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Review

Ecological effects of aquaculture on living and non-living suspended fractions of the water column: A meta-analysis

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ABSTRACT

The effects of aquaculture on the ecology of the water column have been extensively studied in the last two decades. However, to date, it has not been possible to extrapolate homogeneous information from the peer-reviewed literature. In the present study, 68 peer-reviewed articles were analysed and about 1087 study cases were used to test whether worldwide cultivations of aquatic organisms (shrimps, fish, bivalves and polyculture) have a differential effect on living and non-living fractions of the water column (suspended matter, chlorophyll-*a*, particulate organic carbon, nitrogen and phosphorus, bacteria and plankton). Meta-analysis feasibility depends on obtaining an estimate of the effect size from every study, and the most common measure of effect size (Hedges' *d*) is the difference between means of controls and impacts standardised by dividing by the pooled standard deviation. Shrimp, fish and bivalve cultivation differentially affected water column dynamics, with a general major impact on bacteria and phytoplankton. In addition, results showed that the water column dynamics are probably affected by organic aquaculture loading but, due to the substantial heterogeneity across studies, the information available on the effects can be considered partially flawed and therefore not sufficient to either support or exclude the notion that different forms of aquaculture affect ecological processes of the water column.

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Contents

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1. Introduction

Aquaculture in every form affects its surrounding environment to some degree, and as it is constantly growing, constitutes another major human impact on coastal ecosystems. There is already considerable knowledge about the effect of aquaculture on sediments, which are seen to provide the best evidence of anthropogenic disturbance (Kalantzi and Karakassis, 2006). In contrast, effects on the water column have often been neglected, because it has always been considered less important than sediments (*sensu* Sarà, 2007). This is quite a short-sighted approach, however, as the water column represents the physical vector of pollution loading, and a greater comprehension of its dynamics would allow us to obtain a clearer vision of the natural world. A more precise knowledge of each ecological variable involved in changes to the environment would enhance our capacity to challenge the detrimental effects potentially generated by aquaculture in coastal ecosystems. Although some information is available regarding the effects of aquaculture on the water column, it comes in the form of thousands of sources, is in no way organised, and is thus hard to access for research purposes. For example, a recent review conducted across the literature on aquaculture effects on dissolved nutrients (Sarà, 2007) highlighted that from thousands of citations found on the Internet, it was really only possible to obtain suitable information from a few tens of peer-reviewed papers. The meta-analytical approach of this review revealed the different response of each nutrient to farming enrichment but, apart from an effect of cultivated species and ecosystem type on nutrient pools, no correlation was found with cultivated biomass or the number of cultivated species. This went some way towards contradicting the common view that cultivated biomass is most likely the primary cause of environmental effects measurable through the nutrient pool (Gowen and Bradbury, 1987; Beveridge, 1996). Thus, thanks to quantitative reviewing techniques, it was possible to disprove this view, which had prevailed for the last two decades, while highlighting other important aspects (e.g. lack of a logical experimental design approach and hydrodynamics effect in dispersal; *sensu* Sarà et al., 2006; Sarà, 2007, in press). Questions arising from this first review (Sarà, 2007) concern the potential effects of aquaculture on suspended fractions of the water column. The suspended material produced from aquaculture is mostly composed of particles greater than a micron. These, once reaching the water column, may induce changes in many chemical and biochemical features and important ecological rates like bacterial and primary productions. Organic particles released from aquaculture facilities can induce deviations from natural common patterns of structures and compositions of suspended (Pitta et al., 1999; Modica et al., 2006), fouling (Angel and Spanier, 2002; Sarà et al., 2007; Mannino and Sarà, in press) and benthic communities (Ye et al., 1991) in the surrounding environments. The suspended material and its particulate organic fraction, representing the core of food availability to most of the primary consumers in aquatic environments (Valiela, 1984; Islam, 2005; Sarà, 2006), can trigger important deviations in ecological processes, ultimately affecting the biodiversity levels of the water bodies (Gowen and Bradbury, 1987). Thus, although effects triggered by particulate loading have only been descriptively reviewed and assumed to be high, detrimental and measurable (Gowen and Bradbury, 1987; Sarà et al., 2006), they have never been quantitatively reviewed across the peer-reviewed literature. Recent review opinions (Rosenberg, 2005) emphasise that the standardised quantitative measures of an effect across the literature can highlight important ecological cues, identify areas with information gaps requiring further investigation and can be used as a tool for revising management criteria of natural resources for better regulation of their exploitation. A meta-analysis enables the quantification of the overall effects across the literature, and is therefore deployed in the present paper to investigate (1) the magnitude of effects generated from aquaculture facilities on suspended living and non-living fractions, (2) which variable commonly used can best describe the effects and lastly (3) areas with information gaps.

2. Materials and methods

2.1. *Literature search, meta-analysis criteria and data eligibility*

Data on the effects of aquaculture loadings on living and non-living variables of the water column were obtained from a literature search using mainly the Aquatic Science and Fisheries Abstracts and some other databases, such as Bio-One or Zoological Records available on-line. The scope of this search ranged between 1980 and the present, and when grey literature, internal reports or unpublished data were not readily available on-line, I personally contacted a number of

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authors to obtain their publications, though to no great degree (38%) of success. The search criteria were similar to those adopted in Sarà (2007). Initially prominent or substantial key words were used, such as “aquaculture and impact”. This method revealed a very large number of publications (more than 700 published by March 2007; e.g. ISI Web of Science) stemming from all possible sources, most of which were immediately discarded, because of their low accessibility to a large audience (internal institutional reports or symposium proceedings and/or language barriers; some of these reports were written only in French, Italian, Chinese, Japanese, Russian, etc.). Due to these hindrances, I therefore focused only on widespread and easily accessible sources, such as those published in peer-reviewed journals after 1985. While the potential loss of useful data found in grey literature and internal sources is an important meta-analytic concern, it is hoped that considering only peer-reviewed articles ensured consistently high-quality data, such as those that are often not found in other (perhaps less established) sources. As major journals tend to publish only significant results (*sensu* Kotze et al., 2004), thereby generating a potential publication bias and distorting the direction of true effect (Hedges and Olkin, 1985), the peer-review process is the best method to reduce the likelihood of potential quality biases in reviewing.

The search process resulted in about 140 peer-reviewed articles, which were then checked against the required criteria for meta-analysis. Unlike descriptive reviews, meta-analysis requires the quantitative measure of variance to be stated by each study (Hedges and Olkin, 1985). I therefore obtained the means for the control and treatment groups, their standard deviations and their sample sizes (Hedges and Olkin, 1985) in order to calculate meta-analytic statistics. In the present meta-analysis, control groups are represented by data collected from areas individuated by each author, where effects of aquaculture facilities were not present. The treatment group is represented by data collected from areas, sites, ponds or tanks used by each author for testing the effects of experimental response variables (hereafter referred to as “impact”). Thus, the first screening of these studies allowed me to include all papers reporting at least means, deviations and sample sizes for both controls and impacts. In 50% of the studies it was not possible to extrapolate deviations or sample sizes, and they were therefore excluded from this meta-analysis.

2.2. *Meta-analysis methodology*

Meta-analysis feasibility (Hedges and Olkin, 1985; Cooper and Hedges, 1994; Rosenberg et al., 2000; Scheiner and Gurevitch, 2001) depends on obtaining an estimate of the effect size (i.e. the magnitude of the effect of interest; but see Hedges and Olkin, 1985 for computational formulae) from every study. The present paper was concerned with the differential effect exerted by each organism (shrimps [SHR], fish [FISH], bivalves [BIV] and polyculture [POLY]) cultivated on living and non-living variables of the water column (see Table 1 for a list of variables and acronyms). Thus I categorised a priori studies as a function of aquaculture type (but see Table 1). The most common measure of effect size is the difference between two means (i.e. controls and impacts), divided by their pooled standard deviation to standardise the effect size (Cohen, 1969; Scheiner and Gurevitch, 2001). Thus, the effect size is the difference in standard deviation units between controls and impacts (Scheiner and Gurevitch, 2001). Because the effect size is not dependent on sample size, meta-procedures are not subject to the problems of different weights among larger and smaller studies (i.e. with larger and smaller sample sizes) (Scheiner and Gurevitch, 2001).

This standardised mean difference, Hedges’ d (hereafter called simply d), is conventionally considered to be “large” for values of 0.8 or higher (i.e. the impact group mean is eight-tenths of a standard deviation greater than that of the control group), “medium” for values of 0.5 and “small” when d equals 0.2 (Cohen, 1969). The usual method is to provide the 95% confidence intervals (CI) for d as well. When CI overlaps zero, there is no significant difference between controls and impacts. Another fundamental part of the meta-analysis is to calculate the cumulative effect size representing the overall magnitude of the effect present in all studies. When the calculated CI of the cumulative effect size does not bracket zero, it is considered to be significantly different from zero ($p<0.05$). The magnitude scale for the cumulative effect size is that proposed by Cohen (1969). The null hypothesis that all effect sizes are equal, as opposed to the alternative hypothesis that at least one of the true effect sizes in a series of comparisons differs for the rest, can be tested with the homogeneity statistics Q, which has an asymptotic χ^2 distribution with $k-1$ degrees of freedom (Scheiner and Gurevitch, 2001). Consequently, the greater the value of Q, the greater the heterogeneity in effect sizes among comparisons (Hedges and Olkin, 1985; Scheiner and Gurevitch, 2001). Thus, for non-significant Q values ($p>0.05$), we interpret results that studies in a certain category are homogeneous (i.e. the effect sizes differ by no more than would be expected due to random sampling variation). Alternatively, significant Q values ($p<0.05$) mean that studies in a certain category exhibited more variation than can be attributed simply to sampling error (i.e. there is a higher effect [the hypothesised effect] dictating the differences among controls and impacts within each category). The meta-analysis approach used here was similar to that reported in Hedges and Olkin (1985) and Scheiner and Gurevitch (2001). I first tested whether all studies shared a common effect size, but having established that the hypothesis of equality among effect sizes was rejected (i.e. studies were highly heterogeneous, only not differing for the sampling errors), I analysed the data in groups. In so doing, I estimated the singular overall effect of aquaculture on each variable and the effect on each cultivated organism.

Means and sample size data were taken from publication tables and figures. Data from figure formats were captured from plots using TechDig (rel. 2.0d; R.B. Jones, 1998), of which the error margin was estimated at around 0.2–0.5%.

Once I had obtained all the data and had entered it into an MS Excel spreadsheet, I standardised the entire dataset for both the type of deviation (standard deviation or standard error) and the measure units. In the present meta-analysis, I transformed all deviations to standard deviations using the calculator included in the MetaWin 2.0 software (Rosenberg et al., 2000). Since one of the major concerns of a

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meta-analyst is publication bias (i.e. the selective publication of articles showing certain types of results in preference to those showing other types of results, substantially increasing the risk of distortion of the true direction of the effect), I plotted the *d* normal quantiles versus the standardised mean effect (Rosenberg et al., 2000). The normal quantile plot also allowed me to study possible deviations of the studied cases. Furthermore, the Rosenthal index enabled me to estimate the fail-safe number, i.e. the number of non-significant, unpublished, low accessible or missing studies that would need to be added to a meta-analytic dataset in order to change the results of the meta-analysis from significant to non-significant (Rosenthal, 1979; Rosenberg et al., 2000; Kotze et al., 2004). All calculations were carried out using MS Excel and MetaWin 2.0 (Rosenberg et al., 2000).

3. Results

3.1. *Overview of the literature*

The range of aquaculture literature consisted of 68 peer-reviewed papers easily accessible via the WWW through all electronic databases available to all scientific audiences (Tables 1 and 2). Of the variables analysed in the present study, 1087 study cases were produced, coming from several different papers; total suspended matter (TSM), chlorophyll-*a* (CHL-*a*), some features of bacteria and phytoplankton accounted for most of the cases. In contrast, some variables, like particulate phosphorus or zooplankton, were studied in only a few instances, producing a very low number of study cases. As it was potentially incorrect to analyse them, due to the low number of cases, I tested them only for purposes of comparison with the other variables. The possible risk of publication bias or possible deviation of meta-analysis structure was investigated by means of the normal quantile plot (Fig. 1). The plot indicated no deviations from meta-analysis assumptions, showing that meta-analytic results were not invalidated by issues in the publication query or by general bias.

3.2. *TSM and its organic fraction*

The heterogeneity among studies reporting data on TSM ($\mathrm{mg\,l^{-1}}$; Table 3) was very high in all those reporting on shrimps and fish, while the overall fail-safe was low. The mean effect size was medium for fish and shrimps and quite low for bivalves.

Only 12 peer-reviewed papers reported valid data to be analysed meta-analytically regarding the organic fraction of the TSM (OSM, $\mathrm{mg\,l^{-1}}$), producing 40 study cases (Table 3). Across all papers the heterogeneity was medium and the overall fail-safe low. Shrimps (Fig. 2) were the only species having an effect on OSM, while fish (Fig. 3) and bivalves (Fig. 4) did not have any effect.

3.3. *Phytopigments*

The overall heterogeneity among studies reporting on CHL-*a* ($\mu\mathrm{g\,l^{-1}}$; Table 3) was the highest among all other variables analysed in the present study, and different for each species. Heterogeneity was higher for fish and shrimps and lower for bivalves and polyculture. The fail-safe number calculated for CHL-*a* was the highest among all variables. The effect of species on CHL-*a* was high for shrimps (Fig. 2), low to medium for fish (Fig. 3) and bivalves (Fig. 4) and absent for polyculture (Table 3). The 28 study cases reporting on phaeopigments (PHAEO, $\mu\mathrm{g\,l^{-1}}$; Table 3) showed quite a low heterogeneity level among studies, a low fail-safe value and a significant size effect exerted by shrimps and zero by fish.

3.4. *Particulate variables: carbon, nitrogen and phosphorus and biopolymeric fractions*

The nine papers reporting on particulate organic carbon (POC, $\mu\mathrm{g\,l^{-1}}$; Table 3) produced 61 study cases. The overall

Table 1 – A synthesis across the literature with papers reporting on each variable (Papers), how many times each variable has been used by authors with respect to the total papers found (% of the total [#68]), number of study cases considered for each variable (Study cases), heterogeneity values across studies (Heterogeneity) and fail-safe number for each variable (Rosenthal)

Variable	Papers	% of the total (#68)	Study cases	Heterogeneity	Rosenthal
Total suspended matter (TSM)	30	44	130	1047.11	1947.20
Organic suspended matter (OSM)	13	19	41	349.78	1438.00
Chlorophyll-*a* (CHL-*a*)	56	82	249	1213.19	22,378.10
Phaeopigments (PHAEO)	3	4	29	155.39	120.90
Particulate organic carbon (POC)	9	13	61	421.13	6.1
Particulate organic nitrogen (PON)	6	9	47	311.10	599.80
Particulate organic phosphorus (POP)	3	4	17	59.36	470.10
Biopolymeric carbon (BPC)	4	6	36	57.12	188.60
Total bacterial abundance (BACT AB)	11	17	169	445.24	5838.80
Total bacterial production (BACT PP)	6	9	129	295.55	1794.20
Bacterial μu (BACT μu)	3	4	17	15.41	0.00
Total phytoplankton abundance (PHYTO AB)	5	7	103	852.62	0.00
Total phytoplankton production (PHYTO PP)	9	13	43	826.40	1377.00
Zooplankton abundance (ZOO)	3	4	16	215.60	588.77
			1087	7509.46	

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Table 2 – List of peer-reviewed papers published from 1982 to 2005 included in the present meta-analysis, shared for each type of cultivated species

#	Study	Species	Studied variables
1	Ball et al. (1997)	BIV	CHL-*a*
2	Biao et al. (2004)	BIV	CHL-*a*
3	La Rosa et al. (2002)	BIV	CHL-a, BPC, BACT AB, BACT PP
4	Lin et al. (2005)	BIV	CHL-*a*
5	Mazzola and Sarà (2001)	BIV	CHL-a, BPC, POC
6	Ogilvie et al. (2000)	BIV	CHL-*a*
7	Pietros and Rice (2003)	BIV	TSM, OSM, CHL-*a*
8	Reitan et al. (2002)	BIV	CHL-*a*, PHYTO PP
9	Soto and Mena (1999)	BIV	CHL-*a*
10	Stirling and Okumus (1995)	BIV	TSM, OSM, CHL-a
11	Vacelet et al. (1996)	BIV	TSM, OSM, CHL-*a*, PHAEO, POC, PON, BACT AB
1	Alongi et al. (2003)	FISH	TSM, CHL-*a*, POC, PON, POP, BACT AB, BACT PP, BACT μ, PHYTO PP
2	Angel et al. (2002)	FISH	CHL-*a*
3	Azim et al. (2002a)	FISH	CHL-*a*, PHYTO AB, ZOO
4	Azim et al. (2002b)	FISH	CHL-*a*
5	Azim et al. (2003)	FISH	CHL-*a*
6	Boaventura et al. (1997)	FISH	TSM
7	Chakraborty et al. (2004)	FISH	BACT AB, PHYTO PP
8	Figueredo and Giani (2005)	FISH	CHL-*a*
9	Galope-Bacaltos et al. (1999)	FISH	CHL-*a*, POC
10	Green et al. (2002)	FISH	CHL-*a*
11	Guo and Li (2003)	FISH	CHL-*a*
12	La Rosa et al. (2002)	FISH	CHL-*a*, BPC, BACT AB, BACT PP
13	Lin et al. (2001)	FISH	TSM, OSM, CHL-*a*
14	Mazzola and Sarà (2001)	FISH	CHL-*a*, BPC, POC
15	McKinnon et al. (2002)	FISH	TSM, CHL-*a*, PON, POP, BACT AB, BACT PP, BACT μ, PHYTO PP
16	Middleton and Reeder (2003)	FISH	CHL-*a*
17	Modica et al. (2006)	FISH	TSM, CHL-*a*, BPC
18	Motzkin et al. (1982)	FISH	CHL-*a*, PHYTO AB, PHYTO PP
19	Nordvarg and Johansson (2002)	FISH	CHL-*a*
20	Pitta et al. (1999)	FISH	CHL-*a*, POC, PON
21	Pitta et al. (2005)	FISH	CHL-*a*, PHAEO, POC, PON, BACT AB, PHYTO AB
22	Sakami et al. (2003)	FISH	CHL-*a*, BACT PP
23	Saha and Jana (2003)	FISH	BACT AB, PHYTO AB, PHYTO PP, ZOO
24	Seo and Boyd (2001)	FISH	TSM, CHL-*a*, PHYTO PP
25	Soto and Mena (1999)	FISH	CHL-*a*
26	Soto and Norambuena (2004)	FISH	CHL-*a*
27	Sumagaysay-Chavoso et al. (2004)	FISH	CHL-*a*
28	Tatrai et al. (2003)	FISH	CHL-*a*
29	Tovar et al. (2000a)	FISH	TSM, OSM
30	Tovar et al. (2000b)	FISH	TSM
31	Wahab and Stirling (1991)	FISH	TSM, OSM
32	Watson et al. (2003)	FISH	CHL-*a*, PHYTO AB, ZOO
33	Wu et al. (1994)	FISH	TSM, CHL-a
34	Yi and Lin (2001)	FISH	TSM, OSM
35	Zambrano et al. (1999)	FISH	TSM, OSM, CHL-*a*
1	Azim et al. (2002c)	POLY	CHL-*a*
2	Rothuis et al. (1998)	POLY	CHL-*a*
3	Saha and Jana (2003)	POLY	BACT AB, PHYTO AB, PHYTO PP, ZOO
4	Soto and Mena (1999)	POLY	CHL-*a*
5	Wahab et al. (2003)	POLY	CHL-*a*
1	Alongi et al. (1999)	SHR	TSM, BACT AB, BACT PP, BACT μ, PHYTO PP,
2	Biao et al. (2004)	SHR	CHL-*a*
3	Burford et al. (2003a)	SHR	TSM, CHL-*a*, POC, PON, POP
4	Burford et al. (2003b)	SHR	TSM, CHL-*a*, PHAEO, POC, BACT AB
5	Chin and Ong (1997)	SHR	TSM, CHL-*a*
6	Costanzo et al. (2004)	SHR	TSM, CHL-*a*
7	Cowan et al. (1999)	SHR	CHL-*a*
8	Guerrero-Galvan et al. (1999)	SHR	TSM, OSM, CHL-*a*
9	Hopkins et al. (1995)	SHR	TSM, OSM
10	Islam et al. (2004)	SHR	TSM, CHL-*a*

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Table 2 (*continued*)

#	Study	Species	Studied variables
11	Jackson et al. (2003)	SHR	TSM
12	Jackson et al. (2004)	SHR	TSM
13	Jones et al. (2001)	SHR	TSM, OSM, CHL-*a*, PHYTO PP
14	Martin et al. (1998)	SHR	TSM, OSM, CHL-*a*, PHAEO
15	Paez-Osuna et al. (1997)	SHR	TSM, OSM, CHL-*a*
16	Samocha et al. (2004)	SHR	TSM
17	Trott and Alongi (2000)	SHR	TSM, CHL-*a*

BIV = bivalves; FISH = fish; POLY = polyculture; SHR = shrimps; and variables studied in each paper.

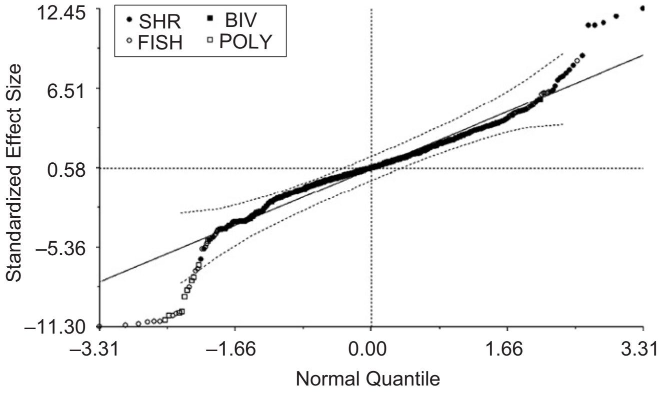

Fig. 1 – Normal quantile plot plotted using all studies ($n = 1087$) (SHR = shrimp; BIV = bivalve; POLY = polyculture).

heterogeneity was medium, higher for fish and lower for shrimps and bivalves, while the fail-safe number was the lowest among all variables considered in the present study. Shrimps had the highest mean size effect on POC among the species considered. Study cases reporting on particulate organic nitrogen (PON, $\mu g\,l^{-1}$; Table 3) numbered 47, coming from six papers. The size effect exerted by shrimps (Fig. 2) was the highest, medium for fish (Fig. 3) and not calculable for bivalves (Fig. 4) due to lack of cases. Although I could only find 17 cases reporting on particulate organic phosphorus (POP, $\mu g\,l^{-1}$; Table 3), the fail-safe value was not as low as expected, also not the heterogeneity. Both shrimps (Fig. 2) and fish (Fig. 3) showed a high mean size effect on POP. In Table 3, meta-statistics data regarding the biopolymeric carbon fraction of the particulate organic matter (BPC, $\mu g\,l^{-1}$) highlighted a non-significant effect exerted by shrimps (Fig. 2) and fish (Fig. 3), low heterogeneity and a low fail-safe value.

3.5. *Bacteria*

I found 17 useful papers reporting on bacteria community composition and structure, producing almost 300 study cases. As regards the abundance of total bacteria living in the water column (cell ml^{-1}; Table 3), the heterogeneity was medium and the fail-safe number was very high. Fish accounted for the highest heterogeneity level, while it was low for shrimps and bivalves. The size effect was significant for shrimps (Fig. 2), the highest, and fish (Fig. 3) and zero for bivalves (Fig. 4). The direction of the effect was also similar for bacteria production ($\mu g\,C\,l^{-1}$; Table 3), higher for fish and shrimps and nil for bivalves. The heterogeneity of study cases was quite low and was higher for fish, while the fail-safe value was very high.

Only in the study cases reporting on fish and shrimps was it possible to extrapolate useful data regarding *μυ* bacteria. For both the organisms the mean size effect was not significant, the heterogeneity was very low and the fail-safe value was zero.

3.6. *Plankton*

The phytoplankton abundance (cell l^{-1}; Table 3) was measured in five papers, producing 103 study cases, with a zero fail-safe number and medium–high heterogeneity among all cases. The mean size effect was not significant for fish (Fig. 3) and polyculture. Details of each phytoplankton taxon analysed across the current literature (data not reported) indicated that Bacillarioficee and Ciliates were the only groups having significant effects. Cultivated species did not have an effect on phytoplankton production (cell l^{-1}; Table 3), the heterogeneity was high for fish and very low for shrimps and bivalves, while the fail-safe number was quite high. Not many study cases were obtained from the literature reporting on zooplankton abundance (cell l^{-1}; Table 3); only 16 coming from only three papers. Nevertheless, it appeared that both fish (Fig. 3) and polyculture did not have a significant effect on the population dynamics of zooplankton. The heterogeneity among studies was higher in fish than in polyculture and the fail-safe number medium.

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Table 3 – Effect of aquaculture on each variable across all studies for each type of organism

Variable	Shrimp						Fish						Bivalve					
	df	d+	95% CI	P_{d+}	Qw	P_{Qw}	df	d+	95% CI	P_{d+}	Qw	P_{Qw}	df	d+	95% CI	P_{d+}	Qw	P_{Qw}
TSM	48	0.55	0.44/0.65	*	548.01	*	71	0.51	0.38/0.66	*	475.27	*	8	0.24	0.02/0.47	*	16.27	*
OSM	20	0.95	0.80/1.11	*	67.33	*	8	−0.18	−0.39/0.04	ns	173.77	*	10	0.25	−0.04/0.54	ns	16.03	*
CHL-*a*	49	1.11	0.99/1.21	*	259.43	*	136	0.38	0.28/0.47	*	642.26	*	39	0.28	0.13/0.44	*	93.30	*
PHAEO	22	1.15	0.84/1.46	*	105.30	*	5	−0.02	−0.28/0.22	ns	3.71	ns	–	–	–	–	–	–
POC	1	0.80	0.04/2.06	*	74.62	*	49	0.08	−0.10/0.28	ns	250.40	*	8	−0.64	−1.21/−0.08	ns	56.58	*
PON	1	2.04	0.03/4.02	*	0.15	*	43	0.53	0.53/0.75	*	248.81	ns	–	–	–	–	–	–
POP	1	1.79	1.34/1.91	*	2.78	ns	14	0.88	0.50/1.27	*	41.25	*	–	–	–	–	–	–
BPC	–	–	–	–	–	–	23	−0.38	−0.64/−0.12	ns	31.92	ns	11	−0.34	−0.73/−0.06	ns	25.13	*
BACT AB	12	1.53	0.85/2.21	*	50.60	*	111	0.65	0.54/0.75	*	307.08	*	43	0.07	−0.27/0.41	ns	67.94	*
BACT PP	12	1.29	0.65/1.93	*	43.83	*	71	0.56	0.33/0.79	*	146.59	*	43	0.10	−0.25/0.45	ns	92.41	*
BACT μ	4	0.11	−0.99/−1.21	ns	4.44	ns	11	−0.02	−0.57/0.53	ns	10.90	ns	–	–	–	–	–	–
PHYTO AB	–	–	–	–	–	–	97	0.13	−0.04/0.21	ns	414.80	ns	–	–	–	–	–	–
PHYTO PP	7	0.39	−0.34/1.11	ns	7.50	ns	30	−1.28	−1.42/1.14	ns	737.64	*	3	0.51	−0.22/1.23	ns	1.54	ns
ZOO	–	–	–	–	–	–	10	−0.17	−0.35/0.01	ns	45.30	*	–	–	–	–	–	–

	Polyculture						All					
	df	d+	95% CI	P_{d+}	Qw	P_{Qw}	df	d+	95% CI	P_{d+}	Qw	P_{Qw}
TSM	–	–	–	–	–	–	127	0.49	0.41/0.57	*	1047.11	*
OSM	–	–	–	–	–	–	38	0.50	0.39/0.61	*	349.78	*
CHL-*a*	21	0.04	−0.14/0.22	ns	52.93	*	245	0.55	0.49/0.61	*	1213.19	*
PHAEO	–	–	–	–	–	–	27	0.56	0.38/0.74	*	155.39	*
POC	–	–	–	–	–	–	58	0.30	0.16/044	*	421.13	*
PON	–	–	–	–	–	–	44	1.00	0.83/1.19	*	311.10	*
POP	–	–	–	–	–	–	15	1.44	1.21/1.68	*	59.36	*
BPC	–	–	–	–	–	–	34	−0.36	−0.58/−0.15	ns	57.12	*
BACT AB	–	–	–	–	–	–	166	0.62	0.52/0.72	*	445.24	*
BACT PP	–	–	–	–	–	–	126	0.51	0.33/0.69	*	295.55	*
BACT mu	–	–	–	–	–	–	15	0.02	−0.43/0.46	ns	15.41	ns
PHYTO AB	4	−1.94	−2.27/−1.62	ns	162.93	ns	101	−0.11	−0.19/−0.03	ns	852.62	*
PHYTO PP	–	–	–	–	–	–	40	−1.07	−1.19/−0.94	ns	826.40	*
ZOO	4	−1.90	−2.2/−0.68	ns	7.19	ns	14	−0.82	−0.96/−0.68	ns	215.60	*

df = degree of freedom; d_+ = mean size effect; 95% CI = 95% confidence interval; P_{d+} = probability level of d_+; Qw = total heterogeneity within each class; P_{Qw} = probability level of Qw; ns = not significant; * = significant.

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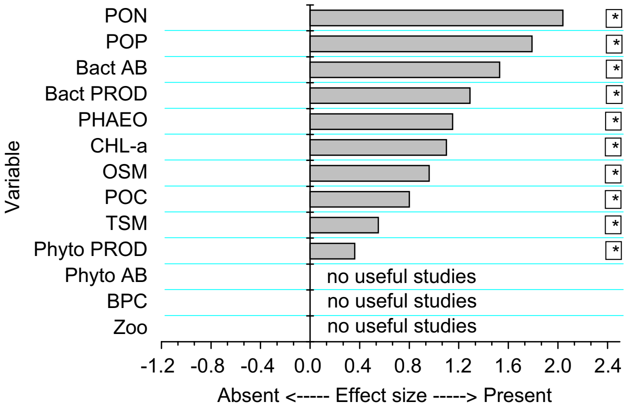

Fig. 2 – Mean ranked effect size of shrimp facilities across all studies on each variable analysed in the present meta-analysis with reported variables whose mean size effect was not possible to calculate due to no useful studies.

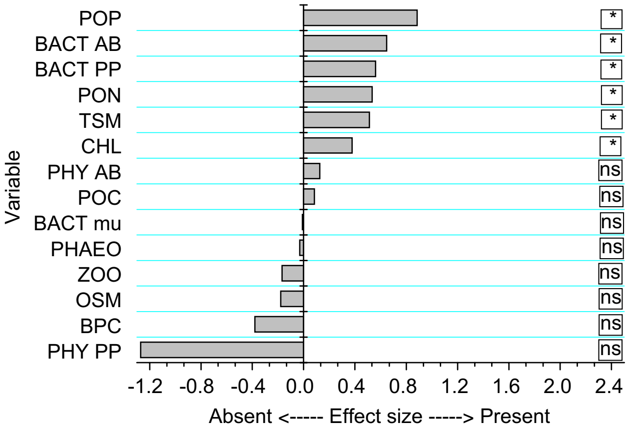

Fig. 3 – Mean ranked effect size of fish facilities across all studies on each variable analysed in the present meta-analysis with reported variables whose mean size effect was not possible to calculate due to no useful studies.

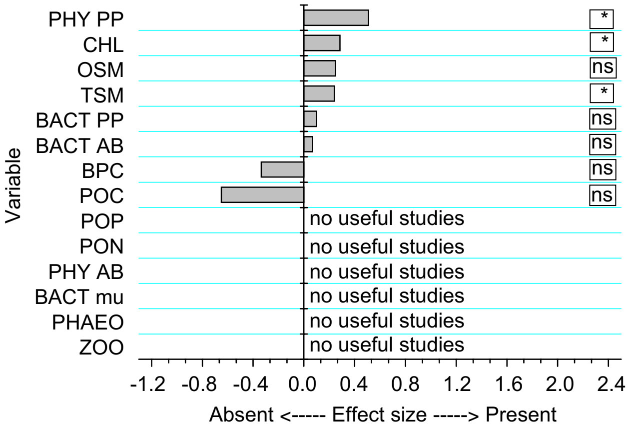

Fig. 4 – Mean ranked effect size of bivalve facilities across all studies on each variable analysed in the present meta-analysis with reported variables whose mean size effect was not possible to calculate due to no useful studies.

4. Discussion

The largest number of study cases investigating the effects on the water column concerned fish, about three times less shrimps and bivalves, while the effects dealing with polyculture were substantially under-represented (i.e. only 32 study cases). Conversely, the effect on the water column was large regarding shrimp aquaculture, small in the case of fish and bivalves and nil for polyculture (Table 3). Worldwide, shrimp and bivalve culture is carried out in many coastal populations and geographic areas, and exceeds that of fish culture in terms of cultivated biomass. It would seem that the topic in most need of research is the effect of shrimp culture on the environment.

4.1. *A particular case: shrimp aquaculture*

The effect of shrimp culture is more site-specific and linked to facilities than fish and bivalve aquaculture. The shallowness of ponds, the integration with food from the external environment, the particular physical environmental (e.g. high water temperatures) and climatic conditions of the shrimp's vocational areas (mostly SE Asia and Africa) and the integration at different levels with other human activities (e.g. pig, rice cultivation, etc.; Middendorp and Verreth, 1986) represent the main reasons for the larger effect (Islam et al., 2004). The effect was significant for all 10 suspended variables studied (no studies reporting on phytoplankton abundance, zooplankton and biopolymeric carbon were found; Fig. 2) and it was almost always very large ($d > 0.8$). Although the largest effects were detected by PON and POP, which indicates an alteration in the most important substrata for decomposing bacteria in shallow waters (Pusceddu et al., 2003), no ecological indications could be extrapolated from them due to the small number of cases. The external food integration combined with shrimp excreta and the high water temperatures would seem to explain the higher production of bacteria (Valiela, 1984). A minor effect, though quite large from a meta-analytical point of view ($0.4 < d < 0.8$), was evident for phytopigments and suspended matter. Such a result would imply that in shrimp ponds, the effects of organic loading are probably recorded more quickly by bacteria than by phytoplankton, while the larger effect of PHAEOs would highlight the ageing of the detritus in this type of system (Trott and Alongi, 2000).

4.2. *Fish aquaculture: a key role of hydrodynamics*

The effect of fish aquaculture on the water column has been studied extensively and across the literature, and authors have used all 14 variables analysed in the present study. The effect of fish aquaculture was significant only for 6 of 14 variables (Fig. 3) and, apart from POP (a few cases were found; $n = 14$), bacterial abundance, bacterial production and PON had the largest effect size. CHL-a underwent a medium effect ($d = \sim 0.4$), indicating that organic waste effluent could also have had a certain effect on phytoplankton biomass, though not as large as on bacteria. Surprisingly, TSM had a lower effect than expected, although most studies usually used this

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variable as a main descriptor. Indeed, most of the studies considered in the present meta-analysis reported data of fish farm plants in open water systems, only partially sheltered, with high depths of the water column. Thus, hydrodynamics can play an important role in the dispersion of organic waste (Cromey et al., 2002; Modica et al., 2006; Sarà et al., 2006) and the reduction of estimable effects on suspended variables of the water column.

Although hydrodynamics is invoked as the major factor in determining the extent of dispersal of organic waste in these types of system, across the current literature, few papers have reported on the hydrodynamic features of sites and little organised data exist on the estimation of effects as a function of distance from the focus of waste emission. However, some influential reviews (Gowen and Bradbury, 1987; Iwama, 1991; Enell, 1995; Iversen, 1995; Wu, 1995; Beveridge, 1996; Pillay, 2004) have attempted to establish general schemes of waste spatial dispersion: the higher the distance from the cages, the lower the detectable effects. Consequently, based on this assumption, in most studies, the effects on the water column have been surprisingly researched within only a couple of hundred of metres from the cages. This notwithstanding, indications of a new dispersal pattern are appearing in the recent literature on hydrodynamics: the greatest effects are found 100–300 m from cages, while there is an attenuation of effects due to lateral drifting or particular hydrodynamic features (*sensu* Sarà, 2006), recorded at several hundreds of metres further away from cages, possibly reaching new peaks (Cromey et al., 2002; Sarà et al., 2006). Furthermore, substantial new evidence shows that hydrodynamic conditions combined with local situations enlarge the effects of organic loading, which can also be detected up to 1 km from cages. Hydrodynamics appeared to be proportionally causative of effect magnitude as a function of distance from the cages (Sarà et al., 2006) and are therefore key to the interpretation of the results of ecological effects due to organic loading on the water column. However, in the meta-analysed dataset there is no trace of this, and attempts to link hydrodynamics and trophic effects are rarely made.

4.3. *Bivalves and polyculture: the underestimation of effects*

Apart from a significant medium effect on phytoplankton production ($d = 0.51$) and a smaller effect on TSM and CHL-*a* ($d = 0.25$ and 0.30, respectively), the effect of bivalve aquaculture on the water column (Fig. 4) was generally negligible on most of the variables (e.g. bacteria and POC). In contrast to fish and shrimps, which exerted a positive effect, bivalves appeared to reduce the magnitude of effects in the water column. There is evidence that highlights the role of the bivalve filtration pump on the water column (Dame, 1993). The ecological features of these organisms can explain the overall result of the present meta-analysis: bivalves filter water, retaining mostly detritus of different origins (Mazzola and Sarà, 2001), bacteria and phytoplankton (Dame, 1996) according to a scheme of ranked diet preference demonstrated for many bivalves (Asmus and Asmus, 1991; Sarà et al., 2003; Sarà, 2006). Results of the present meta-analysis correspond to this ranked scheme, thereby supporting indirect evidence that bivalves are not strictly phytoplankton feeders (Sarà, 2006): large aggregations of bivalves filtering water over time would exert the major effect on suspended detritus with a direct effect on POC (Smaal and Prins, 1993) and BPC (Mazzola and Sarà, 2001), reducing the differences among controls and impacts (i.e. the effect size) of these variables to almost nil (Fig. 4). The phytoplankton biomass (i.e. CHL-*a*) and its production had a significant effect size (Fig. 4), which could be explained by both the grazing effect on phytoplankton (Asmus and Asmus, 1991) and the fertilisation of the water by bivalve excreta. Bivalve excreta mainly consist of ammonia (Smaal and Prins, 1993) that enhances the local productivity (Asmus and Asmus, 1991), having, in turn, a subsequent effect on CHL-*a* and phytoplankton.

No effect was observed on polyculture due to the lack of study cases. Nevertheless, polyculture is often invoked as the panacea in the mitigation of effects in many situations (Naylor et al., 2000; Neori et al., 2000, 2004), but to date no robust experimental evidence, as far as can be determined across the current literature, has supported this view.

4.3.1. *Choice of suitable descriptors*

Choosing ecological descriptors to best describe the effects should be based on the function of the ecology of each cultivated organism; the cultivation technology and its timing should also be considered. For example, the nature of excreta loading of shrimps, fish and bivalves differs, and while shrimps and fish need external food sources, bivalves do not. Thus, effects should be prudently described using efficient and suitable descriptors for each cultivation form and every environmental condition. Across the literature there is no uniform trend in using ecological descriptors to detect the effect, although there is a quite evident "flattening" of approach. For example, CHL-*a* concentration has been widely used in shrimp, fish and bivalve cultures, while PON appears to have been used mainly in fish situations. This choice appears to be causal rather than supported by effective ecological causes. The present meta-analysis has thus highlighted which descriptor seems to best describe the effect generated by each aquaculture form, except for the fact that there is a huge information gap for most of the variables.

In shrimp culture, PON, POC and POP seem to be the most powerful descriptors of trophic processes triggered by shrimps, although no conclusive information has been obtained due to a paucity of study cases. The most utilised bacteria variables and phytoplankton biomass appeared to provide a good description of trophic processes in the shrimp ponds, indirectly supporting the idea that shrimp culture would affect the whole detritus chain, i.e. the microbial loop dynamics that, in shallow ponds, is enhanced by sedimentary contribution via resuspension (Pusceddu et al., 2003; Sarà, 2006).

In fish situations, particulate phosphorus and bacteria variables appeared to be the best descriptors, followed by PON, TSM and CHL-*a*. Thus, effects in the water column caused by fish organic loading could be sufficiently described by variables indicating a possible alteration of the nitrogen pool and quantity of particulate in the water column.

In the case of bivalves, the measure of phytoplankton production and CHL-*a* seem to be the best modus for describing trophic processes induced by their cultivation.

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The present meta-analysis also shows that the role of zooplankton in describing possible deviations from common natural patterns is not evident, because the energetic threshold required by a system to change the zooplankton abundance equilibrium would be very high.

Thus, aquaculture loading has some effect on the water column, but this effect should be studied differentially depending on the cultivated organism, and descriptors should be chosen separately for each situation. However, it is clear that the detritus cycle is part of a trophic web and the process most affected by aquaculture loading, and further studies should be addressed in that direction.

4.3.2. *Choice of the best number of replicates*

A general question in aquaculture impact studies regards the correct number of replicates to be used for each descriptor. Usually, across the aquaculture literature, research teams use a similar number of replicates for all chosen variables. To investigate this aspect, the cumulative correlation between all size effects and number of replicates both of controls and of impact is reported in Fig. 5. In general, most of the information on the effect direction is not gained with less than 8–10 replicates. For any successive increase in replicate number, the information gained remains constant up to 100. However, the cumulative information obtained by using this approach can be biased by a cumulative effect because all cases, forms and variables were compared. Thus, for each variable, I calculated the number of controls and impacts needed to detect at least a small difference among impacts and controls ($d > 0.2$; Table 4). In theory, the number of controls should be higher than the number of impacts (Black, 2001; but see Sarà, 2006). This view is not always supported in the studies analysed, because in most cases the number of controls is similar to impact, and sometimes less. Thus, from this analysis, it is possible to extrapolate some information about the sensitivity of each variable, because a lower number of replicates is needed to detect differences that would indicate a major efficiency in describing an effect.

4.3.3. *Information gaps and possible new research trends*

The main question in impact studies is often the following: is it better to investigate effects using many ecological variables with the collection of a lot of samples or to use a few of the best descriptors included in experimental design (*sensu* Underwood, 1997)? From the current analysed literature regarding the impact of different aquaculture forms on the water column, the first choice appeared more popular. Indeed, across studies, the most frequent choice is to adopt robust analytical protocols, leading researchers to analyse a lot of water column variables with a lot of samples, but very rarely, the collection of samples is arranged in a hypothesis-based rationale (Hurlbert, 1984; Underwood, 1997; Oksanen, 2001). Consequently, the range of resulting aquaculture effects on the water column is flawed, not by a lack of data availability, but by a lack of logical experimental design.

Thus, the present meta-analysis would seem to highlight an overall tendency of results: aquaculture has a general effect on the suspended fraction of the water column, which is neither new nor original, but which has been only presumed in the past rather than supported by data. An unexpected macroscopic result also came to light: the current data available on this topic are insufficient to obtain definitive conclusions on the aquaculture effects on the surrounding water column. The overriding conclusion is that water column variables should not be excluded from protocols of environmental assessment.

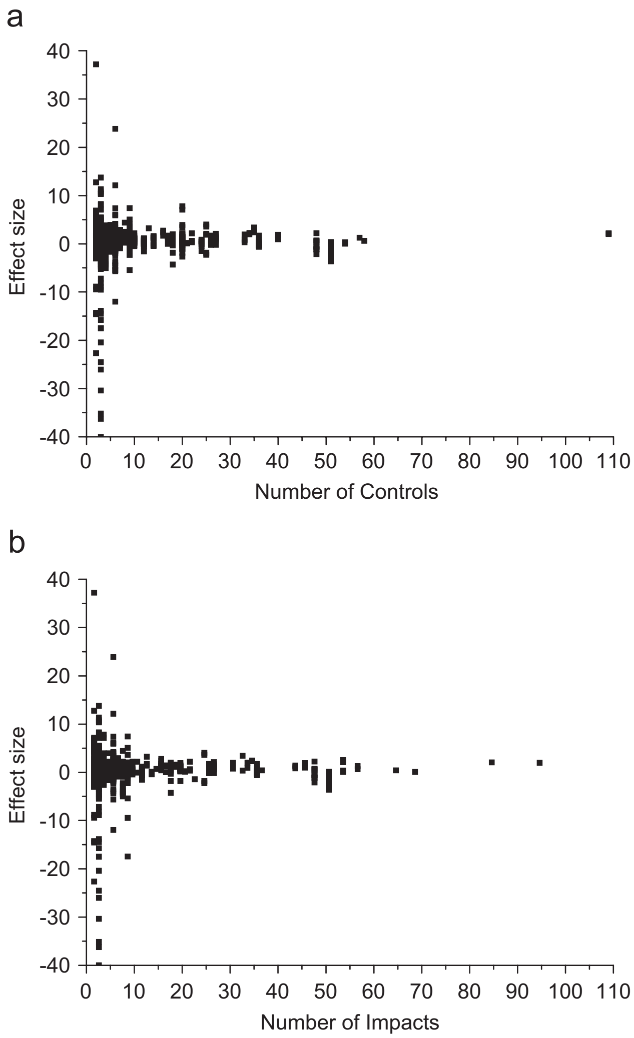

Fig. 5 – Relationship between mean size effect and number of controls (a) and impacts (b) across all studies cumulated together.

5. Conclusion

The main purpose of the present meta-analysis was to investigate if there were overall differences among studies investigating the effects of aquaculture on the surrounding environments. This involved starting with differences among controls and impacts in each study, and for each variable (i.e. descriptor) usually considered in the current literature. In most cases, I detected significant differences, which means that aquaculture activities "push" the system to significantly deviate from natural patterns (in terms of the magnitude of each variable observed in controls vs impacts). In other words, differences among controls and impacts across many

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Table 4 – Mean number of replicates used both in controls and in impacts across the literature to study the impact of fish, shrimp, bivalves and polyculture (Poly) on the water column

Variable	N replicates of controls				N replicates of impacts			
	Fish	Shrimp	Bivalve	Poly	Fish	Shrimp	Bivalve	Poly
TSM	6	9	2	–	3	9	2	–
OSM	18	8	12	–	18	8	12	–
CHL-*a*	5	5	8	3	4	10	8	3
PHAEO	ne	ne	–	–	ne	ne	–	–
POC	6	ne	4	–	6	ne	8	–
PON	6	ne	–	–	6	ne	–	–
POP	5	–	–	–	10	–	–	–
BPC	4	–	4	–	6	–	4	–
BACT AB	3	ne	ne	–	3	ne	ne	–
BACT PP	2	ne	ne	–	2	ne	ne	–
BACT μu	3	3	ne	–	2	2	ne	–
PHYTO AB	4	–	–	ne	4	–	–	ne
PHYTO PP	4	ne	ne	–	4	ne	ne	–
ZOO	4	ne	ne	ne	4	ne	ne	ne

ne = not estimable.

studies imply that there is a certain effect due to human disturbance (in this case from aquaculture), but that it does not implicitly correspond to biological consequences and environmental costs according to the current understanding of the term "impact". Thus, in agreement with Pitta et al. (1999), we need to reconsider the concept of impact, addressing future investigations by considering each variable not only as mere descriptors of a local situation, but as descriptors of ecological processes. This can be achieved by changing the perspective of our approach, using variables (e.g. POC, PON or bacterial abundance) as descriptors of an ecological system functioning by cascade. Thus, the greater the deviation of a certain variable in impacts with respect to controls, the greater the possibility that the system will respond with ecological consequences, implying environmental costs.

Thus, to date, it has not been possible to extrapolate homogeneous information from the peer-reviewed literature (but see Table 3). The water column dynamics are doubtless affected by organic aquaculture loading (i.e. there is an effect) but, due to the substantial heterogeneity across studies (thanks to the huge local and environmental differences), the information available on the effects can be considered partially flawed. Indeed, the degree of heterogeneity across studies was very high, denoting a high level of fractionation of information probably due to the intrinsic differences of cultivated organisms, study areas, but above all, experimental designs adopted in each study. In other words, I detected a precise effect that in some cases could be large, but the difficulty in generalising (due to weak experimental designs) abruptly limits the power of each study, and no definitive conclusions can be achieved. When we work with highly heterogeneous systems (i.e. the water column), the only way to achieve logical conclusions for comparing effects and detecting possible differences is to adopt powerful experimental designs for generalising results.

A criticism of the present meta-analysis could be that it is not appropriate to combine different forms of aquaculture in this context. Although it is clear that each form of aquaculture is different from another, no review, to date, has attempted to compare each single effect on each single variable taken as an ecological descriptor. I saw this as an important ecological cue, in that the present meta-analysis permits a better understanding of the results found scattered across the literature, highlighting those ecological variables that could be good descriptors for a certain form of aquaculture and poor for another.

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