Estuarine, Coastal and Shelf Science 83 (2009) 577–590

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Trophic network model of the Northern Adriatic Sea: Analysis of an exploited and eutrophic ecosystem

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ARTICLE INFO

Article history:
Received 2 October 2008
Accepted 5 May 2009
Available online 12 May 2009

Keywords:
trophic structure
food webs
fishing
eutrophication
discard
network analysis
Italy
Slovenia
Croatia
Northern Adriatic Sea
43°38′–45° 46′ N, 12°16′–15°06′ E

ABSTRACT

A quantitative model of the trophic network of Northern Adriatic Sea marine ecosystem during the 1990s has been constructed, with the goal of analysing its trophic structure, identifying the key trophic groups and assessing the anthropogenic impacts on the ecosystem using the Ecopath modelling protocol. The Northern Adriatic Sea is an eutrophic, shallow basin, and one of the most heavily fished areas in the Mediterranean Sea. The network aggregation into discrete trophic levels sensu Lindeman shows that low trophic levels dominate biomass and energy flows, with 40% of the total system throughput flowing out from trophic level 2. Instead, upper trophic levels appear bottom-up controlled, highly depleted and not exerting any control on the trophic network, as shown by mixed trophic impact-based analyses. Microbial loop is comparable to grazing with respect to the magnitude of flows involved, as 66% of the trophic network flows originate from detritus, which is mainly consumed by bacteria. Key trophic groups are plankton groups, macro-crustaceans and detritus, and other r-selected organisms like squids and small pelagics, which have a great influence on the ecosystem. In particular, zooplankton acts as a bottleneck for energy flows, limiting the energy from the low trophic levels effectively reaching the upper food web. The high pelagic production caused by eutrophication sustains high fishery landings and impressive discard quantities, as well as the benthic compartment. Overall, the ecosystem appears quite productive and in a stressed and developmental status. Model results and comparisons with few existing historical data suggest that the low maturity and stressed state of the Northern Adriatic Sea are not only due to natural characteristics, but mainly to anthropogenic pressures.

1. Introduction

During the last decade, the collapse of several fish stocks and their scarce capability to recover after severe depletion (Pauly et al., 1998; Hutchings, 2000; Jackson et al., 2001; Reynolds et al., 2005), together with the awareness that fishery impacts the ecosystems altering food webs and damaging habitats (Jennings and Kaiser, 1998; Kaiser and De Groot, 2000; Pauly et al., 2002; Garcia et al., 2003), gave evidence that fishery management based on single species is not sufficient. Thus, fishery research is shifting towards an ecosystem approach, widely recognised as the most promising in formulating lines of conduct for a sustainable exploitation (Garcia et al., 2003). This approach implies a good understanding of how ecosystems function.

Following the demand for tools capable of managing information regarding interactions within ecosystems, trophic network models of aquatic ecosystems are increasingly appearing in literature, among them Ecopath (Polovina, 1984; Christensen and Walters, 2004) and NTWRK (Ulanowicz, 2004). These models require large amounts of input data whose quality must be assured if we want to increase the certainty of the outputs and, consequently, the feasibility of robust management applications. Quantitative food-web models are constituted by a static picture of the trophic network of the considered ecosystem, represented as a steady-state "snapshot" of energy flows averaged over time. These models can provide insights into how marine ecosystems function and into the effects of different levels of exploitation or changes in environmental conditions (Baird and Ulanowicz, 1989; Baird et al., 1991; Heymans et al., 2004) through network analysis (Ulanowicz, 1986; Ulanowicz and Puccia, 1990; Baird et al., 1991). Trophic network models represent powerful tools for identifying the control that energy flows can be subjected to in a marine ecosystem: bottom-up (control by primary producers), top-down (control by predators) and wasp-waist (control by dominant species) (Cury et al., 2001;

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0272-7714/$ – see front matter
doi:10.1016/j.ecss.2009.05.003

Daskalov, 2002; Shannon et al., 2004). The understanding of which control is operating is critical for exploring and applying management policies. For example, climate or more in general environmental changes may indirectly cause collapse in commercial stocks of bottom-up controlled ecosystems (Cury et al., 2001), while trophic cascades may be driven by fishing in top-down controlled ecosystems (Frank et al., 2005).

In the Mediterranean, the Northern Adriatic Sea constitutes a unique ecosystem. It is a shallow and very productive basin, characterised by wide inter-seasonal and inter-annual variations in environmental parameters (e.g. temperature, salinity) and circulation, which are strongly influenced by atmospheric forcings and riverine inputs (Russo and Artegiani, 1996). Anthropogenic pressures include coastal pollution, eutrophication, caused by the huge nutrient loads discharged by the Po river and resulting, mainly in the 1980s, in anoxic conditions and fish kills (Vollenweider et al., 1992; Caddy, 2000), and commercial fishing. Indeed this basin is one of the major fishing grounds of the Mediterranean Sea, thus having a great socio-economic importance. It is hard to quantify the real magnitude of the human impacts on this ecosystem, because of the great environmental variability and the presence of fishing since ancient times. However, the understanding of trophic interactions in such a complex ecosystem and the type of control that is operating appears of primary importance for a responsible management, particularly in the global change era (McCarty, 2001).

For these reasons, a trophic network model of the Northern Adriatic Sea marine ecosystem (Italy, Slovenia, Croatia) averaged over the years 1996–1998 has been developed, with the goal of:

- analysing the trophic structure of the ecosystem;
- identifying the key groups in the food web;
- gaining a better understanding of the human impacts (e.g. eutrophication, exploitation) on the ecosystem.

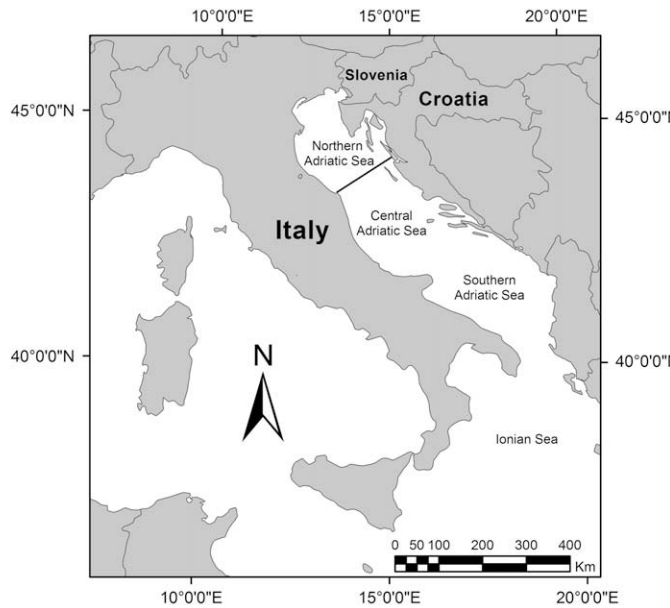

Fig. 1. Northern Adriatic Sea (Italy, Slovenia, Croatia). The straight line represents the southern boundary of the modelled area dividing it from the Central Adriatic Sea.

2. Materials and methods

2.1. Study site

The Northern Adriatic Sea is a semi-enclosed basin of about 32,000 km^2. The surrounding countries (Italy, Croatia and Slovenia) are characterised by markedly different anthropogenic pressures, ranging from the strongly-inhabited Po river plain in Italy to the Slovenian forests.

The imaginary line linking the Croatian island of Pago to the Italian city of Ancona has been chosen as the southern boundary of the model (Fig. 1), coastal lagoons and the Po river delta are not included. The basin is narrow (210 km wide at maximum), shallow (average depth 29 m) and characterised by a very short residence time of less than 3.3 months on average (Artioli et al., 2008). Circulation is primarily driven by air-sea interactions and freshwater discharge (Artegiani et al., 1997). A mean water temperature of about 14.5 °C was calculated from the Medatlas database (MEDAR group, 2002), however extreme seasonal variations for the Mediterranean sea of about 12 °C offshore and 22 °C near the coast are observed (Russo and Artegiani, 1996). The combined effects of freshwater input, wind and seasonal heat budgets contribute to further complexity leading to changing stratification of the water column and extension of the Po river plume (Fonda Umani, 1996). River discharge had a major impact also on the trophic network due to the high nutrients loads (351,000 t y^{-1} of total nitrogen, 12,000 t y^{-1} of total phosphorus, Artioli et al., 2008), particularly by the Po river, responsible for half of the total runoff (about 3000 m^3 s^{-1}) into the Northern Adriatic Sea (Raicich, 1994). The Po inflow, summed up to that of the other rivers from Northern Italy, is about 20% of the river runoff into the whole Mediterranean Sea (Russo and Artegiani, 1996). Spatial heterogeneities are marked, too. The main freshwater inputs are on the western coast, where slopes are gentler and muddy–sandy, while the eastern coasts are steeper, rocky and reach greater depths. In addition, temperature and salinity patterns are different (Russo and Artegiani, 1996). Consequently the two sides of the Northern Adriatic generally present different habitats for marine species. Phytoplankton standing crop and productivity (592 mg C m^{-2} d^{-1}, Giordani et al., 1999) decrease eastward (Fonda Umani, 1996) due to the large influence of nutrient discharge coming from western rivers, even if nutrient release from sediment plays an important role (Artioli et al., 2008). Furthermore wind-driven upwelling events are observed on both coasts and mesoscale eddies contribute to spread offshore the Po river discharge (Russo and Artegiani, 1996).

The planktonic productivity sustains an equally high production of fish and invertebrates that are heavily exploited by industrial and artisanal fleets: landings are more than 100,000 t y^{-1} (this study), consisting mainly of small pelagics and invertebrates. The Northern Adriatic Sea makes up to 25–30% of Italian marine landings (e.g. ISTAT 1998, 2000a,b, 2002) and it is possibly the most fished of the Mediterranean basins. During 1990–2005 on average 6.8–8.6% of landings from the Mediterranean Sea came from the Northern Adriatic Sea, which represents only 1.3% of its surface (recalculated from FAO (2007) GFCM dataset; Black Sea and Azov Sea were excluded).

Two previous Ecopath models have been published for this area, but one covers only a small portion (14,000 km^2) with a high degree of group aggregation (Zucchetta et al., 2003), whilst the other one considers the Northern and Central Adriatic as a whole, although they are markedly different (Coll et al., 2007).

2.2. Ecopath modelling approach

The static trophic network model was constructed using Ecopath software version 5.1.0.205 (Christensen and Walters, 2004). The ecosystem is described in terms of standing stocks and fluxes connecting the compartments, called “groups”, each group