Environmental consequences of poor feed quality and feed management

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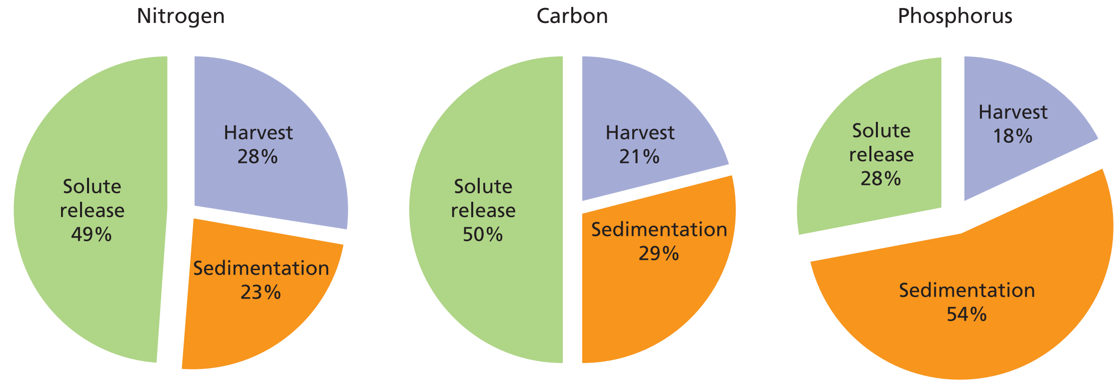
ABSTRACT

Feed costs account for up to 60 percent of total production costs, and inappropriate feeding and feed management can therefore be detrimental to the profits of farmers. Optimal feed management includes the use of well-balanced feeds covering the nutritional and energy requirements of the species and cost-efficient feeding regimes. The large variation among generally poor industrial feed conversion ratios (FCR) obtained in some fish production in Asia (such as milkfish, *Chanos chanos*) is a clear indication of inappropriate feeding. The accurate determination of the basic nutritional requirements throughout the production cycle and best practices in feeding regimes and technology is required in order to achieve a significant reduction in production FCR values. Specifically, the optimum dietary protein and energy levels, which are crucial parameters for effective feed formulation, need to be determined and evaluated on the farm. In addition, better knowledge is required for the main influencing biotic and abiotic factors, which are fish size, diet composition, feeding level and frequency, and water temperature and oxygen levels. The cost-efficient use of diets with formulations targeting the specific seasonal and developmental needs of the fish will effectively improve production FCR and have a significant economic benefit for aquaculturists. Optimizing feed utilization efficiency, fish growth, health and welfare, besides promoting production efficiency and economy, will also have a significantly positive environmental impact. Overfeeding results in excess nutrients entering the environment that need to be assimilated or they will accumulate. The paper includes a case study in the Philippines where poor feed quality and poor feeding practice for milkfish cage culture has had major environmental impacts on water and sediment quality.

1. IMPACT OF AQUACULTURE ON THE ENVIRONMENT

Aquaculture produces wastes that may negatively affect the environment. In intensive aquaculture where feed is given, a considerable amount of organic wastes are produced in the form of particulate (mainly uneaten food and faeces) and soluble substances (excreta) that increase biochemical oxygen demand and the concentration of dissolved nitrates and phosphates. Only a small proportion of the feed that is fed is taken up in fish production. Around 50 percent of the total nitrogen (N) and total carbon (C) is

FIGURE 1
Proportion of nutrients taken up in fish production and released into the environment

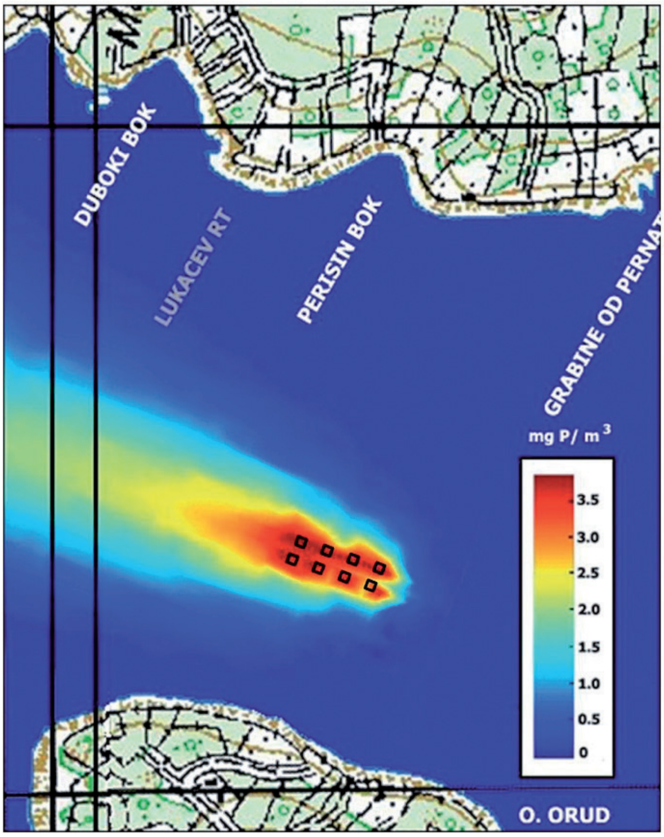


Source: Holby and Hall (1991); Hall *et al.* (1992).

excreted by the gills and dissolves into the water column, and over 50 percent of the total phosphorus (P) is released as particulate matter and settles on the sea bed (Figure 1).

Poor feed quality and poor feeding strategy have major influence on the environmental impact from shore-based and open-water farming systems. Excess nutrients not utilized by the fish or shrimp are released into the environment and have to be assimilated or they accumulate. Whether a nutrient becomes a pollutant in an aquatic system or not depends on whether it is a limiting nutrient in a given environment, and on its concentration and the carrying capacity of that ecosystem. In freshwaters, phosphorus is typically the limiting nutrient (Hudson, Taylor and Schindler, 2000), so its addition will dictate the amount of primary production (algal growth). In marine environments, nitrogen is typically the limiting nutrient (Howarth and Marino, 2006), so its addition will do likewise. The excess nutrients are released into the environment in two forms, dissolved nutrients and particulate nutrients.

FIGURE 2
Model simulation of phosphorus plume released by fish cages



Source: Legovic, Janekovic and Gecek (2003).

1.1 Dissolved nutrients

Dissolved nutrients from fish farms arise from feed and faeces (Nash, 2001; Pawar, Matsuda and Fujisaki, 2002), fish respiration and metabolites and benthic flux; rereleased nutrients from the sedimented wastes are major sources of dissolved nutrients from cage farming (Nash, 2001). Soluble nutrients arising from the digestion processes of farmed individuals will dissolve in the water column, and their dilution and transport is a function of water current dynamics (Figure 2).

Dissolved nutrients are typically dispersed rapidly and utilized by bacteria, phytoplankton and zooplankton. However, if there are high levels of nutrients released on a continuous basis, then this can lead to eutrophication and/or algal blooms. Eutrophication, low oxygen events and fish kills affecting local fisheries and fish-cage production are common events in some lakes and reservoirs in Asia; in these there is a high density of small-scale fish cage farms that together produce excess nutrients in dissolved and particulate form, and therefore exceed the carrying capacity of the waterbody (e.g. in Indonesia, Abery *et al.*, 2005). According to Olsen *et al.* (2006), the most important factors determining the impact of fish farming on water column nutrients, water quality and pelagic ecosystems are:

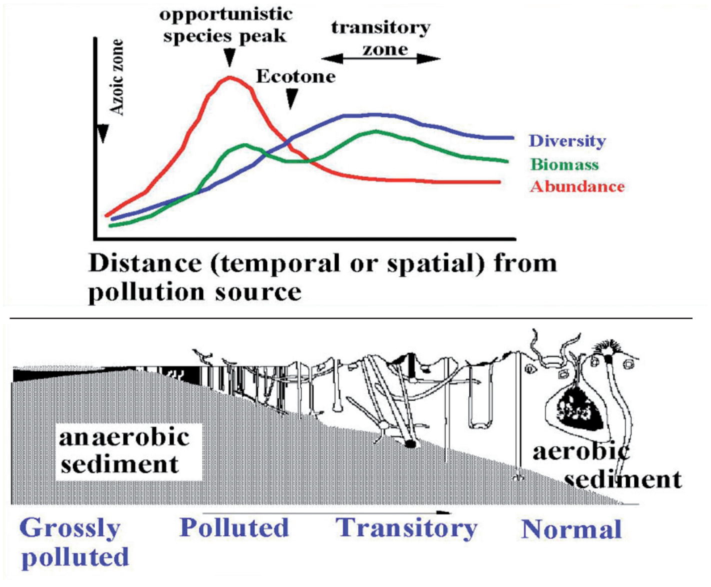
- the loading rate of inorganic nutrients, especially nitrogen for marine systems and phosphorus in freshwaters;
- the local hydrodynamics and depth of the cage sites;
- the degree of exposure of bays and near-shore coastal areas in terms of water re-freshment; and
- the stocking density and FCR of fish (local farm scale) and the density of fish farms (waterbody scale).

Of these factors, the most important driver of the impacts of nutrients on water quality in the water column is hydrodynamics. A large farm (or a large number of small farms) located in an enclosed waterbody will have a higher local severity of impact than will the same farm (or farms) when located in a more open or exposed site with stronger hydrodynamic conditions; the latter will have a less severe impact but one which will extend over a larger area. Excess inorganic nitrogen and phosphorus from fish cages are available immediately for phytoplankton uptake. Sites with low flushing will exhibit increased phytoplankton biomass with peak soluble nutrient loadings when feed inputs are highest.

1.2 Sedimented nutrients

Solid waste consisting of uneaten feed pellets, feed fines (fine particulates caused by pellet damage during transport or automatic feeding systems) and faecal material can also accumulate below culture cages and in the outflows of aquaculture facilities. Particulate nutrients settle and are assimilated by sediment benthos flora and fauna. If particulate nutrients are in excess of the assimilation capacity, then they accumulate, altering the biodiversity. In extreme cases they cause anoxic conditions devoid of life in the sediment and the smothering of nearby sea grasses and corals (Figure 3). The accumulation will also depend on local currents and depth. Organic sedi-

FIGURE 3
Gradient of benthic impact from a nutrient source



Source: Pearson and Rosenberg (1978).

ments can also impact benthic (e.g. seagrasses) and sensitive habitats (e.g. corals) close to the farm (Holmer *et al.*, 2008). These areas may be important as a food source or as habitats for local wild fisheries. With high FCR, less of the nutrients are taken up by the fish and more are released into the environment. Improvements in FCR will therefore reduce nutrient impact in the vicinity of the cages. Reduction of feed loss and improvements in nutrient conversion efficiency will reduce (improve) FCR. FCR is also affected by fish size, water temperature and fish status.

In pond culture, much of the excess nutrients are either utilized by primary production or accumulate on the pond bottom. However, nutrients are released into the environment during water exchange and at harvest time when pond water is released to the environment as a point source release. In contrast, in cage and pen culture, water passes through the nets freely and the distribution of the nutrients is highly influenced by the hydrodynamics of the site location.

2. NUTRIENT IMPACTS FROM DIFFERENT CULTURE SYSTEMS

2.1 Prawn and tilapia pond culture

In fish and crustacean pond culture, much of the excess nutrients are either utilized by primary production, or eaten by the fish, or accumulate on the pond bottom as sediments. However, nutrients are released into the environment during water exchange and at harvest time when pond water is released to the environment as a point source release into the river, estuary or sea.

However, poor FCR causes a disproportionate increase in total P and N output loadings. Boyd *et al.* (2008) calculate that total P and N loadings from shrimp farms increase by 27.7 percent and 35.8 percent, respectively, for an increase in FCR from 1.6:1 to 2.0:1 (i.e. 25 percent). This pattern also follows in the case of Nile tilapia reared in ponds, where total P and N loadings increase by 47.0 percent and 36.1 percent, respectively, for an increase in FCR from 1.6:1 to 2.0:1 (25 percent) (Table 1).

TABLE 1

Calculated values of nitrogen (N) and phosphorus (P) loadings from fish and shrimp ponds with increasing feed conversion rate (FCR)

Variable	Black tiger prawn		Nile tilapia	
Change in FCR	1.6:1	2.0:1	1.6:1	2.0:1
Fishmeal in feed (%)	30		8	
Protein in feed (%)	40		30	
Nitrogen in feed (%)	6.4		4.8	
Phosphorus in feed (%)	1.65		1.00	
Protein in animal (%)	19.3		14.0	
Nitrogen in animal (%)	3.09		2.36	
Phosphorus in animal (%)	0.26		0.75	
Protein conversion rate	0.64	0.80	0.48	0.60
N load (kg N/tonne)	71.5	97.1	53.2	72.4
P load (kg P/tonne)	23.8	30.4	8.5	12.5

Source: Boyd (2008).

2.2 Fish cage culture

In cage and pen culture, water passes freely through the nets, and the distribution of the nutrients is highly influenced by the hydrodynamics of the site location. All excess nutrients are released to the environment, increasing the dissolved nutrient concentration in the waterbody and enriching the sediment beneath the cages. If the environment is not able to assimilate these nutrients quickly enough, they will tend to accumulate, causing eutrophication and changes in benthic biodiversity.

3. FACTORS AFFECTING FEED QUALITY

3.1 Dry feeds

The quality of the dry compounded feeds is influenced by the digestibility of the ingredients, the suitability of the formulation to individual cultured species and season, the stability of the pellets in water, the storage and handling of the feed and whether the feed is extruded or pelleted.

3.2 Trash fish/low-value fish

There is a potential impact on the environment from the practice of feeding trash fish or low-value fish. The nutritional value of wet feed (trash fish) is influenced by its quality and storage, and whether the trash fish is fed whole or cut up, as this influences the leaching of nutrients into the environment before consumption. The age (days after capture) and storage conditions of the trash fish influence its bacterial levels and thus the addition of bacteria to the culture water.

4. FEED AND FEEDING FACTORS AFFECTING ENVIRONMENTAL IMPACT

4.1 Feeding strategy

The greatest determinant of the amount of excess nutrients entering the environment is the use of a poor feeding strategy by the farmer that leads to overfeeding. Poor feed quality and poor feeding strategy have major influences on environmental impact. Excess nutrients not utilized by the fish or shrimp are released into the environment and have to be assimilated or else accumulate. Factors affecting poor utilization of feed, resulting in poor FCR, include the quality of the dry feed or trash fish and the feeding strategy. FCR can vary between 1.2:1 for salmon to 2.8:1 (or higher) for milkfish (commercial pellets), depending on feed quality and feeding strategy. The farmer can improve FCR by applying the correct feed amount, feeding duration, frequency and timing.

4.2 Importance of feed quality and feeding efficiency

Feed can account for up to 60 percent of the total production costs in commercial aquaculture. Aquacultural feed management strategies control how farmers feed their fish and thus have a considerable influence upon the economic and environmental sustainability of the enterprises (Cho and Bureau, 1998). Feed management regulates ration size, the spatial and temporal dispersal of feed, feed delivery rate and the frequency and duration of feeding events (Talbot, Corneillie and Korsøen, 1999). In addition to influencing key performance indicators, such as growth rate and FCR, each of these components can also have a profound effect upon the environmental impact of the cultured stock.

A primary concern among aquaculturists is to deliver feeds that meet the nutritional requirements of the fish at ration sizes that optimize both growth and FCR. However, the exact energy and nutritional requirements of numerous fish species (in addition to their appetites and FCR) vary within and between days and also between seasons (Noble *et al*., 2007). Nutritional imbalances lead to reduced fish performance, whereas underfeeding has detrimental effects on production efficiency (Bureau, Hua and Cho, 2006), and overfeeding typically increases feed wastage (Thorpe and Cho, 1995), which leads to poor FCR (Talbot, Corneillie and Korsøen, 1999) and the wastage of excess feeds, thus contributing to environmental degradation in cage culture (Cho and Bureau, 1998). Commercial fish farmers must address each of these factors when designing economically and environmentally sustainable feed management strategies.

5. FEED FORMULATION AND FISH PERFORMANCE

FCR is determined by the metabolic capacity of fish to digest a given feed and is influenced by diet quality, feeding regime, fish size, seasonal water temperatures and oxygen levels. The recorded FCR for farmed fish vary widely from farm to farm or fish batch to fish batch. The numerous fish-feed producers have responded to the need for simplicity in daily farm operations by producing generic formulations for species such as milkfish. These species are grown under a range of very different culture conditions (e.g. in ponds and cages); the feed manufacturers therefore offer feed products recommended for specific culture systems. The nutritional requirements of the fish remain the same in both systems; however, due to natural production in the ponds, they do not require the same feed formulation as in cages to meet this requirement. It is important to establish both the cost efficiencies and the potential impacts on animal welfare and the environment when formulating species-specific feeds and developing feeding protocols.

The extent to which the nutritional requirements of farmed animals are met determines to a high degree their performance. Unlike mammals, fish may use dietary protein – which is an expensive nutrient in fish feed formulation – as an energy source, in preference to lipids and carbohydrates. Therefore, the determination of optimum dietary levels of protein and energy (i.e. the combination of protein/lipids and carbohydrates in the diet) is a crucial parameter for effective feed formulation. Moreover, as the protein and energy demands of fish constantly change, multiple diets need to be formulated. It is therefore important to determine the optimal stages in fish growth where a feed formulation change can offer maximal gain (Lupatsch and Kissil, 2003). The nutrient composition of fish feeds is a determining factor in fish performance and feed utilization efficiency.

6. FEED MANAGEMENT

One of the greatest causes of excess nutrients entering the environment is overfeeding due to the use of a poor feeding strategy. Farmers can improve FCR by providing the correct feed amount, feeding duration, frequency and timing. Aquacultural feed management strategies control how a farmer feeds his fish. In addition to influencing key performance indicators, such as weight gain and feeding efficiency, each of these components can also have a profound effect upon fish behaviour and welfare. A primary concern among aquaculturists is to deliver a ration size that optimizes both growth and feeding efficiency; many aquaculturists still rely upon experience or feed tables to establish the daily ration sizes for fish. Although these recommended rations are based upon extensive research into fish nutrition, they assume that fish will consume food whenever it is offered, irrespective of time of day or feed regime. However, farmed fish show marked variations in appetite both within and between days (Noble *et al.*, 2007), and farmers need to understand this appetite variability in order to prevent episodes of underfeeding or overfeeding.

Underfeeding reduces feeding efficiency (Bureau, Hua and Cho, 2006) and growth (Gaylord, MacKenzie and Gatlin, 2001), and increases competition (McCarthy, Carter and Houlihan, 1992) and fin damage (Hatlen, Grisdale-Helland and Helland, 2006). Overfeeding also reduces feeding efficiency (Talbot, Corneillie and Korsøen, 1999) and increases feed wastage (Thorpe and Cho, 1995), which in turn can increase environmental impacts and environmental degradation (Cho and Bureau, 1998). Commercial fish farmers must address each of these factors when designing welfare friendly and economically sustainable feed management strategies.

7. CASE STUDY ON MILKFISH CULTURE IN BOLINAO, THE PHILIPPINES

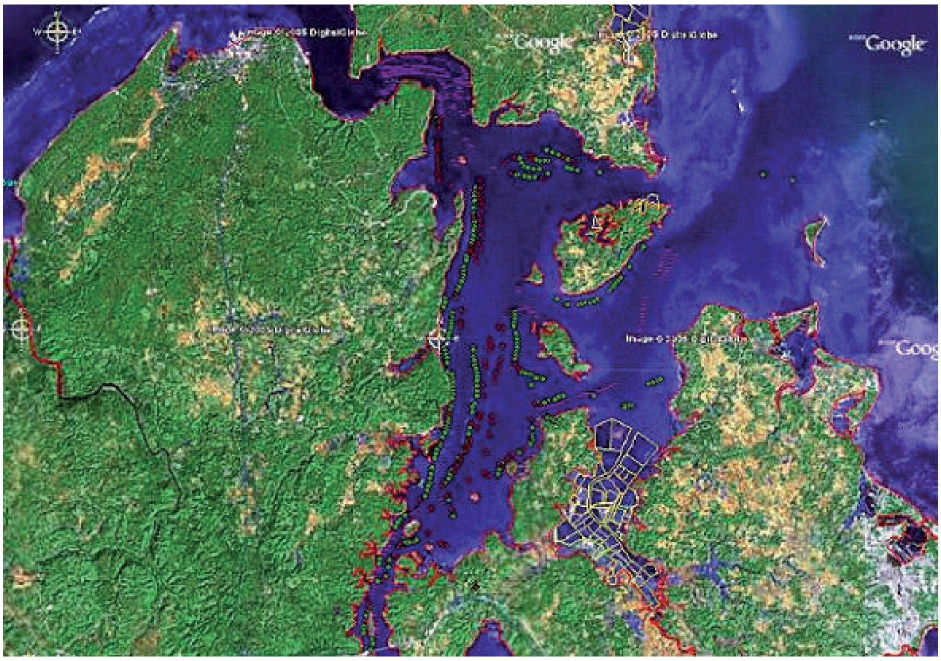
This section describes a case study (White *et al*., 2007) of the impacts of fish culture in Bolinao, Pangasinan Province, the Philippines due to poor feed quality and feeding strategy. It describes the aquaculture production in the enclosed bay and the environmental impacts that it causes. It also describes the possible methods for mitigation, which include improved feed quality, the prevention of overfeeding and the mixing of fed species with unfed (extractive) species *via* integrated multitrophic culture.

In April 2005 there were 460 fish cages in this location, of which 322 were operational (70 percent) and 138 were nonoperational (30 percent). The total operational fish cages had a volume of 371 910 m^3 and were stocked with milkfish (98 percent) at an average size of 304 g and a stocking density of 15.4 kg/m^3. The standing stock was 3 687 tonnes of fish. The fish were fed at 2.85 percent body weight per day using 103 tonnes of feed per day. The production cycle from stocking of fry to harvest (average market size of 433 g) was 6.8 months, giving 1.76 crops per year per cage. The total production per cycle was 5 025 tonnes, and the total production per year from cage culture was 8 867 tonnes.

There were 266 fish pens, of which 217 (82 percent) were operational and 49 were nonoperational. The total operational fish pens had a volume of 3 046 029 m^3 and were stocked with milkfish. There were 11 356 261 fry stocked at an average of 2 g, which were grown to a market size of 466 g in 4.17 months. The pens held milkfish at an average size of 245 g and a stocking density of 1.04 kg/m^3. The standing stock was 3 305 tonnes of fish. The fish were fed at 3.5 percent per day using 117 tonnes of feed per day. The production cycle from stocking to harvest (average market size of 466 g) was 4.17 months, giving 2.88 crops per year per pen. The total production per cycle was 5 027 tonnes and the total production per year from pen culture was 14 467 tonnes.

There were also 254 oyster farms, of which only one was nonoperational. The total operational oyster farms had 253 000 poles with a total length of 819 000 m of pole.

FIGURE 4
Location of fish and mollusc farming structures in Bolinao, 2004
(fish cages – purple, fish pens – green, fish ponds – yellow, oyster farms – red)



Source: Google map overlaid with fish farm structure locations, adapted by R. Palerud and P. White.

The production per cycle from all the oyster farms was 1 638 tonnes. There was only 1 cycle per year, giving a total production per year from oyster culture of 1 638 tonnes.

In April 2005, there was therefore a total standing stock of 6 992 tonnes of fish, giving an annual production of 23 335 tonnes. During this month, an average of 220 tonnes of fish feed was fed per day. There was also an annual production of 1 638 tonnes of mussels (extractive species). The sea surface area in Bolinao (i.e. not including the islands) is 28 882 032 m^2 (2 888 ha). Therefore, there was a production of 8.08 tonnes of fish per ha and 0.57 tonnes of mussels. The location of the fish and shellfish structures in the bay in 2004 is shown in Figure 4.

A survey that was undertaken by the EMMA Project team in 2005 and 2006 to establish the impact of the fish production on the environment (White *et al*., 2007) included the following:

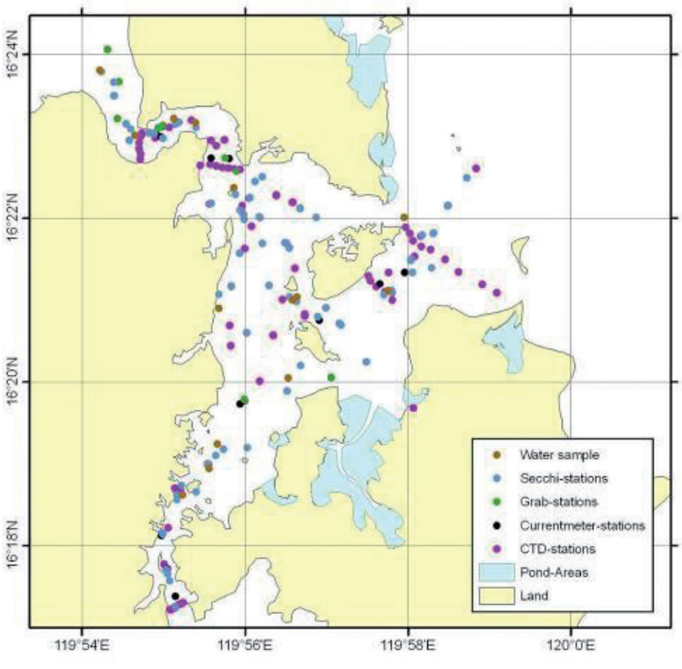
- profiling of water temperature, salinity and oxygen levels;
- determining and analyzing the bathymetry (depth recordings) of the area;
- recording tidal range and current speed, direction and dispersion;
- determining water quality (including chlorophyll, phosphorus, nitrite and ammonia);
- analyzing sediments (biological and chemical); and
- collecting weather data (wind direction, speed, frequency; temperature).

Data were collected from a large number of sampling points within and outside the bay (Figure 5).

Heavy impact on sediments was found in areas with a high density of cages but impacts were less severe in those with fish pens and oyster culture. High levels of chlorophyll and low Secchi depth readings were found in the central areas of the bay, where residence time was the greatest. Poor sediment conditions were found in the channel areas, where the concentration of cages were greatest; however, surprisingly, sediment conditions were relatively good in central parts of the bay and close to areas of oyster culture, leading to the hypothesis that oyster culture was in some way mitigating the environmental impact on sediments (Figure 6).

In areas with poor environmental conditions, the sediments had a high organic content and smelled of hydrogen sulphide (H_2S). In these samples, there were no live animals recorded. Stations with bad sediment conditions were often related to areas with high fish farming activity. In areas with a lower density of fish cages, there was no H_2S smell or high organic content, and live benthic fauna was found.

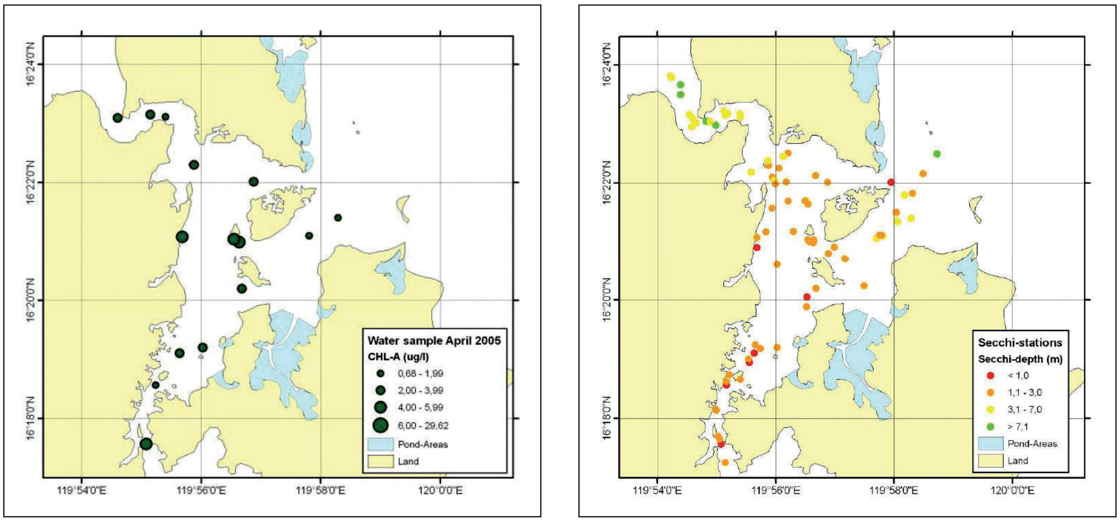
FIGURE 5
Sampling sites in Bolinao



Source: EMMA project results (White *et al*., 2007).

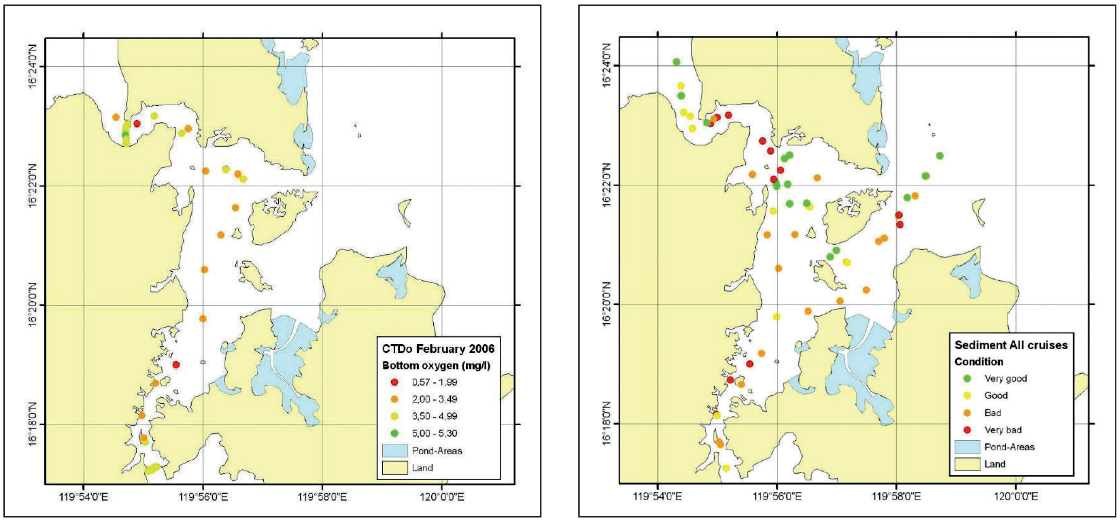
FIGURE 6

Water and sediment quality in Bolinao, 2005 and 2006



Chlorophyll-*a* measurements

Secchi-disk measurements



Oxygen levels in bottom water

Sediment conditions

Source: EMMA project results (White *et al*., 2007).

7.1 Modelling carrying capacity

Environmental carrying capacity for fish aquaculture is defined as the maximum number of fish of a given species that may be grown sustainably in the waterbody being considered. This maximum is limited by a variety of factors, such as the water residence time and the quantity of nutrient entering the waterbody. Computation of carrying capacity should be based on the condition which limits the stock maximally. In other words, it must be based on the limiting condition, which in this case is the ability of the environment to assimilate the natural and aquaculture nutrients.

The carrying capacity model that was developed was based on three steps (Figure 7):

- the rate of water exchange with neighbouring water is determined;
- the growth of phytoplankton and the concentration that it is able to attain with given natural external sources is calculated, allowing the calculation of the remaining concentration of phytoplankton that may be reached by increasing aquaculture production; and

- the fish stock is increased (or decreased) theoretically until the critical phytoplankton concentration is reached. The value so obtained will define the carrying capacity of the waterbody for a given species of fish.

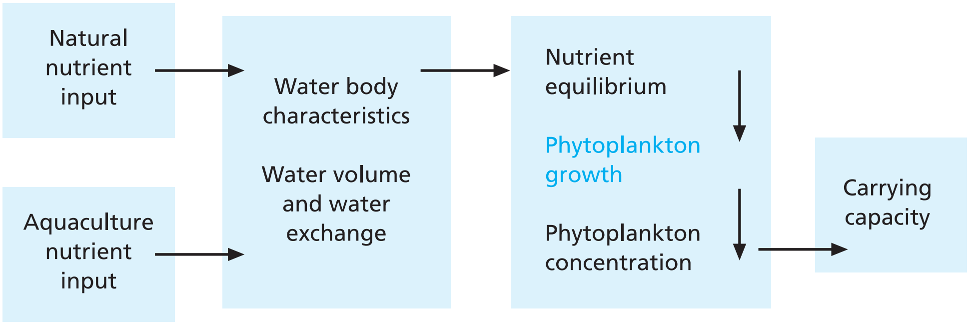


FIGURE 7
The process of determining carrying capacity for fish aquaculture based on determining the critical phytoplankton concentration

Fish aquaculture emits nutrients into the waterbody, seen as an increase in the inflow of nutrients. Since the inflow of water does not change, an increase in fish production results in an increase in average nutrient concentration. Increasing nutrient inflow results in an increase in phytoplankton concentration. Therefore, the increase in steady state of phytoplankton concentration is linearly related to the increase in nutrient inflow. The critical phytoplankton concentration is one of the key parameters that define the carrying capacity of aquaculture in a studied area.

Studies (Florida Lakewatch, 2000) have shown that when algal biomass exceeds 100 µg/litre (measured as chlorophyll concentration), there is an increased probability of a fish kill. Fish kills, however, typically only occur after three or four cloudy days. During this time, algae consume oxygen rather than produce it, because they do not have sunlight available to help them photosynthesize more oxygen. This can lead to oxygen depletion. Without oxygen, aquatic organisms, including fish, die.

The carrying capacity modelling calculations (Legović *et al.*, 2008) suggest that aquaculture in Bolinao Bay is close to carrying capacity during average tidal exchange. This means that during periods of low tidal exchange and no wind, carrying capacity is exceeded.

7.2 Possible mitigation strategies

A number of recommendations to mitigate impacts were drawn up by the project (White *et al.*, 2007), including:

- reducing nutrient output by improved FCR through improving feeding strategy and reducing overfeeding;
- reducing nutrient outputs by increasing food quality through improved species-specific formulation of feeds, including ingredients with higher digestibility;
- increasing the stability of pelleted feeds *via* the use of a good binder or the use of extruded feeds;
- using nutrients from fish production by extractive species, such as oysters in marine and brackishwaters and hydroponics in freshwater; and
- zoning aquaculture into areas away from sensitive habitats and within the local carrying capacity.

The last strategy may require the removal or re-siting of some cages from the area, such that cage culture provides the greatest benefits in terms of livelihoods to the largest number of people in the area.

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