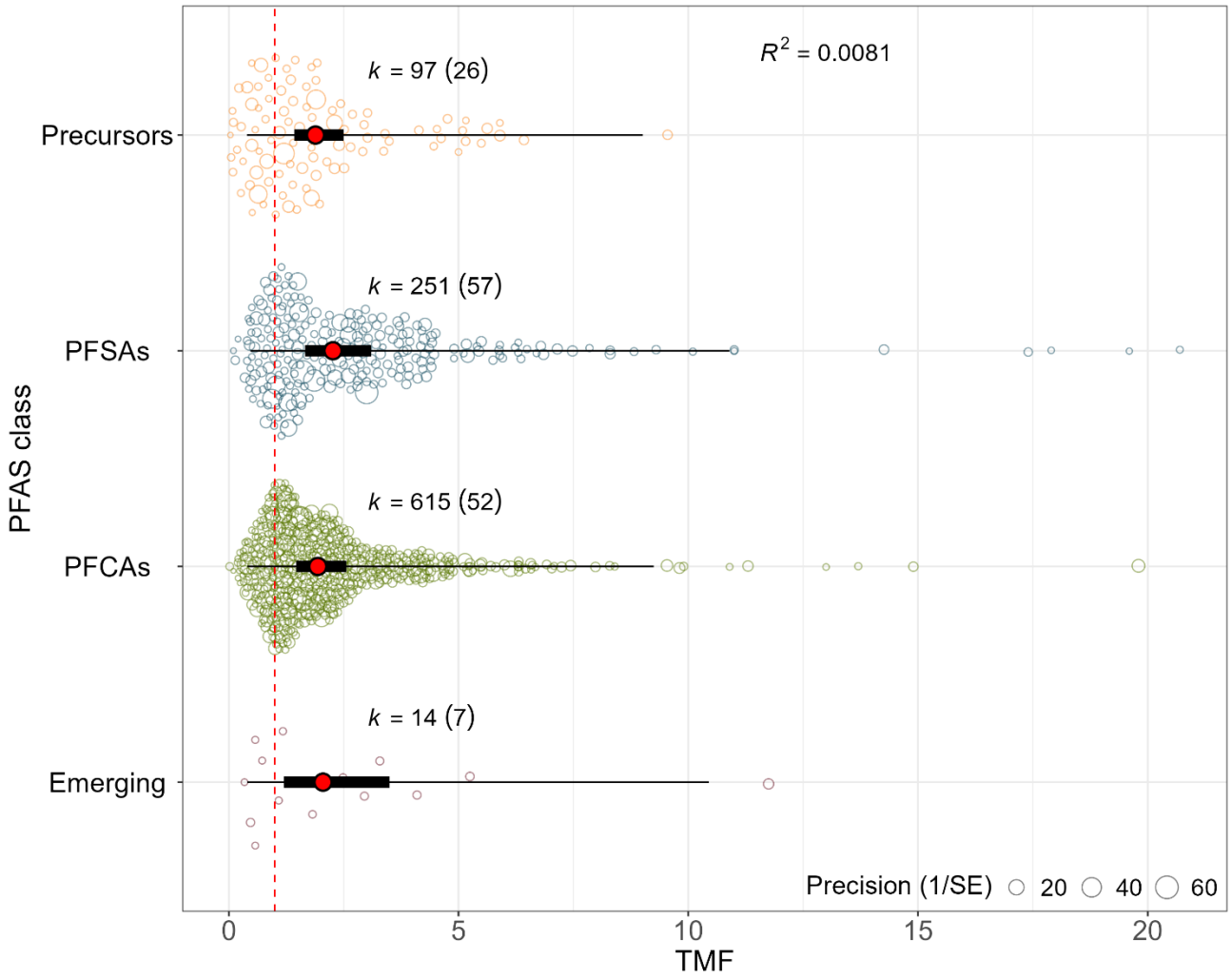

Fig. S11. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS), stratified by PFAS chemical class. *The meta-analytic mean estimate for each stratification is represented by a red-filled circle with a black outline. Thicker bars denote the 95% confidence interval, while thinner bars represent the 95% prediction interval. Light grey circles show individual effect sizes, scaled by precision (inverse of the standard error, as indicated in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line marks a TMF of 1, with values above 1 indicating biomagnification and those below 1 indicating biodilution. The R^2 value represents the proportion of variance explained only by the fixed effect in the model (marginal R^2).*

Supplementary Figure 12

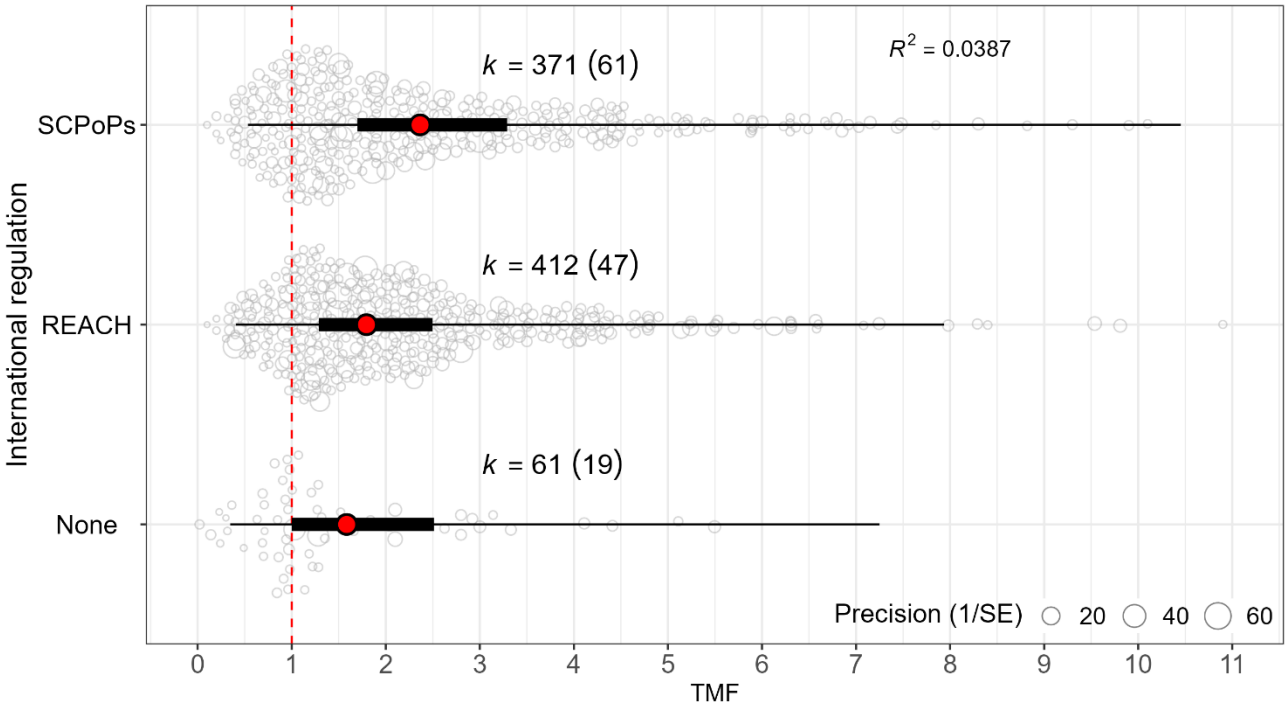

Fig. S12. Trophic magnification factor (TMF) of per- and polyfluoroalkyl substances (PFAS), stratified by chemicals' international regulation status. *'SCPoPs' refers to PFAS listed under one of the annexes of the Stockholm Convention on Persistent Organic Pollutants. 'REACH' represents PFAS regulated within the European Union under the REACH framework. 'None' indicates PFAS that are not subject to any international regulation. The meta-analytic mean estimate for each stratification is represented by a red-filled circle with a black outline. Thicker bars denote the 95% confidence interval, while thinner bars represent the 95% prediction interval. Light grey circles show individual effect sizes, scaled by precision (inverse of the standard error, as indicated in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line marks a trophic magnification factor (TMF) of 1, with values above 1 indicating biomagnification and those below 1 indicating biodilution. TMF values are capped at 11 for improved visual readability. The R^2 value represents the proportion of variance explained only by the fixed effect in the model (marginal R^2).*

Supplementary Figure 13

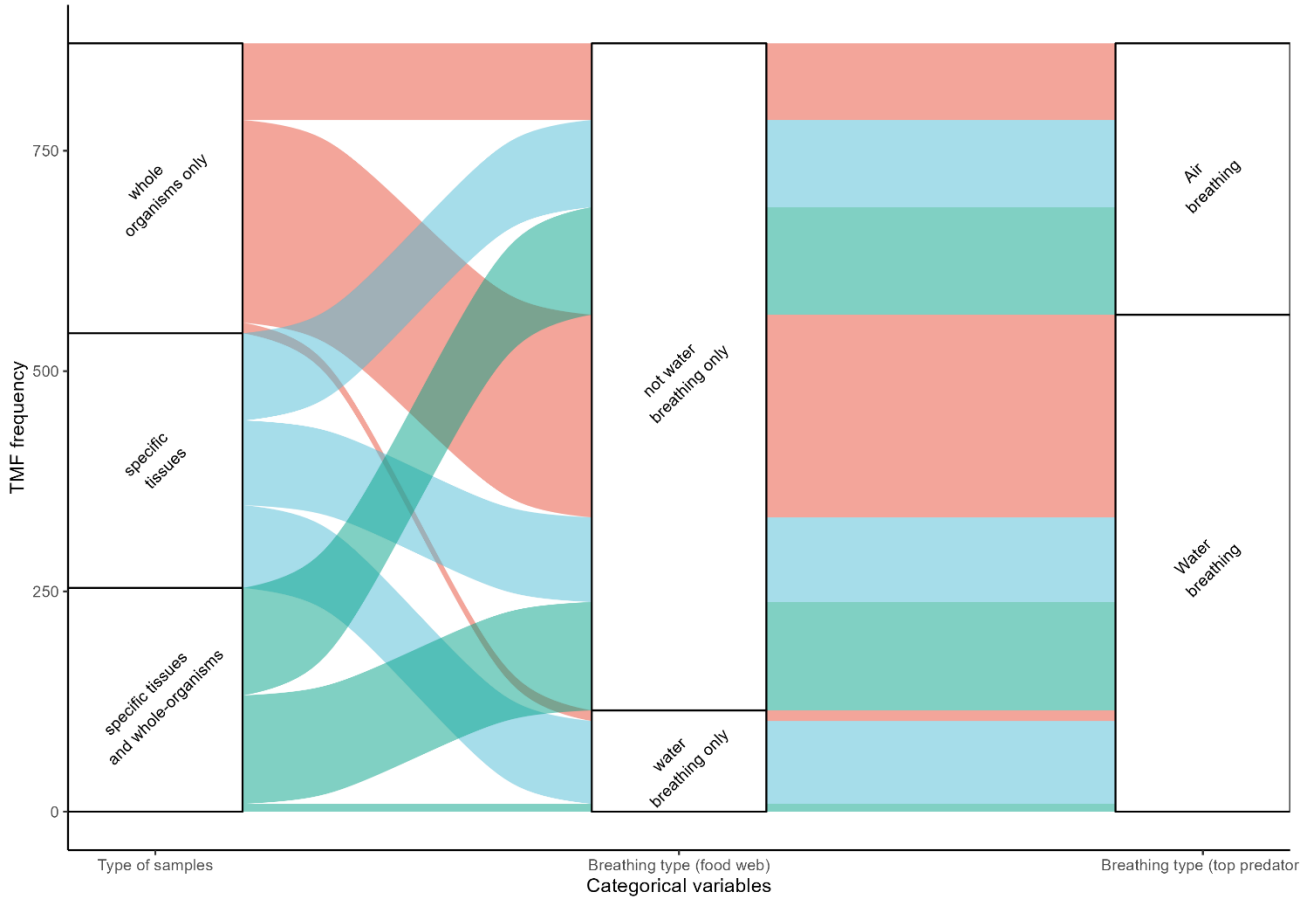

Fig. S13. Alluvial plot of the overlap among the three categorical variables included in the full model (see Methods). *The plot visualises the interrelationships between the categorical variables, providing a clear overview of data distributions and overlaps. TMF frequency defines the number of TMFs. It serves as a tool to identify potential multicollinearity issues that may affect the full model.*

Supplementary Figure 14

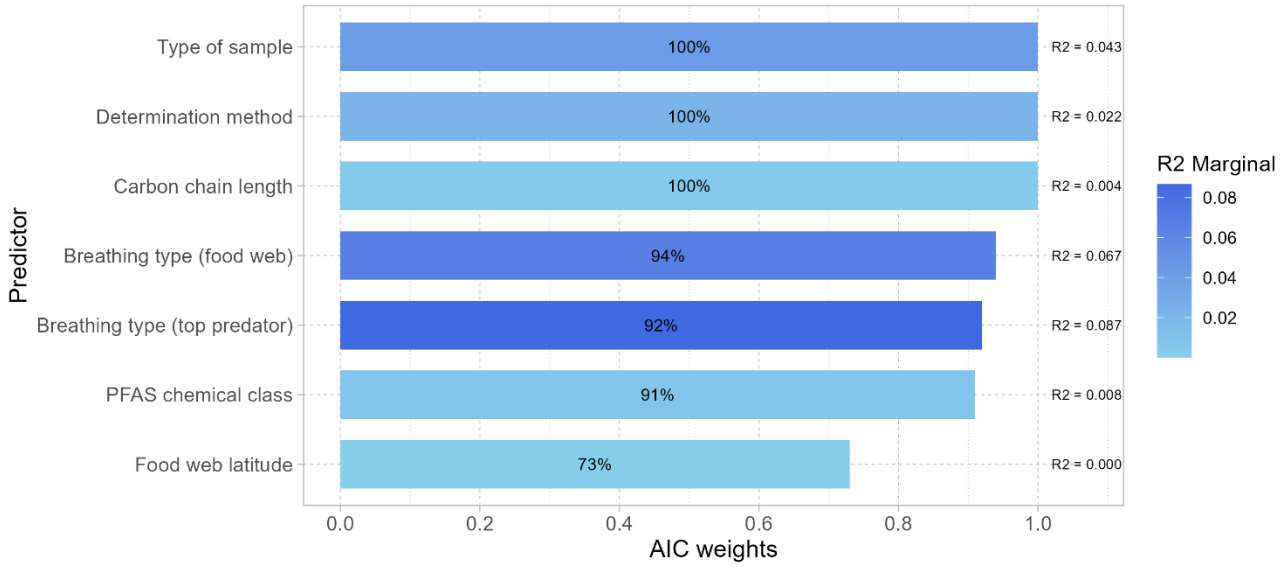

Fig. S14. Relative importance of tested moderator variables based on Akaike weights, calculated from the Akaike Information Criterion (AIC). *Importance was assessed across 256 candidate models by summing the Akaike weights of each moderator variable appearing in all models. These weights indicate the probability of a given candidate model being the best, derived from a Bayesian framework with a prior distribution. Additionally, the marginal R^2 (indicated in red) was estimated using a uni-moderator model, where each moderator variable served as the fixed effect, representing the proportion of variance explained. R^2 values represent the proportion of variance explained only by the fixed effects in the model (marginal R^2).*

Supplementary Figure 15

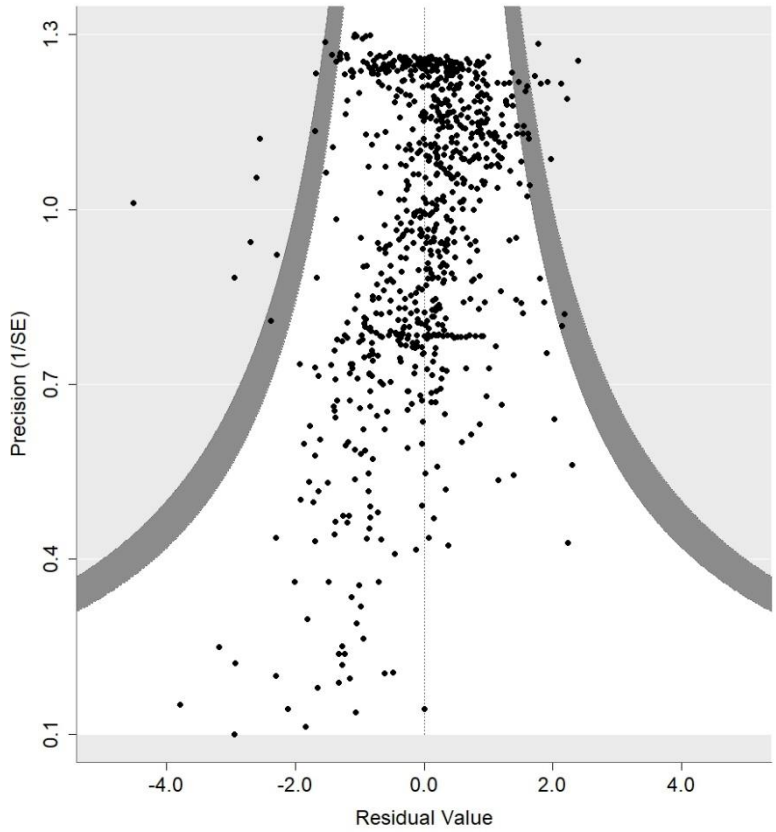

Fig. S15. Funnel plot for visual inspection of studies' precision. *The plot shows the distribution of residual values of effect sizes in relation to their precision (inverse of standard error) from the full model (see the 'Statistical modelling overview' paragraph).*

Supplementary Figure 16

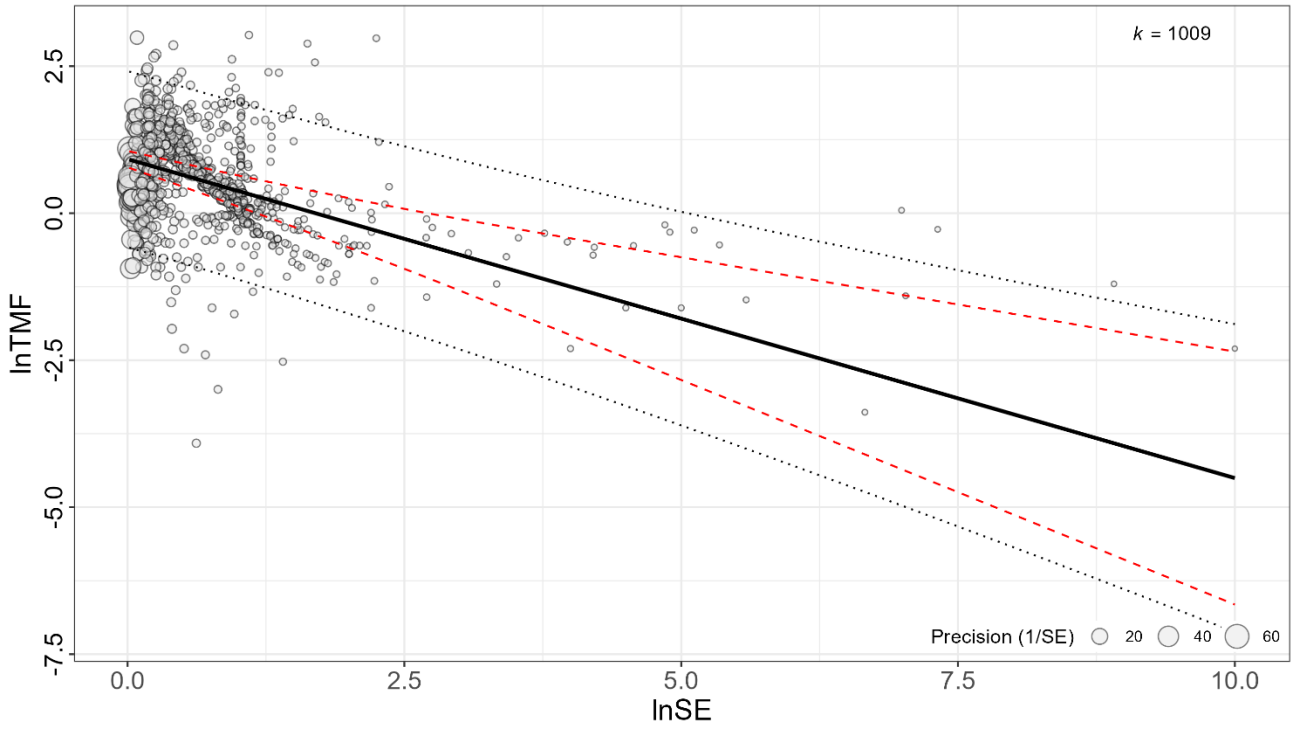

Fig. 16. Publication bias test. *The plot presents the results of a meta-regression using the logarithmic standard error of lnTMF as a moderator. The regression suggests a moderate publication bias ($F(df1 = 1, df2 = 1007) = 22$, $p < 0.001$). To account for this, we applied a two-step robust point and variance estimation to evaluate whether the direction and magnitude of the effect changed significantly (see 'Publication bias and sensitivity analysis' section in the main text).*

Supplementary Figure 17

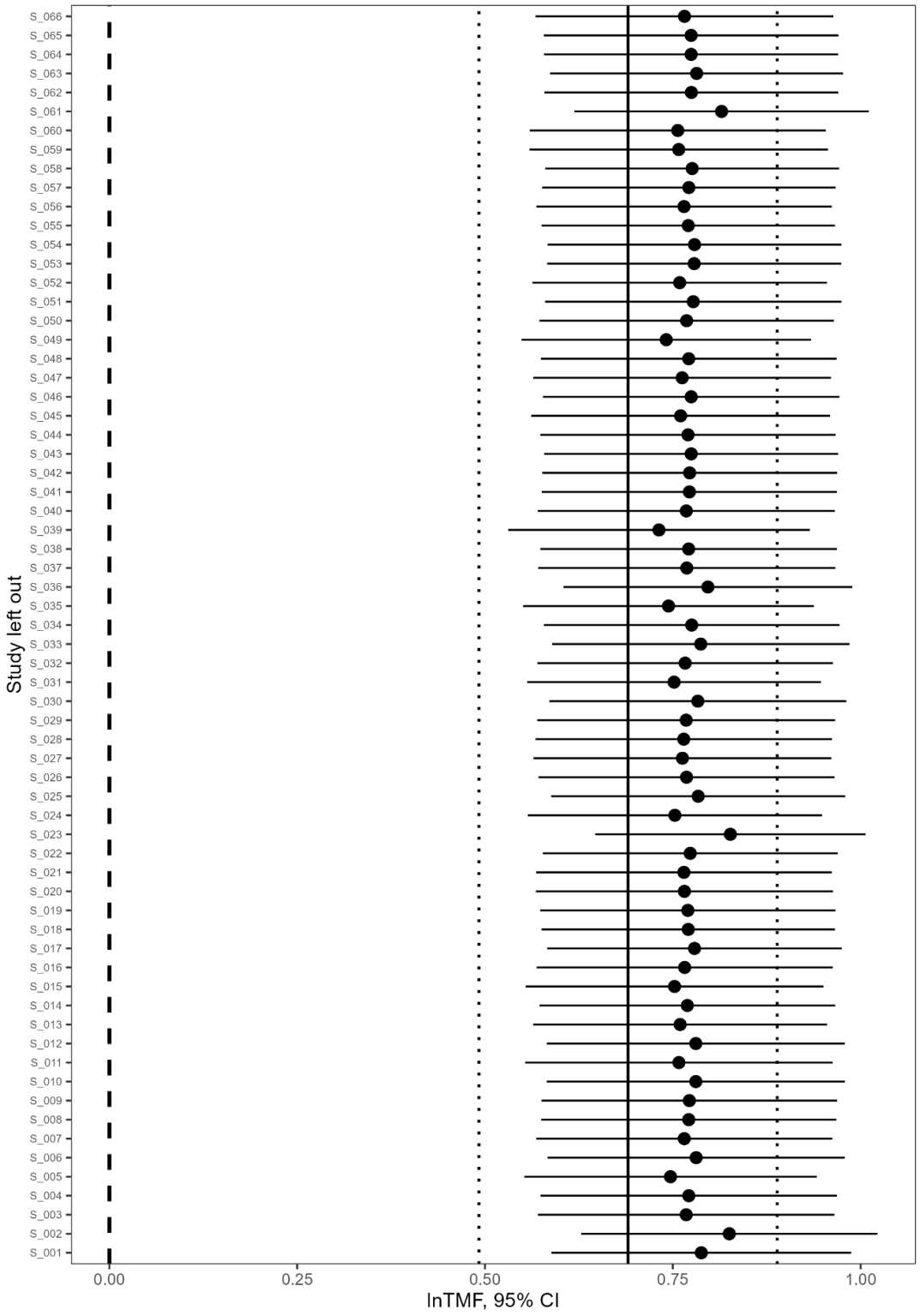

Fig. S17. Forest plot illustrating the results of leave-one-out sensitivity analyses. *The vertical solid line represents the overall meta-analytic estimate, with the dotted lines marking its 95% confidence intervals. Each black point and solid line show the meta-analytic estimate and its confidence intervals, respectively, after excluding individual studies. The plot indicates that no single study significantly influenced the overall meta-analytic result.*

Supplementary Figure 18

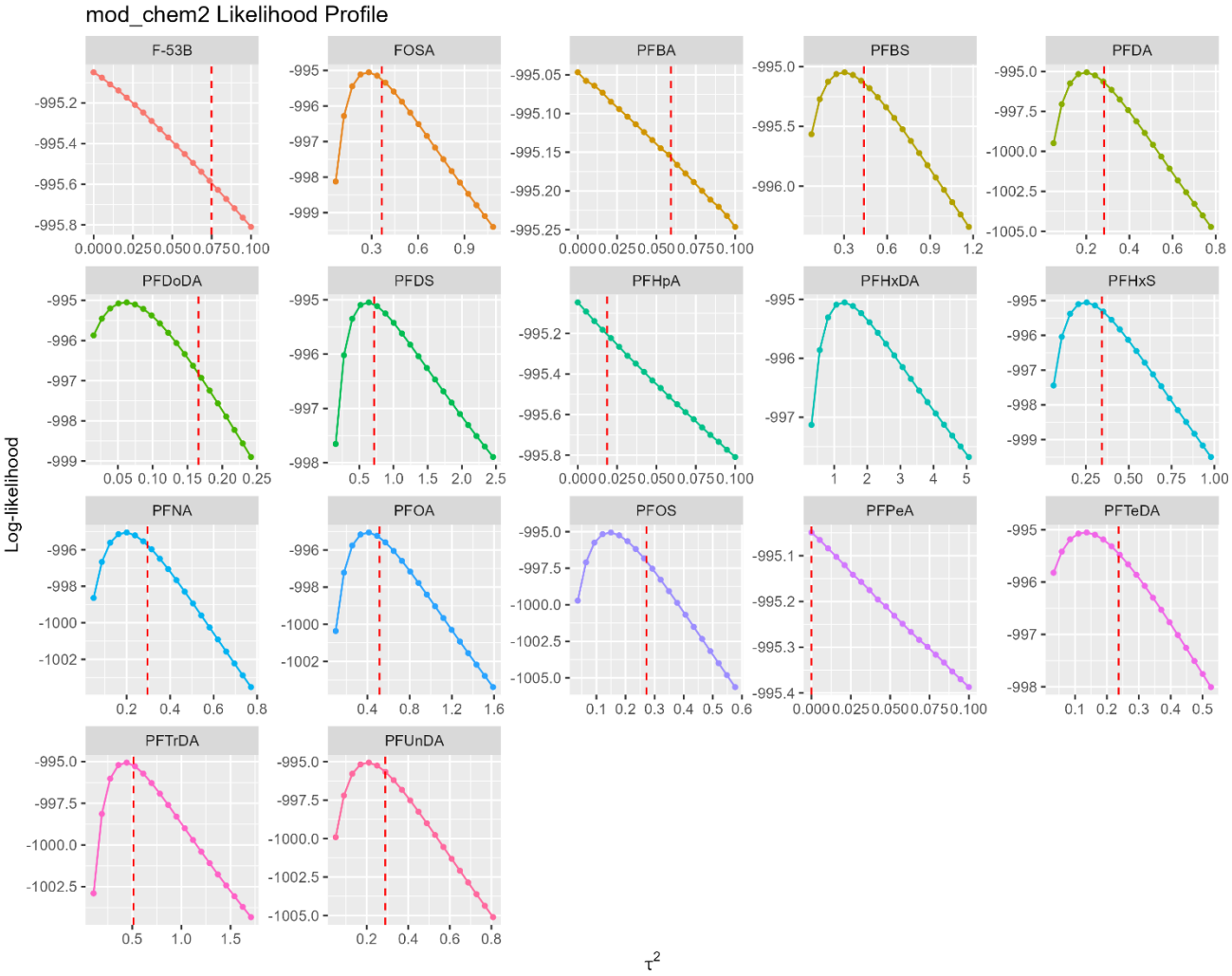

Fig. S18. Model validation and profile likelihood for the 17 PFAS included in the subgroup-correlated effects model*. Profile likelihood plots show how the log-likelihood changes with different values of the between-study variance for various PFAS in the model. The subgroup-correlated effects meta-regression model included PFAS identity as a fixed effect. The red dashed vertical lines represent the variance component relative to the individual PFAS, which resulted from a subgroup analysis, in which the dataset was restricted to observations related to each specific PFAS (see Method S1 for details). Clear peaks indicate a well-defined estimate for the between-study variance, and the maximum log-likelihood (highest point) suggests the best estimate of the between-study variance. If a profile is flat or constantly decreasing, the estimate of the between-study variance might be unreliable or close to zero, meaning there's little between-study variation.*

Supplementary Figure 19

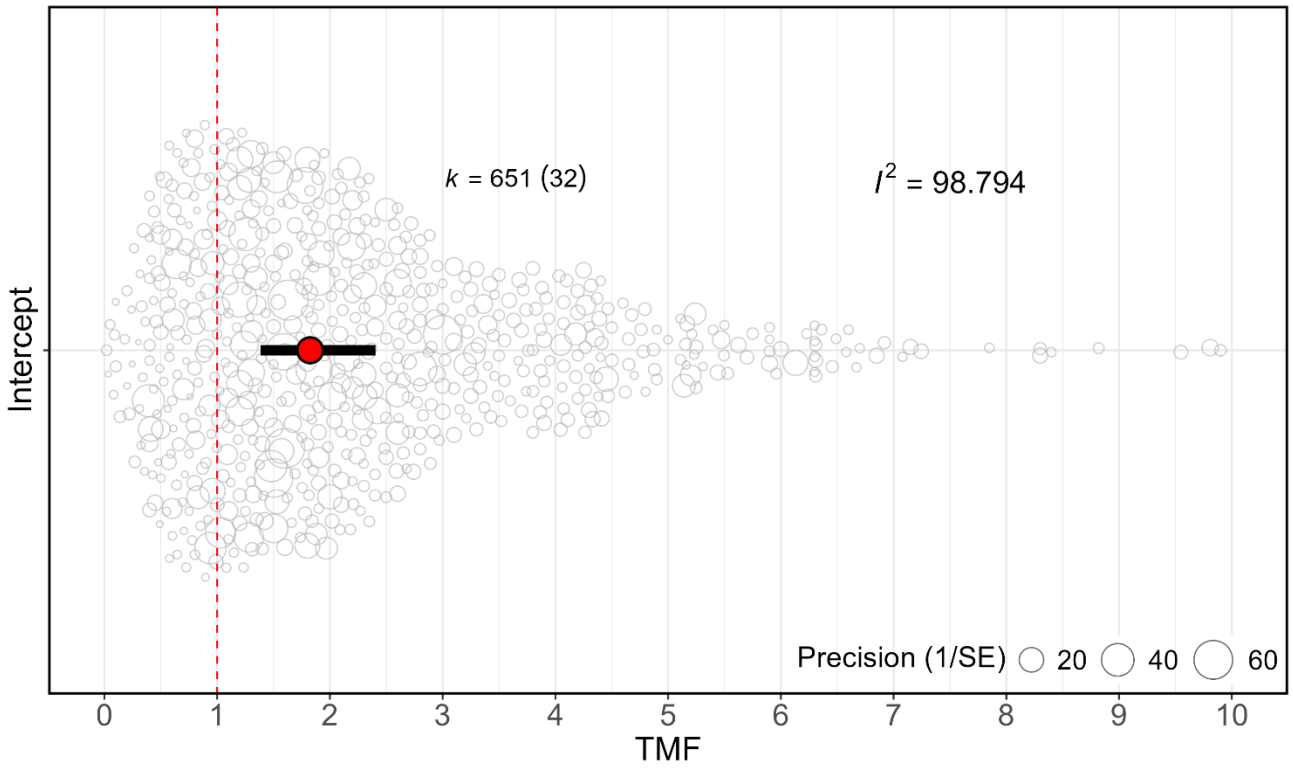

Fig. S19. Overall TMF after filtering out studies flagged by the study validity assessment. *The model excludes any study with at least one high-risk-of-bias item. The mean meta-analytic estimate is represented by a black circle filled with red. The thicker bars indicate the 95% confidence interval, while the thinner bars represent the 95% prediction interval. Light grey circles depict individual effect sizes scaled by precision (inverse of the standard error, as shown in the legend). The number of effect sizes is represented by "k," while the number in parentheses indicates the number of studies. The red dotted line highlights a TMF of 1 (biomagnification above 1 and biodilution below 1). The x-axis was capped at 10 for improved visual readability.*

Supplementary Figure 20

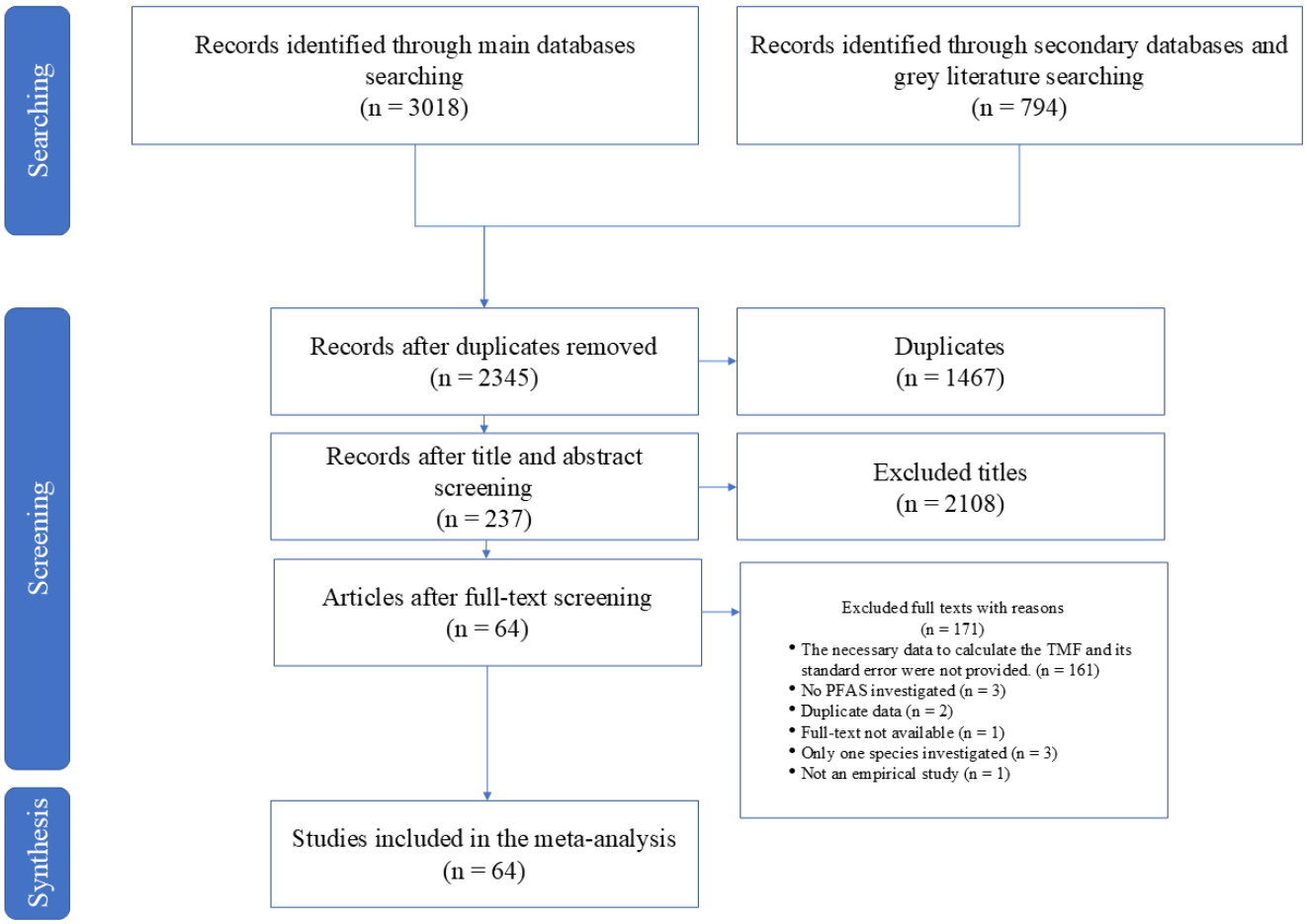

Fig. S20. Search and screening flow PRISMA diagram. *The diagram illustrates the number of records at different stages of the selection process for studies incorporated in the meta-analysis.*

Supplementary Figure 21

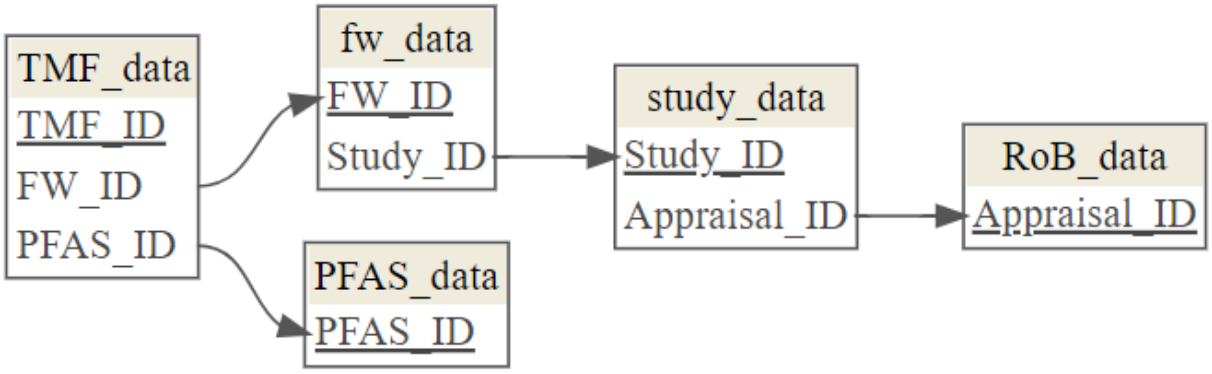

Fig. 21. Diagram illustrating the structure of the relational database of the extracted data. *The database consists of five interconnected tables linked through primary and foreign keys. TMF_data contains quantitative datasets for effect size calculations, PFAS_data includes details on PFAS analytes, fw_data represents food web parameters, study_data captures study characteristics, and RoB_data presents quality assessment results for study validity.*

Supplementary Text

Method S1

We validated our subgroup-correlated effects meta-regression model (*60*) using a three-step approach to ensure the robustness and reliability of our variance estimates:

1) **Model fit comparison**: We evaluated our model's relative fit by comparing its Akaike Information Criterion corrected for small sample sizes (AICc) with the AICc values of two alternative candidate models. We excluded models with higher AICc. A lower AICc value indicates a better balance between model fit and complexity, providing evidence that our model effectively captures key patterns in the data.
2) **Profile likelihood examination**: To assess whether variance components were well-estimated and consistent with model assumptions, we examined the profile likelihood for each individual PFAS. The profile likelihood plots, presented in Fig. S18, depict how the log-likelihood changes across different values of the variance parameter (τ^2). A well-defined peak suggests stable and identifiable variance estimates, whereas a flat or irregular likelihood profile could indicate estimation challenges or weak identifiability of variance parameters. The clear peaks observed in our plots suggest that our variance estimates are well-supported by the data.
3) **Subgroup analysis for variance components**: We further validated our variance estimates by comparing the profile likelihood for each individual PFAS to variance components derived from a subgroup analysis (red dashed lines in plots of Fig. S18), where we restricted the dataset to observations related to each specific PFAS. This step ensured that our model-derived variance estimates were consistent with those obtained from a more traditional subgroup analysis. By demonstrating alignment between the two approaches, we confirmed that the subgroup-correlated effects model appropriately accounts for within-PFAS variation while leveraging information across the full dataset.

Method S2

We assessed the internal validity of the included studies using a modified version of SYRCLE's risk of bias tool for animal studies (Hooijmans et al., 2014). This tool was applied to each study to evaluate five types of bias: selection bias, performance bias, measurement bias, reporting bias, and funding bias. The table below defines each type of bias and outlines the key questions we considered to evaluate the potential risk of bias.

Type of bias	**Definition**	**Evaluated criteria**
Selection bias	Occurs when the sample selected for a study is not representative of the population it is drawn from, leading to results that are not generalisable.	- All organisms were collected within an appropriate or consistent sampling period (e.g., the same season). - Adequate number of trophic levels.
Measurement bias	Occurs when systematic differences exist in how outcomes are measured or assessed between studies.	- The study reports the TMF and its error. If not, it provides data for their calculation. High risk arises when we extract raw data from plots and calculate the TMF and its error by ourselves.
Reporting bias	Happens when certain results are selectively reported based on their nature or direction, often favoring statistically significant findings that are more likely to be published.	- Is there evidence of incomplete or selective reporting of results (e.g., only statistically significant slopes)? - Are measured contaminant concentrations in biota samples above the detection limit? If not, does the study provide an appropriate strategy for handling undetected values?
Funding bias	Occurs when the source of funding influences the study's design, conduct, analysis, or reporting, often in ways that favor the sponsor's interests.	- Are there any apparent conflicts of interest or undue influence from funding sources?

Method S3

We defined the research question components according to the PICO/PECO framework (Richardson et al., 1995) as follows:

- Population: The population in this study refers to the global aquatic and terrestrial food webs (including plants and animals) affected by PFAS contamination.
- Intervention/Exposure: The exposure of interest is the exposure to any PFAS. Thus, PFAS contamination must be present and quantitatively measured in (whole or any part of) organisms within the studied ecosystem.
- Comparator: Not applicable. Instead, we will quantitatively assess the effects of factors that might influence PFAS trophic magnification. These factors include research methodologies, geographical variables, ecosystem characteristics, and food web composition (see Table 1 in the article).
- Outcome: The outcome of interest is the trophic magnification factor (TMF) within a studied food web. The TMF is the anti-log of the slope of the relationship between logarithm-transformed PFAS concentrations and trophic levels of biota within a food web.
- Study design: Any study design, such as field-based observational and mesocosms-based studies, is eligible. Studies must estimate and provide the trophic magnification factor or the trophic magnification slope.
- Other restrictions:
    - Time range: No restrictions.
    - Languages: Only studies published in English or a language spoken by any of the authors (i.e., Italian, Japanese, Polish, Russian, Traditional and Simplified Chinese, French, Portuguese, Spanish) will be eligible due to language constraints.

Method S4

Eligibility criteria at the title plus abstract level:

- The study's title and, optionally, its abstract are available.
- The study is a peer-reviewed journal article, a pre-print, or a thesis (i.e., bachelor's thesis, master's thesis, doctoral and postdoctoral thesis).
- The study likely is an empirical study, not a review.
- The study likely quantified at least one PFAS concentration in more than two organisms in the same food web.

Eligibility criteria at the full-text level:

- The full text is available for examination and data extraction.
- The full text is written in English or any eligible language (i.e., Italian, Japanese, Polish, Russian, Traditional and Simplified Chinese, French, Portuguese, Spanish).
- The study is an empirical study.
- The study quantified at least one PFAS concentration in more than two organisms from the same food web.
- The study provided the trophic magnification factor (TMF) of at least one PFAS and its standard error or 95% confidence intervals. Alternatively, it must provide the trophic magnification slope (TMS) and its standard error or 95% confidence intervals. If neither TMF nor TMS values were provided, the study must report linear regression plots of PFAS concentrations versus trophic levels of organisms or nitrogen isotope analysis (proxy of trophic levels).

Method S5

If the included studies did not provide the trophic magnification factor (TMF) and/or its standard error, we adopted the following calculation scenarios:

1. The study provides the trophic magnification slope (TMS) and its standard error. We calculated the TMF and its standard error back-transforming the TMS by doing an anti-log of the slope and error.
2. The study provides the TMF and its 95% confidence intervals. We calculated the standard error by dividing the difference between the upper and lower confidence intervals by 1.96.
3. The study provides the TMF or TMS and the p-value. We calculated the standard error by dividing the TMS by the z-value. We calculated the z-value by taking the p-value, dividing it by 2, subtracting this result from 1, and then finding the corresponding z-value from the standard normal distribution.
4. The study provides a plot illustrating the regression between PFAS concentrations and trophic levels of organisms or stable nitrogen isotope analysis. We employed the *metaDigitise* R package (version 1.0.1) or its graphical user interface *shinyDigitise* (Ivimey-Cook et al., 2023) to extract the x- and y-axis coordinates (i.e., trophic levels of organisms or stable nitrogen isotope analysis and PFAS concentrations). Then, we run linear regression models to calculate the TMS and its error.

Supplementary Tables

Supplementary Table 1

Tab. S1. List of studies included in the meta-analysis.

Reference	Title	DOI
(*19*)	Perfluoroalkyl contaminants in an Arctic marine food web: trophic magnification and wildlife exposure	10.1021/es9003894
(*15*)	Investigation of the spatial variability of poly-and perfluoroalkyl substance trophic magnification in selected riverine ecosystems	10.1016/j.scitotenv.2019.05.461
(*65*)	Trophic magnification and isomer fractionation of perfluoroalkyl substances in the food web of Taihu Lake, China	10.1021/es405018b
(*66*)	Trophic Magnification of Legacy (PCB, DDT and Hg) and Emerging Pollutants (PFAS) in the Fish Community of a Small Protected Southern Alpine Lake (Lake Mergozzo, Northern Italy)	10.3390/w12061591
(*67*)	Biomagnification of perfluoroalkyl compounds in the bottlenose dolphin (Tursiops truncatus) food web	10.1021/es060233b
(*68*)	Fractionation and bioaccumulation of perfluorooctane sulfonate (PFOS) isomers in a Lake Ontario food web	10.1021/es800906r
(*16*)	Trophodynamics of some PFCs and BFRs in a western Canadian Arctic marine food web	10.1021/es900162n
(*69*)	Fluorinated organic compounds in an eastern Arctic marine food web	10.1021/es049620g
(*70*)	Trophic magnification of poly-and perfluorinated compounds in a subtropical food web	10.1021/es200432n
(*71*)	Evidence for the trophic transfer of perfluoroalkylated substances in a temperate macrotidal estuary	10.1021/acs.est.7b02399
(*72*)	Biomagnification of perfluoroalkyl acids (PFAAs) in the food web of an urban river: Assessment of the trophic transfer of targeted and unknown precursors and implications.	10.1039/C9EM00322C
(*73*)	Bioaccumulation of per- and polyfluoroalkyl substances (PFASs) in a tropical estuarine food web.	10.1016/j.scitotenv.2020.142146
(*74*)	Perfluoroalkyl contaminants in a food web from Lake Ontario.	10.1021/es049331s
(*75*)	Bioaccumulation and trophic transfer of perfluorinated compounds in a eutrophic freshwater food web.	10.1016/j.envpol.2013.09.011
(*76*)	Isomer-specific trophic transfer of perfluorocarboxylic acids in the marine food web of Liaodong Bay, North China.	10.1021/es504445x
(*77*)	Distribution, bioaccumulation and trophic transfer of chlorinated polyfluoroalkyl ether sulfonic acids in the marine food web of Bohai, China.	10.1016/j.envpol.2018.05.087
(*78*)	Residues, bioaccumulations and biomagnification of perfluoroalkyl acids (PFAAs) in aquatic animals from Lake Chaohu, China.	10.1016/j.envpol.2018.05.001
(*79*)	Occurrence and trophic transfer of per- and polyfluoroalkyl substances in an Antarctic ecosystem.	10.1016/j.envpol.2019.113383
(*80*)	Fluorinated precursor compounds in sediments as a source of perfluorinated alkyl acids (PFAA) to biota.	10.1021/acs.est.0c04587
(*81*)	Occurrence, partitioning and bioaccumulation of emerging and legacy per- and polyfluoroalkyl substances in Taihu Lake, China	10.1016/j.scitotenv.2018.03.301
(*82*)	Managing health risks of perfluoroalkyl acids in aquatic food from a riverestuary- sea environment affected by fluorochemical industry.	10.1016/j.envint.2020.105621
(*83*)	Bioaccumulation, trophic transfer and biomagnification of perfluoroalkyl acids (PFAAs) in the marine food web of the South China Sea.	10.1016/j.jhazmat.2020.124681
(*84*)	First report on the bioaccumulation and trophic transfer of perfluoroalkyl ether carboxylic acids in estuarine food web.	10.1021/acs.est.1c00965

(***14***)	Legacy and alternative per- and polyfluoroalkyl substances in a subtropical marine food web from the Beibu Gulf, South China: Fate, trophic transfer and health risk assessment.	10.1016/j.jhazmat.2020.123618
(***85***)	Biomagnification and health risks of perflfluoroalkyl acids (PFAAs) in seafood from the Yangtze river estuary of China	10.1016/j.envpol.2023.122930
(***86***)	Chlorinated polyfluoroalkyl ether sulfonic acids in marine organisms from Bohai Sea, China: occurrence, temporal variations, and trophic transfer behavior	10.1021/acs.est.6b06593
(***87***)	Trophic magnification of short-chain per-and polyfluoroalkyl substances in a terrestrial food chain from the Tibetan Plateau	10.1021/acs.estlett.1c01009
(***88***)	Biomagnification of perfluorinated compounds in a remote terrestrial food chain: lichen–caribou–wolf	10.1021/es201353v
(***89***)	Comprehensive screening of polar emerging organic contaminants including PFASs and evaluation of the trophic transfer behavior in a freshwater food web	10.1016/j.watres.2022.118514
(***90***)	Bioaccumulation and Biomagnification of Perfluoroalkyl Substances (PFAS) in a Subarctic Ringed Seal Food Web in Lake Melville, Northern Labrador, Canada	Thesis
(***91***)	Ecological characteristics impact PFAS concentrations in a US North Atlantic food web	10.1016/j.scitotenv.2023.163302
(***92***)	Biomanipulation impacts on per-and polyfluoroalkyl substances accumulation and trophic transfer in an eutrophic lake	10.1016/j.envint.2021.107057
(***93***)	Food web on ice: A pragmatic approach to investigate the trophic magnification of chemicals of concern	10.1186/s12302-021-00530-x
(***94***)	Bioaccumulation of polyfluoroalkyl substances in the Lake Huron aquatic food web	10.1016/j.scitotenv.2022.152974
(***95***)	Bioaccumulation and trophic magnification of emerging and legacy per- and polyfluoroalkyl substances (PFAS) in a St. Lawrence River food web	10.1016/j.envpol.2022.119739
(***96***)	Sediment-seawater partitioning, bioaccumulation, and biomagnification of perfluorobutane sulfonamide in marine environment	10.1016/j.watres.2024.121466
(***97***)	Bioaccumulation and biomagnification of emerging poly-and perfluoroalkyl substances in marine organisms	10.1016/j.scitotenv.2022.158117
(***98***)	Legacy and Emerging Per- and Polyfluoroalkyl Substances in a Subtropical Marine Food Web: Suspect Screening, Isomer Profile, and Identification of Analytical Interference	10.1021/acs.est.3c00374
(***99***)	PFAS bioaccumulation in Antarctic breeding south polar skua (Catharacta maccormicki) and its prey items	Thesis
(***100***)	Perfluoroalkyl acids (PFAAs) in the aquatic food web of a temperate urban lake in East China: Bioaccumulation, biomagnification, and probabilistic human health risk	10.1016/j.envpol.2021.118748
(***8***)	Bioaccumulation of per- and polyfluorinated alkyl substances (PFAS) in selected species from the Barents Sea food web	10.1016/j.envpol.2006.09.021
(***101***)	Perfluorinated and Polyfluorinated Compounds in Lake Food Websfrom the Canadian High Arctic	10.1021/es5048649
(***102***)	PFAS accumulation in indigenous and translocated aquatic organisms from Belgium, with translation to human and ecological health risk	10.1186/s12302-021-00477-z
(***103***)	Bioaccumulation and trophic transfer of per- and polyfluoroalkyl substances in a subtropical mangrove estuary food web	10.1016/j.scitotenv.2024.172094
(***104***)	Bioaccumulation of perfluoroalkyl substances in the Lake Erie food web	10.1016/j.envpol.2022.120677
(***105***)	New insights from an eight-year study on per- and polyfluoroalkyl substances in an urban terrestrial ecosystem	10.1016/j.envpol.2024.123735
(***106***)	Uptake of Hydrophobic Organic Compounds, Including Organochlorine Pesticides, Polybrominated Diphenyl Ethers, and Perfluoroalkyl Acids in Fish and Blue Crabs of the Lower Passaic River, New Jersey, USA	10.1002/etc.4354

(***107***)	Trophic behaviors of PFOA and its alternatives perfluoroalkyl ether carboxylic acids (PFECAs) in a coastal food web	10.1016/j.jhazmat.2023.131353
(***108***)	Disclosing the bioaccumulation and biomagnification behaviors of emerging per/polyfluoroalkyl substances in aquatic food web based on field investigation and model simulation	10.1016/j.jhazmat.2022.130566
(***109***)	Comprative study of ecodynamic of halogenated micropollutant of historical and emergent interest in the Seine estuary	Thesis
(***110***)	Bioaccumulation and trophic transfer of perfluorinated alkyl substances (PFAS) in marine biota from the Belgian North Sea: Distribution and human health risk implications	10.1016/j.envpol.2022.119907
(***111***)	Per-and polyfluoroalkyl-contaminated freshwater impacts adjacent riparian food webs	10.1021/acs.est.0c01640
(***112***)	Quantification of Biodriven Transfer of Per- and Polyfluoroalkyl Substances from the Aquatic to the Terrestrial Environment via Emergent Insects	10.1021/acs.est.0c07129
(***113***)	Perfluorooctane sulfonate (PFOS) and other fluorochemicals in fish blood collected near the outfall of wastewater treatment plant (WWTP) in Beijing	10.1016/j.envpol.2008.03.008
(***114***)	Investigation of perfluorinated compounds (PFCs) in mollusks from coastal waters in the Bohai Sea of China	10.1039/b909302h
(***115***)	Perfluorinated Chemicals InfiltrateOcean Waters: Link betweenExposure Levels and Stable IsotopeRatios in Marine Mammals	10.1021/es0345975
(***116***)	The occurrence, tissue distribution, and PBT potential of per- and polyfluoroalkyl substances in the freshwater organisms from the Yangtze river via nontarget analysis	10.1016/j.jhazmat.2023.131868
(***117***)	Bioaccumulation Patterns of Perfluoroalkyl Acids in an Estuary of the Ariake Sea, Japan	10.1007/s00128-018-2282-z
(***9***)	Developing methods for assessing trophic magnification of perfluoroalkyl substances within an urban terrestrial avian food web	10.1021/acs.est.3c02361
(***118***)	Persistent toxic substances in Mediterranean aquatic species	10.1016/j.scitotenv.2014.05.131
(***119***)	Bioaccumulation and risk mitigation of legacy and novel perfluoroalkyl substances in seafood: Insights from trophic transfer and cooking method	10.1016/j.envint.2023.108023
(***120***)	Accumulation and exposure assessment of persistent chlorinated and fluorinated contaminants in Korean birds	10.1016/j.scitotenv.2018.07.040
(***121***)	Levels of chlorinated, brominated, and perfluorinated contaminants in birds of prey spanning multiple trophic levels	10.7589/2012-03-084
(***122***)	Per-and polyfluoroalkyl substances in waterbird feathers around Poyang Lake, China: Compound and species-specific bioaccumulation	10.1016/j.ecoenv.2024.116141

Supplementary Table 2

Tab. S2. Number of effect sizes (TMF) across food webs in different world regions. *Only PFAS with more than 10 effect sizes are reported in the table.*

PFAS	Antarctic Region	Arctic Region	East Asia	West Asia	Europe	Mediterranean Region	North America	South America
F-53B	0	0	31	0	0	0	0	0
PFOS	4	4	33	1	19	1	55	0
PFDA	3	2	27	1	18	0	37	0
br-PFOS	0	0	0	0	9	0	0	3
PFUnDA	4	1	32	1	18	0	35	3
l-PFOS	0	0	0	0	15	0	2	3
PFNA	3	2	24	0	15	0	41	3
PFTrDA	1	0	17	0	16	0	29	3
PFDoDA	1	0	28	1	18	0	34	3
FOSA	0	1	2	0	13	0	12	0
PFHxS	1	0	9	1	12	0	20	0
PFDS	0	0	5	0	6	0	11	0
PFTeDA	0	0	6	0	16	0	24	3
PFOA	1	1	23	0	15	0	35	0
PFBA	1	0	14	1	0	0	0	0
PFPeA	0	0	11	0	0	0	0	0
PFHpA	0	0	12	0	3	0	6	0
PFBS	0	0	13	1	0	0	10	0
PFHxA	0	0	13	0	1	0	1	0

Supplementary Table 3

Tab. S3. Summary of international regulation status of selected per- and polyfluoroalkyl substances (PFAS)*. The table categorises 19 PFAS based on their regulatory status, indicating whether they are listed in the Stockholm Convention, the REACH regulation, or internationally not regulated. A details column provides information on PFAS regulation.*

Chemical	Regulation	Details	Sources
PFOS	Stockholm Convention	Listed under the Stockholm Convention on Persistent Organic Pollutants (POPs). It is also listed in the European Drinking Water Directive and Prior Informed Consent (PIC) regulations. It was banned by the Environment and Climate Change Canada (ECCC). Included in the List of New Pollutants for Priority Management of China.	- Stockholm Convention on POPs, Annex B. - (*123*) - Environment and Climate Change Canada. - List of New Pollutants for Priority Management (China).
PFDA	REACH regulation	Listed in the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Annex XVII Restricted Substances List (C_9-C_{14} PFCSs). REACH restricts its use and mandates reporting for specific applications. Also listed in the Classification, Labelling and Packaging (CLP) regulation. It was banned by the ECCC.	- European Chemicals Agency (ECHA). - REACH regulation. - Thomas et al. (2023). - Environment and Climate Change Canada.
F-53B	Internationally not regulated	Developed as a PFOS replacement. It is not internationally regulated. Currently, F-53B is only used in China. However, it was ubiquitously detected in rivers and lakes in China and the United States, Germany, the United Kingdom, the Netherlands, and South Korea.	- (*33*)
br-PFOS	Stockholm Convention	Considered part of PFOS regulation under the Stockholm Convention.	- Stockholm Convention on POPs, Annex B.

PFUnDA	REACH regulation	Listed in the REACH Annex XVII Restricted C_9-C_{14} PFCSs Substances List. It was banned by the ECCC.	- REACH regulation. - Environment and Climate Change Canada.
l-PFOS	Stockholm Convention	Considered part of PFOS regulation under the Stockholm Convention.	- Stockholm Convention on POPs, Annex B.
PFNA	REACH regulation	Listed in the REACH Annex XVII Restricted Substances List (C_9-C_{14} PFCSs). Also listed in the CLP regulation. It was banned by the ECCC.	- ECHA - REACH regulation. - Environment and Climate Change Canada.
PFTrDA	REACH regulation	Listed in the REACH Annex XVII Restricted Substances List (C_9-C_{14} PFCSs). It was banned by the ECCC.	- REACH regulation. - Environment and Climate Change Canada.
PFDoDA	REACH regulation	Listed in the REACH Annex XVII Restricted Substances List (C_9-C_{14} PFCSs). It was banned by the ECCC.	- REACH regulation. - Environment and Climate Change Canada.
FOSA	Stockholm Convention	Regulated as a derivative and degradation product of PFOS under the Stockholm Convention, Annex B, as it can degrade to PFOS in the environment.	- Stockholm Convention on POPs, Annex B.
PFHxS	Stockholm Convention	Added to the Stockholm Convention in 2022 under Annex A due to its persistence and potential adverse health effects. This means PFHxS and its salts are targeted for elimination. Listed in the List of New Pollutants for Priority Management of China.	- Stockholm Convention on POPs, Annex A. - List of New Pollutants for Priority Management (China).
PFDS	Internationally not regulated	Not covered under major international regulations.	NA
PFTeDA	REACH regulation	Listed in the REACH Annex XVII Restricted C_9-C_{14} PFCSs Substances List. It was banned by the ECCC.	- REACH regulation. - Environment and Climate Change Canada.
PFOA	Stockholm Convention	Listed under Annex A of the Stockholm Convention with restrictions on production and use, effective since 2020. Also listed in the CLP and PIC	- Stockholm Convention on POPs, Annex A. - Environment and Climate Change Canada.

		regulations. It was banned by the ECCC. New Zeland banned Aqueous Film Forming Foam (AFFF) that contain PFOA-related compounds. Listed in the List of New Pollutants for Priority Management of China.	- EPA New Zeland. - List of New Pollutants for Priority Management (China).
PFBA	Internationally not regulated	Not regulated internationally and not covered under major regulations.	NA
PFPeA	Internationally not regulated	Not regulated internationally and not covered under major regulations.	NA
PFHpA	REACH regulation	Listed as an SVHC under REACH (group 3). Also listed in the Classification, Labelling and Packaging (CLP) regulation.	- REACH Regulation.
PFBS	REACH regulation	Considered a lower-risk alternative to PFOS. Listed as an SVHC under REACH (group 2).	- REACH Regulation.
PFHxA	Internationally not regulated	Not regulated internationally and not covered under major regulations. However, it is monitored due to its increasing use as a replacement for long-chain PFAS compounds.	NA

Supplementary Table 4

Tab. S4. Strategies used to handle undetected values. *The table presents the types of strategies employed by the studies included in the meta-analysis to address concentrations below the limit of detection or quantification, along with the corresponding number of effect sizes and studies.*

Strategy for undetected values	Number of TMFs	Number of Studies
Not provided	337	24
The LOQ value divided by two	81	8
The MDL value divided by two	88	7
The LOD value divided by two	95	5
Zero for values < LOD	24	2
Exclusion of data if values were < LOD	11	1
Exclusion of data if values were < LOQ	96	1
Exclusion of data if values were < MDL.	16	1
Exclusion of values < LOD. The LOQ value divided by two for values < LOQ	7	1
Imputation method	31	1
Models accounting for values below the LOD	32	1
Random numbers below half of the MDL	20	1
Random numbers between 0 and the LOD value	36	1
Random numbers between 0 and the LOD value divided by two	24	1
Random numbers between 0 and the MDL value	20	1
The LOD value divided by the square root of two	10	1
The LOD value divided by the square root of two for values < LOD. The LOQ value divided by two for values < LOQ	7	1
The LOD value divided by two or detection frequency multiplied by LOD value or imputation	35	1
The LOQ value divided by the square root of two	1	1
Three method comparison	33	1
Zero for undetected. The MDL value divided by two for values < MDL	4	1
Zero for values < LOD. The LOQ value divided by the square root of two for values < LOQ	12	1
Zero for values < LOD. The LOQ value divided by two for values < LOQ	10	1

Supplementary Table 5

Tab. S5. Deviations and additions to the research protocol*. The table outlines the types of deviations and additions to the research protocol, including their descriptions, justifications, the review stage affected, and the magnitude of each deviation.*

Deviation/Addition	**Description**	**Reason**	**Review stage impacted**	**Impact's magnitude**
Changes to the study validity assessment	We removed the performance bias item and rephrased the selection, measurement, and reporting bias	This deviation was necessary to enhance the tool's applicability to the specific types of studies included in the meta-analysis.	Study validity assessment	Low
Changes to grey literature search databases	We replaced the OpenGrey database with the BASE database	The OpenGrey database was not working on the day of the search.	Grey literature search	Low
Changes to the TMF_data spreadsheet	We added the column “Censored_data_strategy”	The column was added to record the strategy to deal with the undetected data	None	NA
Changes to the fw_data spreadsheet	We moved the columns “Sample_type” and “Biomass_conversion” from the fw_data spreadsheet to the TMF_data spreadsheet	Some studies measured TMF in the same food web but using different biomass conversion and or samples	None	NA

Supplementary Table 6

Tab. S6. PRISMA Eco-Evo checklist*. This table presents the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) Eco-Evo checklist, tailored for ecological and evolutionary research. It includes key reporting items, corresponding checklist sections, and specific guidelines to ensure transparency, reproducibility, and comprehensiveness in systematic reviews and meta-analyses within eco-evolutionary studies.*

Checklist item	Sub-item number	Sub-item	Reported by authors?	Notes
Title and abstract	1.1	Identify the review as a systematic review, meta-analysis, or both	Yes	Title and abstract
	1.2	Summarise the aims and scope of the review	Yes	Abstract
	1.3	Describe the data set	Yes	Abstract
	1.4	State the results of the primary outcome	Yes	Abstract
	1.5	State conclusions	Yes	Abstract
	1.6	State limitations	No	Limitations have their own paragraph
Aims and questions	2.1	Provide a rationale for the review	Yes	Introduction
	2.2	Reference any previous reviews or meta-analyses on the topic	Yes	Introduction
	2.3	State the aims and scope of the review (including its generality)	Yes	Introduction
	2.4	State the primary questions the review addresses (e.g. which moderators were tested)	Yes	Introduction
	2.5	Describe whether effect sizes were derived from experimental and/or observational comparisons	Yes	Introduction
Review registration	3.1	Register review aims, hypotheses (if applicable), and methods in a time-stamped and publicly accessible archive and provide a link to the registration in the methods section of the manuscript. Ideally registration occurs before the search, but it can be done at any stage before data analysis.	Yes	PROCEED (https://doi.org/10.57808/proceed.2024.8)

	3.2	Describe deviations from the registered aims and methods	Yes	Supplementary table 7
	3.3	Justify deviations from the registered aims and methods	Yes	Supplementary table 7
Eligibility criteria	4.1	Report the specific criteria used for including or excluding studies when screening titles and/or abstracts, and full texts, according to the aims of the systematic review (e.g. study design, taxa, data availability)	Yes	Supplementary method 1 and 2
	4.2	Justify criteria, if necessary (i.e. not obvious from aims and scope)	Yes	Supplementary method 1 and 2
Finding studies	5.1	Define the type of search (e.g. comprehensive search, representative sample)	Yes	Supplementary method 1
	5.2	State what sources of information were sought (e.g. published and unpublished studies, personal communications)	Yes	Supplementary method 1
	5.3	Include, for each database searched, the exact search strings used, with keyword combinations and Boolean operators	Yes	Supplementary table 10
	5.4	Provide enough information to repeat the equivalent search (if possible), including the timespan covered (start and end dates)	Yes	Supplementary table 7
Study selection	6.1	Describe how studies were selected for inclusion at each stage of the screening process (e.g. use of decision trees, screening software)	Yes	Materials and Methods
	6.2	Report the number of people involved and how they contributed (e.g. independent parallel screening)	Yes	Materials and Methods
Data collection process	7.1	Describe where in the reports data were collected from (e.g. text or figures)	Yes	Supplementary Data
	7.2	Describe how data were collected (e.g. software used to digitize figures, external data sources)	Yes	NA
	7.3	Describe moderator variables that were constructed from collected data (e.g.	Yes	Table 1

		number of generations calculated from years and average generation time)		
	7.4	Report how missing or ambiguous information was dealt with during data collection (e.g. authors of original studies were contacted for missing descriptive statistics, and/or effect sizes were calculated from test statistics)	Yes	Materials and Methods
	7.5	Report who collected data	Yes	Materials and Methods
	7.6	State the number of extractions that were checked for accuracy by co-authors	No	NA
Data items	8.1	Describe the key data sought from each study	Yes	Pre-registered protocol
	8.2	Describe items that do not appear in the main results, or which could not be extracted due to insufficient information	No	NA
	8.3	Describe main assumptions or simplifications that were made (e.g. categorising both 'length' and 'mass' as 'morphology')	Yes	Discussion
	8.4	Describe the type of replication unit (e.g. individuals, broods, study sites)	Yes	Materials and Methods
Assessment of individual study quality	9.1	Describe whether the quality of studies included in the systematic review or meta-analysis was assessed (e.g. blinded data collection, reporting quality, experimental *versus* observational)	Materials and Methods	Sensitivity analysis
	9.2	Describe how information about study quality was incorporated into analyses (e.g. meta-regression and/or sensitivity analysis)	Materials and Methods	Sensitivity analysis
Effect size measures	10.1	Describe effect size(s) used	Yes	Materials and Methods

	10.2	Provide a reference to the equation of each calculated effect size (e.g. standardised mean difference, log response ratio) and (if applicable) its sampling variance	Yes	Materials and Methods
	10.3	If no reference exists, derive the equations for each effect size and state the assumed sampling distribution(s)	Yes	Materials and Methods
Missing data	11.1	Describe any steps taken to deal with missing data during analysis (e.g. imputation, complete case, subset analysis)	Yes	Materials and Methods & Supplementary Methods
	11.2	Justify the decisions made to deal with missing data	Yes	Materials and Methods & Supplementary Methods
Meta-analytic model description	12.1	Describe the models used for synthesis of effect sizes	Yes	Materials and Methods
	12.2	The most common approach in ecology and evolution will be a random-effects model, often with a hierarchical/multilevel structure. If other types of models are chosen (e.g. common/fixed effects model, unweighted model), provide justification for this choice	Yes	Materials and Methods
Software	13.1	Describe the statistical platform used for inference (e.g. *R*)	Yes	Materials and Methods
	13.2	Describe the packages used to run models	Yes	Materials and Methods
	13.3	Describe the functions used to run models	Yes	Materials and Methods

	13.4	Describe any arguments that differed from the default settings	Yes	Materials and Methods
	13.5	Describe the version numbers of all software used	Yes	NA
Non-independence	14.1	Describe the types of non-independence encountered (e.g. phylogenetic, spatial, multiple measurements over time)	Yes	Materials and Methods
	14.2	Describe how non-independence has been handled	Yes	Materials and Methods
	14.3	Justify decisions made	Yes	Materials and Methods
Meta-regression and model selection	15.1	Provide a rationale for the inclusion of moderators (covariates) that were evaluated in meta-regression models	Yes	Table 1
	15.2	Justify the number of parameters estimated in models, in relation to the number of effect sizes and studies (e.g. interaction terms were not included due to insufficient sample sizes)	Yes	Materials and Methods
	15.3	Describe any process of model selection	Yes	Materials and Methods
Publication bias and sensitivity analyses	16.1	Describe assessments of the risk of bias due to missing results (e.g. publication, time-lag, and taxonomic biases)	Yes	Publication bias section
	16.2	Describe any steps taken to investigate the effects of such biases (if present)	Yes	Publication bias section
	16.3	Describe any other analyses of robustness of the results, e.g. due to effect size choice, weighting or analytical model assumptions, inclusion or exclusion of subsets of the data, or the inclusion of alternative moderator variables in meta-regressions	Yes	Publication bias and sensitivity analyses
Clarification of *post hoc* analyses	17.1	When hypotheses were formulated after data analysis, this should be acknowledged.	Yes	Table 1

Metadata, data, and code	18.1	Share metadata (i.e. data descriptions)	Yes	Pre-registered protocol and Supplementary Data
	18.2	Share data required to reproduce the results presented in the manuscript	Yes	Supplementary Data
	18.3	Share additional data, including information that was not presented in the manuscript (e.g. raw data used to calculate effect sizes, descriptions of where data were located in papers)	Yes	Supplementary Data
	18.4	Share analysis scripts (or, if a software package with graphical user interface (GUI) was used, then describe full model specification and fully specify choices)	Yes	GitHub Repository
Results of study selection process	19.1	Report the number of studies screened	Yes	Results
	19.2	Report the number of studies excluded at each stage of screening	Yes	Results
	19.3	Report brief reasons for exclusion from the full text stage	Yes	Supplementsry Table 2
	19.4	Present a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-like flowchart (www.prisma-statement.org).	Yes	Supplementary Figure 1
Sample sizes and study characteristics	20.1	Report the number of studies and effect sizes for data included in meta-analyses	Yes	Results
	20.2	Report the number of studies and effect sizes for subsets of data included in meta-regressions	Yes	Results
	20.3	Provide a summary of key characteristics for reported outcomes (either in text or figures; e.g. one quarter of effect sizes reported for vertebrates and the rest invertebrates)	Yes	Results

	20.4	Provide a summary of limitations of included moderators (e.g. collinearity and overlap between moderators)	Yes	Results
	20.5	Provide a summary of characteristics related to individual study quality (risk of bias)	Yes	Results
Meta-analysis	21.1	Provide a quantitative synthesis of results across studies, including estimates for the mean effect size, with confidence/credible intervals	Yes	Results
Heterogeneity	22.1	Report indicators of heterogeneity in the estimated effect (e.g. I^2, tau^2 and other variance components)	Yes	Results
Meta-regression	23.1	Provide estimates of meta-regression slopes (i.e. regression coefficients) and confidence/credible intervals	Yes	Results
	23.2	Include estimates and confidence/credible intervals for all moderator variables that were assessed (i.e. complete reporting)	Yes	Results
	23.3	Report interactions, if they were included	Yes	Results
	23.4	Describe outcomes from model selection, if done (e.g. R2 and AIC)	Yes	Results
Outcomes of publication bias and sensitivity analyses	24.1	Provide results for the assessments of the risks of bias (e.g. Egger's regression, funnel plots)	Yes	Results
	24.2	Provide results for the robustness of the review's results (e.g. subgroup analyses, meta-regression of study quality, results from alternative methods of analysis, and temporal trends)	Yes	Results
Discussion	25.1	Summarise the main findings in terms of the magnitude of effect	Yes	Discussion
	25.2	Summarise the main findings in terms of the precision of effects (e.g. size of confidence intervals, statistical significance)	Yes	Discussion

	25.3	Summarise the main findings in terms of their heterogeneity	Yes	Discussion
	25.4	Summarise the main findings in terms of their biological/practical relevance	Yes	Discussion
	25.5	Compare results with previous reviews on the topic, if available	Yes	Discussion
	25.6	Consider limitations and their influence on the generality of conclusions, such as gaps in the available evidence (e.g. taxonomic and geographical research biases)	Yes	Discussion
Contributions and funding	26.1	Provide names, affiliations, and funding sources of all co-authors	Yes	NA
	26.2	List the contributions of each co-author	Yes	NA
	26.3	Provide contact details for the corresponding author	Yes	NA
	26.4	Disclose any conflicts of interest	Yes	NA
References	27.1	Provide a reference list of all studies included in the systematic review or meta-analysis	Yes	NA
	27.2	List included studies as referenced sources (e.g. rather than listing them in a table or supplement)	Yes	NA

Supplementary Table 7

Tab. S7. Digital Object Identifiers (DOIs) of the 25 banchmark bibliographic records. *These records were specifically selected to validate the thoroughness of the search methodology, evaluating our search strategy's sensitivity and comprehensiveness.*

DOIs:
10.1021/es049331s
10.1021/es049620g
10.1021/es060233b
10.1021/es800906r
10.1021/es9003894
10.1021/es900162n
10.1021/es200432n
10.1016/j.envpol.2013.09.011
10.1021/es405018b
10.1021/es504445x
10.1021/acs.est.7b02399
10.1016/j.envpol.2018.05.087
10.1016/j.envpol.2018.05.001
10.1039/C9EM00322C
10.1016/j.scitotenv.2019.05.461
10.1021/acs.est.9b05007
10.1016/j.envpol.2019.113383
10.3390/w12061591
10.1021/acs.est.0c04587
10.1016/j.envint.2020.105621
10.1016/j.scitotenv.2020.142146
10.1016/j.jhazmat.2020.124681
10.1021/acs.est.1c00965
10.1016/j.jhazmat.2020.123618
10.1016/j.jglr.2021.08.013
Benchmark query:
DOI(10.1021/es049331s) OR DOI(10.1021/es049620g) OR DOI(10.1021/es060233b) OR DOI(10.1021/es800906r) OR DOI(10.1021/es9003894) OR DOI(10.1021/es900162n) OR DOI(10.1021/es200432n) OR DOI(10.1016/j.envpol.2013.09.011) OR DOI(10.1021/es405018b) OR DOI(10.1021/es504445x) OR DOI(10.1021/acs.est.7b02399) OR DOI(10.1016/j.envpol.2018.05.087) OR DOI(10.1016/j.envpol.2018.05.001) OR DOI(10.1039/C9EM00322C) OR DOI(10.1016/j.scitotenv.2019.05.461) OR DOI(10.1021/acs.est.9b05007) OR DOI(10.1016/j.envpol.2019.113383) OR DOI(10.3390/w12061591) OR DOI(10.1021/acs.est.0c04587) OR

DOI(10.1016/j.envint.2020.105621) OR DOI(10.1016/j.scitotenv.2020.142146) OR
DOI(10.1016/j.jhazmat.2020.124681) OR DOI(10.1021/acs.est.1c00965) OR
DOI(10.1016/j.jhazmat.2020.123618) OR DOI(10.1016/j.jglr.2021.08.013)

Supplementary Table 8

Tab. S8. Searches records from six online databases. *This table provides details of the systematic searches conducted across six online databases. It includes the database names, search strings tailored to each database's structure, the dates of the searches, and the number of resulting records (hits). The search strings were designed to be comprehensive, aiming to capture all relevant studies on PFAS concentrations within food webs.*

Source	Search string	Date of search	Number of hits
PubMed	("fluoroalkyl" OR perfluo* OR polyfluo* OR organofluorine OR pfas OR pfass OR pfba OR pfpea OR pfhxa OR pfhpa OR pfoa OR pfna OR pfda OR pfdea OR pfdca OR pfunda OR pfuna OR pfua OR pfuda OR pfdoa OR pfdoda OR pftrda OR pftrida OR pftra OR pfta OR pfteda OR pfo4da OR pfo5doda OR pfbs OR pfbus OR pfpes OR pfhxs OR pfhps OR pfos OR pfns OR pfds OR fts OR ftsa OR pfechs OR fosa OR pfosa OR netfosaa OR "Et-PFOSA-AcOH" OR nmefosaa OR "Me-PFOSA-AcOH" OR adona OR "Cl-PFAES" OR "F-53B" OR genx OR "HFPO-TA" OR "Hydro-Eve" OR "Nafion BP2" OR teflon OR tefal OR c8 OR "emerging pollutant*" OR organohalogen* OR ptfe OR fluorotelomer*) AND ("trophic level*" OR "trophic position*" OR tropho* OR "trophic amplification" OR "trophic magnification*" OR "trophic transfer" OR bioamplification* OR biomagnif* OR "biological magnification*"OR "cumulative concentration*" OR "food chain*" OR "food web*" OR TMF OR "magnification factor*") NOT review[pt]	08/04/2024	526
Web of Science (Core Collection)	TS=("fluoroalkyl*" OR perfluo* OR polyfluo* OR organofluorine OR pfas OR pfass OR pfba OR pfpea OR pfhxa OR pfhpa OR pfoa OR pfna OR pfda OR pfdea OR pfdca OR pfunda OR pfuna OR pfua OR pfuda OR pfdoa OR pfdoda OR pftrda OR pftrida OR pftra OR pfta OR pfteda OR pfo4da OR pfo5doda OR pfbs OR pfbus OR pfpes OR pfhxs OR pfhps OR pfos OR pfns OR pfds OR fts OR ftsa OR pfechs OR fosa OR pfosa OR netfosaa OR "Et-PFOSA-AcOH" OR nmefosaa OR "Me-PFOSA-AcOH" OR adona OR "Cl-PFAES" OR "F-53B" OR genx OR "HFPO-TA" OR "Hydro-Eve" OR "Nafion BP2" OR teflon OR tefal OR c8 OR "emerging pollutant*" OR organohalogen* OR ptfe OR fluorotelomer*) AND TS=("nitrogen isotope*" OR "stable isotope*" OR "trophic level*" OR "trophic position*" OR tropho* OR "trophic amplification" OR "trophic magnification*" OR "trophic transfer" OR bioamplification* OR biomagnif* OR "biological magnification*" OR	08/04/2024	949

	"cumulative concentration*" OR "food chain*" OR "food web*" OR TMF OR "magnification factor*") NOT DT=(Review)		
Scopus	TITLE-ABS-KEY (*fluoroalkyl* OR perfluo* OR polyfluo* organofluorine OR pfas OR pfass OR pfba OR pfpea OR pfhxa OR pfhpa OR pfoa OR pfna OR pfda OR pfdea OR pfdca OR pfunda OR pfuna OR pfua OR pfuda OR pfdoa OR pfdoda OR pftrda OR pftrida OR pftra OR pfta OR pfteda OR pfo4da OR pfo5doda OR pfbs OR pfbus OR pfpes OR pfhxs OR pfhps OR pfos OR pfns OR pfds OR fts OR ftsa OR pfechs OR fosa OR pfosa OR netfosaa OR "Et-PFOSA-AcOH" OR nmefosaa OR "Me-PFOSA-AcOH" OR adona OR "Cl-PFAES" OR "F-53B" OR genx OR "HFPO-TA" OR "Hydro-Eve" OR "Nafion BP2" OR teflon OR tefal OR c8 OR "emerging pollutant*" OR organohalogen* OR ptfe OR fluorotelomer*) AND ("trophic level*" OR "trophic position*" OR "trophic amplification" OR "trophic magnification*" OR "trophic transfer" OR bioamplification* OR biomagnif* OR "biological magnification*" OR "magnification factor*" OR TMF) AND (EXCLUDE (DOCTYPE,"re"))	08/04/2024	1543
GreenFile (EBSCO)	(fluoroalkyl OR perfluo* OR polyfluo* OR organofluorine OR pfas OR pfass OR pfba OR pfpea OR pfhxa OR pfhpa OR pfoa OR pfna OR pfda OR pfdea OR pfdca OR pfunda OR pfuna OR pfua OR pfuda OR pfdoa OR pfdoda OR pftrda OR pftrida OR pftra OR pfta OR pfteda OR pfo4da OR pfo5doda OR pfbs OR pfbus OR pfpes OR pfhxs OR pfhps OR pfos OR pfns OR pfds OR fts OR ftsa OR pfechs OR fosa OR pfosa OR netfosaa OR "Et-PFOSA-AcOH" OR nmefosaa OR "Me-PFOSA-AcOH" OR adona OR "Cl-PFAES" OR "F-53B" OR genx OR "HFPO-TA" OR "Hydro-Eve" OR "Nafion BP2" OR teflon OR tefal OR c8 OR "emerging pollutant*" OR organohalogen* OR ptfe OR fluorotelomer*) AND (nitrogen isotope* OR stable isotope* OR trophic level* OR "trophic position*" OR tropho* OR "trophic amplification" OR "trophic magnification*" OR "trophic transfer" OR bioamplification* OR biomagnif* OR "biological magnification*" OR "cumulative concentration*" OR "food chain*" OR "food web*" OR "magnification factor*" OR TMF)	08/04/2024	392
BASE (Bielefeld Academic Search Engine)	(PFAS* OR *fluoroalkyl* OR PFOS OR PFOA) AND (trophic magnification OR tmf OR biomagnification) doctype:(18* 19)	08/04/2024	89

ProQuest - Theses and Dissertations Database	(noft("perfluoroalkyl*") OR noft(“polyfluoroalkyl*”) OR noft(pfas) OR noft(pfos) noft(pfoa)) AND (noft("biomagnification") OR noft("trophic magnification") OR noft("magnification factor") noft("food web") noft("TMF")) NOT noft(DocumentType:Review)NOT noft(DocumentType:Review)	08/04/2024	313

Supplementary Table 9

Tab. S9. Excluded studies at the full-text screening stage*. This table provides detailed information on studies excluded from the meta-analysis following the full-text screening, along with specific reasons for their exclusion.*

Title	Year	DOI	Exclusion reason
Per-and poly-fluoroalkyl compounds in freshwater fish from the Rhcircumflex˜ ne River: influence of fish size, diet, prey contamination and biotransformation.	2017	10.1016/j.scitotenv.2017.06.111	The necessary data to calculate TMF and standard error were not provided.
Identification, Tissue Distribution, and Bioaccumulation Potential of Cyclic Perfluorinated Sulfonic Acids Isomers in an Airport Impacted Ecosystem	2016	10.1021/acs.est.6b01980	The necessary data to calculate TMF and standard error were not provided.
Bioaccumulation of Fluorotelomer Sulfonates and Perfluoroalkyl Acids in Marine Organisms Living in Aqueous Film-Forming Foam Impacted Waters	NA	10.1021/acs.est.9b00927	The necessary data to calculate TMF and standard error were not provided.
The driving factors of per- and polyfluorinated alkyl substance (PFAS) accumulation in selected fish species: The influence of position in river continuum, fish feed composition, and pollutant properties	NA	10.1016/j.scitotenv.2021.151662	The necessary data to calculate TMF and standard error were not provided.
Bioaccumulation of emerging organic compounds (perfluoroalkyl substances and halogenated flame retardants) by earthworm in biosolid amended soils	2016	10.1016/j.envres.2016.05.004	The necessary data to calculate TMF and standard error were not provided.
Perfluorinated compounds in aquatic organisms at various trophic levels in a Great Lakes food chain	NA	10.1007/s00244-004-0133-x	The necessary data to calculate TMF and standard error were not provided.
Polyfluorinated chemicals in a spatially and temporally integrated food web in the Western Arctic	NA	10.1016/j.chemosphere.2007.06.067	The necessary data to calculate TMF and standard error were not provided.

The impact of precursors on aquatic exposure assessment for PFAS: Insights from bioaccumulation modeling	NA	10.1002/ieam.4414	The necessary data to calculate TMF and standard error were not provided.
A nationwide survey of perfluorinated alkyl substances in waters, sediment and biota collected from aquatic environment in Vietnam: Distributions and bioconcentration profiles	NA	10.1016/j.jhazmat.2016.04.010	The necessary data to calculate TMF and standard error were not provided.
Bioaccumulation and effects of novel chlorinated polyfluorinated ether sulfonate in freshwater alga Scenedesmus obliquus	2018	10.1016/j.envpol.2017.10.039	The necessary data to calculate TMF and standard error were not provided.
Persistent organic pollutants in lakes of Broknes peninsula at Larsemann Hills area, East Antarctica	NA	10.1007/s10646-019-02045-x	No PFAS.
Perfluorinated Chemicals in Meromictic Lakes on the Northern Coast of Ellesmere Island, High Arctic Canada	2012	NA	The necessary data to calculate TMF and standard error were not provided.
Bioaccumulation and metabolic response of PFAS mixtures in wild-caught freshwater turtles (Emydura macquarii macquarii) using omics-based ecosurveillance techniques	2022	10.1016/j.scitotenv.2021.151264	The necessary data to calculate TMF and standard error were not provided.
Perfluorinated contaminants in sediments and aquatic organisms collected from shallow water and tidal flat areas of the Ariake Sea, Japan: environmental fate of perfluorooctane sulfonate in aquatic ecosystems	NA	10.1021/es0603195	The necessary data to calculate TMF and standard error were not provided.
Characterisation of PFASs and Organofluorine in Freshwater Environments : Transfer from water to land via emergent aquatic insects	2020	NA	Duplicate data
Levels, Patterns, and Biomagnification Potential of Perfluoroalkyl Substances in a	NA	10.1021/acs.est.9b02533	The necessary data to calculate TMF and standard error were not provided.

Terrestrial Food Chain in a Nordic Skiing Area			
Bioaccumulation and biomagnification of perfluoroalkyl acids and precursors in East Greenland polar bears and their ringed seal prey	NA	10.1016/j.envpol.2019.06.035	The necessary data to calculate TMF and standard error were not provided.
Bioaccumulation of Perfluoroalkyl Sulfonamides (FASA)	2024	10.1021/acs.estlett.4c00143	The necessary data to calculate TMF and standard error were not provided.
Persistent organic pollutants in biotic and abiotic components of the Orange-Senqu River basin	2023	NA	The necessary data to calculate TMF and standard error were not provided.
Pollution Characteristics of Perfluorinated Alkyl Substances (PFASs) in Seawater, Sediments, and Biological Samples from Jiaozhou Bay, China	2019	10.13227/j.hjkx.201901104	Full-text not available.
Perfluoroalkyl acids and sulfonamides and dietary, biological and ecological associations in peregrine falcons from the Laurentian Great Lakes Basin, Canada	NA	10.1016/j.envres.2020.110151	Only one species was investigated.
Levels and profiles of perfluorinated alkyl acids in liver tissues of birds with different habitat types and trophic levels from an urbanized coastal region of South Korea	NA	10.1016/j.scitotenv.2021.151263	The necessary data to calculate TMF and standard error were not provided.
Bioaccumulation characteristics of perfluoroalkyl acids (PFAAs) in coastal organisms from the west coast of South Korea	2015	10.1016/j.chemosphere.2014.06.023	The necessary data to calculate TMF and standard error were not provided.
Dietary bioaccumulation of persistent organic pollutants in the common sole Solea solea in the context of global change. Part 2: Sensitivity of juvenile growth and contamination to toxicokinetic parameters uncertainty and	2020	10.1016/j.ecolmodel.2020.109196	The necessary data to calculate TMF and standard error were not provided.

environmental conditions variability in estuaries			
Perfluoroalkyl acids in various edible Baltic, freshwater, and farmed fish in Finland	2015	10.1016/j.chemosphere.2014.08.077	The necessary data to calculate TMF and standard error were not provided.
Direct evidence of the important role of proteins in bioconcentration and biomagnification of PFASs in benthic organisms based on comparison with OPEs	NA	10.1016/j.scitotenv.2022.161012	The necessary data to calculate TMF and standard error were not provided.
Dietary bioaccumulation of perfluorophosphonates and perfluorophosphinates in juvenile rainbow trout: evidence of metabolism of perfluorophosphinates	NA	10.1021/es204533m	The necessary data to calculate TMF and standard error were not provided.
A food web bioaccumulation model for the accumulation of per- and polyfluoroalkyl substances (PFAS) in fish: how important is renal elimination?	NA	10.1039/d2em00047d	The necessary data to calculate TMF and standard error were not provided.
PFAS and Precursor Bioaccumulation in Freshwater Recreational Fish: Implications for Fish Advisories	NA	10.1021/acs.est.2c03734	The necessary data to calculate TMF and standard error were not provided.
Bioaccumulation of perfluoroalkyl carboxylates (PFCAs) and perfluoroalkane sulfonates (PFSAs) by earthworms (Eisenia fetida) in soil	2013	10.1016/j.envpol.2013.04.002	The necessary data to calculate TMF and standard error were not provided.
Bioaccumulation of perfluoroalkyl substances in exploited fish and crustaceans: Spatial trends across two estuarine systems	2018	10.1016/j.marpolbul.2018.04.029	The necessary data to calculate TMF and standard error were not provided.
Per- and polyfluoroalkyl substances (PFAS) in ski products: Environmental contamination, bioaccumulation and effects in rodents	2021	NA	The necessary data to calculate TMF and standard error were not provided.

Nonlethal detection of PFAS bioaccumulation and biomagnification within fishes in an urban- and wastewater-dominant Great Lakes watershed	NA	10.1016/j.envpol.2023.121123	The necessary data to calculate TMF and standard error were not provided.
Environmental fate of poly- and perfluoroalkyl substances (PFAS) in aquatic systems : identification of urban sources and trophic transfer assessment ; Ecodynamique des substances poly- et perfluoroalkylÃ©es (PFAS) dans les systÃ¨mes aquatiques : identification des sources en milieu urbain et Ã©valu...	NA	NA	Duplicate data
Field-Based Distribution and Bioaccumulation Factors for Cyclic and Aliphatic Per- and Polyfluoroalkyl Substances (PFASs) in an Urban Sedentary Waterbird Population	2022	10.1021/acs.est.2c01965	The necessary data to calculate TMF and standard error were not provided.
Understanding PFAAs exposure in a generalist seabird species breeding in the vicinity of a fluorochemical plant: Influence of maternal transfer and diet	2021	10.1016/j.envpol.2020.116355	Only one species investigated.
Bioaccumulation of perfluoroalkyl substances in marine echinoderms: Results of laboratory-scale experiments with Holothuria tubulosa Gmelin, 1791	2019	10.1016/j.chemosphere.2018.10.037	The necessary data to calculate TMF and standard error were not provided.
Effect of abiotic factors and environmental concentrations on the bioaccumulation of persistent organic and inorganic compounds to freshwater fish and mussels	NA	10.1016/j.scitotenv.2021.149448	The necessary data to calculate TMF and standard error were not provided.
Distribution of perfluorooctanesulfonate (PFOS) isomers in a Norwegian arctic food web	2021	NA	The necessary data to calculate TMF and standard error were not provided.

Perfluorinated compounds in surface water and organisms from Baiyangdian Lake in North China: source profiles, bioaccumulation and potential risk	NA	10.1007/s00128-012-0745-1	The necessary data to calculate TMF and standard error were not provided.
First insights into per-and polyfluoroalkyl substance contamination in edible fish species of the Indus water system of Pakistan	NA	10.1016/j.chemosphere.2023.140970	The necessary data to calculate TMF and standard error were not provided.
Assessment of metal and organic pollutants in combination with stable isotope analysis in tunas from the Gulf of Cadiz (east Atlantic)	NA	10.1016/j.marenvres.2024.106432	No PFAS.
Bioaccumulation and risk assessment of per- and polyfluoroalkyl substances in wild freshwater fish from rivers in the Pearl River Delta region, South China	2014	10.1016/j.ecoenv.2014.05.031	The necessary data to calculate TMF and standard error were not provided.
A survey of perfluorinated compounds in surface water and biota including dolphins from the Ganges River and in other waterbodies in India	NA	10.1016/j.chemosphere.2009.02.055	The necessary data to calculate TMF and standard error were not provided.
The relationship between perfluorinated chemical levels in the feathers and livers of birds from different trophic levels	NA	10.1016/j.scitotenv.2009.07.032	The necessary data to calculate TMF and standard error were not provided.
Tissue distribution and bioaccumulation of legacy and emerging per- and polyfluoroalkyl substances (PFASs) in edible fishes from Taihu Lake, China	2021	10.1016/j.envpol.2020.115887	The necessary data to calculate TMF and standard error were not provided.
Survey of legacy and emerging per- and polyfluorinated alkyl substances in Mediterranean seafood from a North African ecosystem	NA	10.1016/j.envpol.2021.118398	The necessary data to calculate TMF and standard error were not provided. PFAS concentrations pooled in major taxa and not provided at the species level.

Perfluorinated alkyl substances (PFAS) in terrestrial environments in Greenland and Faroe Islands	2015	10.1016/j.chemosphere.2014.11.044	The necessary data to calculate TMF and standard error were not provided.
STUDIO DELLA BIODISTRIBUZIONE DI SOSTANZE BIOLOGICAMENTE ATTIVE IN ORGANISMI ACQUATICI	2022	NA	The necessary data to calculate TMF and standard error were not provided.
Biomagnification and temporal trends (1990-2021) of perfluoroalkyl substances in striped dolphins (Stenella coeruleoalba) from the NW Mediterranean sea	NA	10.1016/j.envpol.2023.122738	The necessary data to calculate TMF and standard error were not provided.
Characterisation of perfluorooctane sulfonate (PFOS) in a terrestrial ecosystem near a fluorochemical plant in Flanders, Belgium	NA	10.1007/s11356-013-2449-4	The necessary data to calculate TMF and standard error were not provided.
The fate of poly- and perfluoroalkyl substances in a marine food web influenced by land-based sources in the Norwegian Arctic	NA	10.1039/d0em00510j	The necessary data to calculate TMF and standard error were not provided.
Enantiospecific perfluorooctane sulfonate (PFOS) analysis reveals evidence for the source contribution of PFOS-precursors to the Lake Ontario foodweb	NA	10.1021/es301160r	The necessary data to calculate TMF and standard error were not provided.
Fractionation of perfluoroalkyl acids (PFAAs) along the aquatic food chain promoted by competitive effects between longer and shorter chain PFAAs	NA	10.1016/j.chemosphere.2023.137931	The necessary data to calculate TMF and standard error were not provided.
Accumulation of per- and polyfluoroalkyl substances (PFAS) in a terrestrial food web	2023	10.1101/2023.12.12.571392	The necessary data to calculate TMF and standard error were not provided.
Transfer of perfluorinated compounds from sediment to benthic invertebrates and fish	2014	NA	The necessary data to calculate TMF and standard error were not provided.
Bioaccumulation of organohalogenated compounds in	NA	10.1016/j.envres.2014.12.022	no PFAS.

sharks and rays from the southeastern USA			
Dietary accumulation of perfluorinated acids in juvenile rainbow trout (Oncorhynchus mykiss)	2003	10.1002/etc.5620220125	The necessary data to calculate TMF and standard error were not provided.
Perfluorinated compounds in the aquatic food chains of two subtropical estuaries	NA	10.1016/j.scitotenv.2019.135047	The necessary data to calculate TMF and standard error were not provided.
Perfluorinated alkyl substances in water, sediment, plankton and fish from Korean rivers and lakes: A nationwide survey	2014	10.1016/j.scitotenv.2014.01.045	The necessary data to calculate TMF and standard error were not provided.
Detection of a Cyclic Perfluorinated Acid, Perfluoroethylcyclohexane Sulfonate, in the Great Lakes of North America	2011	10.1021/es200135c	The necessary data to calculate TMF and standard error were not provided.
Dietary exposure and accumulation of per- and polyfluoroalkyl substances alters growth and reduces body condition of post-metamorphic salamanders	NA	10.1016/j.scitotenv.2020.142730	The necessary data to calculate TMF and standard error were not provided.
Ecosystem specific accumulation of organohalogenated compounds: A comparison between adjacent freshwater and terrestrial avian predators	NA	10.1016/j.envres.2022.113455	The necessary data to calculate TMF and standard error were not provided.
Perfluorinated compounds in the Great Lakes	2006	10.1007/698_5_046	Review.
Identification of long-chain perfluorinated acids in biota from the Canadian Arctic	NA	10.1021/es034727+	The necessary data to calculate TMF and standard error were not provided.
Legacy and emerging organohalogenated contaminants in wild edible aquatic organisms: Implications for bioaccumulation and human exposure	NA	10.1016/j.scitotenv.2017.10.296	The necessary data to calculate TMF and standard error were not provided.
Trophic transfer of PFAS from tomato (Solanum lycopersicum) to	2022	10.1016/j.envpol.2022.119814	The necessary data to calculate TMF and standard error were not provided.

tobacco hornworm (Manduca sexta) caterpillars			
Accumulation of perfluorooctane sulfonate (PFOS) in the food chain of the Western Scheldt estuary: Comparing field measurements with kinetic modeling	NA	10.1016/j.chemosphere.2007.08.038	The necessary data to calculate TMF and standard error were not provided.
Perfluoroalkyl substances in freshwater and marine fish from northern Vietnam: Accumulation levels, profiles, and implications for human consumption	2022	10.1016/j.marpolbul.2022.113995	The necessary data to calculate TMF and standard error were not provided.
Perfluoroalkyl substances in the surface water and fishes in Chaohu Lake, China	NA	10.1007/s11356-022-20753-6	The necessary data to calculate TMF and standard error were not provided.
Elevated levels of per- and polyfluoroalkyl substances (PFAS) in freshwater benthic macroinvertebrates from the Hudson River Watershed	2022	10.1016/j.chemosphere.2021.132830	The necessary data to calculate TMF and standard error were not provided.
Spatial (bio)accumulation of pharmaceuticals, illicit drugs, plasticisers, perfluorinated compounds and metabolites in river sediment, aquatic plants and benthic organisms	NA	10.1016/j.envpol.2017.11.090	The necessary data to calculate TMF and standard error were not provided.
Perfluorinated compounds: levels, trophic web enrichments and human dietary intakes in transitional water ecosystems	NA	10.1016/j.marpolbul.2013.09.014	The necessary data to calculate TMF and standard error were not provided.
Targeted PFAS analyses and extractable organofluorine â€“ Enhancing our understanding of the presence of unknown PFAS in Norwegian wildlife	2023	10.1016/j.envint.2022.107640	The necessary data to calculate TMF and standard error were not provided.
Investigation of levels of perfluoroalkyl substances in freshwater fishes collected in a contaminated area of Veneto Region, Italy	2022	10.1007/s11356-021-17236-5	The necessary data to calculate TMF and standard error were not provided.

Point source characterization of per-And polyfluoroalkyl substances (PFASs) and extractable organofluorine (EOF) in freshwater and aquatic invertebrates	2019	10.1039/c9em00281b	The necessary data to calculate TMF and standard error were not provided.
Diet and metabolic state are the main factors determining concentrations of perfluoroalkyl substances in female polar bears from Svalbard	NA	10.1016/j.envpol.2017.04.100	Only one species investigated
Perfluoroalkyl acids in marine organisms from lake Shihwa, Korea	2009	10.1007/s00244-008-9282-7	The necessary data to calculate TMF and standard error were not provided.
Fate of perfluoroalkyl substances within a small stream food web affected by sewage effluent	NA	10.1016/j.watres.2018.01.066	The necessary data to calculate TMF and standard error were not provided.

Other Supplementary Material

Legends for Data S1 - S5:

- Data S1: raw data related to characteristics of the included studies in the meta-analysis
- Data S2: raw data related to parameters of food webs
- Data S3: raw data related to PFAS analytes
- Data S4: quantitative datasets used for effect size calculations
- Data S5: study validity assessment results