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A meta-analysis on the ecological effects of aquaculture on the water column: Dissolved nutrients

G. Sarà

Dipartimento di Biologia Animale dell'Università, Via Archirafi, 18, Palermo 90123, Italy

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Abstract

Environmental effects of aquaculture loadings have often been reviewed descriptively, and thus have not provided quantitative estimates of the overall response in the water column. Meta-analytical reviewing techniques allow the contextualisation of quantitative effects in the domain of current literature. In the present paper, more than 50 peer-reviewed articles were analysed and about 425 study cases used to test whether worldwide cultivations have a differential effect on dissolved nutrient levels. 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. Across all study cases, irrespective of cultivation and organism type, the cumulative effect size was large and significant ($d > 0.8$) for ammonium, nitrite and nitrate, medium ($0.8 > d > 0.5$) for dissolved phosphorus, and not significant ($d < 0.2$) for silicates. Effects were mainly correlated with the degree of openness in water bodies, and ammonium and the other nitrogen forms were the most highly informative descriptors of effects in the area surrounding farms, even though weakness in statistical approach was highlighted. The results partially contradict the common view that effects of aquaculture and associated environmental patterns are well defined throughout the current literature.

Keywords: Meta-analysis; Aquaculture impact; Water column; Dissolved nutrients; Fish; Shrimp; Bivalve; Polyculture

E-mail address: gsara@unipa.it

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1. Introduction

Since aquaculture was first considered an important anthropic activity with potential detrimental effects on the environment (Naylor et al., 1998), a number of descriptive reviews on this issue have been published. Aquaculture facilities have effects on both the water column (Modica et al., 2006) and on sediments (Kalantzi and Karakassis, 2006) along many different axes of variability. Numerous questions have therefore arisen as to how, where and when aquaculture has had measurable effects on the environment. It has often been noted (Gowen and Bradbury, 1987; Iwama, 1991; Enell, 1995; Iversen, 1995; Wu, 1995; Beveridge, 1996; Bardach, 1997; Carpenter et al., 1998; Naylor et al., 2000; Black, 2001; Fernandes et al., 2001; Islam et al., 2004; Pillay, 2004; Islam, 2005) that the type of cultivated organisms (e.g. fish, shrimps, bivalves), the locations of cultivation (i.e. ecosystems and water types such as fresh, mixed [brackish] and marine waters), the cultivated biomass, the number of species, the quality and quantity of supplied food or management practices (i.e. intensive, semi-intensive, extensive) are the prime factors in determining the extent of effects on the environment, in that they represent the direct causal factors of eutrophication risk. Many authors have pointed out that aquaculture is an anthropogenic activity, which has only limited effects on the environment compared to other forms of pollution (e.g. Islam and Tanaka, 2004). Others have proposed conceptual nutrient mass balance models to extrapolate the level of nitrogen and phosphorus discharged from a hypothetical culture system (e.g. Islam, 2005). Nevertheless, only rarely has there been an attempt in the primary literature to estimate the how, where and when of environmental effects of aquaculture. The present review, using meta-analytic techniques, aims to provide a quantitative estimate of aquaculture effects using data amassed from current peer-reviewed literature, and is directed at understanding whether dissolved nutrients in the water column are generally affected by aquaculture facilities. Gurevitch et al. (1992) pointed out that meta-analysis, as opposed to other review techniques, offers major advantages for research synthesis in ecology. Indeed, meta-analysis is a quantitative tool available to ecologists who wish to obtain general knowledge about the magnitude of a certain effect, whether that effect is different among contrasting categories of studies and how much variation is explained both within and among categories. The specific aims of the present meta-analysis are to estimate: (1) the degree of heterogeneity of results reported from aquaculture studies investigating the effects on dissolved nutrient levels; (2) the cumulative effect of aquaculture loadings on nitrogen, phosphorus and silica across the peer-reviewed literature; (3) the differential effects of aquaculture loadings on each form of the dissolved nutrients; (4) which factors mainly affect the variability of cumulative dissolved nutrient levels and lastly (5) whether a possible deviation from common natural patterns induced by aquaculture loadings is generally similar as a function of the ecosystem and cultivated organism types.

2. Materials and methods

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

Data on the effects of aquaculture loadings on the water column through dissolved nutrients as descriptors were obtained from a literature search using mainly the Aquatic Science and Fisheries Abstracts (ASFA) and some other databases, such as Bio-One or

Zoological Records available on-line on the internet. 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 authors to obtain their publications, though to no great degree (22%) of success. The search was initially carried out using prominent or substantial keywords such as "aquaculture and impact". This method revealed a very large number of publications (11,656 published by January 2006) stemming from all possible sources, most of which were immediately discarded, either 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.). Many of the documents published prior to 1985 were ruled out due to the physical difficulty of obtaining these papers from authors or libraries, despite the fact that 450 studies among those published in peer-reviewed journals had been initially retained. Due to these hindrances, therefore, I focused only on widespread and easily accessible sources, such as those published in peer-reviewed journals after 1985. Whilst 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 that are often not found in other (perhaps less established) sources. Although major journals tend to publish only significant results, thereby generating a potential publication bias and distorting the direction of a true effect (Hedges and Olkin, 1985), the peer-review process is the best method to reduce the likelihood of potential quality biases in reviewing.

Most of the contemporary peer-reviewed articles, however, reported the words "aquaculture" and "impact" in contexts not relevant to the present meta-analysis. I thus reduced the scope of the search, using keywords such as "aquaculture and impact and nutrient", "aquaculture and impact and ammonium", "... and nitrite", etc., which resulted in a database of about 100–120 peer-reviewed articles, which were then checked for 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 distinct areas identified by each author, where effects of aquaculture facilities were not present. The treatment group is represented by data collected from areas directly affected by farm loadings. 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 farmed areas. In 30–40% 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; Rosemberg 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) from every study. The effect of interest in the present paper was the differential effect exerted by each organism (shrimps [SHR], fish [FISH], bivalves [BIV] and polyculture [POLY]) cultivated in different water bodies (i.e. ecosystem; freshwater, mixed or marine conditions) on dissolved nutrients

(NH_4, NO_2, NO_3, PO_4, SiO_2). The most common measure of effect size is the difference between means of the controls and farmed areas, standardised by dividing by the pooled standard deviation (Cohen, 1969). 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 farmed area 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 farmed areas.

Another fundamental part of 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 (in the case of the present topic, for example, a significant CI would indicate significant evidence that farm loadings would have a certain effect on dissolved nutrients). The magnitude scale for the cumulative effect size is that proposed by Cohen (1969). In addition, to calculate the degree of heterogeneity among case studies and to estimate whether effect size *d* was homogenous among studies, I used the *Q* statistics (Q_{tot}; Hedges and Olkin, 1985).

The meta-analysis approach used here was similar to that reported in Gurevitch et al. (1992) and Hedges and Olkin (1985). 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 not differing only for the sampling errors), the data was analysed in groups. In so doing, I estimated the singular overall effect of aquaculture on each nutrient, the effect on each cultivated organism and, where the deviation from a common natural pattern was different, the ecosystem factor was also tested.

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

Once all the data had been obtained and entered into a MS Excel spreadsheet, the entire dataset was standardised for the type of deviation (standard deviation or standard error) and the units of measure (μM or mg l^{-1}). Most of the papers reported means and standard deviations, while others reported means and standard errors (as a function of their experimental design). Some papers expressed the concentration in water of each nutrient in μM and others in mg l^{-1}. In the present meta-analysis, I transformed all deviations to standard deviations using the calculator included in the MetaWin 2.0 software (Rosemberg et al., 2000), while all concentrations were transformed into mg l^{-1}. Since one of the major concerns of a meta-analyst is the 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) the *d* normal quantiles were plotted versus the standardised mean effect (Rosemberg et al., 2000). The normal quantile plot also allowed possible deviations of the studied cases to be examined (Wang and Bushman, 1998). Furthermore, the Rosenthal index enabled the fail-safe number to be estimated, 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; Rosemberg et al., 2000). All calculations were carried out using MS Excel and MetaWin 2.0 (Rosemberg et al., 2000).

3. Results

3.1. Overview of literature

A total of 52 articles published between 1982 and 2005 in peer-reviewed journals (Table 1) were included in the present meta-analysis. This resulted in 427 independent cases wherein all variables were considered together (NH_4, NO_2, NO_3, PO_4, SiO_2). Although the total number of studies represented substantially less than 10% of all accessible and useful information published on this topic in the last two or three decades, it provided sufficient information and gave a reliable estimate of the true effect of aquaculture loadings on the water column. The Rosenthal Index was calculated to be in the order of 7053. This high Rosenthal value confirmed that the observed results, even with some publication bias, could be treated as a reliable estimate of the true effect. In addition, the possible risk of publication bias or possible deviation of meta-analysis structure were 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. The overall effect size of aquaculture loadings on the nutrient pool

When all case studies were analysed together, aquaculture facilities appeared to have an overall effect on dissolved nutrients. This was evident from the cumulative mean effect size ($d = 0.45$) which, according to Cohen (1969), indicated a medium effect of aquaculture loading on the dissolved nutrients in the water column. It was significantly different from a zero effect because its confidence limits did not bracket zero (95% CI = 0.22–0.57). The total heterogeneity (Q_{tot}) among all studied cases was very high, in the order of 3563.0 (df = 426; $p < 0.05$) suggesting that variance among effect sizes was greater than expected by sampling error. Thus, assuming this meta-analytic outcome, the studies were broken into groups to test possible influences on the direction of the effect size raised by other factors such as the type of cultivated organisms or ecosystems.

3.3. General factors affecting the variability of the dissolved nutrients

Nutrient species were differentially influenced by aquaculture facilities across all studies (Table 2). Ammonium appeared to be the nutrient most affected by loadings from aquaculture facilities irrespective of organisms and ecosystem; nitrites and nitrates and then phosphorus were other compounds to be significantly influenced, while silicates did not show any significant effect (Fig. 2a) as the d value turned out negative and confidence limits bracketed zero.

The grand mean effect size was calculated as a function of each organism type irrespective of the nutrient type and ecosystem. The mean size effect was large, in the order of 0.94 (95% CI = 0.80–1.1; $p < 0.05$), while the total heterogeneity was 816.59 ($p < 0.05$). Almost all organisms had an effect on the water column, and polycultures in particular appeared to have a major effect on the dissolved nutrients, followed by fish and shrimps. Bivalves did not show any significant influence on the dissolved nutrient levels as the d value turned out negative and confidence limits bracketed zero (Table 3; Fig. 2b).

Table 1
The list of peer-reviewed papers published from 1982 to 2005 included in the present meta-analysis, reporting also countries ($n = 30$) where experiments were carried out, areas, type of ecosystem (mixed, freshwater and marine) and cultivated organism (SHR = shrimps; FISH = fish; BIV = bivalves; POLY = polyculture)

#	Study	Country	Area	Ecosystem	Type	Topography
1	Alongi et al. (1999)	Vietnam	Pacific	Mixed	SHR	Pond
2	Alongi et al. (2003)	Malaysia	Pacific	Mixed	FISH	Open field
3	Azim et al. (2003)	Netherland	Inland	Freshwater	FISH	Controlled
4	Ball et al. (1997)	Ireland	Atlantic	Marine	BIV	Open field
5	Bechara et al. (2005)	Argentina	Atlantic	Freshwater	FISH	Controlled
6	Biao et al. (2004)	China	Pacific	Marine	BIV	Pond
7	Boaventura et al. (1997)	Portugal	Atlantic	Freshwater	FISH	Open field
8	Burford (1997)	Australia	Pacific	Mixed	SHR	Pond
9	Burford et al. (2003a)	Australia	Pacific	Mixed	SHR	Pond
10	Burford et al. (2003b)	Belize	Atlantic	Marine	FISH	Pond
11	Chandra Das et al. (2005)	India	Indian	Freshwater	FISH	Controlled
12	Chin and Ong (1997)	Singapore	Pacific	Freshwater	SHR	Pond
13	Christensen et al. (2003)	New Zealand	Pacific	Marine	BIV	Open field
14	Costanzo et al. (2004)	Australia	Pacific	Mixed	SHR	Pond
15	Costa-Pierce (1998)	California, USA	Pacific	Freshwater	POLY	Controlled
16	Cowan et al. (1999)	Thailand	Pacific	Mixed	SHR	Pond
17	De Casabianca et al. (1997)	France	Mediterranean	Marine	BIV	Open field
18	Figueredo and Giani (2005)	Brasil	Inland	Freshwater	FISH	Controlled
19	Galope-Bacaltos et al. (1999)	Phillippines	Pacific	Freshwater	FISH	Open field
20	Green et al. (2002)	Egypt	Mediterranean	Freshwater	FISH	Controlled
21	Guerrero-Galvan et al. (1999)	Mexico	Pacific	Mixed	SHR	Pond
22	Guo and Li (2003)	China	Inland	Freshwater	FISH	Open field
23	Hopkins et al. (1995)	South Carolina, USA	Atlantic	Mixed	SHR	Open field
24	Hussenot (2003)	France	Atlantic	Marine	FISH	Open field
25	Islam et al. (2004)	Bangladesh	Indian	Mixed	SHR	Pond
26	Jackson et al. (2004)	Australia	Pacific	Mixed	SHR	Pond
27	Jones et al. (2001b)	Australia	Pacific	Mixed	SHR	Pond
28	La Rosa et al. (2002)	Italy	Mediterranean	Marine	BIV	Open field
29	Martin et al. (1998)	New Caledonia	Pacific	Marine	SHR	Controlled
30	McKinnon et al. (2002)	Australia	Pacific	Mixed	FISH	Open field
31	Merceron et al. (2002)	France	Atlantic	Marine	FISH	Open field
32	Motzkin et al. (1982)	Israel	Mediterranean	Marine	FISH	Pond
33	Neori et al. (2000)	Israel	Mediterranean	Marine	POLY	Controlled
34	Nordvarg and Johansson (2002)	Finland	Atlantic	Marine	FISH	Open field
35	Ogilvie et al. (2000)	New Zealand	Pacific	Marine	BIV	Open field
36	Paez-Osuna et al. (1997)	Mexico	Pacific	Mixed	SHR	Pond
37	Pietros and Rice (2003)	Rhode Island, USA	Atlantic	Marine	BIV	Controlled
38	Pitta et al. (1999)	Greece	Mediterranean	Marine	FISH	Open field
39	Pitta et al. (2005)	Greece	Mediterranean	Marine	FISH	Open field
40	Ruiz et al. (2001)	Spain	Mediterranean	Marine	FISH	Open field
41	Samocha et al. (2004)	Texas, USA	Atlantic	Mixed	SHR	Pond
42	Soto and Norambuena (2004)	Chile	Pacific	Marine	FISH	Open field
43	Sumagaysay-Chavoso et al. (2004)	Philippines	Pacific	Mixed	FISH	Open field
44	Tang et al. (2002)	China	Inland	Freshwater	FISH	Controlled
45	Tovar et al. (2000a)	Spain	Atlantic	Marine	FISH	Open field

(continued on next page)

Table 1 (*continued*)

#	Study	Country	Area	Ecosystem	Type	Topography
46	Tovar et al. (2000b)	Spain	Atlantic	Marine	FISH	Open field
47	Trott and Alongi (2000)	Australia	Pacific	Mixed	SHR	Pond
48	Wahab and Stirling (1991)	Scotland, UK	Inland	Freshwater	FISH	Controlled
49	Wahab et al. (2003)	Bangladesh	Indian	Freshwater	POLY	Controlled
50	Wu et al. (1994)	Hong Kong, China	Pacific	Marine	FISH	Open field
51	Zambrano et al. (1999)	Mexico	Inland	Freshwater	FISH	Controlled
52	Zimba et al. (2003)	Mississipi, USA	Inland	Freshwater	FISH	Controlled

The total cultivated species were 45 among fish ($n = 24$), shrimps ($n = 11$), bivalves ($n = 7$) and algae or plants ($n = 3$). The topological features of each study have been also reported (controlled = environment controlled-by-researchers with variable volumes from a few litres [mesocosm] to some hundred or thousand of m^3 [enclosure]; open field = open environment mostly in the sea or in estuaries uncontrollable by researchers; pond = earthen basins usually used for shrimp cultivation).

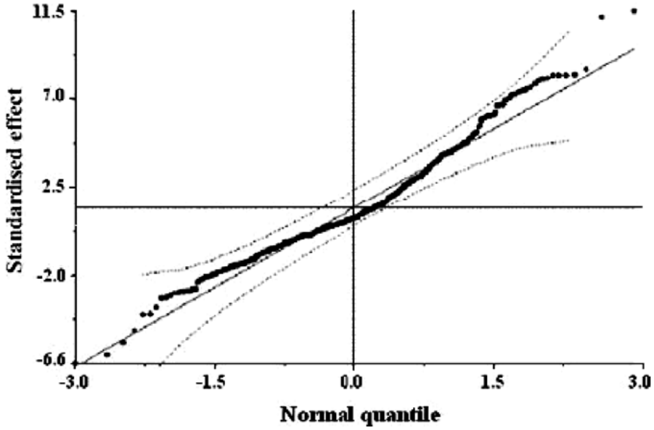

Fig. 1. The normal quantile plot plotted using all studies ($n = 427$).

Table 2
Effect of aquaculture facilities on each dissolved nutrient across all studies, in all ecosystems and for each type of organism

Nutrient	df	d_+	95% CI	P
NH_4	101	1.53	1.23–1.83	<0.05
NO_2	69	0.85	0.49–1.20	<0.05
NO_3	58	1.31	0.92–1.71	<0.05
PO_4	172	0.68	0.45–091	<0.05
SiO_2	27	−0.18	−0.80–0.41	>0.05
All	426	0.94	0.79–1.08	<0.05

NH_4 = ammonium; NO_2 = nitrite; NO_3 = nitrate; PO_4 = phosphorus; SiO_2 = silicates ALL = all nutrient cumulated together; df = degree of freedom; d_+ = mean size effect; 95% CI = 95% confidence interval; P = probability level.

The overall effect of organism type on nutrients appeared to be significant in each ecosystem analysed (Table 4; Fig. 2c). Indeed, the meta-analysis suggested that the effect was higher in freshwater environments than in mixed waters and lowest in marine waters. All these effects were significantly higher than zero.

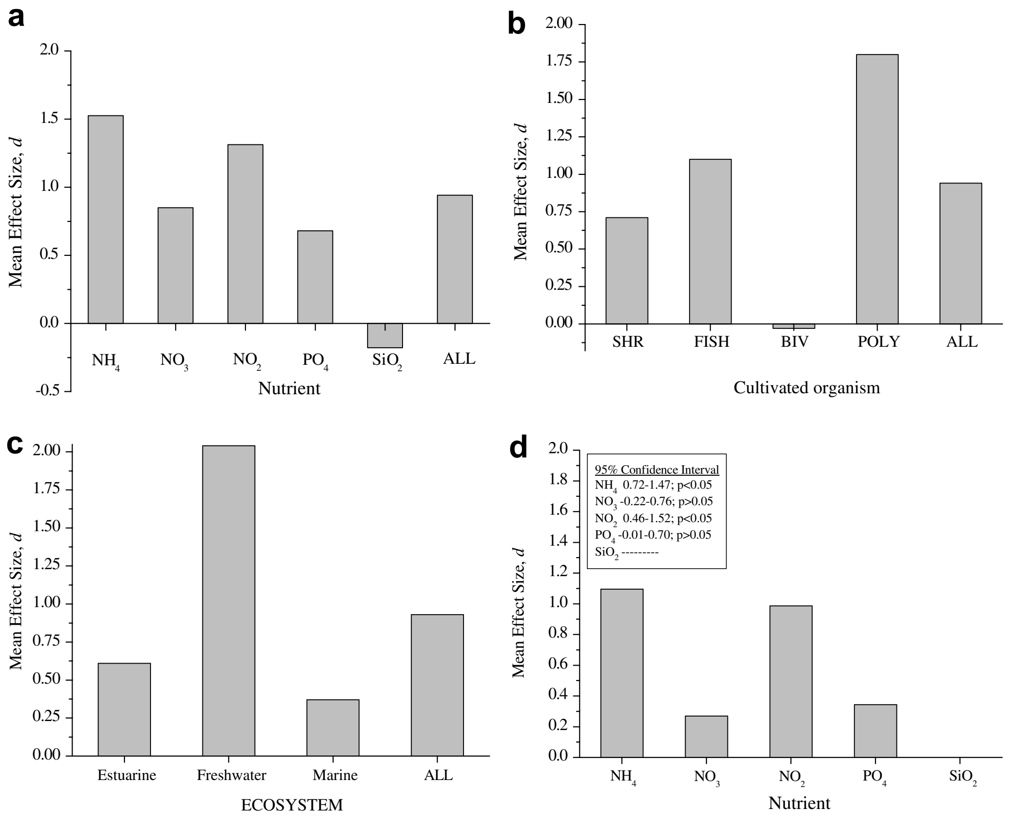

Fig. 2. General meta-analytical results with (a) the mean effect size of all cumulated aquaculture facilities across all studies on each nutrient (NH_4 = ammonium; NO_2 = nitrite; NO_3 = nitrate; PO_4 = phosphorus; SiO_2 = silicates ALL = all nutrient cumulated together); (b) the mean effect size of each organism type on dissolved nutrient levels across all studies and in all ecosystems cumulated together (SHR = shrimps; FISH = fish; BIV = bivalves; POLY = polyculture; ALL = all organisms cumulated together); (c) the mean effect size of aquaculture facilities in each ecosystem analysed irrespective of dissolved nutrient type and organism across all studies and (d) the mean effect size of shrimp aquaculture only in mixed water on each nutrient (NH_4 = ammonium; NO_2 = nitrite; NO_3 = nitrate; PO_4 = phosphorus; SiO_2 = silicates).

Table 3
Effect of organism type on the sum of dissolved nutrients through all studies and in all ecosystems

Organism	df	d_+	95% CI	P
SHR	132	0.71	0.46–0.96	<0.05
FISH	257	1.10	0.92–1.29	<0.05
BIV	22	−0.03	−0.69–0.62	>0.05
POLY	12	1.80	0.91–2.65	<0.05
ALL	426	0.94	0.80–1.10	<0.05

SHR = shrimps; FISH = fish; BIV = bivalves; POLY = polyculture; ALL = all organisms cumulated together; df= degree of freedom; d_+ = mean size effect; 95% CI = 95% confidence interval; P = probability level.

Table 4
Effect of aquaculture facilities in each ecosystem analysed irrespective of dissolved nutrient type and organism across all studies

Ecosystem	df	d_+	95% CI	P
Mixed waters	153	0.61	0.39–0.84	<0.05
Freshwater	116	2.04	1.78–2.30	<0.05
Marine waters	125	0.37	0.14–0.61	<0.05
All	426	0.93	0.76–1.11	<0.05

ALL = all nutrient cumulated together; df = degree of freedom; d_+ = mean size effect; 95% CI = 95% confidence interval; P = probability level.

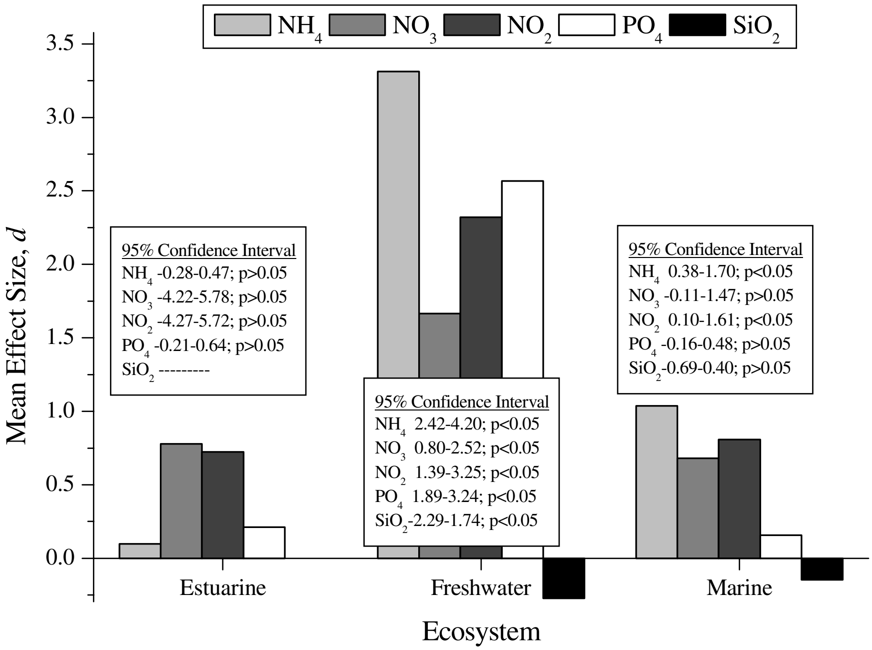

Fig. 3. The mean effect size of fish aquaculture in all ecosystems on each nutrient (NH_4 = ammonium; NO_2 = nitrite; NO_3 = nitrate; PO_4 = phosphorus; SiO_2 = silicates) (95% confidence limits were reported).

From a differential point of view, the valid shrimp cases regarding only mixed waters showed that they affected mainly ammonium and nitrite, while other nutrients were not influenced (Fig. 2d). It was not possible to make a comparison between shrimp farming in mixed waters and marine or freshwater conditions.

Fish appeared to have a major effect in fresh waters, where all nutrients significantly responded to farm loadings. In marine waters only ammonium and nitrites appeared to be significantly affected, while in mixed waters, few cases were available and these showed no significant effect elicited by fish on the sum of the dissolved nutrients (Fig. 3). Valid cases of bivalve cultivations could only be studied in marine waters regarding ammonium, nitrates and phosphorus (Fig. 4). Bivalves appeared to have no effect among nutrient levels. Polyculture appeared to have the biggest effect size among all cultivation types in

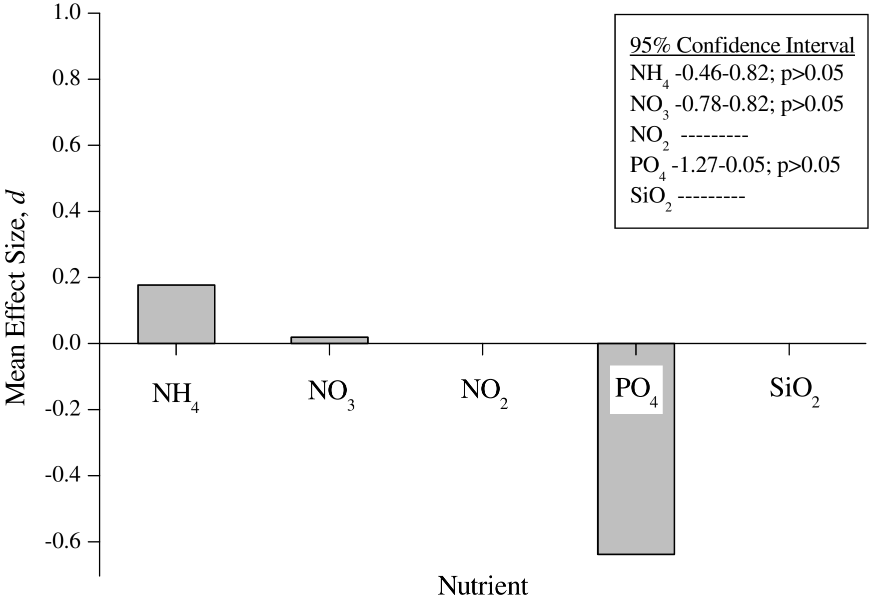

Fig. 4. The mean effect size of bivalve aquaculture in marine waters on each nutrient (NH_4 = ammonium; NO_2 = nitrite; NO_3 = nitrate; PO_4 = phosphorus; SiO_2 = silicates) (95% confidence limits were reported).

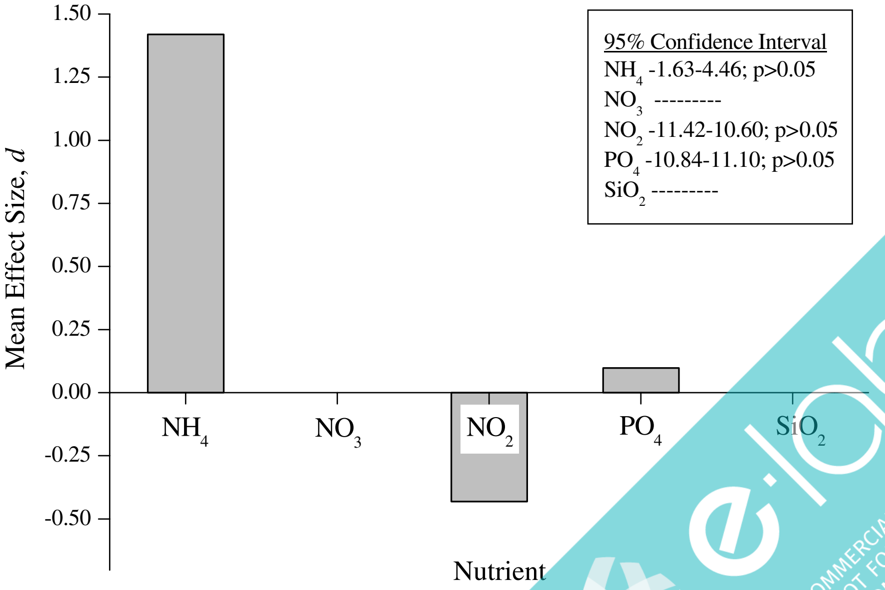

Fig. 5. The mean effect size of polyculture in fresh waters on each nutrient (NH_4 = ammonium; NO_2 = nitrite; NO_3 = nitrate; PO_4 = phosphorus; SiO_2 = silicates) (95% confidence limits were reported).

marine waters and, although only a few cases were available, it was possible to estimate the effect on ammonium, which was very high ($d = 6.84$; 95% CI = 4.06–9.61; $p < 0.05$). In contrast, in fresh waters, polyculture had an apparent effect on ammonium, nitrites and phosphorus, but these effects were not significant (Fig. 5). Finally, a correlation between the size effect on biomass expressed as total biomass (tonnes) and the number of species cultivated was attempted. In both cases, there was no relationship ($p > 0.05$) with biomass or the number of species.

4. Discussion

The ecological effects of aquaculture on water column quality have still not received sufficient critical examination (*sensu* Islam, 2005). This view is supported by the high heterogeneity of studies available in the current literature. High values of heterogeneity are not common throughout the ecological literature (Cote et al., 2001) except for some rare cases (Gurevitch et al., 1992). This seems to demonstrate, in contrast with other ecological topics, that the present topic may be affected strongly by several sources of variability producing high levels of heterogeneity in studying the response of dissolved nutrients in the water column to aquaculture loadings.

Features of cultivated organisms (fish, shrimps and molluscs) and their metabolic processes, ecosystem type (mixed, marine and fresh water), typology of cultivation (ponds, cages in open waters, land-based, etc.), influence from receiving aquatic ecosystems (e.g. hydrodynamics of water bodies and water residence time), and management practices (e.g. annual biomass productions, feed supply, etc.) have been invoked as major factors affecting the area surrounding farms (Islam, 2005). These high and complex sources of variability lead only to a very fragmented panorama, from which one can generalise only with great difficulty about the phenomenon of environmental effects of aquaculture. Nevertheless, the results from the present meta-analysis quantitatively contextualise, in the domain of the current literature, the effects of aquaculture loadings on the surrounding water column. The overall direction of the size effect is indubitably corroborated; i.e. farm loadings stemming from different types of cultivated organisms and in different locations appear to induce a significant deviation from common natural patterns (as measured by each authors in their respective chosen controls) of almost all dissolved descriptors in a water column. Although this result may no longer be an assumption in the current literature, it could provide a synthesis of the direction of aquaculture effects, not least because some authors do not use a common scientific methodology or direction in their research effort, or in the way they report their data and results (*sensu* Riley and Edwards, 1998; Karakassis, 2001; Ling and Cotter, 2003). To some extent, the present meta-analysis provides confirmation of this perspective, because not all factors usually cited among the main causal factors appeared to have a true effect across the analysed literature.

4.1. The cumulative effect

When examining the cumulative results, all nutrients commonly used to describe possible eutrophication risks induced by aquaculture appeared to be affected by loadings, except for silicates. Ammonium was the nitrogen form that more often deviated under cultivation conditions, followed by nitrates and nitrites and lastly by phosphorus. The differing chemical behaviour and the origin of each nutrient could explain these results (Valiela, 1984; Hargreaves, 1998; Quian et al., 2001). For example, as ammonium is mainly produced by the excretion of organisms (both fish and shrimps) and in shallow waters (shallow basins, ponds, estuaries) from sediment-flux derived from the mineralisation of organic matter (e.g. food), it could be expected that it would be the first nutrient greatly affected by aquaculture loadings. More than 80% of nitrogen excretion by shrimps (Paez-Osuna et al., 1997) and fish, however, is represented by ammonium (Wood, 1958; Tanaka and Kadowaki, 1995). Phosphorus originating from the decomposition of organic matter and metabolic activities has usually been invoked as the nutrient mainly affected after ammonium (Beveridge, 1996) by aquaculture loading, which is an important limiting factor to primary productivity in most aquatic environments (Valiela, 1984). Nevertheless, across the current literature the phosphorus pool appeared less affected with respect to nitrogen forms. Silicates mostly of terrigenous-continental origin (Valiela, 1984) did not seem to be affected by aquaculture loadings.

4.2. The effect of the type of organism and ecosystem

The major factors generating differences among studies in determining differences in dissolved pool appeared to be (1) the type of cultivated organism and (2) the ecosystem where they are cultivated, irrespective of management practices and site-specific features.

Accordingly, in most of the studied cases, types of organism depicted the same direction of the effect on dissolved nutrients, although each organism affected specific nutrients differently, depending on the ecosystem where they are cultivated and the intrinsic biology of each organism (metabolic processes, excreta quantity, etc).

The size effect of fish and shrimps appeared to be significantly higher, comparable among each other and effective in determining a nutrient-rich environment in farmed areas regarding the common natural patterns as measured in controls. By contrast, bivalve case studies, although reduced in number ($n = 22$), did not produce a significant effect. The differences in metabolic processes and biological features among these cultivated organisms combined with the type of management practices could explain these differences. Furthermore, dissolved waste release, for example, showed higher results in these experiments in fish than in bivalves, while shrimps were in the middle (Quian et al., 2001). This observation supports the direction of size effect (see Fig. 2) because the pattern of size effect could appear to correlate with the quantity of excreta release, which is a group-specific factor. However, this pattern is also linked to the type of management practice. Fish are mostly cultivated under intensive conditions and feed is provided by an external source; cultivation of shrimps is often carried out under semi-intensive conditions (Paez-Osuna et al., 1998) and the *quantum* of feed provided is smaller than for fish. In contrast, bivalves, such as suspensivores, collect their food directly from the environment without any other external input (Hickman, 1992). Thus, the direction of the size effect can be further affected by the quality or the quantity of feed supplied to each type of organism (Enell, 1995; Beveridge, 1996; Islam, 2005) and moreover can be linked indirectly to the cultivated biomass. However, the dependence between the total cultivated biomass and the number of species was tested and there was no significant relationship, which is surprising, because in many reviews these two factors are those most often invoked to explain differences in dissolved nutrient levels among farmed areas and controls.

Polyculture seems to be a separate case, having been cited on many occasions as a practice able to increase the environmental sustainability of aquaculture and economic incoming (Troell et al., 2003; Neori et al., 2004). The high magnitude of the measured size effect shows that the combination of different organisms coming from different trophic levels cultivated together did not minimise differences between controls and farmed areas with respect to monoculture. Such a result is quite puzzling but is very likely strongly divergent due to the low number of studies analysed from very different types of papers (Costa-Pierce, 1998; Neori et al., 2000; Wahab et al., 2003) which resulted from the low accessibility of other data meeting all the requirements of reliability to be analysed with meta-analytic procedures. Thus, although reliable papers used in this meta-analysis were very few and highly heterogeneous, I wanted to analyse them to emphasise the scarcity of reliable information existing on this topic across the peer-reviewed literature.

Ecosystem type seems to be the other main causal factor determining differences among studies. The effect of aquaculture appeared highly location-specific, linked to width of the water body and consequently to the hydrodynamic regime, rather than to the cultivated biomass or number of cultivated species or type of species. In contrast, the direction effect seems, in general, inversely correlated to the size of the water body (*sensu* Fernandes et al., 2001) and indirectly to hydrographic conditions (Sarà et al., 2006): the higher the degree of enclosure of water bodies, the bigger the effect size (i.e. effects of cultivation in fresh waters were greater than effects in mixed waters, and these in turn were greater than the effects in marine waters). Consequently, it was possible to extrapolate that nutrient loadings could be a function of degree of enclosure of water bodies, that indirectly determines both the flushing rate levels and the intrinsic chemical features of waters (Pillay, 2004). In closed lakes, allochthonous nutrient loadings coming from farms amass to the autochthonous dissolved pool that in limited hydrodynamics (*sensu* Sarà, in press; Sarà et al., 2006) can more easily induce a deviation of farmed areas from controls, thus altering the chemical equilibrium of the water column. In closed fresh waters, throughout the literature studied, the difference between controls and farmed areas was very high, and the highest for the resulting effect size. In mixed ponds or estuaries, where there is a concomitance of fresh- and marine waters, and where the circulation within ponds is often forced by gravity or pumps, allochthonous nitrogen and phosphorus loadings are often forced out of basins, which partially limits their accumulation. Therefore, the direction of the effect size suggests a general significant difference between controls and farmed areas, although it was lower than in fresh waters. In marine open waters, the intrinsic feature of openness would appear to limit the accumulation of allochthonous nutrients, reducing differences between controls and farmed areas and the overall size effect throughout the literature. To better investigate the link between the degree of openness of water bodies in the sea (an important concern highlighted in many reviews; Enell, 1995) and the extent of effects, I attempted to classify the structure of aquaculture areas in semi-closed, sheltered, open, etc. for each study. The results obtained were highly subjective due to limited knowledge of each site, conditions of which could not be ascertained and, because of this, the attempt was abandoned.

4.3. Statistical issues

The present meta-analysis based on the quantitative estimates of variance among all studies led me to exclude a high percentage of peer-reviewed papers not responding to meta-analytic criteria (∼40%). In addition, most of the papers reported the deviation tendency as standard deviations and only rarely as standard errors for means. This suggests that the accuracy of measures is quite low, and that, due to the limited reporting of standard errors, there is an overall weakness in experimental design across the literature (Fernandes et al., 2001; Ling and Cotter, 2003). The study of effects of aquaculture on the surrounding environment seems to suffer from this deficiency, i.e. authors appeared rather lax in designing their experiments. This is quite typical of ecological studies carried out in large experimental fields (*sensu* Oksanen, 2001) and is a genuine cause for concern. In most of these cases, however, it is simply not possible to plan experimental designs with the same rigour as with those in small enclosures, aquaria, a laboratory or similar controlled conditions (*sensu* Oksanen, 2001). The degree of replication in large field conditions (*sensu* Hurlbert, 1984) is doubtlessly affected by several variables and factors that very often can be controlled only with difficulty (*sensu* Oksanen, 2001). In my view, this is the cause of the high variance between studies that is greater than the intrinsic sampling errors from each study. Throughout the scientific literature on this subject, it is clear that the effort involved in sampling has been huge; more often than not, however, it is not channelled into building a good experimental design (Schmitt and Osemberg, 1996; *sensu* Underwood, 1997). The resulting situation is that in most of the studies, it is hard to detect the true effect of aquaculture facilities on the surroundings (Schmitt and Osemberg, 1996), which enhances the risk of statistical errors (*sensu* Hurlbert, 1984; Underwood, 1997).

4.4. Research priorities, new perspectives and trends

The results of the present meta-analysis, even when cautiously interpreted, raise many more questions than they have answered. At the start of my data collection, it seemed that the huge quantity of publications would lead to a clear view of aquaculture effects on the environment. However, although a large amount of data had been published about this topic, the difficulty in finding them, the overall lack of useful information and the weakness in experimental designs all limit the conveying of such knowledge to the audience. Consequently, although we can find several thousands of citations through the WWW, the number of papers offering useful, accessible and substantially prominent information is only small. This has serious implications for potential environmental repercussions. More effort should be directed towards understanding the extent to which, and in what way, this anthropogenic disturbance can affect water column quality. Some of the present findings, in particular, should be made priority issues in any future research.

Some authors have suggested polyculture as a potential solution to some aspects of eutrophication, because the contextual cultivation of species from different trophic levels (e.g. algae and bivalves together with carnivorous fish) would reduce the impact that would emerge from the cultivation of only one carnivorous species (Troell et al., 2003). Although theoretically this may be a satisfactory assumption, there is no evidence in the current literature, apart from a few (influential) in-yard and open field experiments, to support the notion that polyculture reduces environmental impacts. Thus, due to the scant information on this topic, greater effort should be directed towards examining this assumption that as yet is only theory.

Although bivalves are among the primary cultivated species in the world, involving large coastal populations and often political concerns (Hickman, 1992), there is very limited information in the current literature about their potential impact on dissolved nutrient levels. This is very unusual, as they have received much attention from researchers over the last three or four decades, of which physiological aspects and, in particular, excretion rates have been the most investigated features (see for example Dame, 1996; or Wildish and Kristmanson, 1997 as reviews).

Although the choice of descriptors of dissolved nutrients is widely consolidated, some studies still pay attention to silicates. However, they appear to be poor descriptors of behaviour of heterotrophic loadings in a water column. In contrast, nitrogen forms appeared to be the more highly informative descriptors of eutrophication risks in a water column, while *in sensu stricto*, the role of dissolved phosphorus in describing the risk of eutrophication results was limited only to small water bodies, contradicting the commonly held view that phosphorus is, in most cases, the best descriptor.

Lastly, the present meta-analysis was not aimed at investigating the consequential effects of dissolved pool changes on suspended biological communities (phytoplankton, free-living bacteria, etc.). Thus, since a deviation from a common natural pattern of dissolved nutrients does not necessarily imply a direct response of the suspended biota (*sensu* Pitta et al., 1999; Sarà et al., 2006), the discovery of contextual reporting, within the same article, of both chemical and biological data, would possibly reveal the true detrimental effects of aquaculture loadings on the environment.

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