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Reconstructing the trophic history of the Black Sea shelf

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ABSTRACT

In the last 50 years the Black Sea has undergone large changes driven by increasing anthropogenic pressures. We estimated the integrated annual primary production (APP) for different shelf regions during the early eutrophication phase (1963–1976) using chlorophyll *a* and winter nitrate concentrations as proxy observations of primary production to describe its seasonal variation. For comparison, APP was estimated during the period when eutrophication peaked (1985–1992). In the early eutrophication period APP was estimated at 64–89 g C m^{-2} yr^{-1} for most part of the shelf, except the shelf part influenced by the Danube River (the shallow waters off the Romanian and Bulgarian coasts) where APP was ~126 g C m^{-2} yr^{-1}. In these two different shelf parts, APP increased to 138–190 and 266–318 g C m^{-2} yr^{-1} during the peak eutrophication period. These spatial differences are attributed to the large nutrient inputs from the Danube River. The APP estimates provide new insight into the eutrophication history of the Black Sea shelf, documenting stronger signs of eutrophiction than observed in other enclosed seas such as the Baltic Sea. Since the peak eutrophication period APP is estimated to have decreased by approximately 15–20%.

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1. Introduction

The Black Sea is considered one of the most susceptible to eutrophication among the large European enclosed seas (McQuatters-Gollop et al., 2009; Mee, 1992; Unluata et al., 1993). It has restricted exchange with the Mediterranean Sea, a relatively large catchment (five times the surface area of the Black Sea) and a high river runoff (~350 km^3 yr^{-1}). During the second half of the 20th century, nutrient inputs from land to the entire Black Sea increased multifold (Mee, 1992). From the 1950s–1960s to the late 1980s–early 1990s annual discharges of dissolved inorganic nitrogen and phosphate from the Danube River rose by factors of 5 and 3, respectively (Cociasu et al., 1996; Konovalov et al., 1999; Zaitsev et al., 2006). These anthropogenically enhanced nutrient discharges resulted in significant increases in nutrients concentrations on the northwestern shelf (Bodeanu et al., 1998; Cociasu et al., 1996; Zaitsev et al., 2006; Yunev et al., 2007).

An observable immediate impact of elevated nutrient levels was the increase in frequency, intensity and spatial extent of phytoplankton blooms on the shelf, caused by abnormal proliferation of one or a few species (Bodeanu et al., 1998; Moncheva et al., 1995; Velikova, 1998; Velikova et al., 1999). In the 1980s, phytoplankton biomass on the shelf off the Danube River (May-September, 0–25 m) was approximately 8–9 times higher than in the 1950s and 1960s (Bodeanu et al., 1998; Yunev et al., 2009). Similarly, a tenfold increase in chlorophyll *a* (Chl *a*) concentrations was observed for the same area: 0.66 mg m^{-3} in 1963, 1.67 mg m^{-3} in 1976 and reaching 9.0 mg m^{-3} in 1980–1992 (Yunev et al., 2007). These trends were paralled by similar changes in phytoplankton, bio-optical and hydrochemical characteristics for the open Black Sea (Konovalov and Murray, 2001; Mikaelyan et al., 2013; Vedernikov and Demidov, 1993; Vladimirov et al., 1997; Yunev et al., 2002; 2005).

These consistent trends in nutrient inputs and concentrations of nutrients, Chl *a*, and phytoplankton biomass during the second half of the 20th century would naturally lead to assume a synchronous increase in primary production (PP) (Nixon, 1995). For the open Black Sea, Yunev (2011) reported a doubling in annual primary production (APP) from about 63 C m^2 yr^{-1} in the 1960s to 135 g C m^2 yr^{-1} in the late 1980s–early 1990s. However, changes in PP over time in the shelf region remain an issue of discussion. For instance, Sorokin (2002) reported that primary production on the northwestern shelf had not increased from the 1960s to the late 1970s–1980s. Other recent studies have similarly reported lack of positive trends in the Black Sea PP (Finenko et al., 2009) and no change in the trophic status of the sea for the last 50 years (Parhomenko and Krivenko, 2011).

Given the controversy over PP trends in the Black Sea shelf region, this paper has three main aims: (1) describe and compare seasonal variations of PP on the shelf in periods with relatively low (1963–1976) and high (1985–1992) nutrient inputs,

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(2) identify linkages between changing nutrient levels and APP, and (3) assess trends in trophic status for the whole Black Sea by combining APP values from the shelf with published data from the open Black Sea.

2. Material and methods

2.1. Study area

The Black Sea continental shelf is characterized by large spatial heterogeneity of biological and hydrochemical characteristics (Konovalov and Murray, 2001; Kopelevich et al., 2002; Yunev et al., 2007; Zaitsev et al., 2006). Hence, annual and long-term variability of Chl *a* and PP were examined separately for six shelf regions (Fig. 1): Regions 1, 2 and 3 – inner shelves with depths <50 m; Regions 4 and 5 – outer shelves with depths 50–200 m; Region 6 – shelf strip excluding the northwestern and western shelves with depths <200 m. These regions were designated on the basis of Black Sea characteristics (bathymetry, surface currents, surface phytoplankton biomass and surface Chl *a* maps from satellite images, as well as riverine influence), which were described in detail by Yunev et al. (2002, 2005, 2007).

Riverine nutrient inputs largely determine primary production on the Black Sea shelf (Zaitsev et al., 2006). In this context, the designated regions have the following peculiarities. Region 1 is predominantly influenced by runoff from the rivers Dniester, Southern Bug and Dnieper (totalling ~63 $km^3\ yr^{-1}$). These rivers discharge into the Black Sea through estuaries, which act as biogeochemical filters altering nutrient concentrations and their ratios before reaching the Black Sea shelf. Region 2 receives inputs from the Danube River (~210 $km^3\ yr^{-1}$), which discharges into the sea through a large delta. Due to the dominating counterclockwise direction of the Black Sea Rim Current (Oguz et al., 1993), Region 3 is also moderately affected by the Danube River (Aubrey et al., 1996). The influence of the Danube River can even be traced to the deeper Region 5, whereas Region 4 is considered unaffected by Danube waters (Friedrich et al., 2002). Region 6 is a narrow shelf strip along the southern, eastern and northeastern coasts, which is not significantly influenced by rivers and anthropogenic nutrient pressure (Cociasu et al., 1996, Konovalov et al., 1999; Sur et al., 1996; Zaitsev et al., 2006).

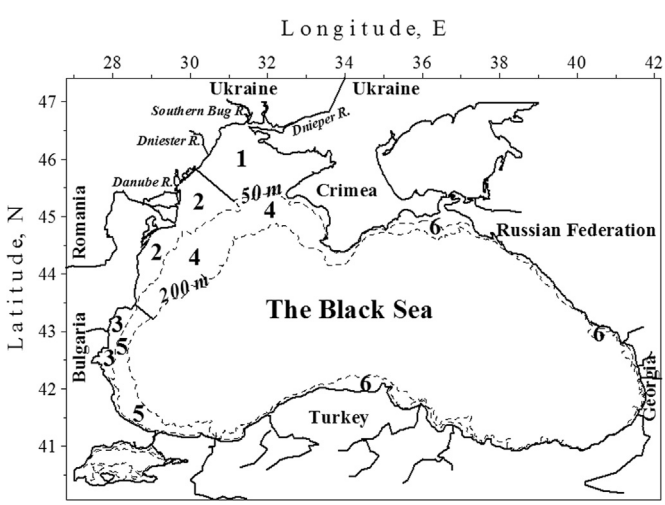

Fig. 1. Regions (1–6) of the Black Sea shelf used in the present study.

2.2. Data sources

Depth-integrated PP (^{14}C method) and surface Chl *a* data were obtained from the international database (TU-BS DB) compiled within the framework of the NATO TU Black Sea Project (TU Black Sea Data Base, 2003). Sampling and measurement methods underlying these data, and the comparability of data in the TU-BS DB, obtained with differing methodologies in the Black Sea countries, have already been described in the literature (Ivanov et al., 1998; Kopelevich et al., 2002; Stelmakh et al., 1998; Yilmaz et al., 1998; Yunev, 2011; Yunev et al., 2002; 2005; 2007; 2009). The TU-BS DB data were supplemented with PP and Chl *a* data from the early literature (Bologa, 1977; Finenko, 1967; 1979; Skolka, 1968).

2.3. Statistics

Seasonal variations in Chl *a* and PP were analyzed based on monthly arithmetic mean values, which have been shown to be approximately normal distributed for the Black Sea (Demidov, 2008; Vedernikov and Demidov, 2002; Yunev et al., 2002). Robust relationships between Chl *a* and PP were established from a large data set (entire shelf area; 1980–1995) of simultaneous measurements using linear regressions for the log-transforms of both variables, stratified by seasons (spring, summer, autumn, and winter). Relationships for spring, autumn and winter observations were not different and consequently observations from these seasons were pooled. Estimated relationships for summer and the other seasons were compared by F-tests within the framework of general linear models. The estimated relationships were used to predict PP from Chl *a* observations, taking into account the bias correction (13.3%) when back-transforming from the log-log regression.

2.4. Methods of APP calculation

So far, Black Sea APP values have been calculated using different variables (PP, Chl *a* and satellite data) and aggregation approaches for different periods and regions (e.g. Finenko et al., 2009; Sorokin, 1962, 1964, 1982; Yunev, 2011). However, due to the scarcity of *in situ* data before the 1980s and unreliability of early satellite (CZCS) data (Kopelevich et al., 2002) seasonal variations in PP were not fully resolved to assess APP on the Black Sea shelf in the early phase of eutrophication. The only exception for this period was the Romanian inner shelf region (Region 2), where Chl *a* measurements were carried out more regularly in 1963 and 1976 (Bologa, 1977; Skolka, 1968), allowing APP to be estimated. General relationships between PP and Chl *a* were estimated on data collected in all regions of the Black Sea shelf in the period from 1980 to 1995, and used to reconstruct PP monthly means from Chl *a* observations in the early phase of eutrophication in Region 2.

In order to estimate APP for other Black Sea shelf regions during the early phase of eutrophication, we applied the approach by Elmgren (1989) for the Baltic Sea. Elmgren (1989) estimated APP in the Baltic Sea above the natural background assuming spring primary production to be proportional to the standing stock of winter-early spring inorganic nitrogen (Larsson, 1986), and consequently the increase in spring PP was similar to the increase in winter-early spring nitrate concentrations observed during the period with excessive nutrient inputs (Nehring et al., 1987). Elmgren (1989) further scaled the increase in spring PP to other seasons using heuristically derived factors, acknowledging that summer and autumn PP is mainly fueled from regenerated nutrients. This approach could also be applied to the Black Sea shelves, since nutrient data from the early phase of eutrophication

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