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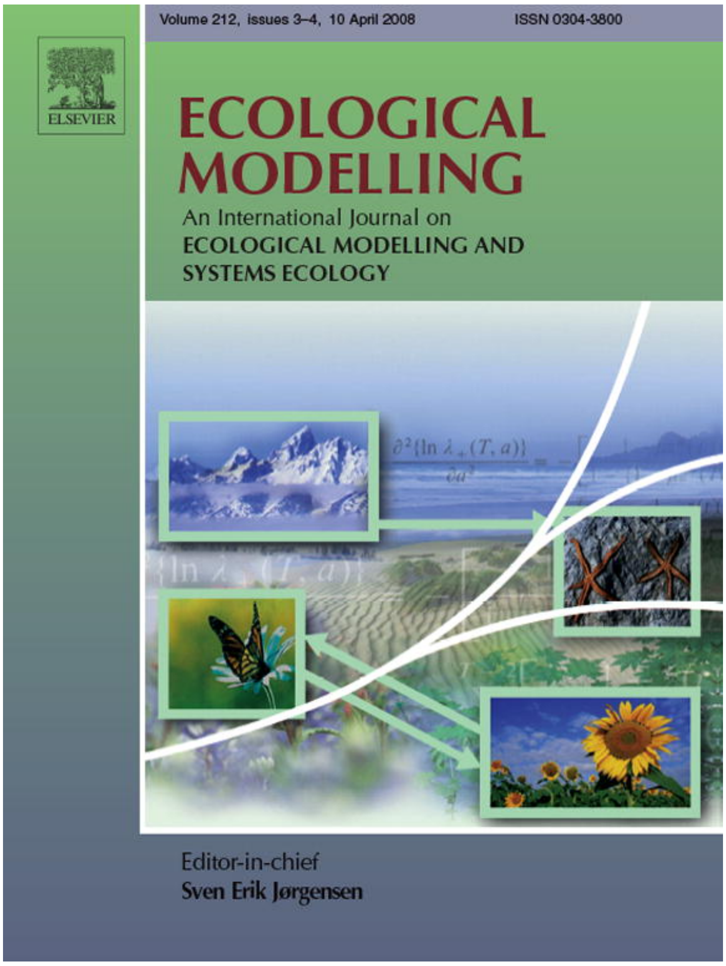

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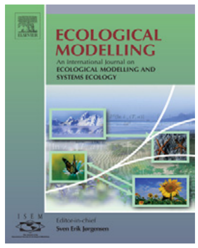

Marine aquaculture off Sardinia Island (Italy): Ecosystem effects evaluated through a trophic mass-balance model

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ABSTRACT

Marine aquaculture is an important growing worldwide industry. An ecosystem approach to study the effects of aquaculture on the Aranci Bay (Sardinia, Italy) was implemented by using a trophic mass-balance model in order to estimate the potential effects of finfish aquaculture and, therefore, to identify the species playing a key-role in ecosystem. Additionally, this study was used to evaluate the conflict between top predators and aquaculture. Mass-balance models were built using Ecopath software to characterize and compare the present state of the ecosystem versus a reconstructed past model representing the bay before the start of aquaculture activities. This modelling approach to the study of the fish farm activities in Aranci Bay has shown its appropriateness to describe the modifications induced, at an ecosystem level, by the nutrient loading into the area. Increased nutrient loading into the fish farm area may result in greater biological activity and may induce a strong coupling between the pelagic and benthic subsystems. Based on the results, the possible effect of top predators in the fish farm activities is not substantial. Furthermore, the use of mass-balance models can provide important additional information, complementary to the normal environmental assessment impact studies, before starting fish farm activities in an area.

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1. Introduction

Marine aquaculture is an important industry that continues to grow more rapidly than all other animal food-producing sectors, with an average annual growth rate for the world of 8.8% per year since 1970, compared with only 1.2% for capture fisheries and 2.8% for terrestrial farmed meat production systems (FAO, 2007). Marine aquaculture and, in particular intensive fish farming, have shown a large expansion in most Mediterranean countries over the last 10 years (UNEP/MAP/MED POL, 2004). The culture of finfish farming differs from that of shellfish farming in that food must be added, whereas shellfish use natural phytoplankton for nutrition. Even though technological advances have increased conversion efficiencies (Cole, 2002), most of the impacts of finfish aquaculture are derived from waste feed. Intensive fish farming effects are expressed at various spatial and temporal scales, depending on the nature of the waste released, the physical, hydrographic and ecological characteristics of the site, and the efficiency of the management of the farms (Machias et al., 2005).

Most of the previous studies have indicated that the effects of aquaculture on the benthic environment are found within a short distance, normally not exceeding 25–30 m from the edge of fish cages (reviewed in Machias et al., 2005). However, it is well-known that fish farming releases a substantial amount of nutrients into the marine environment (Holby and Hall, 1991; Hall et al., 1992) and it would, therefore, be reasonable to expect effects at larger spatial scales, particularly when an

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area of farms is established in a coastal bay. Effects on wild fish have been investigated at short spatial scales (Carss, 1990, 1994; Dempster et al., 2004), indicating a considerable increase in wild fish abundance and biomass in the immediate vicinity of fish cages.

Coastal sea-cage finfish farms have been introduced into an environment that has a natural complement of fish eating predators. A potential impact on top predators as a result of aquaculture interaction is death or injury through entanglement in gear (Díaz López and Bernal Shirai, 2007). Furthermore, aquaculture directly affects the carrying capacity of marine ecosystems by altering the structure of food webs and changing their potential productivity (Jiang and Gibbs, 2005).

Mass-balance models, such as Ecopath (Christensen et al., 2000), could be useful tools to investigate effects of the biological community changes induced by external sources of disturbance (e.g., finfish culture) on the ecosystem structure. Moreover, mass-balance models could be useful to identify the species which play a key-role in driving ecosystem processes. Under the precautionary approach to ecosystem management, Ecopath allows investigators to perform exploratory data analysis on an ecosystem using a common framework by joining together single-species data resources into a coherent food web (Christensen and Pauly, 1992).

This kind of model gives a steady-state representation for a given period of the energy flows of ecosystems, including the trophic relations among organisms and the outgoing flow due to fisheries. On the whole, these flows represent the network structure of the food web (Christensen et al., 2000). The major advantage of this network approach is its suitability to the application of a broad field of theories that are useful for ecosystem studies. These include thermodynamic concepts, information theory, trophic level description and network analysis (Müller, 1997).

The area under investigation is the Aranci Bay, on the northeastern coast of Sardinia (Italy). We choose this study area based on the environment assessment and field studies conducted before and during the fish farm activities (Lonta and Masala, 1991; Cottiglia, 1993, 1994; Cottiglia and Masala, 1995; Díaz López et al., 2005; Díaz López, 2006b; Díaz López and Bernal Shirai, 2007). Before the beginning of fish farm operations, the area was characterized as an oligotrophic environment (Lonta and Masala, 1991; Cottiglia, 1993, 1994). The presence of a floating marine finfish farm in the area has been linked to an increase of organic matter (Cottiglia and Masala, 1995). Moreover, changes in marine top predators' distribution as a result of high fish density in the farming area have also been observed (Díaz López et al., 2005; Díaz López, 2006b). Although top predators benefit from feeding around the fish farm cages (Carss, 1993; Lekuona, 2002; Quick et al., 2004; Díaz López, 2006b), this relationship with aquaculture is harmful due to antipredator methods employed (Díaz López and Bernal Shirai, 2007).

According to FAO (1995), "the achievement of real marine ecosystem-based management of fisheries implies the regulation of the use of the living resources based on the understanding of the structure and dynamics of the ecosystem of which the resource is a part". This premise requires an improvement of our understanding of the structure of marine ecosystems, and the interactions between ecosystem compartments and their changes due to human and environmental factors.

The present study, the first of its kind to use a mass-balance model of trophic interactions in the Mediterranean basin, focuses on how changes induced by the presence of a marine finfish farm affect fish communities in an oligotrophic environment where nutrient scarcity limits productivity. This type of information is important in order to estimate the potential effects of finfish aquaculture on coastal ecosystems and, therefore, to identify the species which play a key-role in the processes of ecosystems affected by coastal aquaculture. Additionally, this study was used to evaluate the conflict between top predators and the aquaculture.

2. Material and methods

2.1. Defining the system

An Ecopath with Ecosim (EwE) trophic model (Pauly et al., 2000; Christensen and Walters, 2004), was described to represent an average annual situation (1994 and 2006) of the Aranci Bay on the northeastern coast of Sardinia (Italy) (Fig. 1). The considered depth range was between 0 and 50 m, covering a total area of soft and rocky bottom sediments of 16.25 km^2. This is an area where organic matter enrichment occurs due to environmental events, mainly related to wind conditions and to the fish farm presence (Cottiglia and Masala, 1995). The water temperature in the Aranci Bay undergoes yearly variation, with surface temperatures ranging between 11 °C (March) and 26 °C (August). Water clarity, measured by Secchi disc, varied between 11 m (January) and 22 m (July).

The coastal sea-cage fish farm (40°59′N 9°37′E) was set up in 1995 in Aranci Bay and consists of 21 floating cages. The volume of each floating cage is around 22,000 l with a fish biomass per cage of approximately 40 t. The fish farm is situated at approximately 200 m from the shoreline, with a minimum depth of 18 m and a maximum depth 26 m. The fish farm covers 0.04 km^2, which is approximately 0.25% of the Aranci Bay, and contains 850 t of ichthyic biomass, with sea bass (*Dicentrarchus labrax*), gilthead sea bream (*Sparus auratus*), and corb (*Sciaena umbra*). The sea bottom in the fish farm area is characterized by mostly mud with scattered areas of rock and sand.

Moreover, Aranci Bay is also an important area for marine vertebrate conservation, sheltering a resident bottlenose dolphin population (Díaz López et al., 2005), the Mediterranean endemic Audouin's Gull (*Larus audouinii*) and important colonies of other terns and gulls (Díaz López pers. observation). Some of these species forage actively on the marine finfish farm and find a complementary food source in the discards generated by the aquaculture activities (Carss, 1993; Lekuona, 2002; Díaz López, 2005, 2006b; Quick et al., 2004).

2.2. Modelling approach

Ecopath (Christensen and Pauly, 1992) was developed as a useful tool incorporating algorithms for the retrieval of the ecological, thermodynamic and informational indices needed for network analysis (Ulanowicz, 1993). Through a system of linear equations describing the mass (or energetic) balance for

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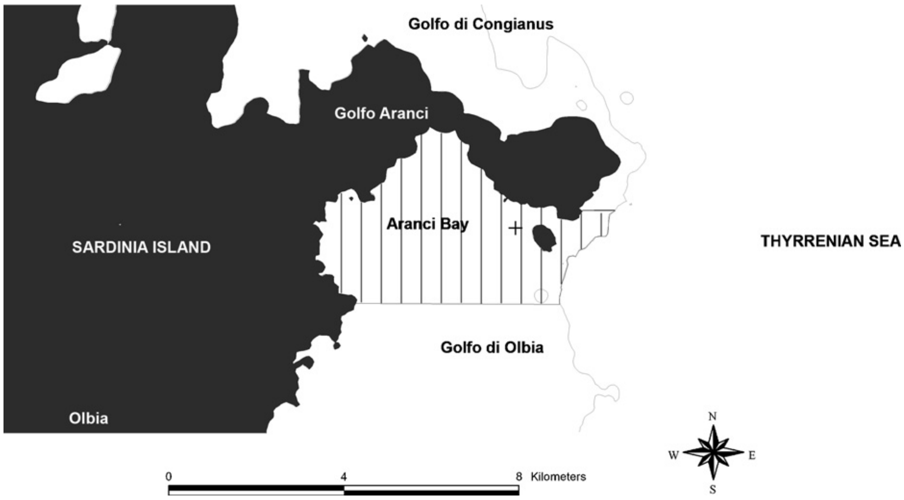

Fig. 1 – Map of the north-eastern coast of Sardinia, showing the area influenced by aquaculture (Cottiglia and Masala, 1995) with a line pattern. A cross indicates the location of the marine finfish farm (40° 59.98′N 9°37.09′E).

each functional component of the system, the overall ecosystem balance is obtained (Christensen and Pauly, 1992, 1993; Pauly et al., 1993).Ecopath models rely on the truism that:

$$\text{production by}\,(i) = \text{all losses by predation on}\,(i) + \text{non-predation losses on}\,(i) + \text{export of}\,(i). \quad (1)$$

This applies for any group (e.g., a given fish population) and time (e.g., a year or season). Groups are linked through predators consuming prey, where

$$\text{consumption} = \text{production} + \text{non-assimilated food} + \text{respiration}. \quad (2)$$

The basic equation that represents the balance for each trophic group, *i*, of the network is:

$$B_i \frac{P_i}{B_i} EE_i - \sum_{j=1}^{n} B_j \frac{Q_j}{B_j} DC_{j,i} - EX_i = 0 \quad (3)$$

where DC is the diet matrix, which describes the relationships among groups whose elements $DC_{j,i}$ represent the fraction of the prey *i* in the average diet of the predator *j*; B_i the biomass of each group; P_i/B_i is the production/biomass ratio (equal to the instantaneous rate of total mortality *Z* in steady-state systems) and Q_j/B_j is the consumption/biomass ratio of predator; and EE_i is the ecotrophic efficiency, which represents the part of the total production that is consumed by predators or exported; while EX_i is the export of the compartment *i* towards other ecosystems such as net migration and harvest by fishery (Christensen and Pauly, 1993). Since the currency of the model is energy-related, the unassimilated/consumption ratio (UN/Q) is used to quantify the fraction of the food (Qx) that is not assimilated. More details on capabilities and limitations of the Ecopath software are given in Christensen and Walters (2000).

2.3. *The mass-balance model for Aranci Bay "scenario 2006"*

A steady-state mass-balance model of Aranci Bay was constructed using Ecopath V software (Pauly et al., 2000; Christensen and Walters, 2004; http://www.ecopath.org) to describe the trophic interactions for the year 2006. This best guess estimate, called "scenario 2006", was considered as representative of the "present" status of the ecosystem to show how aquaculture influences the ecosystem.

In order to consider fish farm activities, the fish nourishment and discards, as well as outflow from the group representing farmed fish species, were introduced into the model. The mortality of some groups affected by incidental captures in the fish farm (dolphins, cormorants and seabirds) were increased according to field data collected during the study, information available in the literature (Díaz López, 2006a; Díaz López and Bernal Shirai, 2007) and from the Bottlenose Dolphin Research Institute database. This relationship with aquaculture is harmful to top predators due to the antipredator nets employed (0.6 entangled dolphins per year; 54 comorants and 141 seabirds).

The model included 12 functional groups spanning the main trophic components of the ecosystem and including fish predators, fish species and invertebrate groups (Table 1), and three detritus groups (natural detritus, discards and farm nourishment). Definition of the groups was based on similarities in their ecological and biological features (i.e. functional trophic groups; Pinnegar and Polunin, 2004), based on the abundance and how they are affected by aquaculture (Cottiglia, 1993, 1994; Carss, 1993; Lekuona, 2002; Díaz López et al., 2005; Díaz López, 2006b).

All the available data for biomass, annual landings and discards were converted into the same unit ($t\,km^{-2}$) and expressed as wet weight. An annual average model was described, in which biomass, diets and species composition in different seasons were averaged. In some cases, due to data availability for 2006, annual average biomass was calculated for an extended period (2004–2007).

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Table 1 – Basic input parameters for the "present state" model

Group	Biomass (t km^{-2})	P/B (year^{-1})	Q/B (year^{-1})	EE	U/Q	Catches (t km^{-2})
1. Bottlenose dolphin	6.246[a]	0.331[a]	3.766[a]		0.2[g]	
2. Cormorant	0.554[a]	0.315[a]	4.225[a]		0.2[g]	
3. Seabirds	0.583[a]	0.251[a]	1.190[a]		0.2[g]	
4. Cephalopods		2.340[c]	5.300[c]	0.970[c]	0.2[g]	
5. Common grey mullets		0.624[b]	8.587[b]	0.992[b]	0.2[g]	
6. Piscivorous fish		0.729[b]	2.880[c]	0.970[c]	0.2[g]	
7. Zooplanktivorous fish		1.500[c]	8.860[c]	0.970[c]	0.2[g]	
8. Farmed fish	52.308[a]	0.813[a]	2.400[a]		0.2[g]	36.923[a]
9. Polychaetes		2.670[d]	13.360[d]	0.909[d]	0.4[g]	
10. Mussels	3.614[a]	1.800[e]	6.629[e]		0.2[g]	
11. Zooplankton		50[b]	170[b]	0.97[b]	0.5[g]	
12. Phytoplankton	6.570[f]	112.650[b]	–	0.95[b]		–
13. Discards	1.231[a]	–	–	–		–
14. Nourishment	156.923[a]	–	–	–		–
15. Detritus	631.730[f]	–	–	–		–

Biomasses (B), production rates (P/B), consumption rates (Q/B), ecotrophic efficiency (EE), assimilation rates (UN/Q), and harvesting amounts (catches) used in the mass-balance model of 2006 Aranci Bay Model. Missing values estimated by Ecopath.

[a] Own estimate.
[b] Pinnegar and Polunin (2004).
[c] Coll et al. (2006).
[d] Sánchez and Olaso (2004).
[e] Jiang and Gibbs (2005).
[f] Cottiglia and Masala (1995).
[g] Pranovi et al. (2003).

The model was considered balanced when: (1) realistic estimates of the missing parameters of EE were calculated (EE < 1); (2) gross efficiency values (GE = P/Q) for functional groups were between 0.1 and 0.35 with the exception of fast growing groups with higher values and top predators with lower values; (3) values of R/B were consistent with the group's activities with high values for small organisms and top predators (Christensen et al., 2004).

2.3.1. *Description of mass-balance parameters*

For each group, three out of four of the basic parameters (B, Q/B, P/B, EE) were required to construct the mass-balance model (Table 1). Published and unpublished sources concerning the Aranci Bay were used to generate input parameters; however, in some cases it was necessary to assume from the wider literature, from Sardinia or elsewhere in the western Mediterranean and lastly from outside the Mediterranean Sea. The 'pedigree' of input data was recorded, identifying whether it was taken from a model of a similar system, or based on a rough or precise estimate from local data (*sensu* Funtowicz and Ravetz, 1990). These values were then used to assess model quality (Pauly et al., 2000).

Bottlenose dolphins. Bottlenose dolphins (*Tursiops truncatus*) are present in the study area all year round (Díaz López, 2006a). The regular occurrence of some dolphins (65.3% of days) suggests individual preferences for the study area (Díaz López and Bernal Shirai, 2007) where they spend 37% of their time (Díaz López and Bernal Shirai, 2006). The mean group size observed in previous studies was 3.46 ± 0.18 individuals (Díaz López and Bernal Shirai, 2007). Biomass of bottlenose dolphins was obtained by multiplying the estimated average annual number of individuals and the average weight of 180 kg per individual (López, 2003). We estimated that 564 individuals were present during the whole year, respectively, corresponding to a biomass of 6.246 t km^{-2}. Based on field studies in the area (Díaz López, 2006a; Díaz López and Bernal Shirai, 2007) which included natural mortality and incidental captures, P/B was estimated to 0.331 per year. The daily food intake reported by Shapunov (1971) in wild bottlenose dolphins, of 5.6%, was used to estimate the Q/B to 3.766 per year.

Cormorants. Cormorants (*Phalacrocorax carbo sinensis*) are present all year round in Aranci Bay; the population reaches its maximum in January and some birds leave the area in March–April (Díaz López, pers. observation). Biomass of cormorants was obtained by multiplying the estimated average annual number of individuals and the average weight of 3.170 kg per individual (Auteri et al., 1993). We estimated that 2,839.7 individuals were present during the whole year, corresponding to a biomass of 0.554 t km^{-2}. Based on daily observations in the study area to calculate the mortality caused by incidental captures (Díaz López, unpublished data), and natural mortality reported by Brando et al. (2004), P/B was estimated to 0.315 per year. The daily food intake observed by Grèmillet (1997), of 26%, was used to estimate the Q/B to 4.225 per year.

Seabirds. This group had three species in the study area. The largest percentage was formed by *Larus michahellis* present year round in Aranci Bay (Díaz López, pers. observation). This species was considered representative of the group during the parameters estimations. The other species occasionally present include Audouin's Gull and Heron (*Ardea cinerea*). Based on field observations in the study area we estimated that 9475.4 individuals were present during the whole year, corresponding to a biomass of 0.583 t km^{-2}. Biomass of seabirds was obtained by multiplying the estimated average annual number of individuals and the average weight of 1.0 kg per individual (Tuck and Heinzel, 1992). Based on daily observations in the study area to calculate the mortality caused by incidental

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captures (Díaz López, unpublished data), and natural mortality observed by Coll et al. (2006), *P/B* was estimated to 0.25 per year. Consumption estimated by Coll et al. (2006) was used to calculate the *Q/B* to 4.225 per year.

For the following groups. Octopus (*Octopus vulgaris*), common grey mullets (*Mugil cephalus*), piscivorous fish (*Conger conger*, *Serranus cabrilla*, *Scorpaena scrofa* and *Dentex dentex*), zooplanktivorous fish (*Boops boops*, *Alosa alosa*, *Sardina pilchardus* and *Spicara* spp), polychaetes and Zooplankton, appropriate estimates were not obtainable, and assumptions were made based on studies in other regions of similar latitudes. In these groups biomass was left for the Ecopath model to estimate using the other parameters.

Mussels. Mussels (*Mytilus galloprovincicalis*) biomass was obtained by estimating the average weight of this species in the finfish farm, because there were no observed mussels in the rest of the study area (Díaz López, pers. observation). We estimated 58.726 t of mussels, corresponding to a biomass of 3.613 t km^{-2}. *P/B* and *Q/B* appropriate estimates were not obtainable, and assumptions were made based on Jiang and Gibbs (2005).

Phytoplankton. The primary production in Aranci Bay was investigated before and after the beginning of the aquaculture activities (Lonta and Masala, 1991; Cottiglia, 1993, 1994; Cottiglia and Masala, 1995). The estimate of the mean biomass and annual primary production for 2006 was obtained from samples carried out after the beginning of fish farm activities (Cottiglia and Masala, 1995). EE and *P/B* values for phytoplankton were derived for values of a similar Mediterranean coastal model (Pinnegar and Polunin, 2004).

Detritus. The estimate of organic matter content of the sediment was obtained from samplings carried out in the Aranci Bay before and after the beginning of the aquaculture activities (Cottiglia, 1993, 1994; Cottiglia and Masala, 1995). The estimate of the mean detritus biomass for 2006 was obtained from samplings carried out after the beginning of fish farm activities (Cottiglia and Masala, 1995).

2.3.1.1. *Placing the mariculture into the model: farmed fish, harvesting, nourishment and discards.* *Farmed fish.* This group included three finfish species (sea bass, gilthead sea bream and corb). Information on the biomass and mortality of this group was provided by the fish farm manager (Graziano, PhD, pers. Comm.). Consumption ratio was derived based on farmed sea bass studies reported by Lemarié et al. (1998). The resulting values were $B = 52{,}308\ \mathrm{t\,km^{-2}}$, $P/B = 0.812$ per year; $Q/B = 2.4$ per year. The amount of fish harvested in the fish farm during the year 2006 was 600 t, corresponding to a biomass of 36.923 t km^{-2}.

The quantity of nourishment introduced to the ecosystem, in form of dry pellets, per year is 2,550 t, corresponding to a biomass of 156.92 t km^{-2} (fish farm manager, Graziano, PhD, pers. Comm.). This amount of nourishment is higher than the consumption rate for farmed fish observed by Lemarié et al. (1998) representing release of nourishment into the environment.

Based on information provided by the fish farm manager around 20 t of fish were discarded per year. This corresponds to a biomass of 1.231 t km^{-2}.

2.3.2. *Unassimilated food and diet*

The assimilation efficiency (AE) of consumers is highly variable (Blanchard et al., 2002). Here we assumed the proportion of the food that is not assimilated (1 − AE) derived for values of a similar Mediterranean coastal model (Pranovi et al., 2003) (Table 1).

The diet matrix in the model (Table 2) was constructed based on information from Barros and Odell (1991), Cockcroft and Ross (1991), Blanco et al. (2001), Stergiou and Karpouzi (2002), Díaz López (2005), Díaz López (2006b), Brando et al. (2004), Sánchez and Olaso (2004), Jiang and Gibbs (2005), Díaz López and Bernal Shirai (2006), Coll et al. (2006), Santos et al. (2007), and from Blanco et al., 2003.

2.4. *Estimating the past "scenario 1994"*

The period 1991–1994 was chosen to represent the state of Aranci Bay before the starting of the aquaculture. Applying a "back to the future" approach (Pitcher, 2001), we combined the model structure of 2006 and some of its estimates with data available for the period 1991–1994, thus obtaining a model representing the beginning of the 1990s, here called "scenario 1994".

Biomasses were estimated for the "scenario 1994" for most trophic groups (bottlenose dolphins, phytoplankton and detritus) based on field studies carried out between 1991 and 1994 by Díaz López et al. (2005), Lonta and Masala (1991) and Cottiglia (1993, 1994).

Information gathered from published sources helped to us to select and delete all groups directly related with the presence of aquaculture (cormorants, farmed fish, mussels, nourishment and discards). Species such as mussels were absent in the area, characterized as oligogotrophic (Lonta and Masala, 1991; Cottiglia, 1993), before the beginning of aquaculture operations. Cormorants were not abundant like in the "scenario 2006" because their presence is related with predation in finfish farms (Carss, 1993; Lekuona, 2002).

Seabird biomass was estimated in function of the data reported in a coastal area of similar characteristics to Aranci Bay before the aquaculture was present (Pinnegar and Polunin, 2004).

Where biomass estimates for the past were not available, the ecotrophic efficiency estimated by Ecopath for the year 2006 was used as input parameter in the model for the year 1994, that allowed us to estimate the lacking biomasses for the past by using the model. In this way, Ecopath estimated biomasses under the assumption that the fraction of production used within the system is the same in the past and the present.

For the "scenario 1994" we followed the assumption that the artisanal fishery effort, although extremely low in the area, was constant between 1994 and 2006. For this reason we did not include this fishery activity into both scenarios (1994 and 2006).

The model was balanced by adjusting the basic input parameters for cephalopods, piscivorous fish and common grey mullets, until the estimated ecotrophic efficiency (EE) was less than one. This was done as EE values greater than one are not plausible, i.e. it is not possible that more biomass is used than produced by a group under conditions of steady-state.

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Table 2 – Diet Composition for the Aranci Bay mass-balance model

Prey	Predator										
	1	2	3	4	5	6	7	8	9	10	11
1											
2											
3											
4	0.078		0.043	0.032		0.212					
5	0.298	0.343	0.013			0.035					
6	0.268			0.012		0.141					
7	0.229	0.637	0.065	0.116		0.425					
8	0.035	0.020									
9	0.059			0.248		0.177					
10											
11			0.229	0.582	0.500		0.527			0.027	0.086
12							0.273			0.273	0.564
13	0.033		0.050	0.010		0.010					
14					0.200		0.200	1.00			
15					0.300				1.00	0.700	0.351
16		0.600									
Sum	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

1, Bottlenose dolphins; 2, cormorants; 3, seabirds; 4, cephalopods; 5, common grey mullets; 6, piscivorous fish; 7, zooplanktivorous fish; 8, farmed fish; 9, polychaetes; 10, mussels; 11, zooplankton; 12, phytoplankton; 13, discards; 14, nourishment; 15, detritus; 16, import.

Although the "present" model is inherently more accurate than the resulting "past" model, the latter represent useful estimates of the possible community states before aquaculture activities.

2.5. *Network description and analysis*

In order to compare the status of the two ecosystem scenarios (1994 and 2006), we calculated various indices using Ecopath. A comparison of these two snapshots of the ecosystem structure and trophic network was conducted. Following the ecological considerations proposed by Odum (1971), we calculated total net primary production (NPP), total primary production/total respiration (PP/TR), net system production (NP), total primary production/total biomass (PP/*B*), total biomass/total system throughput (*B*/TST) and total biomass of the system (*B*) as indices related to ecosystem maturity and stability. We also considered the thermodynamic indices "ascendency" (Ulanowicz, 1986), "system overhead" (Monaco and Ulanowicz, 1997), and cycling indices as proposed by Finn (1976) and Christensen (1995).

The use of "Trophic aggregations" (Ulanowicz, 1995) provides an accurate picture of the system and allocates the different dietary interactions in the systems to discrete trophic levels (sensu Ulanowicz, 1986). Aggregation was carried out in order to evaluate how each component of the ecosystem contributes to the trophic levels of the idealized linear food chain (Ulanowicz, 1995). Data on trophic aggregation of flows allows estimation of the sum of all flows reaching detritus and the upper trophic levels, as well as transfer efficiencies. The trophic levels of each of the groups (TL) were computed by the model, thereby providing an estimation of the mean trophic level of the aquaculture catch in 2006 (MTL; Pauly et al., 1998).

The omnivory index (OI) is calculated as the variance of the trophic level of a consumer's prey groups (Christensen and Pauly, 1993). It ranges from 0 to 1, where 0 indicates a highly specialized consumer and higher values indicate predation on many trophic levels (Christensen et al., 2000). Search values are provided by Ecopath and can be used as an estimate on how long a predator spends looking for a prey species (Christensen et al., 2000).

Mixed trophic impact (MTI; Ulanowicz and Puccia, 1990) was calculated by the difference between the diet composition term of the group *i* in the diet of group *j* ($DC_{j,i}$) and the proportion of the predation on *i* due to the predator *j* ($FC_{i,j}$):

$$MTI_{j,i} = DC_{j,i} - FC_{j,i} \quad (4)$$

The MTI allows us to quantify the direct and indirect impacts that a group (impacting group) has on each of the others (impacted group), through the evaluation of the effect (positive and negative) of an increase of the biomass of the impacting group on the impacted one; it is calculated for each pair of groups in the system, including aquaculture activities (Christensen et al., 2000). The resulting matrix of MTIs for the model with presence of aquaculture "scenario 2006" was used to estimate the effect of a group on the whole ecosystem by adding all its MTIs (summed by rows of the MTI matrix) weighted by the inverse of the biomass of impacted groups, thus providing an estimate of the effect of varying the biomass of a particular group on the whole community.

Due to the complexity of the input parameters, no statistical tests are available to evaluate differences in the values of the various indices between different phases of the same system (Monaco and Ulanowicz, 1997). However, these indices, when taken as a whole and based on rank ordering, help to determine differences and similarities between trophic networks (Monaco and Ulanowicz, 1997).

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2.6. Conflicts between top predators (bottlenose dolphins, cormorants and seabirds) and aquaculture

In Aranci Bay, cormorants and bottlenose dolphins are considered problematic to aquaculture because of their annual high presence in the area (Díaz López, 2005; Díaz López and Bernal Shirai, 2007; fish farm manager Graziano PhD, pers. comm.). The consumption by cormorants and bottlenose dolphins has a direct effect on aquaculture by exploitation of farmed fish (Díaz López, 2005, 2006b; fish farm manager Graziano PhD, pers. comm.). In addition, bottlenose dolphins could cause an indirect effect by stressing the farmed fish and increasing their mortality (Díaz López, 2005, 2006b).

In order to evaluate the conflict between top predators and the aquaculture, for each predator we calculated the ratio of consumption to total farmed fish harvest (Q/TFFH). To evaluate "positive" effects of top predators predation, reducing the amount of discards into the environment, we introduced the ratio of consumption by top predators to discarded farmed fish (Q/DF).

3. Results

3.1. Structural analysis of the two models

Quality (*P*) for the 2006 and 1994 models was estimated at 0.428 and 0.332, respectively. The overall measure of fit t^*, which takes into account the number of living groups in the system (12 and 9, respectively) was estimated at 1.5 and 0.93.

The structures of the ecosystem for Aranci Bay in "scenario 1994" and "scenario 2006" show substantial differences in biomass values estimated for each group. This change in all trophic groups demonstrates an increase in the biomass in 2006 of 327.8 t km^{-2}, or 92% (Table 3). Biomass values were estimated by the model for zooplankton, polychaetes, zooplanktivorous fish, piscivorous fish, cephalopods and common grey mullets. The estimated biomass increased by values ranging from 0.6 to 47 times higher after the start of aquaculture activities.

Bottlenose dolphin biomass increased by 4.56 t km^{-2}, or 272%; and seabird biomass increased by 0.571 t km^{-2} or 4758%. For fish species the increase in biomass varied between 64% in piscivorous fish to 380% in common grey mullets. In cephalopods and polychaetes the increases in biomass were similar (73% and 74%, respectively). Similar values of increasing biomass were observed in zooplankton and phytoplankton (87% and 83%, respectively). Detritus also show an important increase in biomass of 275.7 t km^{-2}, or 77%. However, detritus biomass in relation with the total biomass decreased in the 2006 model (87% in 1994 and 66% in 2006).

Bottlenose dolphin diet consumption values increased in the presence of aquaculture, reducing the consumption of wild species (common grey mullets, zooplanktivorous), and increasing the consumption of new resources (discarded fish and farmed fish); while in seabirds the presence of aquaculture increased the consumption of zooplanckton, zooplancktivorous fish and new resources (farmed and discarded fish). Omnivory index shows important changes in bottlenose dolphins (increasing a 22%) and in seabirds (decreasing a 35%). The rate of time searching for prey in top predators was reduced drastically with the presence of aquaculture in the area by 87% in bottlenose dolphins and by 75% in seabirds.

3.2. Network analysis

The results of the aggregation of biomasses and flows (t km^{-2} per year) into trophic levels (TLs) in both models show the presence of six levels. For each trophic group, the fractions of flows and biomasses involved in the six TLs are reported in Fig. 2 and Table 4, respectively.

A 482% increase in biomass of the network in 2006 occurred in the trophic level II. At TLs V and VI the increase was about 125% and 189%, respectively, while at TLs I, III and IV it was 82%, 94% and 66%, respectively (Table 4).

The transfer efficiencies (TEs) at TL II were slightly lower in the 2006 model (3%). Additionally, TEs at levels III–V were lower for 2006 than for 1994 (25%, 32% and 18%) (Fig. 2). The flows from detritus and primary producers were of completely different magnitude for the two models, increasing 148% and 82%, respectively in the 2006 model.

Table 5 reports some of the indices estimated through Ecopath for the trophic networks of 1994 and 2006. A generalized

Table 3 – Estimated biomass (t km^{-2}) of trophic groups for the 1994 and 2006 Aranci Bay networks

Group	1994	2006	Variation (%)
Bottlenose dolphin	1.679	6.246	272
Cormorant	–	0.554	–
Seabirds	0.012	0.583	475.8
Cephalopods	4.409	7.607	72.5
Common grey mullets	3.399	16.466	384.4
Piscivorous fish	14.054	23.076	64.2
Zooplanktivorous fish	15.826	27.401	73.1
Farmed fish	–	52.308	–
Polychaetes	5.468	9.538	74.4
Mussels	–	3.614	–
Zooplankton	3.514	6.58	87.3
Phytoplankton	3.593	6.57	83.9
Discards	–	1.231	–
Nourishment	–	156.92	–
Detritus	356.02	631.73	77.4
Total biomass	407.969	950.427	92

Table 4 – Estimated biomass (t km^{-2}) at each trophic level for the 1994 and 2006 Aranci Bay networks (*sensu* Ulanowicz, 1995)

Trophic level	1994	2006	Variation (%)
VI	0.009	0.026	189
V	0.549	1.237	125
IV	9.338	15.478	66
III	22.382	43.466	94
II	16.084	93.765	483
I	3.593	6.57	83
Total (no detritus)	51.955	160.542	

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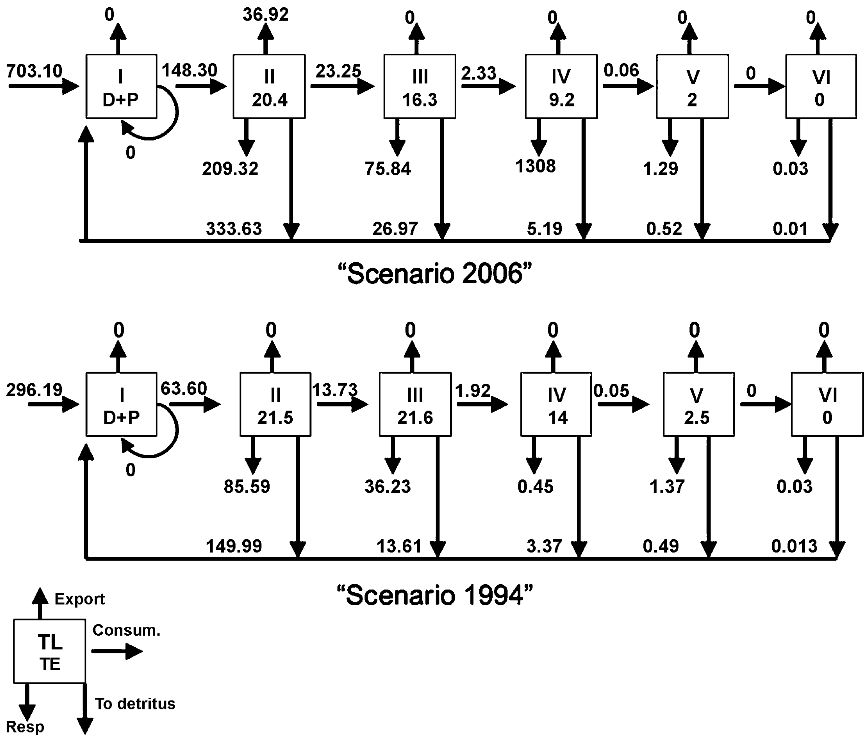

Fig. 2 – The aggregation of the flows (t km^{-2} per year) into a concatenated chain of transfers through six trophic levels. Flows out of the tops of the compartment represent exports and flows out to the bottom represent respiration. Recycling of non-living material is through compartment D (detritus). The percentages in the boxes represent annual trophic efficiencies.

Table 5 – Summary of the indices estimated for the 1994 and 2006 using the relative trophic networks built for Aranci Bay

	Unit	1994	2006	Variance (%)
Ecosystem theory indices				
Total system throughput (TST)	t km^{-2} per year	1730	3,667	111.9
Sum of all consumption	t km^{-2} per year	919.17	1,912.91	108.1
Sum of all exports	t km^{-2} per year	110.35	267.29	142.2
Sum of all respiratory flows	t km^{-2} per year	294.40	677.47	130.1
Sum of all flows into detritus	t km^{-2} per year	406.55	809.03	99
Total biomass (excluding detritus)	t km^{-2}	51.95	160.54	209
Sum of all production	t km^{-2} per year	653	1232	88.7
Total biomass/total throughput (B/TST)	year	0.03	0.04	44.67
Total primary production/total respiration (PP/TR)		1.37	1.09	−20.6
Net system production (PP − TR)	t km^{-2} per year	110.34	62.63	−43.2
Total primary production/total biomass (PP/B)	per year	7.79	4.61	−40.8
Total catches	t km^{-2} per year		36.92	
Calculated total net primary production	t km^{-2} per year	404.75	740.11	82.8
Gross efficiency (catch/net primary production)			0.05	
Mean trophic level of the catch			2	
System omnivory index		0.19	0.16	−16
Cycling indices				
Throughput cycled (excluding detritus)	t km^{-2} per year	57.34	107.24	87
Throughput cycled (including detritus)	t km^{-2} per year	431.92	785.77	82
Finn's cycling index	%	24.96	21.43	−14
Predatory cycling index	%	6.25	5.81	−7
Finn's mean path length		4.27	3.88	−9.2
Finn's straight-through path length (no detritus)		2.92	2.43	−16.7
Finn's straight-through path length (with detritus)		3.20	3.05	−4.9
Informational indices				
Ascendancy	Flowbits	1790.6	4,483.8	150
Overhead	Flowbits	4970.3	11,371.4	128
Capacity	Flowbits	6760.9	15,855.2	134

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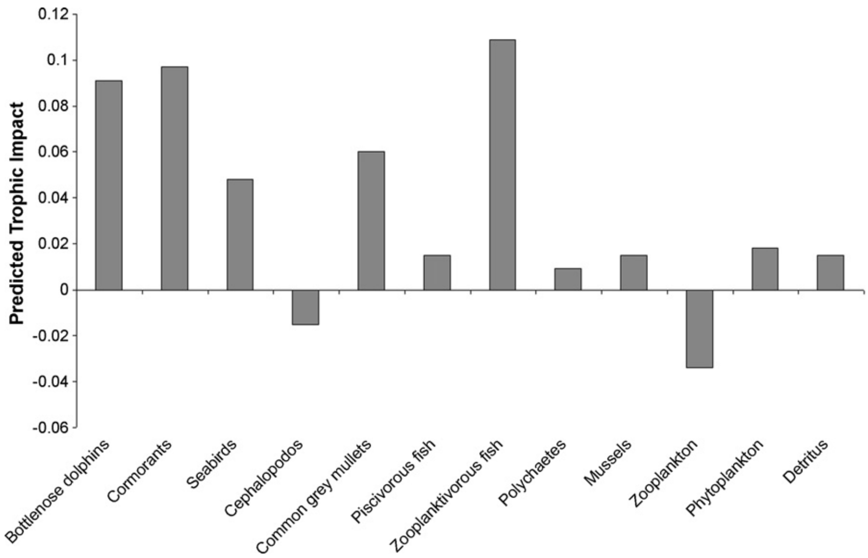

Fig. 3 – Predicted trophic impacts of aquaculture activities (farmed fish, nourishment and discarded fish) on biota.

increase in the indices of the system from 1994 to 2006 was evident (increases are estimated between 44.6% and 142%), thus giving an analogous increase of B/TST and on the informational indices (ascendancy, overhead, capacity), the decrease of Net System Production (NP) and Primary Production on Total Biomass (PP/B). A decrease of −20.6% was also observed for Primary Production on Total Respiration Index (PP/TR).

3.3. *Mixed trophic impact analysis*

The mixed trophic analysis (MTI) in the Model 2006 indicated that the aquaculture harvesting does not have a strong impact on the rest of the groups, except directly on farmed fish and nourishment. However, the fish farm effects that include harvesting, farmed fish, nourishment and discards, have a slight positive impact on zooplanktivorous, cormorants, bottlenose dolphins and common grey mullets (Fig. 3).

The greatest impact of a small biomass change of one group on another is seen from detritus, where a small increase of the biomass of detritus had a positive impact on polychaetes but a negative impact on phytoplankton.

Positive indirect influences (Ulanowicz and Puccia, 1990), resulting in a net impact, were observed mainly in bottlenose dolphins with a slight impact on cephalopods, zooplanktivorous, farmed fish, and polychaetes.

3.4. *Conflicts between top predators and fishery activities*

The trophic level (TL) of bottlenose dolphins and cormorants (TL = 3.82 and 3.55, respectively) and the trophic level of the aquaculture (TL = 2) are different because the aquaculture has a restricted "diet". In 2006, the total consumption of farmed fish was 37.8 t km^{-2}, of which the aquaculture harvested 97.7%, bottlenose dolphins 2.18%, and cormorants 0.12%.

The ratio of consumption by bottlenose dolphins and cormorants to total aquaculture harvest (Q/TFFH) was 0.022 and 0.001, respectively. Moreover, the ratio of consumption by bottlenose dolphins and seabirds to discarded farm fish (Q/DF) was 0.41 and 0.21, respectively.

4. Discussion

Inspection of the marine literature indicates that the most robust way to apply deterministic models in the marine environment is to use them as prognostic tools to elucidate particular aspects and processes in the system in question. Following this approach, here we use a mass-balance model to investigate the potential effect of a coastal sea cage finfish culture on the north-eastern coast of Sardinia, Italy (Mediterranean Sea).

With this study we show how the mass-balance model is a useful tool to describe the aquaculture effects on the food chain. The data obtained are consistent with field studies carried out in the study area (Díaz López et al., 2005; Díaz López, 2006a,b) and in other fish farms in the Mediterranean Sea (Dempster et al., 2004; Machias et al., 2005; Klaoudatos et al., 2006).

Increased nutrient loading into the fish farm area may result in greater biological activity and may induce a strong coupling between the pelagic and benthic subsystems. As a consequence, the pelagic system could be strongly affected by the large flux of organic matter from the water column to the benthos (Prins et al., 1998). This situation is reflected in our model by increases in biomass groups after the starting of the aquaculture. Increase in biomass of polychaetes was quantified with Mediterranean areas where fish farms are present (Klaoudatos et al., 2006), and the increase in biomass seen in fish species such as common grey mullets (detrial feeders) is in accordance with field studies done by Dempster et al. (2004) in the Mediterranean Sea. Furthermore, increases in biomass of top predators, such as bottlenose dolphins, are in agreement with studies of Díaz López et al. (2005). Their studies show that dolphins are attracted by the high density of wild fish species concentrated in the fish farm area. Additionally, studies of

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Díaz López (2006b) show the importance of fish species such as common grey mullets on the feeding behaviour of dolphins in the area.

The estimated increase in biomass after the starting of the aquaculture (92%) was non-monotonic, although an increase in primary producer biomass should propagate monotonically through all trophic levels in a system based almost entirely on primary producers (Odum, 1971). The non-monotonic increase in biomass could be related with several factors (mortality, migration, etc.) different from primary producers. This result gives an indication of the important role that may be played by detritus groups, and in particular those related with aquaculture (fish farm nourishment and discarded fish) in this trophic network. In cases of strong coupling between the pelagic and benthic subsystems, the bottom-up control of phytoplankton development (i.e. nutrient loading) becomes less important and the ecosystem could be more resilient to changes in external nutrient loading (Prins et al., 1998).

The lower search prey rate seen after the start of aquaculture activities could explain the attraction of top predators to the area (seabirds, cormorants and bottlenose dolphins). By reducing the time spent searching for prey, these predators reduce the energy required to feed. This effect has been associated with opportunistic feeding due to concentrated resource of food (high density of prey) in a coastal environment characterized by the patched distribution of food resources (Díaz López, 2006b; Díaz López and Bernal Shirai, 2007).

Although the presence of aquaculture adds two detritus groups to the Aranci Bay, the biomass stored in detritus groups in relation with the total biomass is lower after the start of aquaculture activities. This could be explained by the high concentration of wild fish feeding around sea cages, which may diminish the amount of organic matter that reaches the sea floor (Dempster et al., 2004). In addition, another explanation for this situation could be that several of the species, common grey mullets and mussels, have been described as buffers to the eutrophication process, reducing the organic matter present in the area (Porter et al., 1996 in Lupatsch et al., 2003; Nizzoli et al., 2005). Mazzola and Sara (2001) also suggested that bivalve culture near fish cages could reduce the environmental impact (by removing nutrients) of finfish farming.

The relation between stability and the structure of an ecosystem has been widely discussed in the literature (Pinnegar and Polunin, 2004). The capacity of an ecosystem to entrap, withhold and cycle nutrients increases with system "maturity" (Odum, 1969), and this "maturity" has been correlated with the FCI (Finn's cycling index) (Christensen, 1995). The FCI values reported here (24.96% in 1994 and 21.43% in 2006) were relatively high, indicating a substantial degree of recycling before and after the starting of the aquaculture. The FCI value reported in the present model after the starting of aquaculture was roughly equivalent to values reported for a Mediterranean rocky littoral ecosystem (Pinnegar and Polunin, 2004). It would seem that the ecosystem in presence of a marine finfish farm is relatively resilient and "mature" compared to many other coastal and shelf systems (Pauly et al., 2000; Pinnegar and Polunin, 2004), with a good ability to degrade and dissipate the incoming free energy. In terms of overall community homeostasis, the 2006 status seems to be more "mature" (e.g., ascendency and overhead), despite slightly lower values of the FCI, as suggested by Baird et al. (1991), FCI is inversely related to ascendency. The present state is, thus, more mature than the "pre-aquaculture" state, but less efficient in recycling.

Indeed aquaculture habitats support higher densities of animals. The lower transfer efficiencies at trophic levels II in the 2006 model suggested a low flow of the energy within this network, largely due to the increase in biomass of farmed fish, which is scarcely consumed. The mixed trophic analysis (MTI) in the present model indicates that the aquaculture activities have a slight positive impact on zooplanktivorous fish, cormorants, bottlenose dolphins and common grey mullets. Moreover, the finfish farm activities produce negative effects on cephalopods and zooplankton, since it indirectly produces positive effects on their predators (bottlenose dolphins, cormorants and zooplanktivorous fish).

Based on the results observed in our model, the possible effect of top predators in the fish farm activities is not substantial. These values should be considered a minimum because the indirect effects (stress of farmed fish, Díaz López, 2005) are not quantified. Additionally, the low value observed in cormorants could be related with the efficiency of anti-predator nets employed that avoid the attack of airborne predators. Lastly, the role that bottlenose dolphins and seabirds could play in the elimination of discarded fish (reducing the organic matter) implies that these species may be buffers to the eutrophication process, reducing the organic matter present in the area.

5. Conclusion

The Aranci Bay mass-balance model provides a summary of current knowledge of the biomass, consumption, production, food web and trophic structure in an ecosystem influenced by aquaculture activities. The Ecopath model can be a valuable tool for understanding ecosystem functioning, and for design of ecosystem-scale adaptive management experiments. This study demonstrates how the mass-balance model could be a useful tool to describe the aquaculture effects on the food chain. This modelling approach to the study of the fish farm activities in Aranci Bay has shown its appropriateness to describe the modifications induced, at an ecosystem level, by the nutrient loading into the area. Furthermore, the use of mass-balance models can provide important additional information, complementary to the normal environmental assessment impact studies, before starting fish farm activities in an area.

We suggest that the main management issue raised by this study relates to the not substantial effect of top predators in the fish farm activities. A fish farm manager should be aware of the very important role detrial feeders and top predators could have in ecosystem structure. Assessing the consequences of fish farm activities with relatively obvious effects on marine predators can be difficult. The effects of aquaculture management (i.e. the employ of control methods which exclude, harass or remove predators) could indirectly affect the ecosystem structure, and biological responses to these effects should be investigated.

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Ecopath is a steady-state model and therefore cannot be used to simulate changes to flows with time. By contrast, the model has been used to investigate the functioning of the system and how this has changed with the introduction of intensive aquaculture. Using Ecosim and Ecospace routines, in a future step, it could be possible to simulate the consequences of certain management measures, such as changes in farmed fish biomass, on the ecosystem. Nevertheless, further research is required in order to improve input data and to support or refute the results presented in this model. In particular, the limited availability of parameter estimates on an annual basis for some groups reflects a need for such studies. Predictions resulting from the present model may form the basis for hypotheses to be tested in the future.

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