# Environmental impact of aquaculture in the Mediterranean: Nutritional and feeding aspects

Dosdat A.

*in*

Uriarte A. (ed.), Basurco B. (ed.).
Environmental impact assessment of Mediterranean aquaculture farms

Zaragoza : CIHEAM
Cahiers Options Méditerranéennes; n. 55

2001
pages 23-36

# Environmental impact of aquaculture in the Mediterranean: Nutritional and feeding aspects

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**SUMMARY –** Animal rearing has an impact on the natural environment, like all human activity. The major changes caused by aquaculture are related to the basic biological processes of living animals. Intensive farming of aquatic animals can modify the environment as a result of organic and inorganic nutrient loss, the discharge of veterinary products, genetic introgression, etc. The major causes of damage are associated with feeding and nutritional waste but appropriate methods to quantify the various forms of nutritional end-products are lacking. The major reported effect concerns the modifications affecting the benthos, the water quality and the fauna resulting from the build-up of organic matter. The adverse effects of dietary waste products can be avoided or reduced through improved nutrition, feeding management, water treatment and integrated aquaculture. This has encouraged the development of low pollution diets.

**Key words:** Aquaculture, environment, excretion, faeces, waste, nutrition, feeding, water treatment.

***RESUME –*** *"Impact environnemental de l'aquaculture en Méditerranée : Aspects nutritionnels et alimentaires". Toute production animale entraîne des impacts sur le milieu naturel, comme toute activité humaine. Les principales modifications induites par l'aquaculture sont reliées aux processus fondamentaux de la matière vivante. L'élevage intensif d'animaux aquatiques peut entraîmer des impacts environnementaux dus à des rejets de matière organique ou inorganique, des rejets de produits vétérinaires, d'introgression génétique, etc. Les causes principales d'impact sont associées aux rejets alimentaires et nutritionnels. Des méthodes spécifiques sont nécessaires pour quantifier les divers produits émis par les animaux. Les principaux impacts recensés sont dus aux rejets de matière organique et ses conséquences sur le benthos, la qualité de l'eau et les modifications de la faune. Des moyens sont disponibles pour réduire ou éliminer les impacts négatifs, grâce à l'amélioration de l'aliment et de la gestion de l'alimentation, le traitement de l'eau et l'aquaculture intégrée. Ils ont permis la mise en place d'aliments à faible charge polluante.*

***Mots-clés :*** *Aquaculture, environnement, excrétion, fèces, rejets, nutrition, alimentation, traitement de l'eau.*

## Introduction

Aquaculture systems depend on the use of natural water and natural food chains. As such, they are part of the environment and two-way interactions are numerous. In an analogous way to agriculture, aquaculture can affect the environment. However, aquaculture is not the only activity to affect natural resources in freshwater and marine environments, it is simply the latest in a long list. The rapid development of the aquaculture industry during the past decade has made decision makers keenly aware that the huge demand for sites requires more environmental controls in order to avoid detrimental impacts and conflicts.

Among the potential sources of environmental pollution, the release of waste products derived from animal metabolism is the most serious. Many forms of metabolic waste are released into the natural environment, and a better understanding of their actual consequences will be necessary to facilitate the integration of aquaculture within the coastal zones and to avoid conflicts of interest. This is of particular importance for the industry itself, because it is generally the first to suffer from any disturbance due to environmental degradation. The degradation of natural ecosystems in the past have resulted from the mismanagement of natural resources. The experience gained from this may help the aquaculture sector to develop tools and strategies to minimize the detrimental effects to the environment.

In consequence, in this article we shall look at farming of animals, fish and molluscs. To understand the ways in which aquaculture may be harmful to the environment, an understanding of the biological functions involved and the nature of the waste products is required. The range of known effects will be reviewed and some indications given concerning the means available to attenuate them.

## Biological basis of waste production

Every animal (mollusc, shrimp and fish) is heterotrophic i.e. obtains its vital energy by feeding on complex molecules. These molecules are processed by the animal to increase its biomass (anabolism), the remainder being transformed into heat and excretory products (catabolism). Thus, animals have qualitative nutritional requirements (proteins, lipids, carbohydrates, minerals, vitamins) and quantitative ones, including nutrients and oxygen. All living animals release metabolic waste products at levels which correspond to their requirements and the feeding level they are subject to.

Compared to terrestrial animals, aquatic animals have some specific adaptations that make them different. Being cold blooded animals, their energy requirement is ten fold lower than mammals, which have to maintain their temperature at a constant level and are temperature dependent. Thus, in rainbow trout for example, this maintenance requirement increases from 12 to 42 $kJ/kg^{0.82}/d$ at temperatures ranging from 7.5 to 20°C. Moreover, both fish and molluscs grow continuously throughout their lives. Their requirements also vary with age. Due to the different capacity to metabolise proteins and lipids, one thousand 5 g rainbow trout need twice as much energy to increase their combined biomass by one kg as five 1 kg ones do. Generally speaking, protein is incorporated more efficiently by fish and shrimp than other farmed animals. The protein retention efficiency is more than 30% in salmonids while it is only 18% in chickens and 13% in hogs. This explains why the protein content of the feed, usually provided as fish meal, is so high in fish culture.

Bivalve molluscs belong to the first two steps of the trophic chain in the aquatic ecosystem. Bivalves are herbivorous and feed on phytoplankton which contains large amounts of carbohydrates. Higher levels (shrimp, fish, aquatic mammals) are mainly carnivorous animals, and have a great ability to use proteins and lipids as metabolic fuels. Very few fish species are herbivorous or omnivorous (tilapia, carp, milkfish, mullet).

In aquaculture, irrespective of the species, water is the vehicle for both food and waste. The oxygen content of water is very low (generally less than 10 g per ton) compared to air (200 kg per ton). In that sense, oxygen is extremely limiting in aquaculture production and the energy required to extract it from the water is higher for aquatic animals than terrestrial ones. Its concentration can decrease very rapidly and this is associated with an increase in the level of $CO_2$, which is a toxic molecule. The fact that all waste, soluble or not, is released into the water makes it very difficult to remove. Thus, the degradation in water quality has a great impact on the animals, wild or not, that live in it.

Food derived waste has four sources:

(i) Uneaten feed. This is the case with artificial feeding, generally due to bad husbandry, fish diseases or unsuitable environmental conditions.

(ii) Undigested feed. This is the case mainly in bivalves when the control of intake and repletion is insufficient. Thus, they ingest more than they can process and release the intact microalgae in the form of faeces called pseudo-faeces.

(iii) Indigestible compounds. Complex molecules present in the feed are split into small molecules that either can or cannot cross the intestinal barrier during digestion. Those that cannot, due to their size or their shape, are rejected in the form of particulate matter (faeces).

(iv) Excreta. Excretion is the physiological phenomenon by which molecules that come into the body and dissolve in the plasma are released after being processed and degraded. These are soluble compounds that are discharged into the water through particular organs, such as the gills and the kidney. Thus aquatic animals are directly subjected to the effect of their own waste products. Fig. 1 summarizes these processes.

The remainder of input feed minus uneaten and undigested feed, indigestible compounds and excreted metabolites are retained in the fish for growth and gamete production.

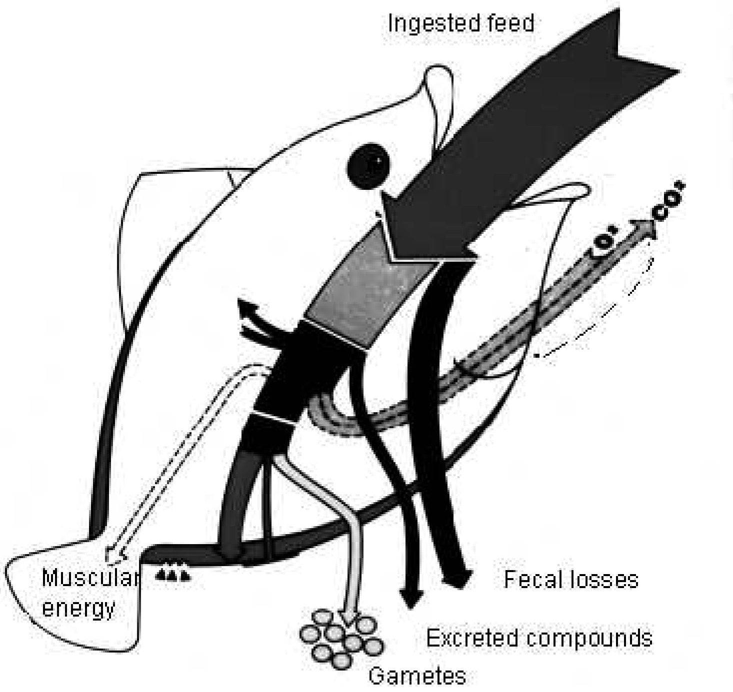


Fig. 1. Metabolic processing of ingested feed (by courtesy of J. Guillaume).

## Characterization and quantification of waste

### Methods

Generally speaking, the relationship between feed and waste characterization is easier in fish than in shellfish farming. Feeding fish using artificial food provides a powerful tool to investigate fish feeding behaviour and metabolism. The two major limiting elements in both marine and freshwater environments are nitrogen and phosphorus, and the following will concentrate mainly on these.

*Non-ingested feed*

Fine control of feed intake is more difficult for aquatic animals than terrestrial ones. The use of traps and collectors to capture pellets under sea cages or tanks is the most common method used to quantify uneaten feed in fish farming (Fig. 2). Indirect methods can also be used, for example by evaluating the proportion of food eaten using X rays. The major problem to predict feed losses is that it relies on the skill of the operating personnel in determining the amount of lost feed, making the prediction of pellet loss unreliable. In the particular case of pseudo-faeces production by shellfish, estimates can be made by the selective collection of faeces, pseudo-faeces being voided through another tract. Filtered phytoplancton numbers can be calculated from the difference between the input and output concentrations.

*Faeces*

The concentration of various components and/or nutrients in faeces can be measured by indirect digestibility trials. Evaluation using direct methods is not recommended in fish rearing but is necessary for shellfish, for which external non-digestible markers, usually chromic oxide, cannot be incorporated into the feed. The use of a marker enables partial collection of the faeces and is independent of feeding level. These measurements should be carried out in artificial experimental rearing systems (Fig. 3) where errors from faeces leaching and the collection of non-faecal material can be avoided. Other methods are available, including abdominal pressure, anal aspiration and dissection of the digestive tract. These methods are stressful to the fish and give approximate values of the digestive losses (Table 1). The indirect method gives the apparent digestibility of a nutrient as follows: Indigestible part of nutrient (%) = 100(% marker in diet × % nutrient in faeces)/(% marker in faeces ×

% nutrient in diet)

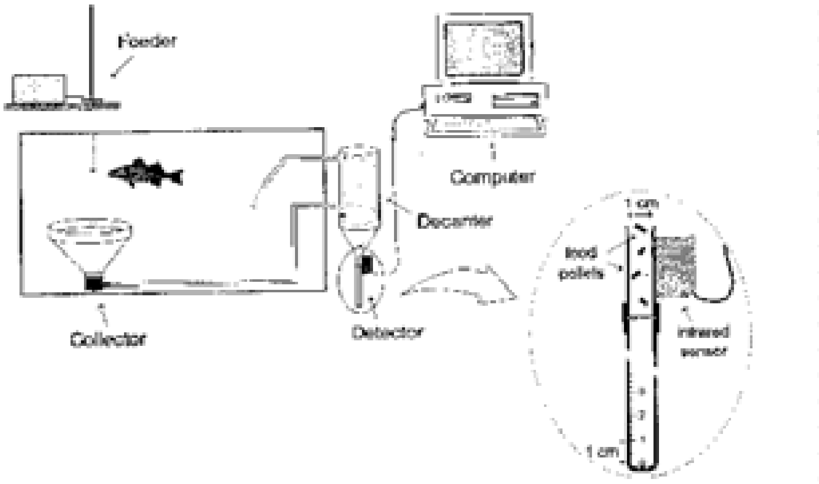


Fig. 2. Experimental device to estimate food losses (from Madrid *et al.*, 1997).

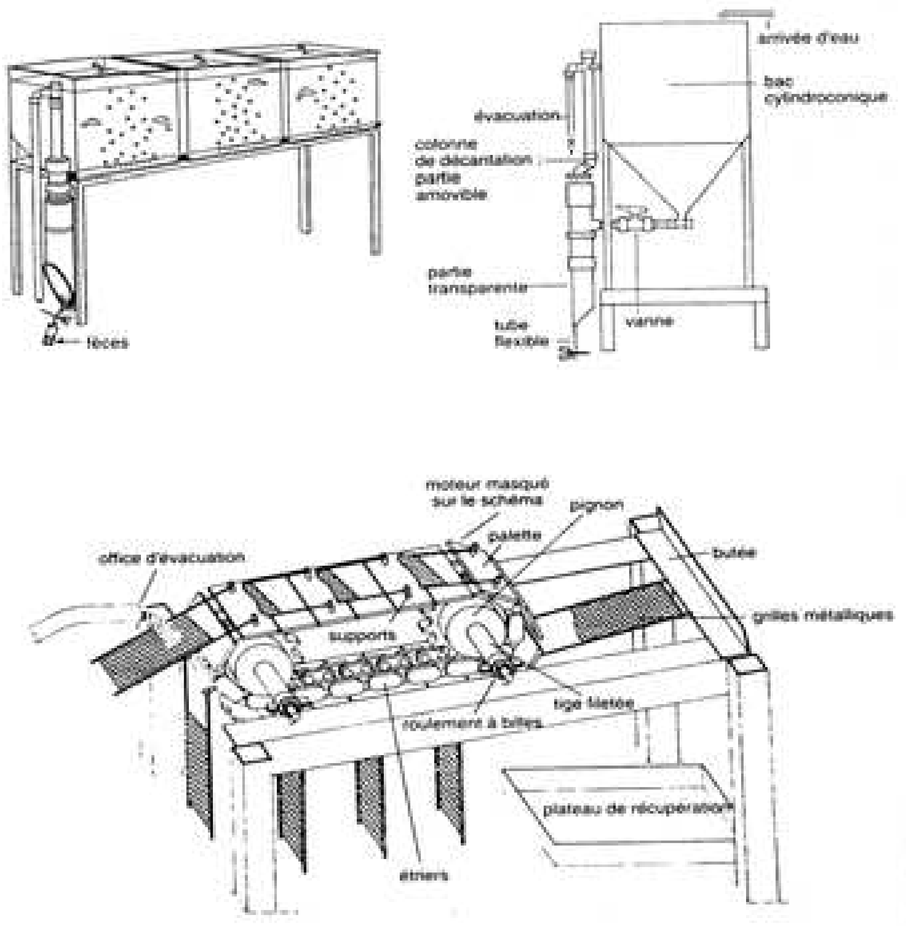


Fig. 3. Experimental devices to collect faeces (from Guillaume *et al.*, 1999).

This provides an apparent coefficient because it includes metabolic losses such as digestive bacteria, digestive enzymes, mucus and cells. The direct method needs exhaustive and continuous measurement of feed and collection of faeces.

Table 1. Apparent digestibility coefficient of protein and lipid for sea bass, using different methods (from Spyridakis *et al.*, 1989)

| | Collection method | | | | | |
|---|---|---|---|---|---|---|
| | Abdominal pressure | Digestive tract dissection | Anal aspiration | Thieving | Tank siphoning | Clarification |
| Protein digestibility | 82.5±1.4 | 84.4±0.8 | 86.6±0.3 | 90.4±0.6 | 90.6±0.3 | 94.2±0.1 |
| Lipid digestibility | 94.1±0.8 | 95.0±0.4 | 96.3±0.4 | 96.0±0.2 | 97.3±0.2 | 97.1±0.3 |

Digestibility is additive and only a few interactions between components have been reported (e.g. starch). So the digestibility of a given diet can be calculated and predicted from the digestibility of each of its components. This technique can be used for nitrogen, phosphorus and carbon, but is not accurate for lipids and carbohydrates because interconnections between the carbohydrate and lipid metabolic pathways are possible.

### *Excretion*

Excretion can be quantified using either the direct or indirect method, or by the *in-situ* method. The direct method is based on measuring metabolite concentrations in the water. This requires a sophisticated apparatus (Fig. 4) and is subject to errors. It provides instantaneous values and excretion profiles for each metabolite. The indirect method infers metabolite excretion by subtracting faecal losses and compounds absorbed from the ingested feed. Faecal losses are estimated by a digestibility trial, absorbed compounds by proximate analysis of the whole fish at the beginning and the end of the trial, and the ingested feed by monitoring the feeding level and proximate analysis of the feed. Indirect methods give average values for excretion. In situ methods are based on the statistical analysis of the levels of particulate and soluble matter downstream from the farms and comparing this to delivered feed (Lemarié *et al.*, 1998). This method does not require experimental equipment but has to be repeated time after time and analysed statistically. It is hardly used in the marine environment, but a lot of data from the freshwater environment, and with marine species, are obtained using this method.

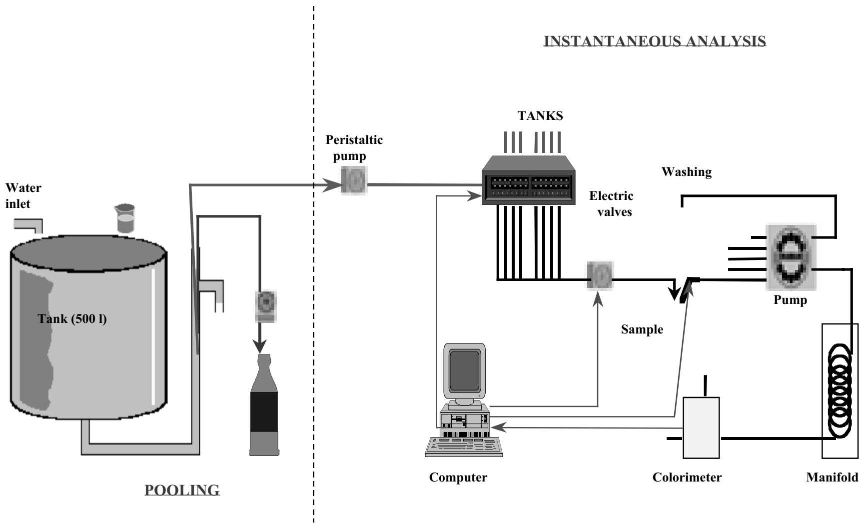


Fig. 4. Experimental apparatus to evaluate excretion rates.

### *Accretion*

Accretion is easily measured by proximate analysis of fish. It is commonly used for measuring nitrogen (or protein, the conversion factor between protein and nitrogen is usually 6.25), phosphorus and energy retention. The gross protein efficiency ratio (GPE), for example, is the percentage of nitrogen (or protein) absorbed from ingested nitrogen (or protein). It represents a rough approximation of the biological value (BV) of proteins which is given by the following: BV = 100 $\times$ [Ingested nitrogen – (Faecal nitrogen + Excreted nitrogen)]/(Ingested nitrogen – Faecal nitrogen).

The BV is dependent on the amino acid balance of the ingested proteins. It is not additive, which explains why it is rarely used. Thus, the biological value of a mixture of proteins may be more relevant than the BV of each component.

## Results

### *Non-ingested feed*

Due to their sedimentation velocity (5-15 cm/s, Elberizon and Kelly, 1998), food pellets distributed in sea cages cannot all be ingested and some settle on the bottom. Food wastage, except when disease occurs, has been evaluated at 2% and 9% for extruded and pelleted feed respectively. It appears that, in cage farming, most of the uneaten feed is consumed by wild fish that congregate around fish farms, thus diminishing the load on the bottom. But these observations have still to be quantified. A better control of feed loss can be achieved with land based systems. In the sea-bass and sea-bream industry, bad conversion indices can very often be explained by feed wastage.

### *Faeces*

The release of faeces and the apparent digestibility coefficient may vary on an hourly basis. Faeces and pseudo faeces are solid particles from 1 µm to 5 mm in diameter that contain about 80-85% water and naturally sink at a speed of 1.5-3 cm/s (Elberizon and Kelly, 1998). They are a source of organic enrichment of the sea bed sediment, although the effect of the quality of the organic matter on the benthic ecosystem has not been well documented. Usually, the most important factor is the concentration of carbon. In artificial feed, the average carbon content is 40-50% of dry weight, of which around 30% remains in the faeces. In salmonid farming, one kg of feed (dry weight) is necessary to produce one kg of fish and 100-200 g of faeces are produced. In Mediterranean fish farming, where 1.5-2.0 kg of feed are necessary, 300-400 g of faeces are released into the environment per kg fish produced. Thus the carbon content of the faeces is higher (60-70%) than in the feed. The organic matter released in these faeces also contains nitrogen and phosphorus, amounting respectively to 10-15% and 40-50% of the ingested feed, although this is highly dependent on feed quality. Leaching of complex molecular forms of nitrogen and phosphorus from faecal material into the soluble fraction may also occur. In filter feeders, the amount of nitrogen and phosphorus in the faeces may be as high as 80 and 90% respectively. Some other feed components, such as lipids, pigments and minerals, are also released into the environment via this pathway. With the increasingly high lipid content currently used in salmon diets, lipid loss to the environment has recently been studied. These molecules have a high carbon content and need more oxygen to be oxidized, but are easily digestible by fish. Table 2 gives some experimental values for nutrients released from some food; these values are comparable between species, except for carbohydrates.

Particulate organic matter transits through the water before sedimenting. Routine excretion rarely adds more than an 5-10 mg/l even close to fish farms, which is usually within the standard variation for concentrations of natural solids in suspension in continental coastal waters. Detrimental effects can also occur during cleaning in pond culture. In both marine and freshwater environments, the benthos suffers most from aquaculture output. Organic matter from the farm usually settles in the vicinity and accumulation occurs when the mineralization process is slower than the sedimentation process. One square meter of oysters cultivated on ground racks produces 1.5-2.0 kg of organic sediment every day. A fish farm produces 100 kg per year. Drainage water from pond culture is a particular case in. The reduced sediments are re-suspended during fishing or cleaning and generally accumulate in irrigation canals, with similar results.

### *Excretory products*

The end products of the glycolysis of carbohydrates and the beta-oxidation of lipids are excreted through the gills in the form of $CO_2$ (which accounts for 50% of the carbon loss) and $H_2O$, which generally have only a limited impact on the natural environment. Conversely, the end products of protein metabolism are more complex and result in the release of soluble nitrogen into the water. Ammonia accounts for 70% of the nitrogen excreted by bivalves and 85-90% of that excreted by shrimp and fish, the remainder being excreted in the form of urea, creatinin or other complex nitrogenous molecules. In the environment, ammonia is quickly oxidized to nitrate, which is less toxic. Ammonia is a toxic molecule that is excreted through the gills in fish and molluscs. Aquatic animals can tolerate a high concentration in their blood: fish plasma concentrations can reach 4 mg/l, whereas a concentration of 0.4 mg/l is toxic in mammals. Ammonia excretion is controlled by the nutritional status and depends on size. It ranges from 100 to 1200 mg $N\text{-}NH_4$ per hour per kg of body weight in fish, but only 1-10 mg $N\text{-}NH_4$/kg/h in filter feeders (Zhu *et al.*, 1999). Excretion of urea and other nitrogenous catabolites is low, except in some atypical species.

Table 2. Faecal to ingested nutrient ratios in salmonids for nutrients from different sources (from Guillaume *et al.*, 1999; Kaushik, 1998)

| Nutrient type | Origin | Proportion (in % of intake) |
|---|---|---|
| Dry matter | Blood mill | 10 |
| | Fish meals | 15 |
| | Fish soluble protein concentrate | 10 |
| | Soybean cake | 25 |
| Protein | Blood mill drum dried | 68 |
| | Soybean cake | 15-25 |
| | Beer yeast | 15-18 |
| | Fish meals | 10-20 |
| | Fish soluble protein concentrate | <7 |
| Lipid | Fish meals | 5-10 |
| | Palmitic (C16:0) and stearic (C18:0) acids | 50 |
| | Oleic acid (C18:1) | 20 |
| | Linoleic (C18:2) and linolenic (C18:3) acids | 10 |
| Carbohydrate | Potato | 95 |
| | Corn amylopectin | 46 |
| | Pre-gelatinized starch | 4 |
| Phosphorus | Phosphorus phytate | 80 |
| | Fish meals | 40 |
| | Beer yeast | 10 |
| | Sodium monophosphate | 2 |

Phosphorus excretion (in the form of orthophosphate) is generally low: 10 to 20% of intake (10-20 mg $P\text{-}PO_4$/kg/d) in fish, and 5% in bivalves. It has been estimated that a total of 10 kg of phosphorus and 70 kg of nitrogen are released by a salmonid farm for each ton of fish produced. Overall, it is estimated that 40-45% of nitrogen intake is retained in fish and 2-5% in filter feeders. Some excretion values for Mediterranean fish species are given in Table 3.

The consequences of the animal metabolism described above contribute to a modification of the water content by:

(i) Decreasing the oxygen concentration. This is particularly perceptible in lakes, lochs and generally in areas where water turnover is low. Usually, farmed animals are the first affected and act as sentinels. Wild animals are very susceptible to oxygen depletion and generally move away accordingly. In the open sea, this parameter has been proved not to be pertinent.

(ii) Increasing nutrient concentrations. $CO_2$, ammonia, phosphate and other excretory compounds are intermediary constituents in the aquatic ecosystem that are used by plants (primary production of micro- and macro-algae). Still, they may have unwelcome effects on the water quality within the farm (particularly in ponds or tanks).

Table 3. Metabolite excretion by some Mediterranean fish (from Company *et al.*, 1999; Dosdat, 1992a,b; Dosdat, unpublished). % CP indicates the protein content of the diet

| | Total ammonia excretion (mg N/kg BW/d) | Urea excretion (mg N/kg BW/d) | Phosphorus excretion (mg P-$PO_4$/kg BW/d) |
|---|---|---|---|
| Sea-bass, 10 g, 40% CP | 950 | | |
| Sea-bass, 10 g, 55% CP | 1300 | 80 | |
| Sea-bass, 100 g, 50% CP | 400 | 30 | 20 |
| Sea bream,100 g, 50% CP | 600 | 25 | 10 |
| Common dentex, 20g, 55% CP | 1340† | | |

†For ammonia and urea.

## Modelling

The use of a physiological model, based on energy utilization, is a more valid tool for predicting metabolic losses (Thorpe and Cho, 1995; Kaushik, 1998; Stigebrand, 1999). We describe here the principle of these models, which can be applied to all fish species, and their application to sea-bass. Nevertheless, the basic data necessary to build sound parameters are very often lacking.

The first model to be employed is a growth model. Numerous models have been developed. The most integrative is the one developed by Muller-Feuga (1990) for which the formula is:

$$dW / dt = aW^{b} \times [e^{t(k_M - T_m)}] - e^{t'(k_M - T_m)}]$$

where: dW/dt is the growth rate, a and b growth coefficients, t and t' exponential coefficients, $T_m$ the average temperature and $k_M$ a thermal coefficient (maximum sustainable temperature). These coefficients vary according to the species. For sea-bass, the growth coefficients are :

a = 0.980 $k_M$ = 33.6
b = 0.466
t = 0.110 t' = 0.161

This growth model is then combined with an energy model, the concept of which is:

$$Q_r - (Q_f + Q_n) = Q_s + Q_l + Q_{sda} + Q_g + Q_p$$

where: $Q_r$ (in calories per day) is the energy content of ingested food, $Q_f$ the excreted feces, $Q_n$ the excreted nitrogen (other sources of energy loss are considered negligible), $Q_s$ the standard energy metabolism, $Q_l$ the locomotion (or activity) metabolism, $Q_{sda}$ the specific dynamic action (i.e. the cost of food processing), $Q_g$ the energy retained during growth and $Q_p$ the reproductive energy. Every component can be described by a specific equation. For example, $Q_g$, $Q_f$ and $Q_n$ can be described by the following equations:

$$Q_g = Cfi \times dW/dt$$

where: Cfi is the energy content of the fish.

$$Q_f = [(1 - Ap)Ep + (1 - Af)Ef + (1 - Ac)Ec] \times Q_r$$

where: Ap (respectively Af, Ac) is the apparent digestibility coefficient for protein (for fat and carbohydrate respectively), Ep (Ef and Ec respectively) the percentage of the feed energy in the form of protein (fat and carbohydrate respectively).

$$Q_n = 0.4 \times (Ep \times Ap \times Q_r - Fp \times dW/dt)$$

where: Fp is the protein energy content of the fish.

All the formulae can be used in a spreadsheet to calculate N, P and C concentrations according to environmental temperature, feed characteristics, growth rates, fish species, age, etc.

In practice, the level of impact depends on the relationship between the concentration of a given element and the holding and assimilation capacity of the animal. An equilibrium has to be respected to avoid any harmful and undesirable environmental disorder. Nested models, including farm management, hydrodynamic compartment, loading evaluation and potential impact estimation are now used for a range of aquaculture production systems. The difficulty lies in the choice of threshold to determine the level at which the impact can be said to switch from positive to negative.

## Reducing the impact: Towards sustainability

### Upstream management

*Species selection*

Not all species have similar metabolisms and have different capacities to process energy and nutrients. Figure 5 presents the excretion patterns of five different fish species reared in similar environmental conditions and using the same diet and feeding level.

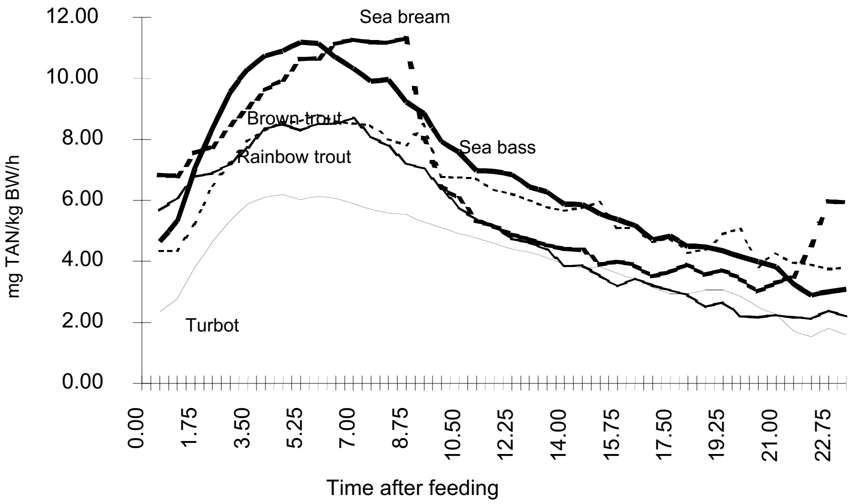


Fig. 5. Postprandial ammonia excretion in various marine fish species (from Dosdat *et al.*, 1996).

The same specific differences have been observed by Company *et al.* (1999) on GPE and feed gain ratio, where common dentex compared favourably with sea bass and sea bream.

Thus, selecting the right species based on these metabolic "indices" can work to protect the environment. Along the same lines, it is possible to breed selected populations or stains of a given species in order to genetically improve their metabolic indices, and metabolic capacity can also be improved through selective breeding. This could prove to be a valuable method that could be used with both fish and shellfish.

*Improved feeding*

Improvements in feed and feeding are of use only for controlled rearing. In shellfish, except in very specific production systems, such as artificial pre-growing, direct nutritional control is impossible. The use of an extruded diet in place of a pelleted diet enabled small particle dispersion during feeding to be reduced, thus limiting the amount of scattered nutrients and the impact of non-ingested feed. This also contributes to a greater stability of the feed in the water, and to a decrease in the sedimentation velocity of the pellets. In some cases, when faecal traps are used downstream, faeces stability and clearing can be enhanced by appropriate additives.

Whenever possible in controlled aquaculture, the appropriate management of feeding helps to optimize the overall efficiency of feed use through improvements in the conversion index, protein and energy yields, and growth. This adaptation can be achieved by matching fish appetite and feed distribution in terms of feed quantity, feeding frequency and feeding time. An inappropriate feed distribution is often correlated with bad food intake and direct feed loss. Improvements in feeding tables, correlated with each species and its genotype, temperature, size and feed quality have reduced pellet loss to the environment in fish farming. Self feeding devices are powerful tools in that respect, in that they allow voluntary ingestion of feed to be measured over various time scales (Fig. 6) and under various environmental conditions. These devices are utilized more and more in industry. A responsible management must also make animal behavior an important parameter in farming.

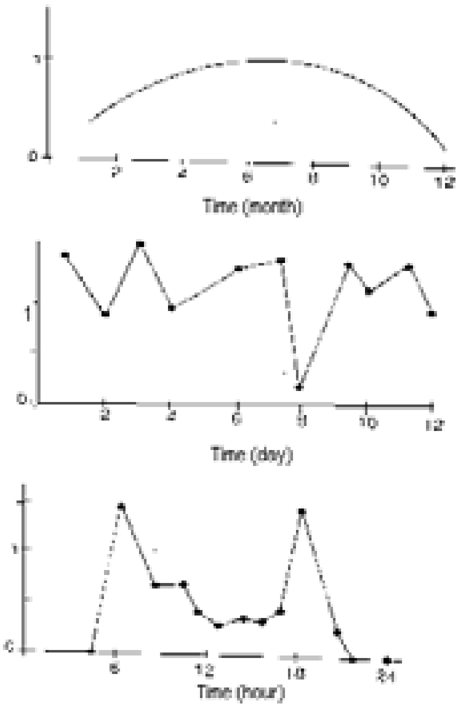


Fig. 6. Temporal variations of voluntary feed ingestion at different time scales (adapted from Guillaume *et al*., 1999).

### *Nutritional improvement*

Given the constant values of nitrogen digestibility and phosphorus availability in food, the release of these nutrients in faecal material is a linear function of ingestion. By contrast, ammonia and phosphorus excretion may increase if the animals' requirements are exceeded. In that sense, minimizing faecal waste comes only through maintaining high food quality, although minimizing excretion may come from high food quality and good feeding management. Nutritional disorders may also result in pathological disorders.

When artificial food is used, choosing highly digestible ingredients in the formula may reduce organic loss in the faeces. These are the labelled "high digestibility (HD)" diets. The use of enzymes (phytase for phosphorus) may also improve the digestibility of the ingredients, particularly in the case of plant meal. Recent work by Oliva-Teles *et al.* (1998) showed that plant meals could be used to replace fish meals, which could alleviate the threat to wild stocks. Little work has been carried out on the digestibility of foodstuffs in Mediterranean fish species.

In the same way, it is possible to decrease the amount of protein required to meet the animal's energy needs by increasing the energy in the feed in the form of lipids or, to a lesser extent, carbohydrates. To summarize, when the protein requirement is met, the remaining amino acids are transformed to produce energy. These amino acids can theoretically be replaced by other energy sources. This economy reduces the proportion of excreted nitrogen and increases the amount of nitrogen retained by the animal. The development of these "high energy diets" was reinforced by the use of pellet extrusion technology, which allows high levels of lipid to be included in the diet. Substantial advances have been made in the protein sparing effect of lipids. The changes in salmonid diet is a good example of these improvements. During the last decade, which saw a 50% increase in growth rates, lipid content in salmonid diets has increased from 15-20% to 30-35% and the phosphorus content has decreased from 2.0 to 1.0%. Nitrogen, phosphorus and organic matter loss has decreased by a factor of two during this period. At the same time, the proportion of nitrogen harvested in the fish (= GPE) has increased from 30% to 50% of nitrogen intake. At an experimental level, ratios of over 60% have been obtained. By comparison, the best GPE reported in sea bass culminated at 25-30%. The GPE doesn't seem to improve in sea bass when they are fed a high protein diet. Conversely, this diet seems to be efficient in sea bream and dentex (Company *et al.,* 1999).

Another way to reduce nitrogen loss is to adapt the essential amino acid (EAA) profile of the feed to the requirements of the fish. Fish species have an EAA requirement that closely corresponds to their body composition. In the case of an unbalanced EEA diet the GPE decreases, thus contributing to an increase in nitrogen loss to the environment (Fig. 7). Nevertheless, EAA requirements in Mediterranean fish are not well known and substantial work has still to be undertaken.

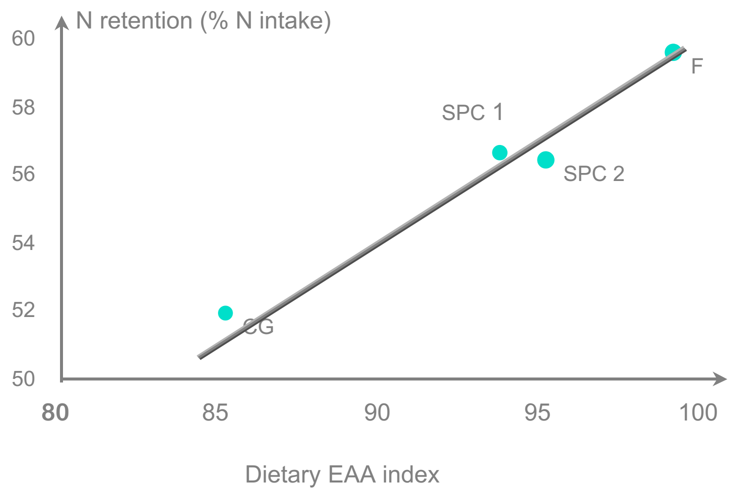


Fig. 7. Relation between EAA content of the diet and nitrogen retention (from Dias, unpublished).

Fish require between 0.4 and 0.7% of phosphorus in their diet. The availability of dietary phosphorus is dependent on the chemical form and digestibility of the food components. The bioavailability of phosphorus is higher in fish meal than in plant meal due to the fact that phytase is not one of the digestive enzymes of fish. The reduction in ash content of fish meals, an addition of phytase to the diet (Oliva-Teles *et al*., 1998) and the use of soluble inorganic salt as a supplement will act to reduce the amount of phosphorous released into the environment.

## Downstream management

### *Mitigating factors*

Where possible, the rotation of rearing infrastructures (in an analogous way to crop rotation), and leaving them fallow allows the benthos to recover. The return to reference status depends on the environmental characteristics. This can be enhanced by ploughing, dredging, etc.

In some cases, an artificial increase in the current speed (in closed bays) using propellers or artificial sediment removal (in pond aquaculture) have been employed. In the latter case, the problem remains as to the final destination of these wastes.

*Waste treatment*

Effluent water from farming does not contain large amounts of waste. Waste water from land based facilities could conceivably be treated. This is more difficult in shellfish and cage farming where the process is not completely controlled. The easiest material to remove from the water are the solids that sediment. These settle either within the rearing structure (in the case of ponds) or in a specific apparatus (lamellar, centrifugal, clearing basins). Sedimentation ponds used in freshwater trout farming are known to remove up to 90% of the suspended solids if correctly adapted to the water flow. The latest developments make use of filters (drum, triangle, rotating), the advantage being the rapid removing of sludge, thus avoiding the leaching and mineralization that occur in settling ponds. These devices can remove 70% of faecal organic phosphorus and 40% of nitrogen. Their efficiency is limited by the filtering capacity of the sifter (about 60 µm). The sludge produced would probably make a good crop fertilizer but this possibility is still being studied.

The removal of soluble compounds requires transforming them into solids. This can be achieved by using macrophytes such as hyacinth in freshwater, or marine macroalgae or microalgae. In contrast to animals, plants incorporate inorganic compounds for their metabolism. They can remove large amounts of nitrogen, phosphorus and heavy metals from the water. An experiment conducted in Chile associated cage rearing of Atlantic salmon with seaweed (*Gracillaria*) culture and was relatively successful in enhancing algal yield and in reducing the nutrient content of the surrounding waters. Phytoplancton have the same effect but are difficult to remove and are rapidly diluted in the environment. This method could be adapted to lagooning systems, when space is available, and used to feed shellfish.

Another method is to use bacteria. A succession of treatments using aerobic and anaerobic bacteria can transform ammonia into nitrate, which is less toxic, and then into gaseous nitrogen. This can occur naturally in ponds or be carried out artificially in biological reactors.

*Integrated systems*

The different techniques for treating water can be combined in order to minimize the impact of waste on the environment. We describe here two typical systems, keeping in mind that there are a large range of intermediary systems. These systems have only been developed for land based production, even though they could theoretically be used in the open sea, associating seaweed (to absorb soluble nutrients), filter feeders (to use up suspended matter) and fish, for example.

(i) Semi-intensive production. The best known is the integrated fish production system, which is used in China and East Asia. It is based on recycling manure from fish ponds and agriculture for use in crop production. In return, secondary products derived from manure and crop production are recycled in fish ponds (Fig. 8 ). The integrated system retains 80-85% of organic matter, nitrogen and phosphorus in the sediment, compared with intensive systems, where 75-85% of the nutrients pass into the water. These systems are used mainly with herbivorous fish (carp, milkfish, tilapia). They help by providing valuable proteins. They may profitably be adapted to developed countries, although problems of sanitation (bacteria) and space allocation have still to be resolved.

(ii) Intensive production. The best controlled is the closed system developed in Europe (Fig. 9). It is based on the recycling of water from fish tanks. After appropriate treatment, water is returned to the fish tank. This treatment includes sieving to remove faeces from the water. Purified water is transported to nitrifying bacterial filters where toxic ammonia is transformed into nitrate. If necessary, a denitrification filter can be added. Water is then reintroduced into the fish tank. Faeces and water from the filter are separated in a clearing pond and the residual water is purified in an algal pond before injection into the fish tank. Presently, this type of system is mainly used with carnivorous fish species (sea bass, sea bream, flatfish). It reduces the detrimental impact on the environment by decreasing the quantity of waste released into the aquatic environment, and allows farms to be built away from the coast, where space is at a premium in developed countries.

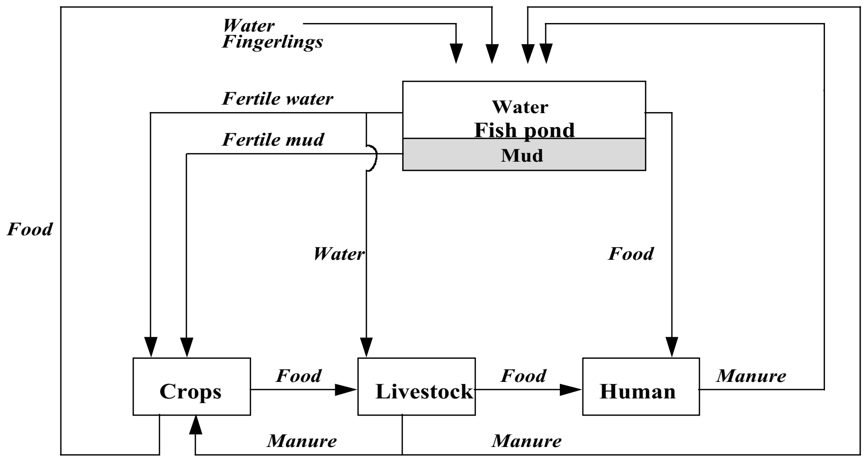


Fig. 8. The integrated semi-intensive fish production system (from Dosdat, 1999).

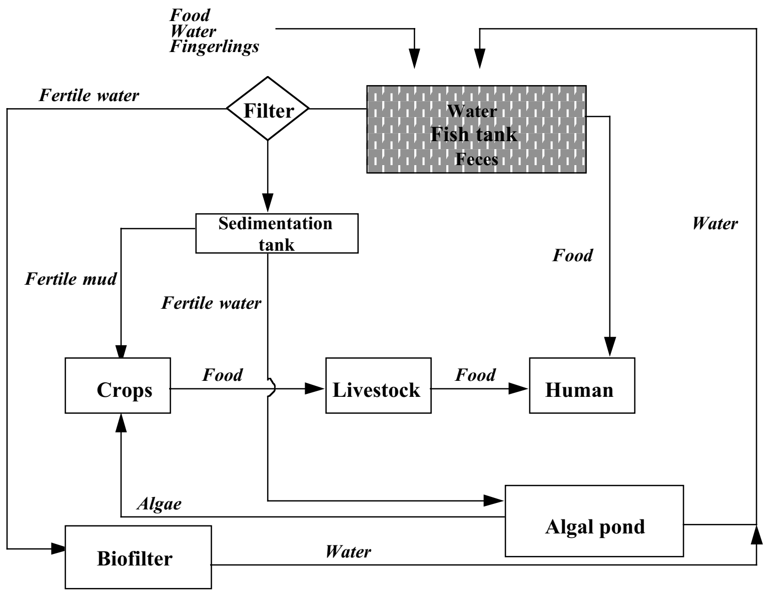


Fig. 9. The recirculating intensive fish production system (from Dosdat, 1999).

## Conclusion

Quantitatively, Mediterranean aquaculture is not a major source of pollution for the marine environment. In many cases, there is no consensus of opinion as to whether the ecological changes should necessarily be regarded as negative. But a consensus does exist as regards the protection of the aquatic environment. Fortunately, in terms of the nutritional aspects, any effort made to improve nutrient utilization has a positive effect on productivity as well as on the protection of the environment. Most research has been done on salmonids, but the general principles can be applied to all marine fish. There is a lack of scientific information on the metabolism and physiology of Mediterranean species, and more generally on species that have recently become interesting for aquaculture. Nutritional data concerning food intake, digestibility and nutrient retention are the most relevant for measuring and reducing the levels of nutrients in the environment.

Aquaculture should not be abandoned because of the anticipated pollution. If well managed, its effects can be positive (nutrient enrichment, landscape conservation, waterway preservation, conservation of species, integrated farming) or attenuated, and are generally reversible. It should be recognized that, while negative environmental impacts have received more attention, aquaculture may also contribute to the conservation of the environment. Aquaculture needs high quality water, and may serve as an environmental probe to detect pollution and to protect non cultured species, if the industry is properly run.

Research has a major role to play in the outcome of all of these issues.

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