Received: 19 January 2020 | Accepted: 10 July 2020

DOI: 10.1111/1365-2656.13329

REVIEW

Journal of Animal Ecology | BRITISH ECOLOGICAL SOCIETY

Negative effect of turbidity on prey capture for both visual and non-visual aquatic predators

Jean C. G. Ortega[1] | Bruno R. S. Figueiredo[2] | Weferson J. da Graça[3,4] | Angelo A. Agostinho[3,4] | Luis M. Bini[5]

[1]Programa de Pós-Graduação em Ecologia e Evolução, Universidade Federal de Goiás, Goiânia, Brazil

[2]Departamento de Ecologia e Zoologia, Universidade Federal de Santa Catarina, Florianópolis, Brazil

[3]Núcleo de Pesquisas em Limnologia, Ictiologia e Aquicultura, Universidade Estadual de Maringá, Maringá, Brazil

[4]Programa de Pós-Graduação em Ecologia de Ambientes Aquáticos Continentais, Universidade Estadual de Maringá, Maringá, Brazil

[5]Departamento de Ecologia, Universidade Federal de Goiás, Goiânia, Brazil

Correspondence
Jean C. G. Ortega
Email: ortegajean@gmail.com

Present address
Jean C. G. Ortega, Programa de Pós-Graduação em Ecologia e Manejo de Recursos Naturais, Universidade Federal do Acre, Campus Universitário, Rio Branco, AC, 69915-900, Brazil

Funding information
Conselho Nacional de Desenvolvimento Científico e Tecnológico

Handling Editor: Eoin O'Gorman

Abstract

1. Turbidity plays an important role in aquatic predator–prey interactions. Increases in turbidity are expected to reduce prey capture rates, especially for visually oriented predators. However, there is also evidence indicating that turbidity may have little or no effect on predation rates.
2. Here, we conducted a systematic review and meta-analysis of the relationship between turbidity and capture rate. We explored possible sources of heterogeneity in the effect sizes (capture strategy, predator's body size, relative eye size and turbidity range in the experiments) while controlling for the dependence among effects sizes and phylogenetic relationships among predator species.
3. We found a consistent negative effect of turbidity on prey capture and that turbidity range (manipulated in the experiments) was the main factor accounting for between-study variation in effect sizes. Also, capture rates of both visually and non-visually oriented predators decreased with an increase in turbidity. In addition, for visually oriented fish predators, the relative eye size did not influence the effect sizes.
4. Despite the paucity of studies for some groups of aquatic predators (mainly in tropical regions), we provide corroborative evidence that turbidity is a critical environmental factor controlling predator–prey interactions. This result is especially relevant considering that changes in turbidity is a human-induced pervasive environmental alteration resulted from, among other mechanisms, runoff after deforestation, eutrophication or oligotrophication in reservoir cascades, which imply changes in predator–prey interactions.

KEYWORDS

freshwater, marine, meta-analysis, predation, predator–prey interactions, water transparency

1 | INTRODUCTION

The outcome of interactions between predators and prey can shape the structure of an entire community, influencing species composition, size structure and spatial distribution (Englund, Johansson, Olofsson, Salonsaari, & Öhman, 2009; Hall, Threlkeld, Burns, & Crowley, 1976; Orrock et al., 2008). The introduction of top predators can lead to massive declines in prey species diversity (Pelicice & Agostinho, 2009; Pelicice, Latini, & Agostinho, 2015; Sharpe, Léon, González, & Torchin, 2017), which may remain low for decades (Sharpe et al., 2017). Predation does not only influence the populations of interacting species but it can also affect other organisms in different trophic levels of a community (Carpenter, Kitchell, & Hodgson, 1985; Ripple & Beschta, 2012). For example,

the reintroduction of grey wolves *Canis lupus* into Yellowstone National Park-USA decreased the population size of elks *Cervus elaphus*, which reduced the grazing pressure on cottonwoods *Populus* spp. and willows *Salix* spp. (Ripple & Beschta, 2012).

The effect of predation on a community is mainly driven by the ability of predators and prey detect to each other (Thetmeyer & Kils, 1995). Being the first to detect provides an advantage either to predator to eat (Lima & Dill, 1990; Rodríguez & Lewis, 1997) or prey to escape (Chacin & Stallings, 2016; Green, Blumstein, & Fong, 2015). Therefore, environmental factors that hamper the detection of both predator and prey, such as presence and quantity of refuges or low light availability, have a strong influence on the outcome of interactions between predators and prey (Abrahams & Kattenfeld, 1997; Chacin & Stallings, 2016; Gregor & Anderson, 2016; Hansen & Beauchamp, 2015; Schwalbe & Webb, 2015; VanLandeghem, Carrey, & Wahl, 2011).

In aquatic systems, underwater light availability decreases as turbidity increases (Anthony, Ridd, Orpin, Larcombe, & Lough, 2004; Davies-Colley & Nagels, 2008). Increased turbidity is often a result of increased concentration of suspended particles (Davies-Colley & Nagels, 2008; Nieman, Oppliger, McElwain, & Gray, 2018). Increased turbidity decreases the ability of visually oriented predators to see their prey (Higham, Stewart, & Wainwright, 2015; Ranåker, Nilsson, & Brönmark, 2012; Sweka & Hartman, 2003; Turesson & Brönmark, 2007), which negatively influences their prey consumption (Figueiredo et al., 2019; Sweka & Hartman, 2003). The reduced efficiency in capturing prey in turbid waters of visually oriented predators may even result in their low abundance and local extinction (dos Santos et al., 2017; Manning, Mayer, Bossenbroek, & Tyson, 2013; Tejerina-Garro, Fortin, & Rodríguez, 1998). Hence, traits that attenuate the impact of turbidity on prey capture, such as big eyes, can be favoured by natural selection (Caves, Sutton, & Johnsen, 2017; Nilsson, Warrant, & Johnsen, 2014). Moreover, some predator species can use chemical (Liao & Chang, 2003; Webster, Atton, Ward, & Hart, 2007) and mechanical cues to find their prey (Janssen & Corcoran, 1993; Junges, Lajmanovich, Peltzer, Attademo, & Bassó, 2010; Liao & Chang, 2003). Therefore, non-visual predators are less likely to be affected by increases in turbidity than visual predators (as demonstrated by Eiane, Aksnes, Bagøien, & Kaartvedt, 1999; Lunt & Smee, 2015).

Although a negative relationship between turbidity and predation rate is intuitive, there are also studies indicating that turbidity has little or no effect on predation rates of both visually (e.g. Figueiredo, Mormul, & Benedito, 2015) and non-visually oriented predators (e.g. Ohata, Masuda, Ueno, Fukushini, & Yamashita, 2011). This lack of effect may be associated with habitat characteristics, such as refuge availability (Figueiredo et al., 2015; Gregor & Anderson, 2016), or with the sensory compensation of predators, which perceive non-visual cues more efficiently in the absence of visual information (Hartman & Abrahams, 2000). Understanding the causes of discrepancies between studies that evaluated the effect of turbidity on predation rates allows to determine whether hypotheses related to the environmental effects (Chacin & Stallings, 2016) or presence of prey refuges (Figueiredo et al., 2015; Gregor & Anderson, 2016) are more plausible explanations of why prey capture rates differ between aquatic predators. This is especially important because the predicted increase in extreme events of rainfall due to global changes may increase the flow of terrestrial material into aquatic systems (Weyhenmeyer, Muller, Norman, & Tranvik, 2016) and the turbidity of aquatic bodies (Graneli, 2012; IPCC, 2014; van der Sluijs et al., 2011). The increase in extreme climatic events such as heavy precipitation and wind storms may also resuspend the sediment, increasing inorganic and organic turbidity (Cózar, Gálvez, Hull, García, & Loiselle, 2005; Schälchli, 1992). On the other hand, habitat changes, such as reservoir construction decreases turbidity level by transforming a lotic into a lentic environment with low flow (a process known as oligotrophication; Barbosa, Padisák, Espíndola, Borics, & Rocha, 1999; dos Santos et al., 2017; Roberto, Santana, & Thomaz, 2009). Previous meta-analyses assessed the effect of human disturbances, specifically siltation (Chapman et al., 2014) and sediment dredging (Wenger et al., 2017) which increased turbidity. Both these meta-analyses observed a reduction in many population parameters, including reproduction, survival and feeding behaviour (Chapman et al., 2014; Wenger et al., 2017). However, they did not explore the potential causes of variation in the results (i.e. heterogeneity). Thus, quantifying the effect of turbidity on the capture rate of aquatic predators and assessing potential reasons of variation of turbidity effect between studies can help in the construction of more realistic models that seek to predict how increased turbidity will affect aquatic communities (Evans, 2012).

Here, we conducted a meta-analysis to test whether increased turbidity negatively affects the prey capture rate. We expected that (a) the relationship between turbidity and prey capture rate would be negative and (b) more pronounced for visually oriented species than for those that do not primarily use vision to detect their prey (e.g. species guided by chemical or tactile stimulus). We also expect that (c) the magnitude of the negative relationship between turbidity and prey capture rate would decrease with the size of the eye in visually oriented predators. Also, considering that different studies often differ in relevant ecological characteristics, especially in the predator and prey identity, their body sizes and the range of turbidity manipulated in experiments, we assessed whether such ecological characteristics influence the turbidity–prey capture rate relationship.

2 | MATERIALS AND METHODS

2.1 | Search strategy

We performed a systematic search on the Web of Science database, Scopus and Google Scholar on 31 January 2018, using the following set of keywords and Boolean operators: ('predation rate*' OR 'consumpt* rate*' OR 'ingest* rate*' OR 'forag* success') AND ('turbidit*' OR 'transparen*' OR 'sediment*'). The systematic search was performed in the 'topic' field in Web of Science. In Scopus, the search was restricted to the document type 'Article' and to the subject area 'Agricultural and Biological Sciences' on 'Title, Abstract and

keywords'. Google Scholar search involved the use of a single combination of each keyword relating predation to turbidity with singular terms in the Scholar Google. For instance, 'predation rate, turbidity', 'predation rate, sediment' or 'foraging success, transparency'.

We found 1995 studies using our search queries and after screening studies included in two related meta-analyses (i.e. Chapman et al., 2014; Wenger et al., 2017; Figure 1a). We evaluated the abstract of 1,319 studies, after deleting the duplicates. We excluded 1,191 studies which were (a) out of the scope of our meta-analysis, (b) not published in English, Spanish or Portuguese (language restrictions) or (c) did not present enough data (Figure 1b). Then, we evaluated the full text of the remaining 128 studies. After this step, we excluded 68 studies because, among other reasons, they were out of the scope of the meta-analysis or they did not present enough data (even after contacting the corresponding authors; Figure 1b). We also did not consider studies that measure predation rates on frozen, dead or artificial food.

We considered as predation the consumption (and death) of a prey individual. The included studies measured capture rates of both unicellular (e.g. Jones, Carrasco, & Perissinotto, 2015) and larger prey species (e.g. invertebrates and fishes; see Abrahams, Bassett, & Montgomery, 2017; Shoup & Lane, 2015, respectively).

2.2 | Data compilation

We compiled information on sample size, measures of central tendency (mean and median) and dispersion (standard deviation, standard error, range and confidence intervals) in studies comparing a control group to one or more experimental groups. Examples of such studies were experiments that measured predation rates in clear and turbid sample units (e.g. Helenius, Borg, Nurminen, Leskinen, & Lehtonen, 2013). From studies that assessed the relationship between turbidity and predation rates using turbidity as a continuous variable (e.g. Figueiredo et al., 2015; Sweka & Hartman, 2003), we compiled information on sample size and the correlation measure (Pearson correlations and coefficients of determination).

From each study, we recorded predator and prey species identities. Then, based on the literature, we recorded whether the predator species is mainly guided by visual or non-visual cues (Supporting Information S1; Ortega, Figueiredo, da Graça, Agostinho, & Bini, 2020). We compiled the size of the eye of visually oriented predators (eye diameter in relation to total body length; only for fish species) by photos available in technical reports (Hardie, 2003), articles (Benine, Mariguela, & Oliveira, 2009) and the FishBase repository (Froese & Pauly, 2017). We also recorded the average size (in cm) of the predators and the range of turbidity (in nephelometric units; NTU) manipulated in each experiment.

2.3 | Data analysis

Thirteen studies reported Pearson correlation coefficients (*r*). For these studies, we calculated Fisher's *z* as a measure of effect size (Borenstein, Hedges, Higgins, & Rothstein, 2009). Negative *z* values indicate that predation rates in turbid conditions (treatment) are

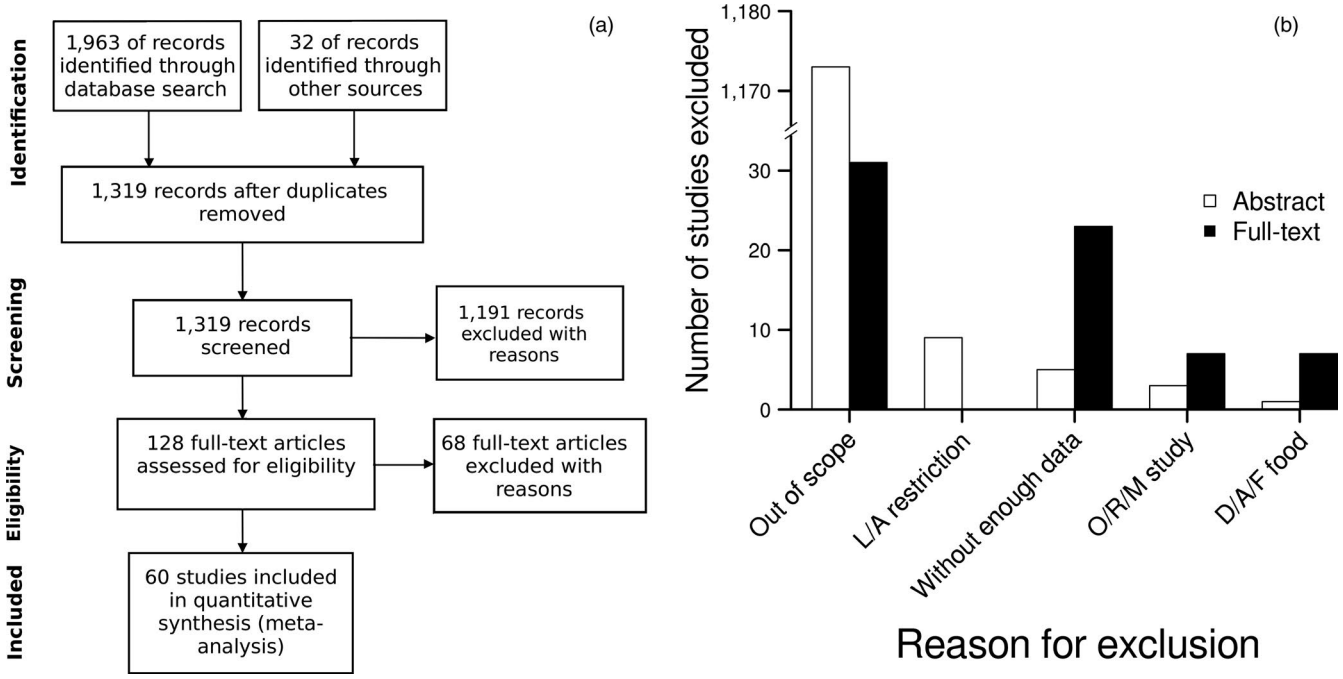

FIGURE 1 Summary of studies' inclusion and exclusion stages. Preferred reporting items for systematic reviews and meta-analyses (PRISMA; Moher, Liberati, Tetzlaff, Altman, & The PRISMA Group, 2009) diagram (a). Other sources were two reviews on turbidity or sediment impacts on aquatic biota found in the systematic search. Reasons for exclusion of articles during the screening of abstracts and full texts (b). L/A: language/accessibility restriction; O/R/M: observational/review/modelling study; D/A/F: dead/artificial/frozen food

lower than in clear waters (control) or that as turbidity increases, predation rates are reduced. For 44 two-group studies, we calculated Cohen's *d* and then transformed to *z*, following Borenstein et al. (2009). Thrity-two of these two-group studies presented standard-error and one study presented 95% confidence interval which we converted to standard deviation following Lajeunesse (2013) prior to *d* estimate. Three of the two-group studies presented medians and ranges in prey capture rates for controls and treatments. In these cases, we estimated the means and standard deviations for controls and treatments (following Hozo, Djulbegovic, & Hozo, 2005), estimated *d* and finally converted these values to *z*. Two of the two-group studies reported *t* and *F* values which were converted to *d* following Lajeunesse (2013). For two studies that measured prey survival rather than predator capture rates, we inverted the sign of the relationship by multiplying the *z* value by −1.

We estimated an accumulated effect size using a multilevel random-effects meta-analysis (Borenstein et al., 2009; Nakagawa & Santos, 2012). We controlled the dependence between effect sizes using a random-effect term coding each study (Nakagawa & Santos, 2012). Dependent effect sizes are multiple effect sizes reported in the same study (Tanner-Smith & Tipton, 2014) which occurred because some studies compared different treatment levels to the same control or because they measured the response variable separately for different taxonomic groups. The use of correlated effects sizes as 'independent' data violates the assumption of independence between observations and artificially inflates the sample size of a meta-analysis (Noble, Lagisz, O'Dea, & Nakagawa, 2017).

We also tested for phylogenetic dependence in effect sizes using two methods. First, we calculated a mean effect size by species of predator, and then estimated the Pagel's λ statistic of phylogenetic signal (Münkemüller et al., 2012). We used 999 random permutations to test the Pagel's λ. Second, we controlled for phylogenetic dependencies when calculating an accumulated effect size (and its variance) in the multilevel random-effects model using a phylogenetic covariance matrix (Lajeunesse, 2009). We estimated the phylogenetic covariance matrix using a phylogeny grouping all species of predators found in the selected studies for the meta-analysis. We constructed a backbone phylogenetic hypothesis for large groups of aquatic predators (phylum, subphylum and class, such as Arthropoda, Crustacea, Vertebrata, Malacostraca, Chordata, Actinopterygii; e.g. Betancur-R et al., 2013, 2017; Nielsen, 2012). We also used phylogenetic hypotheses at the family and genus levels to determine finer relationships (Betancur-R et al., 2013, 2017; Cretê-Lafrenière, Weir, & Bernatchez, 2012; Waters, López, & Wallis, 2000). Although Pagel's λ statistic indicated that there is no phylogenetic signal in the mean effects sizes per species ($\lambda = 0.0$; $p = 1.00$), a model including the predator phylogeny as a random effect showed a lower Akaike information criterion (AIC = 658.31) than a model without phylogeny (AIC = 671.12; see Burnham & Anderson, 2002). Thus, we based our inferences on the multilevel random-effects meta-analysis including the phylogeny.

We estimated the variance of true effect sizes (T^2_{total}) and the proportion of this variance (I^2_{total}) that can potentially be explained by study-level explanatory variables (or moderators; see Borenstein et al., 2009; Borenstein, Higgins, Hedges, & Rothstein, 2017). We used the equations of Nakagawa and Santos (2012) to partition the heterogeneity between effect sizes (T^2_{total} and I^2_{total}) into heterogeneity between studies ($T^2_{between\ studies}$ and $I^2_{between\ studies}$), heterogeneity at the level of studies ($T^2_{study\ level}$ and $I^2_{study\ level}$) and heterogeneity due to phylogenetic effects ($T^2_{phylogeny}$ and $I^2_{phylogeny}$).

We explored the heterogeneity in effect sizes using subgroup and meta-regression analyses. All subgroup and meta-regressions consisted of multilevel random-effects analyses with control for correlated effects size and phylogenetic effects (Nakagawa & Santos, 2012). First, we used a subgroup analysis (Borenstein et al., 2009) to assess whether effects sizes vary between groups of predators (two levels: 'visual' and 'non-visual'). Second, we used a meta-regression (Borenstein et al., 2009) to assess whether effect sizes varied with predator eye size. In this meta-regression, we used only data from visually oriented predators. Eye size relative to body size was transformed by natural logarithm to linearize the relationship. Finally, we explored the influence of mean predator body size and range of manipulated turbidity on the variation of effect sizes with a meta-regression. We log-transformed the mean predator body size and the range in turbidity to increase the linearity of the relationships.

We evaluated publication bias using the Orwin fail-safe number (OFSN; Orwin, 1983), the Egger regression (Egger, Smith, Schneider, & Minder, 1997; Viechtbauer, 2010) and the trim-and-fill procedure (Duval & Tweedie, 2000). The OFSN estimates how many studies with effect sizes equal to zero are needed to reduce the observed (unweighted) mean effect size for a given target value deemed as unimportant (Orwin, 1983). We used as target values effect sizes equal to 50%, 25% and 10% of the observed effect size. The Egger regression consists of a regression between the effect size divided by its variance and a measure of its precision (Egger et al., 1997; Sterne & Egger, 2005). In the presence of funnel plot asymmetry (suggesting bias), the intercept of this regression will be different from zero (Sterne & Egger, 2005). We used a meta-analytic model and the effect size variance as the precision measure for Egger regression. The trim-and-fill procedure is an iterative method where the most imprecise effect sizes are removed until a funnel-plot reaches symmetry (Borenstein et al., 2009; Duval & Tweedie, 2000). Then, the imprecise effect sizes are returned to the funnel-plot with their mirror values (effect sizes of the same magnitude but with the opposite signals), and the cumulative effect size is recalculated. The number of mirror effect sizes is the estimate of potentially omitted studies due to publication bias (Borenstein et al., 2009; Duval & Tweedie, 2000). To accommodate the lack of independence due to the presence of correlated effect sizes, we estimated the OFSN, Egger regression and trim-and-fill procedure with (a) mean effect sizes and variance by study and (b) by resampling (999 times) one effect size and its variance per study (Ortega, Thomaz, & Bini, 2018).

We performed all the analyses in the R software (R Core Team, 2018) using the METAFOR package (Viechtbauer, 2010), APE (Paradis, Claude, & Strimmer, 2004) and PHYTOOLS (Revell, 2012). We used the METAGEAR package (Lajeunesse, 2016) to download '.pdf' files

and METADIGITISE (Pick, Nakagawa, & Noble, 2019) to extract effect sizes from figures. We used a significance level of 5% for all analyses.

3 | RESULTS

Most of the studies analysed were developed in the Northern Hemisphere, mainly in North America and Northern Europe (Figure 2). Some experiments were also carried out in South America, Africa and Oceania. The studies included in our meta-analysis used 56 species, including fish (48 species), crustaceans (seven species) and bivalves (one species; Figure 3). Three field experiments did not specify the predator species, identifying the predator as a fish or decapods only.

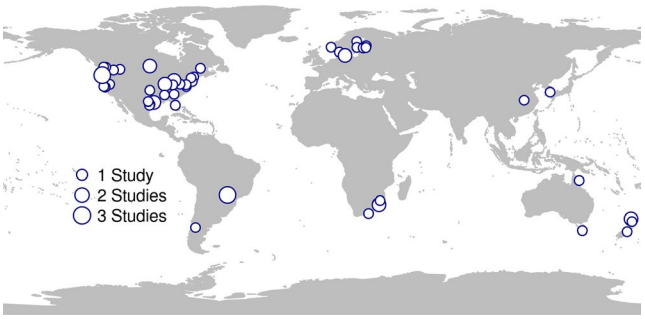

FIGURE 2 Global distribution of the experiments evaluating the effect of turbidity on prey capture rates included in the meta-analysis

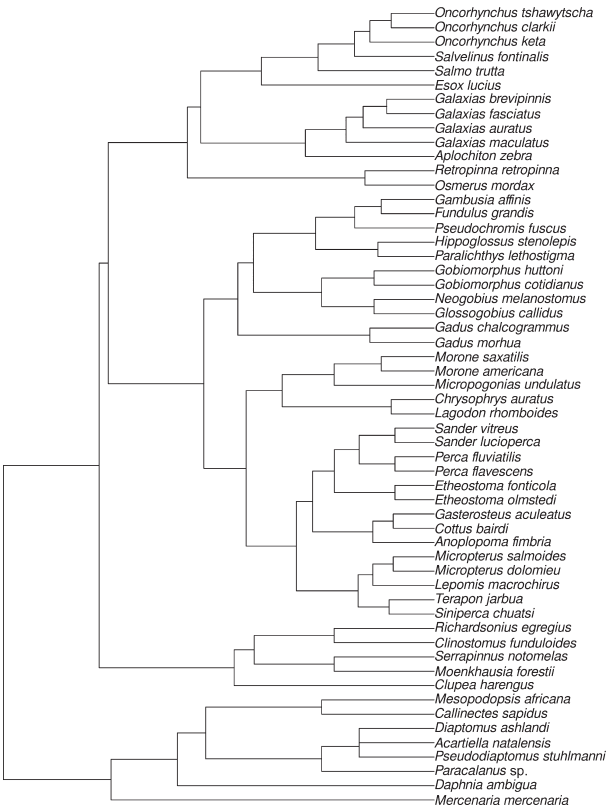

FIGURE 3 Putative phylogenetic relationships of the predator species used in the experiments included in the meta-analysis

We estimated 657 effect sizes from 60 studies. Effect sizes measuring the relationship between turbidity and prey capture rate varied from −2.45 to 1.19. Among all 657 effect sizes, 31 were positive, 313 were negative and 313 were not significant (i.e. with 95% confidence intervals (CI_{95}) overlapping zero; Figure 4). We estimated a negative and significant effect of turbidity on prey capture rate (weighted Fisher's $z \pm CI_{95} = -0.37 \pm 0.13$; $t = -5.38$; number of studies (k) = 60; $p < 0.01$; Figure 4). In addition, we found a significant heterogeneity among the effect sizes ($T^2_{\text{between studies}} = 0.10$; $T^2_{\text{study level}} = 0.07$; $T^2_{\text{phylogeny}} = 0.01$; $Q = 11{,}294.05$; $df = 650$; $p < 0.01$). According to the I^2 statistic, approximately 99.6% (I^2_{total}) of the total heterogeneity can potentially be explained by moderators. Differences between studies ($I^2_{\text{between studies}}$), between effect sizes within studies ($I^2_{\text{study level}}$) and due to phylogenetic effects ($I^2_{\text{phylogeny}}$) accounted for 56.1%, 39.3% and 4.2% of the total heterogeneity, respectively.

We did not find a significant difference in effect sizes between visually oriented and non-visually oriented predators ($F_{1,550} = 1.52$; $k = 49$; $p = 0.22$), indicating that both groups of predators had a reduction in the prey capture rate in environments with higher turbidity. Also, for visually oriented fish predators, the relative eye size did not relate to the effect sizes ($F_{1,483} = 1.68$; $k = 46$; $p = 0.20$).

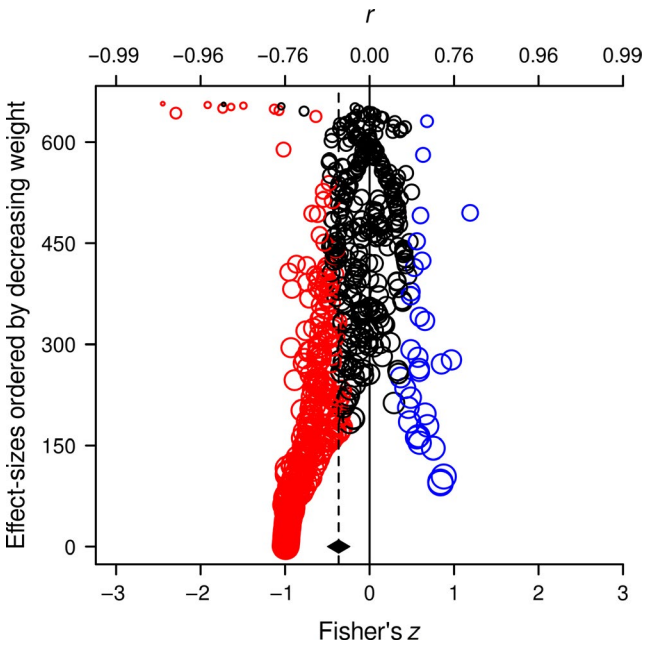

FIGURE 4 Variation of the relationship between turbidity and prey capture rate among the studies (Fisher's z). Dashed and continuous vertical lines indicate the cumulative (weighted) effect size and an effect size equal to zero, respectively. The closed diamond indicates the cumulative effect size and its 95% confidence interval (CI_{95}). Circles in red, blue and black indicate negative, positive and non-significant effect sizes, respectively. The size of the circles indicates the weight of each effect size for the estimate of the cumulative effect size. The second x-axis at the top of the figure indicates Fisher's z values transformed to the correlation (Pearson's r) scale for comparison purposes

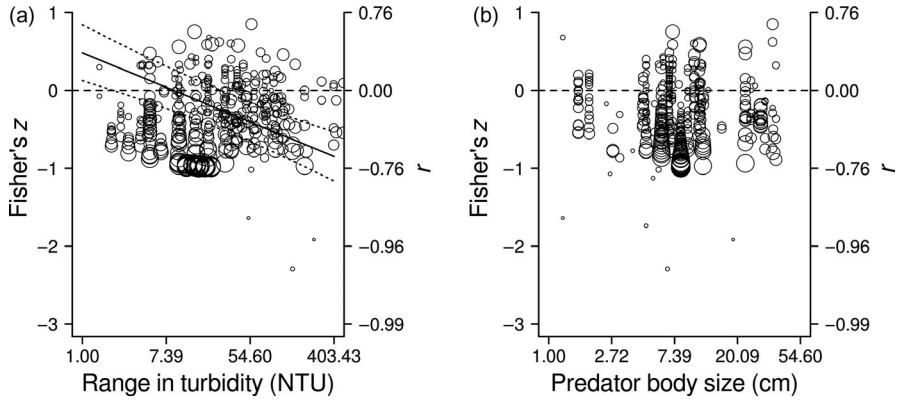

FIGURE 5 Variation of the relationship between turbidity and prey capture rate (Fisher's *z*) in relation to the range of manipulated turbidity (a) and to predator body size (b). The continuous line indicates the values predicted by the meta-regression model and the dotted lines denote the 95% confidence interval of the predicted values. The horizontal dashed line indicates an effect size equal to zero. The size of the circles indicates the weight of each effect size to parameters estimate. The second *y*-axis to the right of figures indicates the correlation (Pearson's *r*). Note the natural logarithm scale in the *x*-axis

TABLE 1 Analysis of publication bias. Number of studies potentially omitted and the cumulative effect size estimated by the trim-and-fill procedure. OFSN: Orwin's fail-safe number. $OFSN_{1/2}$: number of studies required for a 50% reduction in observed effect size; $OFSN_{1/4}$: reduction to 25% of observed effect size; $OFSN_{1/10}$: reduction to 10% of observed effect size

Method	Parameter	Estimate	Measure of dispersion
Mean	Number of studies omitted	0	4.49[a]
	Cumulative effect size	−0.31	0.11[b]
	$OFSN_{1/2}$	60	
	$OFSN_{1/4}$	179	
	$OFSN_{1/10}$	537	
	Egger intercept	−2.84	
	Egger *p* value	0.01	
Resampling	Number of studies omitted	3.06	4.63[a]
	Cumulative effect size	−0.34	0.13[b]
	$OFSN_{1/2}$	46.81	16.54[c]
	$OFSN_{1/4}$	153.08	33.12[c]
	$OFSN_{1/10}$	471.95	82.79[c]
	Egger intercept	−0.93	0.66[c]
	Egger *p* value	0.40	0.27

[a]Standard error.

[b]95% confidence interval.

[c]Standard deviation.

The meta-regression model with turbidity range and mean body size of predators was statistically significant ($F_{2,410} = 39.89$; $k = 36$; $p < 0.01$; Pseudo-$R^2_{\text{between studies}} = 0.67$). This model indicated that effect sizes were significantly and negatively correlated with turbidity range ($b = -0.16$; $t = -8.84$; $p < 0.01$; Figure 5a), but not with predator body size ($b = -0.10$; $t = -1.89$; $p = 0.06$; Figure 5b).

Only the Egger test indicated that there was a publication bias in the literature on the effect of turbidity on prey capture rates. However, the trim-and-fill procedure, either using average effect sizes or the resampling method, indicated that the number of studies potentially omitted ranged between none and 3.06 studies only. The cumulative effect size, including the potentially omitted studies, remains significantly lower than zero (Fisher's $z \pm CI_{95} = -0.31 \pm 0.11$). According to the Orwin fail-safe number, it would be necessary to include approximately 60, 179 and 537 studies with effects sizes equal to zero to reduce the mean effect size to 50%, 25% and 10% of the observed value, respectively. Using a resampling procedure to assess publication bias led to the same pattern (Table 1). Considering these results, it is unlikely that publication bias was a relevant issue in our meta-analysis.

4 | DISCUSSION

We found a consistent negative effect of turbidity on prey capture rates of aquatic predators. This effect did not depend on the type of predator (visually oriented or not) and predator body size. Also, the strength of the relationship between turbidity and prey capture rate increased (i.e. became more negative) with the increase in the range of turbidity manipulated in the experiments. This pattern suggests that an extreme shift in turbidity (as predicted to occur in many systems around the world; IPCC, 2014) can induce more pronounced changes in the outcomes of predator–prey interactions in aquatic ecosystems.

Turbidity negatively affects aquatic predator capture rates (e.g. Abrahams & Kattenfeld, 1997; Lunt & Smee, 2015; Nilsson et al., 2014; Turesson & Brönmark, 2007; van der Sluijs et al., 2011). The most direct interpretation is that turbidity reduces light availability and alters the composition of wavelengths (van der Suiljs et al., 2011), thus reducing the distances at which objects can be discerned (Nilsson et al., 2014; Weiffen, Möller, Mauck, & Dehnhardt, 2006). Therefore, visually oriented predators have their field of prey

detection reduced in more turbid waters (Nilsson et al., 2014; Sweka & Hartman, 2003; Weiffen et al., 2006), reducing their ability to capture their prey. However, an intriguing finding is that both visual and non-visual predators have a reduced ability to capture prey in more turbid waters. This result is especially unexpected because increased turbidity would reduce the distance at which prey should be detected by visual predators (Hartman & Abrahams, 2000), while chemosensory or tactile predators could still find their prey in turbid waters (Eiane et al., 1999; Lunt & Smee, 2015; Sørnes & Aksnes, 2004). A possible explanation for this result is that chemical cues can be used by predators to detect the presence of a given prey, but not to locate such prey (Conover, 2007; Johannesen, Dunn, & Morrell, 2012). Thus, the detection of chemical cues from the presence of prey could stimulate predators to spend more time searching for prey, but this predator behavioural change may not imply in prey capture rates at similar or higher levels than those recorded to clear waters (Johannesen et al., 2012). Furthermore, behavioural studies have demonstrated that under high turbidity prey reduce their activity (Chamberlain & Ioannou, 2019; Kimbell & Morell, 2015) and can aggregate (Johannesen, Dunn, & Morrell, 2014; Ohata, Masuda, Takahashi, & Yamashita, 2014), which could result in reduced encounters between non-visual predators and their prey and decreased prey capture rate in turbid waters. For example, Ohata et al. (2011) attributed the increase in survival of larval ayu *Plecoglossus altivelis* co-occurring with moon jellyfish *Aurelia aurita* (a tactile predator) in turbid waters to a decrease in swimming activity by ayu. Also, Ohata et al. (2014) observed that in moderate turbidity larval ayu increased their shoaling behaviour. Shoaling is a type of aggregation which is an efficient antipredator behaviour against predators with different types of predation (Johannesen et al., 2014; Kullmann, Thünken, Baldauf, Bakker, & Frommen, 2008; Ohata et al., 2014).

Although the mean effect of turbidity on captures rates was negative, some studies included in our meta-analysis estimated positive effects. At least two hypotheses may explain these positive turbidity–prey capture relationships. First, chemosensory or tactile predators may be favoured in turbid waters (Eiane et al., 1999; Lunt & Smee, 2015; Sørnes & Aksnes, 2004). For example, Lunt and Smee (2015) found higher predation rates by a chemosensory crab *Callinectes sapidus* in turbid waters. Also, tactile predators may be less sensitive to low visibility, which may render a competitive advantage over visual predators (Eiane et al., 1999). However, the low number of chemosensory or tactile predators included in our meta-analysis preclude us to explore further whether the turbidity–prey capture is consistently positive for these groups of species. Second, the relationship between turbidity and prey capture may be positive for benthic predators (e.g. Lunt & Smee, 2014, 2015). For example, Lunt and Smee (2014) found crabs to be more abundant in turbid water due to lower predation by fish, and that crab predation was elevated in turbid water due to greater crab abundance. Few studies tested how benthic predators are affected by changes in turbidity, then our results are focused on pelagic-nektonic data.

Species with larger eyes tend to have greater visual accuracy (Caves et al., 2017). Thus, capture rates of visually oriented predators with larger eyes would be less affected by an increase in turbidity than predators with smaller eyes. However, our results indicated that predator eye size does not explain the variation in the strength of the relationship between turbidity and capture rate. It is possible that other traits, such as capture behaviour (e.g. capture by filtration, drift in the water column, active pursuit, lurking or bait attraction; Edgehouse & Brown, 2014; Sazima, 1986; Thom, Bhattacharjee, & Siemann, 2018) may be important in influencing the strength of this relationship.

We did not find that predator body size (despite its large variation) affected the strength of the relationship between turbidity and capture rate. However, the range of turbidity used in the experiments explained much of the heterogeneity in the turbidity–capture rates relationships, suggesting that this methodological difference plays an important role in the outcomes. The ranges of turbidity in the experiments are often chosen to be similar to those observed in environments near the experimental areas (e.g. Abrahams et al., 2017; Lunt & Smee, 2014). While this is justified by realism in the experiment, there were some extreme cases where the difference between clear and turbid treatments exceeded 2,000 NTU (e.g. Carrasco, Perissinotto, & Jones, 2013; Carrasco, Perissinotto, & Miranda, 2007; Jones et al., 2015). A practical implication is that extreme differences in turbidity between treatments can result in an overestimate of turbidity effect on capture rates. Likewise, dichotomies between clear and turbid waters with small differences in turbidity can result in underrated turbidity effect on capture rates. Despite these methodological differences, understanding the influence of turbidity range variation is relevant to known which species can cope well with reduced water transparency and which species are more prone to be locally extinct in a scenario of increased human-induced changes in turbidity. Aquatic environments are experiencing a reduction in water clarity via multiple stressors, including eutrophication and climate change (Asknes et al., 2009; Meyer-Jacob et al., 2020; Škerlep, Steiner, Axelsson, & Kritzberg, 2020). Thus, considering the body of evidence summarized here, an increase in turbidity may reduce the effects of predation on prey populations. On the other hand, some aquatic ecosystems are experiencing an increase in water transparency due to, for example, flow regulation, oligotrophication and climatic factors (Barbosa et al., 1999; Roberto et al., 2009; Vogt, Sharma, & Leavitt, 2015). Where an increase in water transparency can be expected (e.g. in cascade reservoir systems), we predict an increased predation pressure (dos Santos et al., 2017).

Turbidity can ultimately drive food-web dynamics by affecting the predator–prey dynamics. Using a long-term dataset, Lunt and Smee (2020) found that top predators were more abundant in clear waters while first-level carnivores and planktivorous species were more abundant in turbid waters. Also, van Dorst, Gårdmark, Svanbäch, and Huss (2020) found that a visually oriented planktivorous fish was negatively affected by experimental water browning. In sum, increasing turbidity can trigger a regime shift of a food-web, being under top-down control by predation in clear water and bottom-up control in turbid water.

4.1 | Gaps of knowledge in turbidity–capture rates literature

We did not find studies focusing on some important groups of invertebrate (e.g. Schyphozoa, Odonata and Hemiptera) and vertebrate predators [e.g. fish (gymnotiforms and siluriforms), amphibians, reptiles, mammals and birds]. Also, although the experiments are distributed around the globe, it is evident the lack of studies conducted in southern and eastern Europe, Central America, part of South America, Africa, Oceania and the Middle East. Some of these regions are highly diverse and underrepresented in the literature (e.g. Central America, north of South America, Africa and Oceania). These gaps reduce the reach of our results. For example, the capture rates of species that use electrical, chemical and mechanical cues for hunting (as in the case of gymnotiforms, siluriforms and scyphozoans; Eiane et al., 1999; Pohlmann, Grasso, & Breithaupt, 2001; Westby, 1988) can be less affected by increased turbidity. Similarly, assuming that predators in tropical regions evolved mainly in lotic environments with turbid waters (Fernando & Holčík, 1991; Gomes & Miranda, 2001), one would expect a lower effect of turbidity on capture rates. In short, the overall effect of turbidity on capture rates can be changed if studies that fill the knowledge gaps are included.

The predator–prey relationship can be influenced by both predator and prey traits. For instance, Jönsson, Hylander, Ranåker, Nilsson, and Brönmark (2011) observed that transparent copepods were more consumed in brown water treatment compared to algal-induced turbidity treatment. On the other hand, carotenoid-pigmented copepods were more consumed in the algal-induced turbidity treatment (Jönsson et al., 2011). Although collected when available, prey traits were not explored in our synthesis due to little information on potential strategies to avoid predation (e.g. mobility ability, coloration or defensive morphological structures). Therefore, the extent that prey traits explain the negative turbidity–capture rates is still an open question.

5 | CONCLUSIONS

We observed a consistent negative relationship between turbidity and capture rate in aquatic environments. This relationship was mainly explained by the turbidity range used in the experiments. Turbidity is thought to be an important factor controlling predation (Klobucar & Budy, 2016; Lindholm, Wolf, Finstad, & Hessen, 2016; Lunt & Smee, 2015; Sweka & Hartman, 2003; Turesson & Brönmark, 2007). Thus, human-induced changes in turbidity are expected to cause major shifts in predator–prey interactions based on accumulated empirical evidence.

ACKNOWLEDGEMENTS

J.C.G.O. thanks the Brazilian Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for a post-doctoral scholarship. A.A.A., L.M.B. and W.J.d.G. are grateful to CNPq by research productivity fellowships. We thank the comments of two anonymous reviewers and associate editor, and all authors that conducted the primary studies without which this meta-analysis would not be possible. We declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

J.C.G.O. conceived the idea, built the search protocol, conducted the search and collected the data; J.C.G.O. and W.J.d.G. constructed the phylogeny; J.C.G.O. performed the analyses; all authors contributed in writing the first draft and the final version of the manuscript.

DATA AVAILABILITY STATEMENT

All the data and script used are available at the Dryad Digital Repository https://doi.org/10.5061/dryad.qbzkh18fq (Ortega et al., 2020).

ORCID

Jean C. G. Ortega https://orcid.org/0000-0001-5097-9382
Bruno R. S. Figueiredo https://orcid.org/0000-0002-8750-808X
Weferson J. da Graça https://orcid.org/0000-0002-8925-5629
Angelo A. Agostinho https://orcid.org/0000-0002-4707-9444
Luis M. Bini https://orcid.org/0000-0003-3398-9399

REFERENCES

Abrahams, M. V., Bassett, D. K., & Montgomery, J. C. (2017). Sensory biology as a risk factor for invasion success and native fish decline. *Transactions of the American Fisheries Society*, *146*, 1238–1244. https://doi.org/10.1080/00028487.2017.1353545

Abrahams, M., & Kattenfeld, M. (1997). The role of turbidity as a constraint on predator-prey interactions in aquatic environments. *Behavioral Ecology and Sociobiology*, *40*, 169–174. https://doi.org/10.1007/s002650050330

Anthony, K. R. N., Ridd, P. V., Orpin, A. R., Larcombe, P., & Lough, J. (2004). Temporal variation of light availability in coastal benthic habitats: Effects of clouds, turbidity, and tides. *Limnology and Oceanography*, *49*, 2201–2211. https://doi.org/10.4319/lo.2004.49.6.2201

Asknes, D. L., Dupont, N., Staby, A., Fiksen, Ø., Kaartvedt, S., & Aure, J. (2009). Coastal water darkening and implications for mesopelagic regime shifts in Norwegian fjords. *Marine Ecology Progress Series*, *387*, 39–49. https://doi.org/10.3354/meps08120

Barbosa, F. A. R., Padisák, J., Espíndola, E. L. G., Borics, G., & Rocha, O. (1999). The cascading reservoir continuum concept (CRCC) and its applications to the river Tietê-basin, São Paulo state, Brazil. In J. G. Tundisi & M. Straskraba (Eds.), *Theoretical reservoir ecology and its applications* (pp. 425–438). Leiden, The Netherlands: Backhuys Publishers.

Benine, R. C., Mariguela, T. C., & Oliveira, C. (2009). New species of *Moenkhausia* Eigenmann, 1903 (Characiformes: Characidae) with comments on the *Moenkhausia oligolepis* species complex. *Neotropical Ichthyology*, *7*, 161–168. https://doi.org/10.1590/S1679-62252009000200005

Betancur-R, R., Broughton, R. E., Wiley, E. O., Carpenter, K., López, J. A., Li, C., … Ortí, G. (2013). The tree of life and a new classification of bony fishes. *PLoS Currents: Tree of Life*. https://doi.org/10.1371/currents.tol.53ba26640df0ccaee75bb165c8c26288

Betancur-R, R., Wiley, E. O., Arratia, G., Acero, A., Bailly, N., Miya, M., … Ortí, G. (2017). Phylogenetic classification of bony fishes. *BMC Evolutionary Biology*, *17*, 1–40. https://doi.org/10.1186/s12862-017-0958-3

Borenstein, M., Hedges, L. V., Higgins, J. P. T., & Rothstein, H. R. (2009). *Introduction to meta-analysis* (1st ed.). Chichester, UK: Wiley. https://doi.org/10.1002/9780470743386

Borenstein, M., Higgins, J. P. T., Hedges, L. V., & Rothstein, H. R. (2017). Basics of meta-analysis: I^2 is not an absolute measure of heterogeneity. *Research Synthesis Methods*, *8*, 5–18. https://doi.org/10.1002/jrsm.1230

Burnham, K. P., & Anderson, D. R. (2002). *Model selection and multimodel inference: A practical information-theoretic approach* (2nd ed.). Dordrecht, The Netherlands: Springer. https://doi.org/10.1007/b97636

Carpenter, S. R., Kitchell, J. F., & Hodgson, J. R. (1985). Cascading trophic interactions and lake productivity. *BioScience*, *35*, 634–639. https://doi.org/10.2307/1309989

Carrasco, N. K., Perissinotto, R., & Jones, S. (2013). Turbidity effects on feeding and mortality of the copepod *Acartiella natalensis* (Connell and Grindley, 1974) in the St Lucia Estuary, South Africa. *Journal of Experimental Marine Biology and Ecology*, *446*, 45–51. https://doi.org/10.1016/j.jembe.2013.04.016

Carrasco, N. K., Perissinotto, R., & Miranda, N. A. F. (2007). Effects of silt loading on the feeding and mortality of the mysid *Mesopodopsis africana* in the St. Lucia Estuary, South Africa. *Journal of Experimental Marine Biology and Ecology*, *352*, 152–164. https://doi.org/10.1016/j.jembe.2007.07.006

Caves, E. M., Sutton, T. T., & Johnsen, S. (2017). Visual acuity in ray-finned fishes correlates with eye size and habitat. *Journal of Experimental Biology*, *220*, 1586–1596. https://doi.org/10.1242/jeb.151183

Chacin, D. H., & Stallings, C. D. (2016). Disentangling fine- and broad-scale effects of habitat on predator-prey interactions. *Journal of Experimental Marine Biology and Ecology*, *483*, 10–19. https://doi.org/10.1016/j.jembe.2016.05.008

Chamberlain, A. C., & Ioannou, C. C. (2019). Turbidity increases risk perception but constrains collective behaviour during foraging by fish shoals. *Animal Behaviour*, *156*, 129–138. https://doi.org/10.1016/j.anbehav.2019.08.012

Chapman, J. M., Proulx, C. L., Veilleux, M. A. N., Levert, C., Bliss, S., André, M.-È., … Cooke, S. J. (2014). Clear as mud: A meta-analysis on the effects of sedimentation on freshwater fish and the effectiveness of sediment-control measures. *Water Research*, *56*, 190–202. https://doi.org/10.1016/j.watres.2014.02.047

Conover, M. R. (2007). *Predator-prey dynamics: The role of olfaction*. Boca Raton, FL: CRC Press.

Cózar, A., Gálvez, J. A., Hull, V., García, C. M., & Loiselle, S. A. (2005). Sediment resuspension by wind in a shallow lake of Esteros del Ibera (Argentina): A model based on turbidimetry. *Ecological Modelling*, *186*, 63–76. https://doi.org/10.1016/j.ecolmodel.2005.01.020

Cretê-Lafrenière, A., Weir, L. K., & Bernatchez, L. (2012). Framing the salmonidae family phylogenetic portrait: A more complete picture from increased taxon sampling. *PLoS ONE*, *7*, e46662. https://doi.org/10.1371/journal.pone.0046662

Davies-Colley, R. J., & Nagels, J. W. (2008). Predicting light penetration into river waters. *Journal of Geophysical Research*, *113*, G03028. https://doi.org/10.1029/2008JG000722

dos Santos, N. C. L., de Santana, H. S., Ortega, J. C. G., Dias, R. M., Stegmann, L. F., da Silva Araújo, I. M., … Agostinho, A. A. (2017). Environmental filters predict the trait composition of fish communities in reservoir cascades. *Hydrobiologia*, *802*, 245–253. https://doi.org/10.1007/s10750-017-3274-4

Duval, S., & Tweedie, R. (2000). Trim and fill: A simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. *Biometrics*, *56*, 455–463. https://doi.org/10.1111/j.0006-341x.2000.00455.x

Edgehouse, M., & Brown, C. P. (2014). Predatory luring behavior of odonates. *Journal of Insect Science*, *14*, 146. https://doi.org/10.1093/jisesa/ieu008

Egger, M., Smith, G. D., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *British Medical Journal*, *315*, 629–634. https://doi.org/10.1136/bmj.315.7109.629

Eiane, K., Aksnes, D. L., Bagøien, E., & Kaartvedt, S. (1999). Fish or jellies – A question of visibility? *Limnology and Oceanography*, *44*, 1352–1357. https://doi.org/10.4319/lo.1999.44.5.1352

Englund, G., Johansson, F., Olofsson, P., Salonsaari, J., & Öhman, J. (2009). Predation leads to assembly rules in fragmented fish communities. *Ecology Letters*, *12*, 663–671. https://doi.org/10.1111/j.1461-0248.2009.01322.x

Evans, M. R. (2012). Modeling ecological systems in a changing world. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*, 181–190. https://doi.org/10.1098/rstb.2011.0172

Fernando, C. H., & Holčík, J. (1991). Fish in reservoirs. *International Review of Hydrobiology*, *76*, 149–167. https://doi.org/10.1002/iroh.19910760202

Figueiredo, B. R. S., Calvo, C., López-Rodríguez, A., Mormul, R. P., Teixeira-de Mello, F., Benedito, E., & Meerhoff, M. (2019). Short-term interactive effects of experimental heat waves and turbidity pulses on the foraging success of a subtropical invertivorous fish. *Water*, *11*, 2109. https://doi.org/10.3390/w11102109

Figueiredo, B. R. S., Mormul, R. P., & Benedito, E. (2015). Structural complexity and turbidity do not interact to influence predation rate and prey selectivity by a small visually feeding fish. *Marine and Freshwater Research*, *66*, 170–176. https://doi.org/10.1071/MF14030

Froese, R., & Pauly, D. (2017). *FishBase*. Retrieved from www.fishbase.org

Gomes, L. C., & Miranda, L. E. (2001). Riverine characteristics dictate composition of fish assemblages and limit fisheries in reservoirs of the upper Paraná River basin. *River Research and Applications*, *17*, 67–76. https://doi.org/10.1002/1099-1646%28200101/02%2917%3A1<67%3A%3AAID-RRR615>3.0.CO%3B2-P

Graneli, W. (2012). Brownification of lakes. In L. Bengtsson, R. W. Herschy, & R. W. Fairbridge (Eds.), *Encyclopedia of lakes and reservoirs* (pp. 117–119). New York, NY: Springer. https://doi.org/10.1007/978-1-4020-4410-6_256

Green, L., Blumstein, D. T., & Fong, P. (2015). Macroalgal mats in a eutrophic estuary obscure visual foraging cues and increase variability in prey availability for some shorebirds. *Estuaries and Coasts*, *38*, 917–926. https://doi.org/10.1007/s12237-014-9862-x

Gregor, C. A., & Anderson, T. W. (2016). Relative importance of habitat attributes to predation risk in a temperate reef fish. *Environmental Biology of Fishes*, *99*, 539–556. https://doi.org/10.1007/s10641-016-0496-7

Hall, J. D., Threlkeld, S. T., Burns, C. W., & Crowley, P. H. (1976). The size-efficiency hypothesis and the size structure of Zooplankton communities. *Annual Reviews in Ecology and Systematics*, *7*, 177–208. https://doi.org/10.1146/annurev.es.07.110176.001141

Hansen, A. G., & Beauchamp, D. A. (2015). Latitudinal and photic effects on diel foraging and predation risk in freshwater pelagic ecosystems. *Journal of Animal Ecology*, *84*, 532–544. https://doi.org/10.1111/1365-2656.12295

Hardie, S. A. (2003). *Current status and ecology of the golden galaxias (*Galaxias auratus*)*. Hobart, TAS: Inland Fisheries Service.

Hartman, E. J., & Abrahams, M. V. (2000). Sensory compensation and the detection of predators: The interaction between chemical and visual information. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *267*, 571–575. https://doi.org/10.1098/rspb.2000.1039

Helenius, L. K., Borg, J. P. G., Nurminen, L., Leskinen, E., & Lehtonen, H. (2013). The effects of turbidity on prey consumption and selection of zooplanktivorous *Gasterosteus aculeatus* L. *Aquatic Ecology*, *47*, 349–356. https://doi.org/10.1007/s10452-013-9448-x

Higham, T. E., Stewart, W. J., & Wainwright, P. C. (2015). Turbulence, temperature, and turbidity: The ecomechanics of predator–prey interactions in fishes. *Integrative and Comparative Biology*, *55*, 6–20. https://doi.org/10.1093/icb/icv052

Hozo, S. P., Djulbegovic, B., & Hozo, I. (2005). Estimating the mean and variance from the median, range, and the size of a sample. *BMC Medical Research Methodology*, *5*, 13. https://doi.org/10.1186/1471-2288-5-13

International Panel on Climate Change (IPCC). (2014). *Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R. K. Pachauri, & L. A. Meyer (Eds.)]. Geneva, Switzerland: IPCC.

Janssen, J., & Corcoran, J. (1993). Lateral line stimuli can override vision to determine sunfish strike trajectory. *Journal of Experimental Biology*, *176*, 299–305.

Johannesen, A., Dunn, A. M., & Morrell, L. J. (2012). Olfactory cue use by three-spined sticklebacks foraging in turbid water: Prey detection or prey location? *Animal Behaviour*, *84*, 151–158. https://doi.org/10.1016/j.anbehav.2012.04.024

Johannesen, A., Dunn, A. M., & Morrell, L. J. (2014). Prey aggregation is an effective olfactory predator avoidance strategy. *Peer J*, *2*, e408. https://doi.org/10.7717/peerj.408

Jones, S., Carrasco, N. K., & Perissinotto, R. (2015). Turbidity effects on the feeding, respiration and mortality of the copepod *Pseudodiaptomus stuhlmanni* in the St Lucia Estuary, South Africa. *Journal of Experimental Marine Biology and Ecology*, *469*, 63–68. https://doi.org/10.1016/j.jembe.2015.04.015

Jönsson, M., Hylander, S., Ranåker, L., Nilsson, P. A., & Brönmark, C. (2011). Foraging success of juvenile pike *Esox lucius* depends on visual conditions and prey pigmentation. *Journal of Fish Biology*, *79*, 290–297. https://doi.org/10.1111/j.1095-8649.2011.03004.x

Junges, C. M., Lajmanovich, R. C., Peltzer, P. M., Attademo, A. M., & Bassó, A. (2010). Predator–prey interactions between *Synbranchus marmoratus* (Teleostei: Synbranchidae) and *Hypsiboas pulchellus* tadpoles (Amphibia: Hylidae): Importance of lateral line in nocturnal predation and effects of fenitrothion exposure. *Chemosphere*, *81*, 1233–1238. https://doi.org/10.1016/j.chemosphere.2010.09.035

Kimbell, H. S., & Morell, L. J. (2015). Turbidity influences individual and group level responses to predation in guppies, *Poecilia reticulata*. *Animal Behaviour*, *103*, 179–185. https://doi.org/10.1016/j.anbehav.2015.02.027

Klobucar, S. L., & Budy, P. (2016). Consequences of seasonal variation in reservoir water level for predatory fishes: Linking visual foraging and prey densities. *Canadian Journal of Fisheries and Aquatic Sciences*, *73*, 53–64. https://doi.org/10.1139/cjfas-2015-0008

Kullmann, H., Thünken, T., Baldauf, S. A., Bakker, T. C. M., & Frommen, J. G. (2008). Fish odour triggers conspecific attraction behaviour in an aquatic invertebrate. *Biology Letters*, *4*, 458–460. https://doi.org/10.1098/rsbl.2008.0246

Lajeunesse, M. J. (2009). Meta-analysis and the comparative phylogenetic method. *The American Naturalist*, *174*, 369–381. https://doi.org/10.1086/603628

Lajeunesse, M. J. (2013). Recovering missing or partial data from studies: A survey of conversions and imputations for meta-analysis. In J. Koricheva, J. Gurevitch, & K. Mengersen (Eds.), *Handbook of meta-analysis in ecology and evolution* (pp. 195–206). Princeton, NJ: Princeton University Press.

Lajeunesse, M. J. (2016). Facilitating systematic reviews, data extraction, and meta-analysis with the metagear package for R. *Methods in Ecology and Evolution*, *7*, 323–330. https://doi.org/10.1111/2041-210X.12472

Liao, I. C., & Chang, E. Y. (2003). Role of sensory mechanisms in predatory feeding behavior of juvenile red drum *Sciaenops ocellatus*. *Fisheries Science*, *69*, 317–322. https://doi.org/10.1046/j.1444-2906.2003.00623.x

Lima, S. L., & Dill, L. M. (1990). Behavioral decisions made under the risk of predation: A review and prospectus. *Canadian Journal of Zoology*, *68*, 619–640. https://doi.org/10.1139/z90-092

Lindholm, M., Wolf, R., Finstad, A., & Hessen, D. O. (2016). Water browning mediates predatory decimation of the Arctic fairy shrimp *Branchinecta paludosa*. *Freshwater Biology*, *61*, 340–347. https://doi.org/10.1111/fwb.12712

Lunt, J., & Smee, D. L. (2014). Turbidity influences trophic interactions in estuaries. *Limnology and Oceanography*, *59*, 2002–2012. https://doi.org/10.4319/lo.2014.59.6.2002

Lunt, J., & Smee, D. L. (2015). Turbidity interferes with foraging success of visual but not chemosensory predators. *PeerJ*, *3*, e1212. https://doi.org/10.7717/peerj.1212

Lunt, J., & Smee, D. L. (2020). Turbidity alters estuarine biodiversity and species composition. *ICES Journal of Marine Science*, *77*, 379–387. https://doi.org/10.1093/icesjms/fsz214

Manning, N. F., Mayer, C. M., Bossenbroek, J. M., & Tyson, J. F. (2013). Effects of water clarity on the length and abundance of age-0 yellow perch in the Western Basin of Lake Erie. *Journal of Great Lakes Research*, *39*, 295–302. https://doi.org/10.1016/j.jglr.2013.03.010

Meyer-Jacob, C., Michelutti, N., Paterson, A. M., Cumming, B. F., Keller, W., & Smol, J. P. (2020). The browning and re-browning of lakes: Divergent lake-water organic carbon trends linked to acid deposition and climate change. *Scientific Reports*, *9*, 16676. https://doi.org/10.1038/s41598-019-52912-0

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. & The PRISMA Group. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA Statement. *PLoS Medicine*, *6*, e1000097. https://doi.org/10.1371/journal.pmed.1000097

Münkemüller, T., Lavergne, S., Bzeznik, B., Dray, S., Jombart, T., Schiffers, K., & Thuiller, W. (2012). How to measure and test phylogenetic signal. *Methods in Ecology and Evolution*, *3*, 743–756. https://doi.org/10.1111/j.2041-210X.2012.00196.x

Nakagawa, S., & Santos, E. S. A. (2012). Methodological issues and advances in biological meta-analysis. *Evolutionary Ecology*, *26*, 1253–1274. https://doi.org/10.1007/s10682-012-9555-5

Nielsen, C. (2012). *Animal evolution: Interrelationships of the living phyla* (3rd ed.). Oxford, UK: Oxford University Press. https://doi.org/10.1093/icb/ict005

Nieman, C. L., Oppliger, A. L., McElwain, C. C., & Gray, S. M. (2018). Visual detection thresholds in two trophically distinct fishes are compromised in algal compared to sedimentary turbidity. Conservation. *Physiology*, *6*, coy044. https://doi.org/10.1093/conphys/coy044

Nilsson, D.-E., Warrant, E., & Johnsen, S. (2014). Computational visual ecology in the pelagic realm. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*, 20130038. https://doi.org/10.1098/rstb.2013.0038

Noble, D. W. A., Lagisz, M., O'Dea, R. E., & Nakagawa, S. (2017). Nonindependence and sensitivity analyses in ecological and evolutionary meta-analyses. *Molecular Ecology*, *26*, 2410–2425. https://doi.org/10.1111/mec.14031

Ohata, R., Masuda, R., Takahashi, K., & Yamashita, Y. (2014). Moderate turbidity enhances schooling behaviour in fish larvae in coastal waters. *ICES Journal of Marine Science*, *71*, 925–929. https://doi.org/10.1093/icesjms/fss194

Ohata, R., Masuda, R., Ueno, M., Fukushini, Y., & Yamashita, Y. (2011). Effects of turbidity on survival of larval ayu and red sea bream exposed to predation by jack mackerel and moon jellyfish. *Fisheries Science*, *77*, 207–215. https://doi.org/10.1007/s12562-010-0320-9

Orrock, J. L., Grabowski, J. H., Pantel, J. H., Peacor, S. D., Peckarsky, B. L., Sih, A., & Werner, E. E. (2008). Consumptive and nonconsumptive effects of predators on metacommunitites of competing prey. *Ecology*, *89*, 2426–2435. https://doi.org/10.1890/07-1024.1

Ortega, J. C. G., Figueiredo, B. R. S., da Graça, W., Agostinho, A. A., & Bini, L. M. (2020). Data from: Negative effect of turbidity on prey capture for both visual and non-visual aquatic predators. *Dryad Digital Repository*, https://doi.org/10.5061/dryad.qbzkh18fq

Ortega, J. C. G., Thomaz, S. M., & Bini, L. M. (2018). Experiments reveal that environmental heterogeneity increases species richness, but they are rarely designed to detect the underlying mechanisms. *Oecologia*, *188*, 11–22. https://doi.org/10.1007/s00442-018-4150-2

Orwin, R. G. (1983). A fail-safe N for effect size in meta-analysis. *Journal of Educational Statistics*, *8*, 157–159. https://doi.org/10.2307/1164923

Paradis, E., Claude, J., & Strimmer, K. (2004). APE: Analyses of phylogenetics and evolution in R language. *Bioinformatics*, *20*, 289–290. https://doi.org/10.1093/bioinformatics/btg412

Pelicice, F. M., & Agostinho, A. A. (2009). Fish fauna destruction after the introduction of a non-native predator (*Cichla kelberi*) in a Neotropical reservoir. *Biological Invasions*, *11*, 1789–1801. https://doi.org/10.1007/s10530-008-9358-3

Pelicice, F. M., Latini, J. D., & Agostinho, A. A. (2015). Fish fauna disassembly after the introduction of a voracious predator: Main drivers and the role of the invader's demography. *Hydrobiologia*, *746*, 271–283. https://doi.org/10.1007/s10750-014-1911-8

Pick, J. L., Nakagawa, S., & Noble, D. W. A. (2019). Reproducible, flexible and high throughput data extraction from primary literature: The metaDigitise R package. *Methods in Ecology and Evolution*, *10*, 426–431. https://doi.org/10.1111/2041-210X.13118

Pohlmann, K., Grasso, F. W., & Breithaupt, T. (2001). Tracking wakes: The nocturnal predatory strategy of piscivorous catfish. *Proceedings of the National Academy of Sciences of the United States of America*, *98*, 7371–7374. https://doi.org/10.1073/pnas.121026298

R Core Team. (2018). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.r-project.org/

Ranåker, L., Nilsson, P. A., & Brönmark, C. (2012). Effects of degraded optical conditions on behavioural responses to alarm cues in a freshwater fish. *PLoS ONE*, *7*, e38411. https://doi.org/10.1371/journal.pone.0038411

Revell, L. J. (2012). phytools: An R package for phylogenetic comparative biology (and other things). *Methods in Ecology and Evolution*, *3*, 217–223. https://doi.org/10.1111/j.2041-210X.2011.00169.x

Ripple, W. J., & Beschta, R. L. (2012). Trophic cascades in Yellowstone: The first 15 years after wolf reintroduction. *Biological Conservation*, *145*, 205–213. https://doi.org/10.1016/j.biocon.2011.11.005

Roberto, M. C., Santana, N. F., & Thomaz, S. M. (2009). Limnology in the Upper Paraná River floodplain: Large-scale spatial and temporal patterns, and the influence of reservoirs. *Brazilian Journal of Biology*, *69*, 717–725. https://doi.org/10.1590/S1519-69842009000300025

Rodríguez, M. A., & Lewis, W. M. (1997). Structure of fish assemblages along environmental gradients in floodplain lakes of the Orinoco River. *Ecological Monographs*, *67*, 109–128. https://doi.org/10.1890/0012-9615%281997%29067%5B0109%3ASOFAAE%5D2.0.CO%3B2

Sazima, I. (1986). Similarities in feeding behaviour between some marine and freshwater fishes in two tropical communities. *Journal of Fish Biology*, *29*, 53–65. https://doi.org/10.1111/j.1095-8649.1986.tb04926.x

Schälchli, U. (1992). The clogging of coarse gravel river beds by fine sediment. *Hydrobiologia*, *235*, 189–197. https://doi.org/10.1007/BF00026211

Schwalbe, M. A. B., & Webb, J. F. (2015). The effect of light intensity on prey detection behavior in two Lake Malawi cichlids, *Aulonocara stuartgranti* and *Tramitichromis* sp. *Journal of Comparative Physiology A*, *201*, 341–356. https://doi.org/10.1007/s00359-015-0982-y

Sharpe, D. M. T., De Léon, L. F., González, R., & Torchin, M. E. (2017). Tropical fish community does not recover 45 years after predator introduction. *Ecology*, *98*, 412–424. https://doi.org/10.1002/ecy.1648

Shoup, D. E., & Lane, W. D. (2015). Effects of turbidity on prey selection and foraging return of adult largemouth bass in reservoirs. *North American Journal of Fisheries Management*, *35*, 913–924. https://doi.org/10.1080/02755947.2015.1067260

Škerlep, M., Steiner, E., Axelsson, A.-L., & Kritzberg, E. S. (2020). Afforestation driving long-term surface water browning. *Global Change Biology*, *26*, 1390–1399. https://doi.org/10.1111/gcb.14891

Sørnes, T. A., & Aksnes, D. L. (2004). Predation efficiency in visual and tactile zooplanktivores. *Limnology and Oceanography*, *49*, 69–75. https://doi.org/10.4319/lo.2004.49.1.0069

Sterne, J. A. C., & Egger, M. (2005). Regression methods to detect publication and other bias in meta-analysis. In H. R. Rothstein, A. J. Sutton, & M. Borenstein (Eds.), *Publication bias in meta-analysis: Prevention, assessment and adjustments* (pp. 99–110). Hoboken, NJ: John Wiley & Sons. https://doi.org/10.1002/0470870168.ch6

Sweka, J. A., & Hartman, K. J. (2003). Reduction of reactive distance and foraging success in smallmouth bass, *Micropterus dolomieu*, exposed to elevated turbidity levels. *Environmental Biology of Fishes*, *67*, 341–347. https://doi.org/10.1023/A:1025835031366

Tanner-Smith, E. E., & Tipton, E. (2014). Robust variance estimation with dependent effect sizes: Practical considerations including a software tutorial in Stata and SPSS. *Research Synthesis Methods*, *5*, 13–30. https://doi.org/10.1002/jrsm.1091

Tejerina-Garro, F. L., Fortin, R., & Rodríguez, M. A. (1998). Fish community structure in relation to environmental variation in floodplain lakes of the Araguaia River, Amazon Basin. *Environmental Biology of Fishes*, *51*, 399–410. https://doi.org/10.1023/A:1007401714671

Thetmeyer, H., & Kils, U. (1995). To see and not be seen – The visibility of predator and prey with respect to feeding behavior. *Marine Ecology Progress Series*, *126*, 1–8. https://doi.org/10.3354/meps126001

Thom, A. E., Bhattacharjee, M., & Siemann, E. (2018). Predaceous insects may limit algal grazers in high-nutrient environments: Implications for wastewater remediation in open bioreactors. *Aquatic Ecology*, *52*, 107–118. https://doi.org/10.1007/s10452-018-9648-5

Turesson, H., & Brönmark, C. (2007). Predator–prey encounter rates in freshwater piscivores: Effects of prey density and water transparency. *Oecologia*, *153*, 281–290. https://doi.org/10.1007/s00442-007-0728-9

van der Sluijs, I., Gray, S. M., Amorim, M. C. P., Barber, I., Candolin, U., Hendry, A. P., … Wong, B. B. M. (2011). Communication in troubled waters: Responses of fish communication systems to changing environments. *Evolutionary Ecology*, *25*, 623–640. https://doi.org/10.1007/s10682-010-9450-x

van Dorst, R. M., Gårdmark, A., Svanbäch, R., & Huss, M. (2020). Does browning-induced light limitation reduce fish body growth through shifts in prey composition or reduced foraging rates? *Freshwater Biology*, *65*, 947–959. https://doi.org/10.1111/fwb.13481

VanLandeghem, M., Carrey, M. P., & Wahl, D. H. (2011). Turbidity-induced changes in emergent effects of multiple predators with different foraging strategies. *Ecology of Freshwater Fish*, *20*, 279–286. https://doi.org/10.1111/j.1600-0633.2011.00494.x

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*, *36*, 1–48. https://doi.org/10.18637/jss.v036.i03

Vogt, R. J., Sharma, S., & Leavitt, P. R. (2015). Decadal regulation of phytoplankton abundance and water clarity in a large continental reservoir by climatic, hydrologic and trophic processes. *Journal of Great Lakes Research*, *41*, 81–90. https://doi.org/10.1016/j.jglr.2014.11.007

Waters, J. M., López, J. A., & Wallis, G. P. (2000). Molecular phylogenetics and biogeography of galaxiid fishes (Osteichthyes: Galaxiidae): Dispersal, vicariance, and the position of *Lepidogalaxias salamandroides*. *Systematic Biology*, *49*, 777–795. https://doi.org/10.1080/106351500750049824

Webster, M. M., Atton, N., Ward, A. J. W., & Hart, P. J. B. (2007). Turbidity and foraging rate in threespine sticklebacks: The importance of visual and chemical prey cues. *Behaviour*, *144*, 1347–1360. https://doi.org/10.1163/156853907782418222

Weiffen, M., Möller, B., Mauck, B., & Dehnhardt, G. (2006). Effect of water turbidity on the visual acuity of harbor seals (*Phoca vitulina*). *Vision Research*, *46*, 1777–1783. https://doi.org/10.1016/j.visres.2005.08.015

Wenger, A. S., Harvey, E., Wilson, S., Rawson, C., Newman, S. J., Clarke, D., … Evans, R. D. (2017). A critical analysis of the direct effects of dredging on fish. *Fish and Fisheries*, *18*, 967–985. https://doi.org/10.1111/faf.12218

Westby, G. W. M. (1988). The ecology, discharge diversity and predatory behaviour of gymnotiforme electric fish in the coastal streams of French Guiana. *Behavioral Ecology and Sociobiology*, *22*, 341–354. https://doi.org/10.1007/BF00295103

Weyhenmeyer, G. A., Muller, R. A., Norman, M., & Tranvik, L. J. (2016). Sensitivity of freshwaters to browning in response to future climate change. *Climatic Change*, *134*, 225–239. https://doi.org/10.1007/s10584-015-1514-z

DATA SOURCES

Abrahams, M. V., Bassett, D. K., & Montgomery, J. C. (2017). Sensory biology as a risk factor for invasion success and native fish decline. *Transactions of the American Fisheries Society*, *146*, 1238–1244. https://doi.org/10.1080/00028487.2017.1353545

Abrahams, M. V., & Kattenfeld, M. G. (1997). The role of turbidity as a constraint on predator-prey interactions in aquatic environments. *Behavioural Ecology and Sociobiology*, *40*, 169–174. https://doi.org/10.1007/s002650050330

Becker, L. J. S. (2012). *Effects of turbidity on anti-predator response and foraging behavior in the fountain darter*, Etheostoma fonticola (Thesis). Texas State University.

Benfield, M. C., & Minello, T. J. (1996). Relative effects of turbidity and light intensity on reactive distance and feeding of an estuarine fish. *Environmental Biology of Fishes*, *46*, 211–216. https://doi.org/10.1007/BF00005223

Boehlert, G. W., & Morgan, J. B. (1985). Turbidity enhances feeding abilities of larval Pacific herring, *Clupea harengus pallasi*. *Hydrobiologia*, *123*, 161–170. https://doi.org/10.1007/BF00018978

Breitburg, D. L. (1988). Effects of turbidity on prey consumption by striped bass larvae. *Transactions of the American Fisheries Society*, *117*, 72–77. https://doi.org/10.1577/1548-8659(1988)117<0072:EOTOPC>2.3.CO;2

Bricelj, V. M., & Malouf, R. E. (1984). Influence of algal and suspended sediment concentrations on the feeding physiology of the hard clam *Mercenaria mercenaria*. *Marine Biology*, *84*, 155–165. https://doi.org/10.1007/BF00393000

Butler, N. M. (1995). Effects of sediment loading on food perception and ingestion by freshwater copepods. *Marine and Freshwater Behaviour and Physiology*, *26*, 287–294. https://doi.org/10.1080/10236249509378947

Carrasco, N. K., Perissinotto, R., & Jones, S. (2013). Turbidity effects on feeding and mortality of the copepod *Acartiella natalensis* (Connell and Grindley, 1974) in the St Lucia Estuary, South Africa. *Journal of Experimental Marine Biology and Ecology*, *446*, 45–51. https://doi.org/10.1016/j.jembe.2013.04.016

Carrasco, N. K., Perissinotto, R., & Miranda, N. A. F. (2007). Effects of silt loading on the feeding and mortality of the mysid *Mesopodopsis africana* in the St. Lucia Estuary, South Africa. *Journal of Experimental Marine Biology and Ecology*, *352*, 152–164. https://doi.org/10.1016/j.jembe.2007.07.006

Carter, M. W., Shoup, D. E., Dettmers, J. M., & Wahl, D. H. (2010). Effects of turbidity and cover on prey selectivity of adult smallmouth bass. *Transactions of the American Fisheries Society*, *139*, 353–361. https://doi.org/10.1577/T08-159.1

Chacin, D. H., & Stallings, C. D. (2016). Disentangling fine- and broad-scale effects of habitat on predator-prey interactions. *Journal of Experimental Marine Biology and Ecology*, *483*, 10–19. https://doi.org/10.1016/j.jembe.2016.05.008

De Robertis, A., Ryer, C. H., Veloza, A., & Brodeur, R. D. (2003). Differential effects of turbidity on prey consumption of piscivorous and planktivorous fish. *Canadian Journal of Fisheries and Aquatic Sciences*, *60*, 1517–1526. https://doi.org/10.1139/f03-123

DeVanna, K. M., Armenio, P. M., Barrett, C. A., & Mayer, C. M. (2011). Invasive ecosystem engineers on soft sediment change the habitat preferences of native mayflies and their availability to predators. *Freshwater Biology*, *56*, 2448–2458. https://doi.org/10.1111/j.1365-2427.2011.02668.x

Figueiredo, B. R. S., Mormul, R. P., & Benedito, E. (2013). Non-additive effects of macrophyte cover and turbidity on predator-prey interactions involving an invertivorous fish and different prey types. *Hydrobiologia*, *716*, 21–28. https://doi.org/10.1007/s10750-013-1540-7

Figueiredo, B. R. S., Mormul, R. P., & Benedito, E. (2015). Structural complexity and turbidity do not interact to influence predation rate and prey selectivity by a small visually feeding fish. *Marine and Freshwater Research*, *66*, 170–176. https://doi.org/10.1071/MF14030

Figueiredo, B. R. S., Mormul, R. P., Chapman, B. B., Lolis, L. A., Fiori, L. F., & Benedito, E. (2016). Turbidity amplifies the non-lethal effects of predation and affects the foraging success of characid fish shoals. *Freshwater Biology*, *61*, 293–300. https://doi.org/10.1111/fwb.12703

Greer, M. J. C., Crow, S. K., Hicks, A. S., & Closs, G. P. (2015). The effects of suspended sediment on brown trout (*Salmo trutta*) feeding and respiration after macrophyte control. *New Zealand Journal of Marine and Freshwater Research*, *49*, 278–285. https://doi.org/10.1080/00288330.2015.1013140

Gregory, R. S., & Levings, C. D. (1996). The effects of turbidity and vegetation on the risk of juvenile salmonids, *Oncorhynchus* spp., to predation by adult cutthroat trout, *O. Clarkii*. *Environmental Biology of Fishes*, *47*, 279–288. https://doi.org/10.1007/BF00000500

Gregory, R. S., & Northcote, T. G. (1993). Surface, planktonic, and benthic foraging by juvenile chinook salmon (*Oncorhynchus tshawytscha*) in turbid laboratory conditions. *Canadian Journal of Fisheries and Aquatic Sciences*, *50*, 233–240. https://doi.org/10.1139/f93-026

Harvey, B. C., & White, J. L. (2008). Use of benthic prey by salmonids under turbid conditions in a laboratory stream. *Transactions of the American Fisheries Society*, *137*, 1756–1763. https://doi.org/10.1577/T08-039.1

Huenemann, T. W., Dibble, E. D., & Fleming, J. P. (2012). Influence of turbidity on the foraging of largemouth bass. *Transactions of the American Fisheries Society*, *141*, 107–111. https://doi.org/10.1080/00028487.2011.651554

Jacobsen, L., Berg, S., Baktoft, H., Nilsson, P. A., & Skov, C. (2014). The effect of turbidity and prey fish density on consumption rates of piscivorous Eurasian perch *Perca fluviatilis*. *Journal of Limnology*, *73*, 187–190. https://doi.org/10.4081/jlimnol.2014.837

Jones, S., Carrasco, N. K., & Perissinotto, R. (2015). Turbidity effects on the feeding, respiration and mortality of the copepod *Pseudodiaptomus stuhlmanni* in the St Lucia Estuary, South Africa. *Journal of Experimental Marine Biology and Ecology*, *469*, 63–68. https://doi.org/10.1016/j.jembe.2015.04.015

Jonsson, M., Hylander, S., Ranaker, L., Nilsson, P. A., & Bronmark, C. (2011). Foraging success of juvenile pike *Esox lucius* depends on visual conditions and prey pigmentation. *Journal of Fish Biology*, *79*, 290–297. https://doi.org/10.1111/j.1095-8649.2011.03004.x

Jönsson, M., Ranåker, L., Nicolle, A., Ljungberg, P., Fagerberg, T., Hylander, S., … Modenutti, B. (2011). Glacial clay affects foraging performance in a Patagonian fish and cladoceran. *Hydrobiologia*, *663*, 101–108. https://doi.org/10.1007/s10750-010-0557-4

Kang, H. K. (2012). Effects of suspended sediments on reproductive responses of *Paracalanus* sp. (Copepoda: Calanoida) in the laboratory. *Journal of Plankton Research*, *34*, 626–635. https://doi.org/10.1093/plankt/fbs033

Kellogg, K. A., & Leipzig-Scott, P. (2017). The influence of turbidity on prey consumption in the tessellated darter. *Transactions of the American Fisheries Society*, *146*, 508–511. https://doi.org/10.1080/00028487.2017.1281844

Kirk, K. L. (1991). Suspended clay reduces *Daphnia* feeding rate – Behavioral mechanisms. *Freshwater Biology*, *25*, 357–365. https://doi.org/10.1111/j.1365-2427.1991.tb00498.x

Lemke, J. L., & Ryer, C. H. (2006). Relative predation vulnerability of three juvenile (Age-0) North Pacific flatfish species: Possible influence of nursery-specific predation pressures. *Marine Ecology Progress Series*, *328*, 267–273. https://doi.org/10.3354/meps328267

Ljunggren, L., & Sandstrom, A. (2007). Influence of visual conditions on foraging and growth of juvenile fishes with dissimilar sensory physiology. *Journal of Fish Biology*, *70*, 1319–1334. https://doi.org/10.1111/j.1095-8649.2007.01412.x

Lowe, M. L., Morrison, M. A., & Taylor, R. B. (2015). Harmful effects of sediment-induced turbidity on juvenile fish in estuaries. *Marine Ecology Progress Series*, *539*, 241–254. https://doi.org/10.3354/meps11496

Lunt, J., & Smee, D. L. (2014). Turbidity influences trophic interactions in estuaries. *Limnology and Oceanography*, *59*, 2002–2012. https://doi.org/10.4319/lo.2014.59.6.2002

Lunt, J., & Smee, D. L. (2015). Turbidity interferes with foraging success of visual but not chemosensory predators. *PeerJ*, *3*, e1212. https://doi.org/10.7717/peerj.1212

Macia, A., Abrantes, K. G. S., & Paula, J. (2003). Thorn fish *Terapon jarbua* (Forskal) predation on juvenile white shrimp *Penaeus indicus* H. Milne Edwards and brown shrimp *Metapenaeus monoceros* (Fabricius): The effect of turbidity, prey density, substrate type and pneumatophore density. *Journal of Experimental Marine Biology and Ecology*, *291*, 29–56. https://doi.org/10.1016/S0022-0981(03)00097-2e

Meager, J. J., Solbakken, T., Utne-Palm, A. C., & Oen, T. (2005). Effects of turbidity on the reactive distance, search time, and foraging success of juvenile Atlantic cod (*Gadus morhua*). *Canadian Journal of Fisheries and Aquatic Sciences*, *62*, 1978–1984. https://doi.org/10.1139/F05-104

Minello, T. J., Zimmerman, R. J., & Martinez, E. X. (1987). Fish predation on juvenile brown shrimp, *Penaeus aztecus* Ives – Effects of turbidity and substratum on predation rates. *Fishery Bulletin*, *85*, 59–70.

Miner, J. G., & Stein, R. A. (1993). Interactive influence of turbidity and light on larval bluegill (*Lepomis macrochirus*) foraging. *Canadian Journal of Fisheries and Aquatic Sciences*, *50*, 781–788. https://doi.org/10.1139/f93-090

Monteleone, D. M., & Houde, E. D. (1992). Vulnerability of striped bass *Morone saxatilis* Waldbaum eggs and larvae to predation by juvenile white perch *Morone americana* Gmelin. *Journal of Experimental Marine Biology and Ecology*, *158*, 93–104. https://doi.org/10.1016/0022-0981(92)90310-7

Parkinson, M. C., & Booth, A. J. (2011). Effect of turbidity on the foraging success of *Glossogobius callidus* (Teleostei: Gobiidae). *African Journal of Aquatic Science*, *36*, 213–216. https://doi.org/10.2989/16085914.2011.589120

Pekcan-Hekim, Z., Joensuu, L., & Horppila, J. (2013). Predation by a visual planktivore perch (*Perca fluviatilis*) in a turbulent and turbid environment. *Canadian Journal of Fisheries and Aquatic Sciences*, *70*, 854–859. https://doi.org/10.1139/cjfas-2012-0466

Pekcan-Hekim, Z., & Lappalainen, J. (2006). Effects of clay turbidity and density of pikeperch (*Sander lucioperca*) larvae on predation by perch (*Perca fluviatilis*). *Naturwissenshaften*, *93*, 356–359. https://doi.org/10.1007/s00114-006-0114-1

Quesenberry, N. J., Allen, P. J., & Cech, J. J. (2007). The influence of turbidity on three-spined stickleback foraging. *Journal of Fish Biology*, *70*, 965–972. https://doi.org/10.1111/j.1095-8649.2007.01350.x

Ranåker, L., Persson, J., Jönsson, M., Nilsson, P. A., & Brönmark, C. (2014). Piscivore-prey fish interactions: Mechanisms behind diurnal patterns in prey selectivity in brown and clear water. *PLoS ONE*, *9*, e102002. https://doi.org/10.1371/journal.pone.0102002

Rowe, D. K., & Dean, T. L. (1998). Effects of turbidity on the feeding ability of the juvenile migrant stage of six New Zealand freshwater fish species. *New Zealand Journal of Marine and Freshwater Research*, *32*, 21–29. https://doi.org/10.1080/00288330.1998.9516803

Salonen, M., & Engström-Öst, J. (2010). Prey capture of pike *Esox lucius* larvae in turbid water. *Journal of Fish Biology*, *76*, 2591–2596. https://doi.org/10.1111/j.1095-8649.2010.02647.x

Shoup, D. E., & Lane, W. D. (2015). Effects of turbidity on prey selection and foraging return of adult largemouth bass in reservoirs. *North American Journal of Fisheries Management*, *35*, 913–924. https://doi.org/10.1080/02755947.2015.1067260

Shoup, D. E., & Wahl, D. H. (2009). The effects of turbidity on prey selection by piscivorous largemouth bass. *Transactions of the American Fisheries Society*, *138*, 1018–1027. https://doi.org/10.1577/T09-015.1

Sirois, P., & Dodson, J. J. (2000). Influence of turbidity, food density and parasites on the ingestion and growth of larval rainbow smelt *Osmerus mordax* in an estuarine turbidity maximum. *Marine Ecology Progress Series*, *193*, 167–179. https://doi.org/10.3354/meps193167

Sohel, S., Mattila, J., & Lindstrom, K. (2017). Effects of turbidity on prey choice of three-spined stickleback *Gasterosteus aculeatus*. *Marine Ecology Progress Series*, *566*, 159–167. https://doi.org/10.3354/meps12014

Sontag, D. M. (2013). *Predation, turbidity, and other factors influencing juvenile Salmonid survival in the lower Snake River* (Thesis). Eastern Washington University.

Steinmetz, J., Cashmore, J., & Soluk, D. A. (2002). Population viability of mottled sculpin (*Cottus bairdi*) in Black Partridge Creek (Report). *University of Illinois*.

Stuart-Smith, R. D., Stuart-Smith, J. F., White, R. W. G., & Barmuta, L. A. (2007). The effects of turbidity and complex habitats on the feeding of a galaxiid fish are clear and simple. *Marine and Freshwater Research*, *58*, 429–435. https://doi.org/10.1071/MF06240

Sweka, J. A., & Hartman, K. J. (2001). Effects of turbidity on prey consumption and growth in brook trout and implications for bioenergetics modeling. *Canadian Journal of Fisheries and Aquatic Sciences*, *58*, 386–393. https://doi.org/10.1139/cjfas-58-2-386

Vandenbyllaardt, L., Ward, F. J., Braekevelt, C. R., & McIntyre, D. B. (1991). Relationships between turbidity, piscivory, and development of the retina in juvenile walleyes. *Transactions of the American Fisheries Society*, *120*, 382–390. https://doi.org/10.1577/1548-8659(1991)120<0382:RBTPAD>2.3.CO;2

Vinyard, G. L., & Yuan, A. C. (1996). Effects of turbidity on feeding rates of Lahontan cutthroat trout (*Oncorhynchus clarki henshawi*) and Lahontan redside shiner (*Richardsonius egregius*). *Great Basin Naturalist*, *56*, 157–161.

Wellington, C. G., Mayer, C. M., Bossenbroek, J. M., & Stroh, N. A. (2010). Effects of turbidity and prey density on the foraging success of age 0 year yellow perch *Perca flavescens*. *Journal of Fish Biology*, *76*, 1729–1741. https://doi.org/10.1111/j.1095-8649.2010.02612.x

Wenger, A. S., McCormick, M. I., McLeod, I. M., & Jones, G. P. (2013). Suspended sediment alters predator-prey interactions between two coral reef fishes. *Coral Reefs*, *32*, 369–374. https://doi.org/10.1007/s00338-012-0991-z

Zamor, R. M., & Grossman, G. D. (2007). Turbidity affects foraging success of drift-feeding rosyside dace. *Transactions of the American Fisheries Society*, *136*, 167–176. https://doi.org/10.1577/T050316.1

How to cite this article: Ortega JCG, Figueiredo BRS, da Graça WJ, Agostinho AA, Bini LM. Negative effect of turbidity on prey capture for both visual and non-visual aquatic predators. *J Anim Ecol*. 2020;89:2427–2439. https://doi.org/10.1111/1365-2656.13329