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Trophic structure and energy fluxes around a Mediterranean fish farm

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ABSTRACT

A fish farm in Southeastern Spain was described using an Ecopath mass-balanced model, aimed at characterising its structure, the interactions among ecological groups and the impact of fish farms and fisheries. The model comprised 41 functional groups (including the artificial food input). Comparing consumption and respiration to total system throughput suggests lower energy use in the fish farm, resulting in an accumulation of detritus. The production to total system throughput ratio was low due to the low efficiency of the modelled ecosystem. The connectance and system omnivory indexes were low, typical of a simple or immature food web in terms of structure and dynamics. Artificial food pellets provided energy and nutrients to sustain system function and generate a considerable reserve from which it can draw to meet unexpected perturbations. The study shows the substantial effect the artificial food pellets have on the wild aggregated fishes, which could act to buffer the ecosystem and hence prevent environmental degradation.

1. Introduction

Coastal intensive fish farming is widespread and a growing activity throughout the world, producing about 20.1 million tonnes of fish per year (FAO, 2010). In temperate and tropical warm water areas, a wide variety of species are cultured and significant sea-cage industries exist around the world (Tacon and Halwart, 2007). In the Mediterranean Sea, the number of fish farms has increased dramatically from early '80 in coastal waters (Ferlin and LaCroix, 2000), mostly in Greece and Spain (Theodorou, 1999; Sánchez-Mata and Mora, 2000), rearing mainly seabass (*Dicentrarchus labrax*) and seabream (*Sparus aurata*). While there is a clear need for the continued worldwide expansion of aquaculture, this development needs to be promoted and managed in a responsible manner that minimises negative environmental impacts. That decision making and marine management should be based on the ecosystem-based approach, integrating the interactions among economic, environmental, social and equity considerations.

The substantial amount of nutrients (in both forms of organic and artificial pellets) released into the marine environment contribute to the over-accumulation of organic matter beneath cages (Karakassis et al., 1998; Heilskov and Holmer, 2001), degrading benthic communities (Karakassis and Hatziyanni, 2000; Delgado et al., 1999; Karakassis et al., 2000; Aguado-Giménez and Ruiz-Fernández, 2012), as well as increasing nutrient inputs in the water column (Tovar et al., 2000). As a direct ecological effect, fish farming also favours the aggregation of wild fish around the cages (Dempster et al., 2002) due to the artificial structures attaching the cages and the great amount of uneaten artificial food (Sanchez-Jerez et al., 2011). The high abundance and biomass of farm-associated wild fish appear as an important component mediating the final impact of aquaculture in both negative and positive direction: e.g., they can add an important amount of NH_4^+ and DOC to the water column by leaching during faeces sinking, enlarging potentially the spatial dispersion patterns of wastes from the fish farm (Fernandez Jover et al., 2007b); or can reduce the over-sedimentation of uneaten food pellets due to their ingestion and, hence, minimize the final negative impacts on the benthic communities. These issues are not considered in the usual models to predict the impact of fish farming (see Cromey and Black, 2005, for a review) despite the ecological importance of the farm-associated wild fish (Dempster et al., 2002) and the fact that the phenomenon of aggregation of wild fish occurs globally (Dempster et al., 2004, 2009). Additionally, the study of the aggregated wild fish assemblage is as much important, as some managers are promoting the exploitation of these aggregations or asking about the effects on exploited wild fish populations by fisheries (IUCN, 2007).

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Despite controversy over the conflict between fish farming and management of coastal areas around the world, a few true ecosystem approaches exist on the impact of this activity on the environment. Most are focused on some generic ecological groups (e.g., Tsagaraki et al., 2011; Petihakis et al., 2012) or on marine mammals (e.g., Díaz-López et al., 2008; Piroddi et al., 2011), but any considering the interactions of fish farming with other ecological components or human activities as proposed for the ecosystem-based management approach. Ecopath is useful to investigate the direct ecological effects of fish farming, but, as a novelty in respect to other used mass-balanced models on fish farming, it allows a true ecosystemic approach by analysing too indirect effects induced by external disturbances such as fishing or alterations in the food web due to cascade processes. The assessment of indirect effects of fish farming is the unique way to balance diverse societal objectives within ecologically and operationally meaningful boundaries and can also be considered as a form of ordinary sensitivity analysis about how each ecological group vary with respect to the others. The understanding of these fish farming interactions with other anthropogenic stressors is the basis for developing strategies for sustainable aquaculture and integrated coastal zone management. Moreover, Ecopath is a common framework and well balanced between simplicity and the complexity of other ecosystem models, which provides a methodology to standardise model outputs, thereby making it easy to compare across other ecosystems without requiring advanced computer programming skills to operate (Christensen et al., 2005). The application of an Ecopath food web mass-balanced model, such as included in this paper, is of primary interest for both scientific and management purposes, since it allows the combination of an extensive set of diverse ecological data in order to interpret the ecosystem functioning around fish farms and design a more suitable ecosystem approach management.

In this study, we present a trophic model focused on biomass flows among components and species associated to sea-cage fish farms, and especially on those wild fish species aggregated around these man-made structures. The purposes of this study are to obtain a steady-state mass-balanced representation for a certain period of the energy flows and trophic relationships among species from which to derive ecosystem indicators based on the network structure of the food web (using thermodynamic concepts, information theory, trophic level index and network analysis; Müller, 1997), in order to assess the environmental deviation created by the fish farm compared with other modelled ecosystems.

2. Methods and materials

2.1. Study site

We considered a fish farm located in the Santa Pola Bay, Southwestern Mediterranean Sea (38°05.743′N, 000°36.341′W; Fig. 1) operating from July 2000. The installation is 3704 m from the shore, with a maximum water column depth of 21 m at the study site, covering a total area of 140,000 m^2 on soft muddy bottoms. The water temperature undergoes yearly variation, with surface values ranging between 13 °C (February) and 28 °C (August). Water clarity (Secchi disk depth) varied between 8 m and 20 m from winter to summer. The fish farm consists of 24 floating cages, each with an approximate volume of 449 m^3, rearing a total fish biomass of 775 tonnes, with gilthead seabream *S. aurata*, European seabass *D. labrax* and meagre *Argyrosomus regius*. Food pellets were aquafeed extruders formulated with 36% fishmeal, 16% wheat meal, 12% corn gluten feed, 12% soybean meal, 10% wheat gluten meal, 10% fish oil, 4% soybean oil and other additives such as vitamins and antioxidants. Fish are fed by on demand, either manually or by using a manually operated air compressor type feeder, once a day during the cold season (October–April) or twice in the warm season (May–October). The trophic level of the food pellets by definition is 1 because it does not consume living biomass from the modelled fish farm ecosystem.

2.2. The model

Trophic interactions and energy flux were modelled by means of Ecopath with Ecosim model (EwE; Christensen et al., 2005) that provides a static description of an ecosystem at a precise period in time. It can describe principal species, autotrophs and heterotrophs, individually or by aggregating them into functional groups (e.g., species with a similar ecotrophic role). The model is based on the premise that the considered system is balanced in the given time period (Polovina, 1984); that is, production is equal to consumption following the equation:

$$B_i\left(\frac{P}{B}\right)_i \mathrm{EE}_i - \Sigma_j B_j \left(\frac{Q}{B}\right)_j DC_{ji} - Y_i - \mathrm{BA}_i - E_i = 0$$

where for an i group, P_i is production, B_i is biomass (t km^{-2}) in tonnes wet weight and EE_i is ecotrophic efficiency. Q_j is the consumption for predators, BA_i is the biomass accumulation rate for i and E_i is the net migration rate of the group. Because material transfers among groups is through trophic relationships, this equation is re-expressed including the biomass of predators and the instantaneous rate of total mortality (Z) at equilibrium (Allen, 1971) in the form of P/B rate, describing the biomass flow balance between inputs and outputs for each group (see Christensen et al., 2005, for a complete explanation). A system of linear equations was established in which three parameters were introduced: biomass (B); total biological production rate (P/B); total food consumption rate (Q/B), and only one, EE, was estimated by the model. Diet composition is expressed as a fraction of prey in the average diet of a predator. Fishing activities are also included by adding data on landings (t km^{-2}).

2.3. Field data

We used an annual base average on the information gathered between 2001 and 2007 on the study ecosystem. Most species were included in functional groups sharing similar trophic roles. Only those of particular interest were kept as individual groups: wild fish species aggregated around the fish farm (Mediterranean horse mackerel *Trachurus mediterraneus*, mullets, pompano *Trachinotus ovatus*, sparids, bogue *Boops boops*, round sardinella *Sardinella aurita*, planktivorous fishes, bluefish *Pomatomus saltatrix*, striped barracuda *Sphyraena sphyraena*, greater amberjack *Seriola dumerilii*, common eagle ray *Myliobatis aquila*, grey triggerfish *Balistes capriscus*), commercially important species such as striped red mullet *Mullus surmulletus*, red scorpionfish *Scorpaena scrofa* and cephalopods; several groups of invertebrates, juvenile fish species aggregated around sea-cages, the reared species (gilthead seabream, European seabass and maegre) and the artificial food pellets used to nourish the caged fish considered just like detritus. The microbial food web was not directly considered in the model, but it was indirectly considered within the zooplankton diet composition and detritus dynamics (Calbet et al., 2002).

Biomass was compiled from own studies and from published studies (Annex 1), and was calculated with the swept area method (Pauly, 1984) that is based on the densities of organisms (i.e., the weight of the fish caught per unit area covered by an experimental sampling method), from which the potential yield can be obtained. For commercial groups, P/B corresponded to the instantaneous rate of natural mortality (M), and was estimated from data in FishBase