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Effects of changing nutrient inputs on the ratio of small pelagic fish stock and phytoplankton biomass in the Black Sea

Oleg A. Yunev [a, *], Violeta Velikova [a], Jacob Carstensen [b]

[a] SuRDEP, Benksovsi Str., 26, Varna 9000, Bulgaria
[b] Department of Bioscience, Aarhus University, P.O. Box 358, 4000 Roskilde, Denmark

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ABSTRACT

Significant increases in nitrogen and phosphorus inputs to the Black Sea in the second half of the 20th century caused eutrophication and drastically decreasing Si:N and Si:P ratios. Combined with climate change, overfishing of top predators and a huge outbreak of the non-indigenous ctenophore *Mnemiopsis*, the pelagic food web was strongly modified and its efficiency for channeling primary production to higher trophic levels substantially reduced. We used the ratio between small pelagic fish stock and phytoplankton biomass on the Danube shelf and in the open Black Sea to investigate long-term changes in food web functioning. The ratio had 1) highest values for the pre-eutrophication period when diatoms and copepods dominated the pelagic food web (‘muscle food chain’), 2) decreased during the eutrophication period with stronger prevalence of autotrophic pico- and nanophytoplankton, bacteria, heterotrophic nanoflagellates, microzooplankton, *Noctiluca* and jellyfish (‘jelly food chain’ with increased importance of the microbial loop), 3) lowest values during the ecological crisis (1989–1992), when small pelagic fish stocks collapsed, and 4) increased after 1993, indicating that the ecosystem went out of the crisis and exhibited a trend of recovery. However, in the last period (1993–2008) the ratio remained close to values observed in the middle eutrophication phase, suggesting that the ecosystem was far from fully recovered. Since early 2000s, fluctuating pelagic fish stocks, with a tendency to decreasing fish landing again, have been observed in the Black Sea. Additionally, the quality of food for the small pelagic fish has deteriorated due to warming trends and the legacy of eutrophication, giving support for the ‘jelly food chain’, exhibiting low energy transfer and prevalence of organisms with high respiration rate and low nutritional value.

1. Introduction

The Black Sea experienced increasing anthropogenic pressures during the second half of the 20th century, leaving clear signs of environmental degradation (Mee, 1992). Nutrient overenrichment and associated eutrophication effects, including adverse changes in the pelagic food web, were recognized as a key Black Sea environmental problem (Black Sea Commission, 1996, 2008; GEF-UNDP, 2006; Parr et al., 2005). Eutrophication became a basin-wide problem stimulated by trophic cascades and proliferation of non-indigenous species. The first known anthropogenic disturbance of top-down control in the Black Sea occurred before 1970, caused by overfishing the dolphin population and large predatory fish (Daskalov et al., 2007). Later, at the same time as eutrophication culminated (second half of the 1980s – beginning of the 1990s), the small pelagic fish stock collapsed and a huge outbreak of the non-indigenous ctenophore *Mnemiopsis leidyi* was observed, changing the food web to a wasp-waist structure (Gucu, 2002; Shiganova, 1998). However, since the mid-1990s nutrient inputs to the Black Sea have decreased (Cociasu and Popa, 2005; Cociasu et al., 2008; Ragueneau et al., 2002) and signs of oligotrophication were observed (Yunev et al., 2016). This environmental improvement was accompanied by approximately 2-fold increase in the small pelagic fish stock, suppression of *Mnemiopsis* blooms and the appearance of another non-indigenous gelatinous species, *Beroe ovata*, a natural *Mnemiopsis* predator (Daskalov et al., 2007; Kideys et al., 2005; Shiganova et al., 2001).

The mechanisms underlying the alteration of the pelagic food web and the role of different anthropogenic pressures, in combination with climate change, have been studied by interpreting the

* Corresponding author.
E-mail address: yunevoleg@gmail.com (O.A. Yunev).

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long-term changes of various indicators of the food web (Daskalov, 2003; Daskalov et al., 2007; Oguz and Gilbert, 2007; Oguz and Velikova, 2010; Oguz et al., 2012a, b) and through modeling (Akoglu et al., 2014; Berdnikov et al., 1999; Daskalov, 1999, 2002; Gucu, 2002; Knowler, 2007; Llope et al., 2011; Oguz, 2007; Oguz et al., 2008). With the first approach, typical indicators are biomasses of all trophodynamic groups and key species, as well as total fish landing or the small pelagic fish catch. Modeling studies allow for quantifying additional information such as ratios of production and consumption versus biomass and the ecotrophic efficiency (the fraction of production of each trophodynamic group that is utilized in the system). Furthermore, with a static mass-balance modeling approach Akoglu et al. (2014) tested new ecosystem indices and synthetic ecological indicators, such as: 'Total System Throughput' – the sum of all flows within the ecosystem, 'Finn's Cycling Index'– a measure of 'Total System Throughput' recycled in the ecosystem, 'Finn's mean path length'– the average number of steps/levels along which the system production flows throughout the ecosystem and 'Transfer Efficiency'– an index to measure the efficiency with which energy is transferred between adjacent trophic levels.

In the meantime, all published Black Sea pelagic food web studies, based on the numerous indicators mentioned above, only covered periods with extensive field campaigns; thus using large sets of *in situ* data (Black Sea Data Base, 2003). For example, many have studied the 1980s and early 1990s, when 2–7 cruises were conducted annually by the Black Sea countries for monitoring the open-sea waters (Yunev et al., 2002). However, during the second half of the 1990s and especially in the 2000s, the number of field observations drastically decreased for both shelf and open-sea waters (Black Sea Data Base, 2003). The overall lack of *in situ* data in recent years has rendered many of the aforementioned pelagic food web analyses inapplicable and hence, less sophisticated robust methods are needed that can describe the pelagic food web changes over time from sparse data.

Sommer et al. (2002) demonstrated how the ratio of pelagic fish production versus primary production expressed particular qualities of the pelagic food web structure at different levels of nutrient enrichment and that the ratio critically depended on the number of trophic links from phytoplankton to pelagic fish. Thus, this ratio provides information on the pelagic food web structure, as well as a measure of the efficiency of channeling primary production through the pelagic food web (Sommer et al., 2002). Specifically for marine systems where eutrophication is of historical concern, the pelagic fish production:primary production ratio could be a useful indicator of food web changes.

Bearing in mind that: i) the Black Sea ecosystem has undergone different phases of eutrophication and recently oligotrophication (Yunev et al., 2016), ii) overfishing of large predatory fish already occured in the pre-eutrophication period (Daskalov et al., 2007) and iii) the biomass of all marine organisms primarily depends on their production level (Greze, 1979; Odum, 1971; Shulman and Urdenko, 1989), this paper has two main aims: (1) to investigate long-term changes in phytoplankton biomass and small pelagic fish stock as well as their ratio, and (2) to identify linkages between these trends and changes in other components of the pelagic food web in response to increasing or decreasing nutrient loading.

2. Materials and methods

We studied the pelagic food web changes in the open Black Sea as well as the shelf region off the Danube River (Fig. 1) which is the most productive area in the Black Sea due to the large riverine nutrient inputs, creating an important feeding ground for numerous small pelagic fish. Furthermore, the shelf area is the most well studied in the Black Sea and long-term data sets for various components of the pelagic food web are available from the literature.

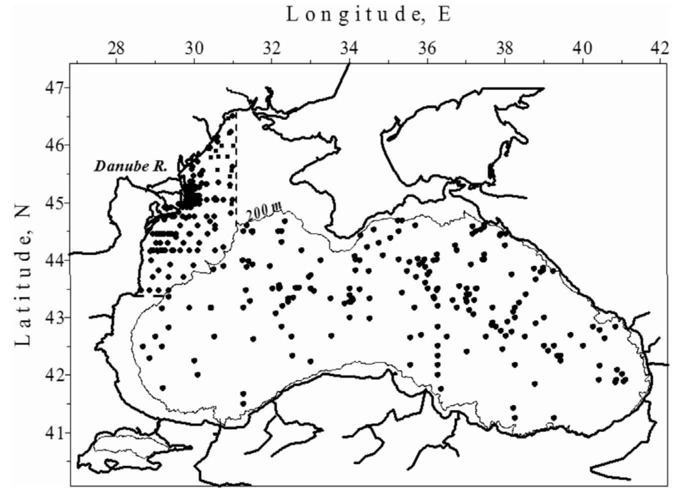

Fig. 1. The open (depths >200 m) Black Sea and shelf region off the Danube River (delineated by dotted lines and the 200 m depth curve), where phytoplankton measurements were sampled (Black Sea Data Base, 2003; Mashtakova and Roukhiyainen, 1979; Mikaelyan et al., 2013; Nesterova et al., 2008).

For the years 1972–2001, phytoplankton biomass data (represented by May–October means) for the shelf area (averaged for the 0–25 m layer) and for the open sea (under 0–100 m water column) originated mostly from the international NATO TU-Black Sea database (Black Sea Data Base, 2003) (Table 1). They were complemented with data from the Azov-Black Sea Scientific Research Institute of Marine Fisheries and Oceanography (Kerch, Crimea, Ukraine) for the earlier period of 1960–1974 (Mashtakova and Roukhiyainen, 1979). Data for more recent years (2002–2008) were derived from the report of the Black Sea Commission (Nesterova et al., 2008) and from Mikaelyan et al. (2013). The choice of May–October for averaging phytoplankton biomass observations was predetermined by data availability and our objectives to describe the most important changes over time. In particular, phytoplankton was monitored in the open sea mainly during the warmer months of the year for extended periods (Mashtakova and Roukhiyainen, 1979; Mikaelyan et al., 2013; Nesterova et al., 2008; Vinogradov et al., 1999).

Besides, the 'seasonal window' May–October is appropriate for investigating long-term interannual changes of phytoplankton characteristics at temperate latitudes both on the shelf and in the open sea (Chebotarev et al., 1983; Raymont, 1980; Vedernikov et al., 1983; Vedernikov and Demidov, 1993; Yunev et al., 2002, 2007), especially when excessive nutrient enrichment is considered. Unusual shifts in the Black Sea ecosystem functioning were first acknowledged when a significant increase in phytoplankton biomass, caused by an increase in the frequency, magnitude and spatial extension of summer algal blooms (Petranu et al., 1999), was associated with critical decrease in oxygen and mass mortalities of many living organisms on the shelf (Nesterova et al., 2008; Zaitsev et al., 2006). The masking effects of other seasons in the open sea (i.e. winter-spring and autumn maxima) were also eliminated using May–October averages to highlight the most prominent long-term changes in phytoplankton biomass.

Phytoplankton characteristics in the open Black Sea does not exhibit significant spatial variability as shown in studies using *in situ* data (Mikaelyan et al., 2013; Vinogradov et al., 1999; Yunev et al., 2002, 2005) and remote sensing (Kopelevich et al., 2002).