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RESEARCH ARTICLE

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A global synthesis of human impacts on the multifunctionality of streams and rivers

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Abstract

Human impacts, particularly nutrient pollution and land-use change, have caused significant declines in the quality and quantity of freshwater resources. Most global assessments have concentrated on species diversity and composition, but effects on the multifunctionality of streams and rivers remain unclear. Here, we analyse the most comprehensive compilation of stream ecosystem functions to date to provide an overview of the responses of nutrient uptake, leaf litter decomposition, ecosystem productivity, and food web complexity to six globally pervasive human stressors. We show that human stressors inhibited ecosystem functioning for most stressor-function pairs. Nitrate uptake efficiency was most affected and was inhibited by 347% due to agriculture. However, concomitant negative and positive effects were common even within a given stressor-function pair. Some part of this variability in effect direction could be explained by the structural heterogeneity of the landscape and latitudinal position of the streams. Ranking human stressors by their absolute effects on ecosystem multifunctionality revealed significant effects for all studied stressors, with wastewater effluents (194%), agriculture (148%), and urban land use (137%) having the strongest effects. Our results demonstrate that we are at risk of losing the functional backbone of streams and rivers if human stressors persist in contemporary intensity, and that freshwaters are losing critical ecosystem services that humans rely on. We advocate for more studies on the effects of multiple stressors on ecosystem multifunctionality to improve the functional understanding of human impacts. Finally, freshwater management must shift its focus toward an ecological function-based approach and needs to develop strategies for maintaining or restoring ecosystem functioning of streams and rivers.

KEYWORDS
food webs, leaf litter decomposition, meta-analysis, multiple stressors, nutrient uptake, secondary production, whole-stream metabolism

1 | INTRODUCTION

The multifaceted nature of global human impacts has given rise to the "Anthropocene," an era in which human activities dominate fundamental processes in ecosystems (Malhi, 2017; Steffen et al., 2007). Streams and rivers are among the most threatened ecosystems globally and face multiple human stressors related to land use and climate change (Albert et al., 2021). Land-use changes, in particular, have often led to increased nutrient inputs from diffuse and point sources, in many cases stimulating freshwater primary production (Bernot et al., 2010) or accelerating the decomposition of organic materials (Woodward et al., 2012). The industrial production and mobilization of nutrients have also amplified global nutrient cycles (Vitousek et al., 1997), and nitrogen loading to streams now generally exceeds the thresholds for preventing widespread eutrophication (de Vries et al., 2013). In addition, changes to flow regimes, loss of active floodplains along river corridors, and ubiquitous channelization have all reduced the hydromorphological complexity of river-floodplain ecosystems, often irreversibly (Grill et al., 2019). As a consequence, there have been significant losses of biodiversity across many biological groups native to streams and rivers (Reid et al., 2019; Su et al., 2021; Vörösmarty et al., 2010), and these losses have a profound influence on ecosystem functions and associated ecosystem services that support humanity (Dudgeon, 2010; Jax, 2005).

Although much is known about individual stressors and their influence on river communities and ecosystem processes, attention is shifting toward understanding the combined or interactive effects of multiple stressors (Sabater et al., 2019). Similarly, there is a new interest in understanding multiple ecosystem functions together, an attribute known as ecosystem multifunctionality (Giling et al., 2019; Manning et al., 2018). Anthropogenic stressors rarely act alone but rather as parts of multiple "stressor ensembles" (Simmons et al., 2021) that may produce unpredictable interactions among stressors as well as unpredictable net responses among ecosystem functions. A given function may respond to different stressors in different directions. For example, mine effluents strongly inhibit leaf litter decomposition rates (Ferreira, Koricheva, Duarte, et al., 2016), while nutrient enrichment stimulates such decomposition (Woodward et al., 2012). Similarly, a given stressor may elicit contrasting responses in different functions, for example, elevated nitrogen concentration may stimulate primary production (Ardón et al., 2021) while reducing nutrient uptake efficiency (Mulholland et al., 2008). Hence, it remains difficult to make general predictions about net responses of ecosystem multifunctionality. In the face of continued anthropogenic global change, a synthetic approach is needed to understand how individual functions and ecosystem multifunctionality respond to individual and combined stressors and the associated loss of biodiversity on a global scale.

Here, we synthesize the responses of food web complexity, leaf litter decomposition, nutrient dynamics, and primary and secondary productivity to six globally important human stressors pervasive in streams and rivers. We first examine how individual ecosystem functions respond to different stressors, characterizing variation in effect size and direction. We then quantify the average response among functions, an absolute value estimate of ecosystem multifunctionality, to each of the six stressors. Our study provides a comprehensive and broad-scale analysis of how stream ecosystem functions respond to different stressors alone and in aggregate. Our results should help stimulating further study of ecosystem multifunctionality in the context of monitoring and managing running waters in the face of global change.

2 | METHODS

2.1 | Literature survey and selection

We conducted a systematic literature survey in electronic reference databases (Google Scholar, Scopus, and Web of Science) for papers published in international, indexed journals that studied the effects of human stressors on running water ecosystem functions. A stressor is a change in environmental conditions that causes a response of an organism, population, or ecosystem (Underwood, 1989). While stressors can be of natural origin, we apply the term to human interventions and their impacts on the functional properties of streams and rivers. Our initial research considered the following stressors: acid mine drainage, acidification, agricultural land use, flow regulation, habitat loss, non-native species, nutrient enrichment, riparian clearcutting, urbanization, and wastewater.

Ecosystem function refers to processes that regulate the fluxes of energy and matter in an ecosystem (Jax, 2005). We considered the following ecosystem attributes in our initial research: retention of dissolved organic carbon (DOC), dissolved organic nitrogen (DON), ammonia, nitrate and soluble reactive phosphorus (SRP), food web complexity, leaf litter decomposition, secondary production and whole-stream metabolism. Pairwise combinations of stressors and functions were used as keywords (e.g., for the pair food web versus agriculture: food web AND [freshwater OR river OR stream] AND [agriculture]. We considered all articles and previous meta-analyses published in English until July 31, 2020. We included primary studies that satisfied the following criteria: (i) they addressed the effect of human stressors on at least one ecosystem function, (ii) they were conducted in the field, that is, streams, rivers, and streamside channels, (iii) they compared at least one reference and one impacted site, and (iv) they reported means, variation, and sample sizes for reference and impacted conditions. We could not obtain uncertainty estimates for 33 of the 288 studies even after contacting the corresponding authors. In such cases, we imputed the standard deviation (*SD*) from similar function-stressor pairs (Lajeunesse, 2013). For studies with estimates from different seasons, seasonal data were pooled as seasonal variation could not be adequately assessed. We included correlative studies if they quantified the response of ecosystem functions along well-defined stressor gradients. In these cases, we considered the minimum values as the reference and the maximum values as the impacted state.

Most studies quantified retention of organic and inorganic nutrients and metabolism with more than one variable, that is, nutrient retention was expressed either as uptake length, uptake rate, or uptake velocity, and ecosystem metabolism was expressed either as gross primary production (GPP), ecosystem respiration (ER), GPP:ER, or as net ecosystem productivity (GPP-ER). We decided to use a single variable for each function that is most representative or commonly used in meta-analyses (Table 2), as our primary aim was to analyse responses across functions and not across variables within functions. However, we acknowledge that comparing the response of individual functional parameters to human stressors may be a fruitful avenue for future meta-analyses. Often, a study quantified ecosystem functions at multiple streams, thus contributing several reference-impacted comparisons to the data set. We did not pool these comparisons for subsequent analyses because their omission would have restricted our analyses. The search and screening produced 288 studies with 1532 effect sizes encompassing eight ecosystem functions and 10 human stressors (Figure S1; Table S1). We tested for publication bias using Rosenberg's fail-safe number, which calculates the number of effect sizes with no significant effect needed to change the model significance (Rosenberg, 2005). If the fail-safe number was large (>5 k +10, where *k* = number of effect sizes), we considered the respective analyses to be robust against publication bias (Nakagawa et al., 2022). Some function-stressors pairs were excluded with fail-safe numbers below this threshold (Figure S1; Table S1). The final data set encompassed 125 studies with 373 effect sizes (Brauns et al., 2022), covering seven functions and six human stressors (see Tables 1 and 2).

2.2 | Statistical analysis

The responses of functions to stressors were calculated as the log-transformed response ratio (log*R*), given by the logarithm of the ratio of

TABLE 1 Definition of stressors analysed in this study

Stressor	Definition
Agriculture	Compound stressor with various individual impacts that often act simultaneously and in opposite directions, for example, pesticide and nutrient inputs, fine sediment inputs, hydromorphological degradation, removal of riparian vegetation
Urbanization	Compound stressor associated with urban development with various individual and often interacting impacts, for example, diffuse inputs from impervious surface areas, high temperatures, riparian clearcutting, hydromorphological degradation, and flashy hydrology
Flow regulation	Encompasses modification of the natural hydrological regime by dams and weirs for hydropower and shipping but also irrigation
Habitat loss	Loss of in-stream habitats such as submerged macrophytes and large woody debris or the replacement of coarse by fine substrates following sedimentation are often associated with human interventions. Studies dealing with stream restoration measures were assigned to this category by treating restored sites as reference and unrestored sites as impact
Nutrient enrichment	Nutrient enrichment refers to increases in dissolved inorganic nitrogen and phosphorus concentrations. Studies on the effects of artificially increased N and/or P concentrations were assigned to this category
Wastewater	Point-source pollution of potentially harmful substances (e.g., pharmaceuticals) and organic and inorganic nutrients and organic carbon from wastewater treatment plants

TABLE 2 Definition of functions and their parameters analysed in this study

Function	Parameter	Definition
Food web complexity	No. of trophic links (L)	Number of interactions between consumers and resources measured by counting all realized trophic links in a food web
Leaf litter decomposition	Decomposition rate (k_{total})	Rate at which leaf litter loses mass due to leaching of soluble compounds, physical effects and the combined activities of microbes and invertebrates
Ammonium uptake efficiency Nitrate uptake efficiency Soluble reactive phosphorus uptake efficiency	Uptake velocity (V_f)	Vertical velocity, measured at stream reach scale, by which dissolved nutrients are removed from the water column and immobilized in particulate form or transformed into gaseous forms
Secondary production	Macroinvertebrate secondary production (P)	Generation of new macroinvertebrate biomass over time
Net ecosystem production	Net ecosystem production (NEP)	Balance between the production (gross primary production; GPP) and respiration (ecosystem respiration, ER) of organic matter calculated as GPP–ER

the mean function in the impacted site to the mean function in the reference site, with a $\log R = 0$ indicating no response. In contrast, $\log R < 0$ and $\log R > 0$ indicate lower or higher ecosystem function in impacted versus reference streams, respectively (Hedges et al., 1999). The variance associated with $\log R$ was calculated using SD and sample size. Effect sizes and variances were calculated using the "escal" function of the "metafor" package (Viechtbauer, 2010) in R (R Core Team, 2022).

We quantified the effects of individual stressors on each function by fitting random-effects models using the "rma.uni" function of the "metafor" package for each stressor-function pair (Viechtbauer, 2010). We used the restricted maximum likelihood estimator to estimate between-study variance and weighted effect sizes by the reciprocal of their corresponding variance. Stressor effects within each function were analysed with random-effects models using stressors as categorical moderators and excluding the intercepts. Models were followed by Tukey honestly significant difference (HSD) multiple comparisons of effect sizes among stressors using the "multcomp" package and P adjustment using the Holms method (Hothorn et al., 2017).

Effects of human stressors on ecosystem functioning may be conditioned by other environmental factors. Meta-analysis tests the significance and the strength of such factors, referred to as environmental moderators, on effect sizes. We included environmental moderators such as geographical location (latitude, longitude), water quality (e.g., nutrient concentrations) and hydromorphological characteristics (e.g., current velocity). A complete description of all moderators and the methods how they were derived are given in Table S2. The role of environmental moderators was evaluated using random-effects meta-regression models (Viechtbauer, 2010). We extracted important moderators using Akaikes' information criterion for small sample sizes (AICc) and the "glmulti" package (Calcagno, 2020). Moderator importance was calculated as the sum of the weights across all possible models in which the moderator appeared. The model with the lowest AICc was chosen as the optimal one. The model improvement was evaluated by comparing residual heterogeneity and heterogeneity due to moderators of models with and without moderators.

We analysed the collective effects of individual stressors across functions considering absolute effect sizes and conducted random-effects meta-analyses with stressors as categorical moderators. The resulting mean effect size across functions for a given stressor represents the average ecosystem multifunctionality (Manning et al., 2018) and was used to rank stressors. We expressed effect sizes as absolute ratios, as we deemed effect magnitude more important than effect direction. Moreover, positive and negative effect sizes for a given stressor would cancel each other out (R ~1) and indicate an insignificant effect even if there is one (type I error). Differences among individual stressors were tested using Tukey HSD multiple comparisons of effect sizes.

To aid comparisons of effect sizes, $\log R$ was back-transformed to achieve proportional response ratios between impacted and reference streams (R). Additionally, response ratios are shown as percentage changes, scaled to be symmetric around zero. The percentage change is naturally asymmetric, with the range of the negative percentage change (−100%–0%) being much smaller than the positive one (0%–∞). Thus, scaled percentage change was calculated as:

$$\text{Scaled}\,\%\,\text{change} = \left(\exp^{|\log R|} \times 100\right) - 100 \times z, \qquad (1)$$

where $z = -1$ if $\log R < 0$ and $z = 1$ if $\log R > 0$.

We ran two sensitivity analyses to examine the extent to which imputing SDs and including non-independent reference-impacted comparisons might have biased our results. We first assessed whether imputing SDs affected effects sizes and their variation by comparing R and 95%CIs between data sets with and without imputations. Concerning the inclusion of non-independent reference-impacted comparisons, we ran the analysis using single effect size and variance per study (calculated as the weighted mean effect size and its weighted variance from reported reference-impacted comparisons) and compared the results (R and 95%CIs) with those obtained using the entire data set.

3 | RESULTS

3.1 | Overview of stressor-function studies

The 125 studies retained for analyses included 373 effect sizes describing the response of seven individual ecosystem functions to six human stressors (Figure 1). The final data set covered 30 countries and 18 climatic regions (Brauns et al., 2022), and the climate space covered by all effect sizes ranged from 228 to 4260 mm in mean annual precipitation and from −12 to 26°C in mean annual temperature. However, most effect sizes were from temperate streams in Europe (42%) and North America (40%). Data scarce regions include the Siberian tundra and the tropics and subtropics of Africa and Asia (Figure 1).

3.2 | Stressor effects on individual functions

Human stressors significantly impacted nine out of 25 stressor-function pairs, and nitrate uptake efficiency exhibited the largest effect sizes of all comparisons and became reduced by, on average, 347% by agriculture (Figure 2; Table S3). Leaf litter decomposition was stimulated by nutrient enrichment (+57%) but inhibited by wastewater effluents (−152%), whereas both stressors significantly stimulated net ecosystem production (Figure 2; Table S3). Nutrient enrichment was the only stressor with consistent effects on all functions and stimulated net ecosystem production (+78%), leaf litter decomposition (+57%), and secondary production (+48%). Habitat loss tended to inhibit all ecosystem functions, but significant effects were found only for food web complexity (−34%) and net ecosystem productivity (−73%). Wastewater effluents stimulated net ecosystem production (+119%) but inhibited leaf litter decomposition (−152%).

Positive and negative effect sizes were common even within individual stressor-function pairs, and there was substantial residual heterogeneity (Table S3), indicating that other environmental factors mediated stressor effects. Meta-regressions with environmental moderators for each stressor-function pair showed that moderators reduced residual heterogeneity from 13% to 98% (median 40%). Forest land use, landscape heterogeneity, and latitude were the most important and significant moderators across all models (Table S5). For example, the latitudinal position of streams determined the effect direction and effects of habitat loss on net ecosystem production, and the response shifted from being inhibited to being stimulated at latitudes >~43°N (Figure S2).

3.3 | Sensitivity analysis

Differences between data sets with and without imputations expressed as scaled percentage change ranged from −118% (food web complexity vs. urbanization) to +42% (SRP uptake efficiency vs. agriculture, Table S6). However, imputations had no significant effect on R as 95% CIs of both data sets overlapped, and significance levels were similar. We deemed the bias induced by imputing *SD* negligible and used the data set with imputed *SD*s for all analyses.

Differences between data sets without and with non-independent reference-impacted comparisons ranged from −136% (nitrate uptake efficiency vs. agriculture) to +16% (net ecosystem production vs. wastewater, Table S7). Not considering non-independent comparisons reduced the number of stressor-function pairs from 25 to 19 and the number of significant effect sizes from nine to four. We attribute these rather substantial effects to the overall low number of reference-impacted comparisons for each stressor-function pair when only one comparison per study is considered.

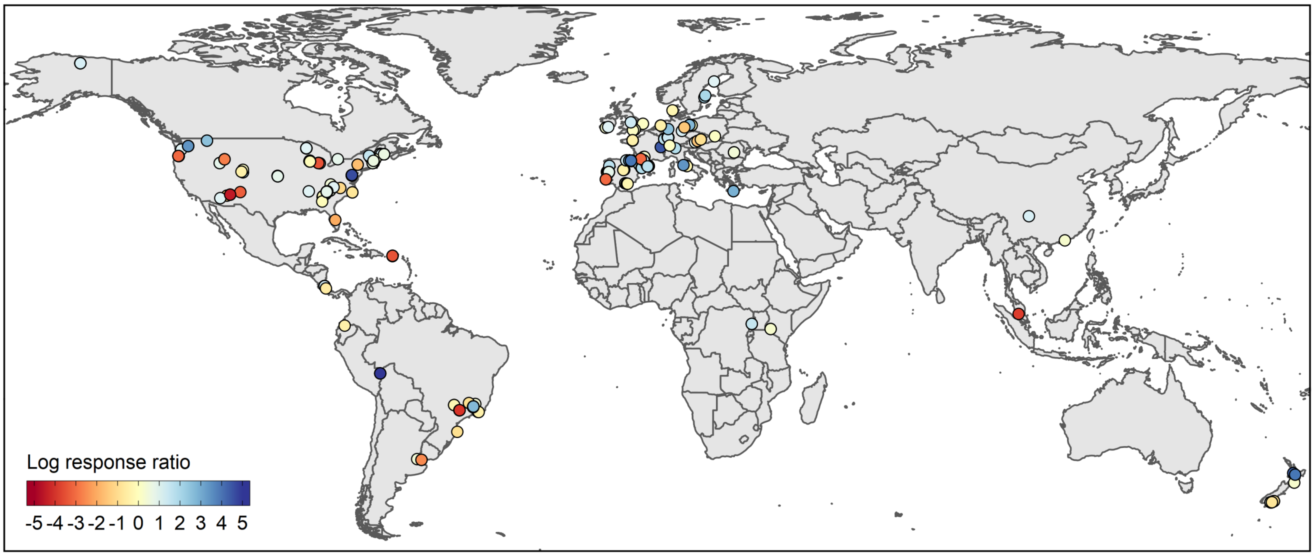

FIGURE 1 Global distribution and extent of 373 effect sizes from the 125 studies on human stressors affecting ecosystem functioning of streams and rivers

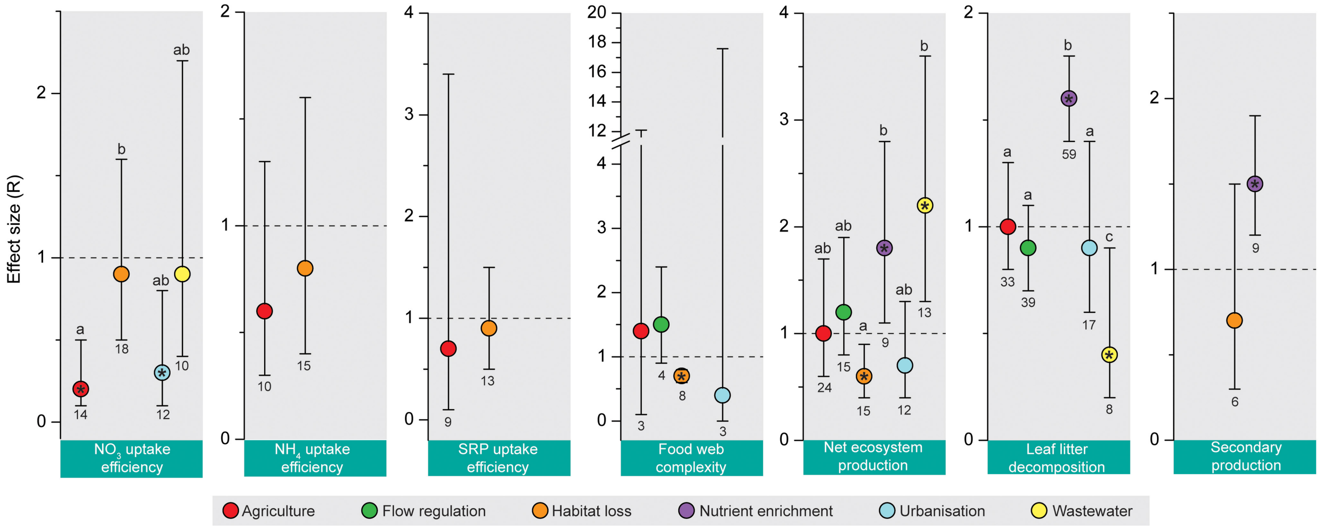

FIGURE 2 Individual responses of ecosystem functions to human stressors. *R* is the effect size calculated as the ratio between impacted and reference streams and presented as means and 95% confidence intervals. The dashed lines ($R = 1$) indicate no response, while $R < 1$ and $R > 1$ indicate that ecosystem functions are lower or higher in impacted than in reference streams, respectively. Asterisks indicate effect sizes significantly different from zero (95% CI does not overlap 1). Different letters indicate significant differences among stressors within ecosystem functions (Tukey honestly significant difference test, $p < .05$), and numbers indicate sample sizes. See Table S3 for the underlying random-effects meta-analyses and Table S4 for pairwise comparisons of effect sizes

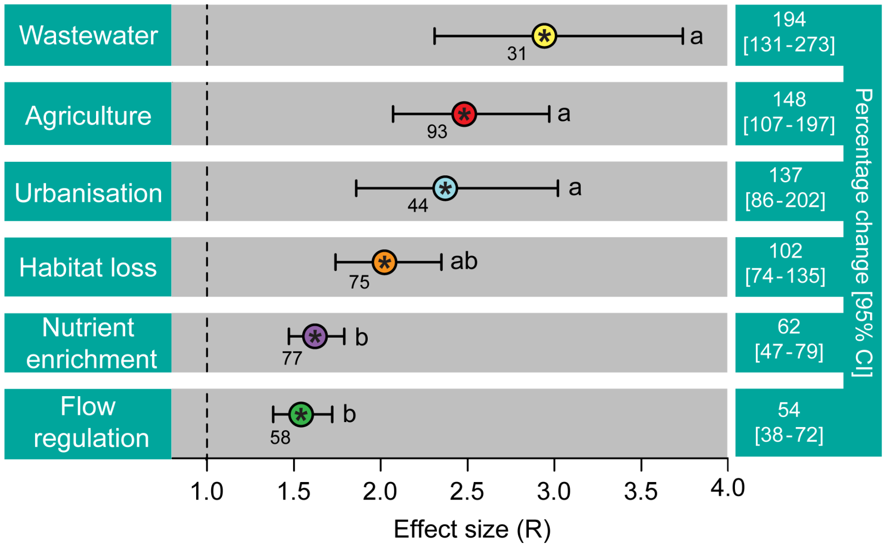

FIGURE 3 Synthesis of the response of ecosystem multifunctionality to individual human stressors. *R* is the effect size calculated as the absolute ratio between impacted and reference streams and presented as the mean (±95% confidence interval) across functions within stressors. Asterisks indicate effect sizes significantly different from zero (95% CI does not overlap 1). Different letters indicate significant differences among stressors (Tukey honestly significant difference test, $p < .05$), and numbers indicate sample sizes

3.4 | Impacts on ecosystem multifunctionality

Averaging the stressor effects across ecosystem functions showed substantial absolute effects of human stressors on ecosystem functions. All effect sizes were significant, and even the least affecting stressor (flow regulation) altered ecosystem function by 54% (Figure 3). However, wastewater effluents, agriculture, and urban land use significantly exceeded the effects of flow regulation by up to four times (Figure 3).

4 | DISCUSSION

Our meta-analysis reveals global-scale patterns of the responses and sensitivities of major ecological functions and multifunctionality to multiple human stressors and their interactions. Most stressors had negative effects consistent with inhibited ecosystem functionality, and impacted streams exhibited reduced nitrate removal efficiency and simplified and less productive food webs. The reduction of nitrate uptake efficiency, in particular, should raise concern, as nitrogen, aside from phosphorus, is primarily responsible for eutrophication and harmful algal blooms (Paerl & Scott, 2010). The remarkable susceptibility of nitrate uptake efficiency to human impacts may be related to saturation effects in response to excessive nitrate loads (Mulholland et al., 2008), where nutrient uptake cannot balance the increase in nutrient delivery to agricultural and urban streams (Beusen et al., 2016). Moreover, nitrate uptake depends on an efficient mass transfer between surface water and reactive streambeds (Grant et al., 2018), which is often reduced in agricultural streams following hydromorphological degradation (Birgand et al., 2007). Our findings on the stimulating effects of nutrient enrichment on ecosystem production and organic matter processing are consistent with a recent meta-analysis that also found an increase in primary production and leaf litter decomposition following experimental nutrient enrichment (Ardón et al., 2021). Although such effects may be expected, the counteracting effects of wastewater as a source of nutrients were surprising. Apparently, the stimulatory effect of wastewater nutrients on leaf litter decomposition, that is, the suppression of nutrient limitation, was counteracted by other wastewater constituents. Modern wastewater treatment facilities efficiently retain nutrients, but effluents can contain significant amounts of toxic compounds (e.g., pesticides, pharmaceuticals; Weitere et al., 2021) that may reduce leaf litter decomposition (Pereda et al., 2021). Alternatively, the reduction in leaf litter decomposition may be attributed to a shift in heterotrophic carbon uptake toward a more easily degradable organic matter of microbial origin associated with wastewater discharge (Chappell & Goulder, 1994; Freixa et al., 2016).

Apart from the significant effects detected, most of the stressor effects on ecosystem functions were not significant. However, this finding does not imply that stressors do not have measurable ecological effects but rather demonstrates a mathematical artefact from positive and negative effects within individual stressor-function pairs that cancel each other out (notice the large 95% CIs that range from $R<1$ to $R>1$, Figure 2). A part of the directional variation and the encountered substantial covariation was explained by forest cover, landscape heterogeneity, and latitude. Effects of latitude have been reported for various ecosystem functions (Patrick et al., 2019; Tiegs et al., 2019) and match with the predictions of the freshwater biome gradient framework, suggesting that global effects of stressors likely depend on regional settings (Dodds et al., 2019). Moreover, the observed effects of landscape heterogeneity and forest cover highlight that, in particular, leaf litter decomposition and nitrate uptake efficiency can be modulated by catchment-related moderators. There is currently not enough data to explain the mechanistic basis for these relationships, but landscape heterogeneity and forest cover usually indicate the presence of a dense riparian canopy, which may shape biological communities involved in organic matter and nitrogen cycling.

Our study provides the first assessment of how the multifunctionality of streams and rivers responds to multiple anthropogenic stressors. We acknowledge that average effects across functions depend on the type of stressor and the number of individual effect sizes included and may change as new studies become available. For instance, previous meta-analyses showed that acid mine drainage and introductions of non-native plant species reduce litter decomposition by up to 125% (Ferreira, Koricheva, Duarte, et al., 2016; Ferreira, Koricheva, Pozo, et al., 2016), and the inclusion of such stressors may have increased effect sizes. Moreover, we could not include DOC and DON uptake efficiencies as there was not enough data for analysis. More studies are needed that evaluate the responses of DOC and DON uptake to anthropogenic stressors because human stressors may severely impact dissolved organic matter processing (Graeber et al., 2015, 2019) and alter the role of streams in the global carbon cycle (Xenopoulos et al., 2021).

Our meta-analysis also revealed the importance of a regional setting in understanding ecosystems' functional responses to stressors. Streams and rivers in the Siberian tundra and the tropics and subtropics of Africa and Asia are underrepresented not only in terms of data on ecosystem functioning but also in aspects of biodiversity (Abell et al., 2008; Sundar et al., 2020). Given this realization, more data from these regions are necessary to improve the global perspective. We advocate for increasing efforts to understand the role humans play for ecosystem functioning, given the ongoing land-use change in these regions (Scholes & Biggs, 2005; Zhao et al., 2006).

4.1 | Implications for management

Our synthesis shows that human stressors impact individual functions and multifunctionality as much as they impact freshwater biodiversity (Jackson et al., 2016; Murphy & Romanuk, 2014; Sabater et al., 2018), underscoring the necessity to monitor the functional status of streams and rivers. However, freshwater management is ill-adapted to this challenge as biomonitoring, and bioassessment approaches in freshwater ecosystems focus on measuring the impacts of human stressors on ecosystem structure. For example, metrics describing biodiversity and community composition are routinely used worldwide for ecological status assessment in streams and rivers (Hering et al., 2006; Lenat, 1988). Such point-in-time measurements are not suited for assessing ecosystem processes, and there have been repeated calls to integrate indicators of ecosystem function into freshwater management (Ferreira et al., 2020; Jankowski et al., 2021; Palmer & Febria, 2012; Palmer & Ruhi, 2019).

Our synthesis revealed four key issues that should be addressed in future studies to facilitate the transfer of indicators of ecosystem functioning into freshwater management. First, we need more empirical data on the responses of ecosystem functions to stressors, including the mechanisms by which single and multiple drivers affect functions. This pertains particularly to compound stressors such as agricultural land use, as examined here. The database underlying our synthesis is not suited for systematically quantifying whether multiple stressors have additive or non-additive effects on ecosystem function or multifunctionality, as not all stressors and functions were quantified in each stream. However, we showed that the multifunctional effects of agricultural land use were larger than the combined effects of flow regulation and nutrient enrichment. Syntheses on multiple stressor effects on stream functioning are not yet available, but two experimental studies demonstrated that leaf litter decomposition could show additive (Piggott et al., 2015) but also non-additive effects (Ferreira & Chauvet, 2011) when two stressors were altered simultaneously. Although we are beginning to understand how multiple interacting stressors affect stream functioning, more direct evidence is needed to demonstrate whether additive or non-additive effects prevail and to better understand the responses of stream multifunctionality.

Second, future studies should rank individual responses to stressors to provide robust suggestions for functional indicators suitable for assessment. Our synthesis shows that metrics describing nutrient retention hold much promise as indicators, but the suitability of other functional metrics needs to be re-evaluated as soon as more data is available.

Third, we need a standardized definition of the functional reference that marks the status in the absence of any human stressor. Most meta-analyses, including ours, have used local reference sites as suggested by the individual studies underlying the analyses. Those sites are typically characterised by the absence of the particular stressor being studied, but sites are not necessarily in a pristine state. For example, the effects of wastewater are commonly quantified by analysing ecosystem functioning upstream and downstream of a wastewater treatment plant. While upstream reaches are not subjected to the stressor being studied and serve as the reference, they are often located in rural or even urban areas (e.g., Gücker et al., 2006). Hence, the effect size of wastewater, and potentially other stressors, may depend on the deviation of the reference site from pristine conditions, and averaging studies with different reference conditions may induce additional variation of stressor effect sizes. Moreover, we showed that stressors act within regional settings, which requires analyses on whether reference conditions differ with, for example, biome. So far, only two studies are available that set regional reference conditions for leaf litter decomposition (Gessner & Chauvet, 2002) and ecosystem metabolism (Young et al., 2008). A classification of near-natural streams and rivers based on the analysis of existing data (Bernhardt et al., 2018) or large-scaled coordinated field experiments (Tiegs et al., 2019) are promising strategies to establish regional reference conditions for ecosystem functions.

Finally, we need robust and potentially regional definitions of desirable levels of ecosystem functioning and whether environmental thresholds delineate their transitions. The magnitude of stressor effects is typically assessed as a significant deviation of impaired from reference conditions, i.e., effect sizes exceeding or falling below a statistical threshold ($R<$ or $R>1$). Such statistical thresholds are suitable for testing significant effects, but a significant statistical effect does not necessarily imply a significant ecological effect. Ecological thresholds or tipping points are a promising management tool because their identification might allow pre-emptive actions to prevent an ecosystem from moving to an alternate state (Dodds et al., 2010).

However, the existence of ecological thresholds (Groffman et al., 2012) or their detectability from empirical data (Hillebrand et al., 2020) is critically debated. As long as ecological thresholds remain unavailable, freshwater management needs to set ecologically accepted levels for a given function. It is currently unclear if this will be possible for all stream functions, but approaches that establish thresholds between "good" and "poor" ecosystem health (Gessner & Chauvet, 2002; Young et al., 2008) or that set thresholds for pesticides (Schäfer et al., 2012; Wijngaarden et al., 2005) may guide this process.

To conclude, more emphasis should be placed on the effects of multiple interacting stressors on individual functions and multifunctionality. We show here that compound stressors such as wastewater effluents produce functional impacts that are not just the sum of the impacts of the individual stressors but that non-additive stressor interactions impede the understanding and prediction of ecosystem responses. We advocate for field and experimental studies along stressor gradients as well as multifactorial experiments to disentangle the unique and interactive effects of multiple stressors. Combining these key issues into a functional approach to managing streams and rivers may help attenuate the impacts that humans have on ecosystem processes.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Dryad (https://doi.org/10.5061/dryad.8pk0p2nqh) and in Supporting Information of this article.

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