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 eutrophication 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%.

Keywords: Annual primary production; Chlorophyll *a*; Nutrients; Early eutrophication phase; Eutrophication; Peak eutrophication period; Trophic status

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 km³ 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 paralleled 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 m² yr⁻¹ in the 1960s to 135 g C m² 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, (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 characterised 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).

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

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 km³/yr). 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 km³/yr), 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).

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 were more abundant (see, e.g. Cociasu et al., 1996; Cociasu and Popa, 2005; Yunev et al., 2007; Zaitsev et al., 2006) and because PP is light limited in winter, similar to the Baltic Sea.

Following Elmgren's approach, APP for the earliest data (APP_{early}) for Regions 1 and 3 were calculated using data on: 1) the PP seasonal variation for the period 1985-1992, 2) increase factor during spring (IF_{spr}) based on the increase in winter-early spring nitrate concentrations and 3) IF values for three other seasons: summer (IF_{sum}), autumn (IF_{aut}) and winter (IF_{win}). Unlike Elmgren (1989), the proportionality between IF_{spr} and the increase in winter-early spring nitrate concentrations as well as the ratios of IF_{sum} , IF_{aut} and IF_{win} values to IF_{spr} for the inner shelf of the Black Sea western part were assessed using observations. In Region 2, seasonal IF values were obtained by comparing the PP seasonal variations observed during the 1985-1992 period with the earlier data. PP was reconstructed using data on Chl *a*, available for this region in both periods (Bologa, 1977; Skolka, 1968; TU Black Sea Data Base, 2003).

APP_{early} values for the outer shelf region of the western Black Sea (Region 4) and for the narrow shelf (0-200 m) in the southern and eastern sea (Region 6) were estimated using data on APP for the 1985-1992 period (APP_{peak}) combined with annual increase factor for PP (AIF) for the deep-open Black Sea (Yunev, 2011) as there were no early data available for these regions. The AIF values applied were assumed close to those from the open Black Sea, since both Regions 4 and 6 experienced insignificant nutrient inputs from land (Aubrey et al., 1996; Sur et al., 1996). Similarly, the APP_{early} values for Region 5, which is influenced by Danube waters (Friedrich et al., 2002), were estimated using the APP_{peak} value for this region combined with an AIF value, which was the average of the values for the open sea and the neighbouring inner shelf (Region 3).

3. Results

3.1. Distribution of Chl *a* and PP data among regions

For the two periods of interest (early and peak eutrophication), Chl *a* and PP data were heterogeneously distributed over time and space (Table 1). In the early phase of eutrophication, PP measurements were conducted for two months only (August and October) in Regions 1, 4, 5 and 6, and Chl *a* was measured in all months in Region 2. In contrast, during the peak eutrophication period PP was generally measured throughout the year in all regions, although there were gaps for some months. However, Chl *a* measurements were carried out in all shelf regions and practically throughout the year.

Table 1

Months and numbers of stations sampled for *in situ* Chl *a* and PP (conventional ^{14}C method) measurements in different Black Sea shelf regions during the early (1963-1976) and peak (1985-1992) periods of eutrophication. “-“ means no data available.

Month	Region	Numbers of stations		Month	Region	Numbers of stations	
		Chl <i>a</i>	PP			Chl <i>a</i>	PP
1963 – 1976 ^a							
January	2	6	-	August	1	-	4
February	2	5	-		2	9	-
March	2	6	-		4	-	5
April	2	8	-		5	-	9
May	2	11	-	September	2	15	-
June	2	12	-	October	2	6	-
July	2	10	-		6	-	6
				November	2	5	-
1985 – 1992 ^b							
January	1	3	-	July	1	10	-
	2	8	3		2	10	4
	3	7	-		3	15	-
	4	12	4		4	26	3
	5	13	3		5	19	-
	6	3	3		6	3	-
February	2	3	-	August	1	3	3
	3	5	-		2	3	3
	4	3	3		3	5	-
	5	6	-		4	3	3
	6	4	-		5	7	-
March	1	4	4		6	5	4
	2	3	3	September	1	9	5
	3	6	-		2	9	4
	4	17	4		3	4	-

	6	8	-		4	45	9
April	1	6	3		5	6	-
	2	5	-		6	6	3
	3	3	-	October	1	5	3
	4	7	-		2	4	4
	5	17	-		3	8	8
	6	3	-		4	3	-
May	1	4	-		5	3	3
	2	5	-		6	17	4
	3	11	4	November	1	4	-
	5	11	4		2	5	-
June	1	5	-		3	4	-
	2	3	-		4	14	6
	3	15	5		5	5	-
	4	11	4		6	8	5
	5	3	-	December	2	3	-
	6	3	-		4	4	4
					6	7	7

^aMetadata for the period were taken from Bologna (1977), Skolka (1968) and Sorokin (1962).

^bMetadata for the period were taken from the TU Black Sea Data Base (2003).

APP could not be estimated directly by simple integration over all months in any region due to the general lack of *in situ* PP data (Table 1). Consequently, the more abundant Chl *a* data were used to reconstruct seasonal variations in PP by filling the gaps, which allowed for estimating APP. Given the data availability, PP was either measured or reconstructed from Chl *a* in all regions during the peak eutrophication period and for Region 2 in the early phase of eutrophication.

3.2 Reconstructing PP seasonal patterns during peak eutrophication period

Chl *a* seasonal patterns differed broadly among regions during the peak eutrophication period (Fig. 2). Region 1 experienced the same Chl *a* level in January and March as between August and November ($\sim 1.5 \text{ mg m}^{-3}$). In three shelf regions off the Romanian and Bulgarian coasts (Regions 2, 3 and 5), the influence of Danube River was clearly visible. Peaks of Chl *a* were observed in May (10.7 ± 4.8 , 4.4 ± 2.2 and $3.4 \pm 1.5 \text{ mg m}^{-3}$ for the three regions), consistent with the months of maximum discharge from the Danube River (April/May, Humborg, 1997). It should also be noted that the monthly means of Chl *a* were generally larger in these regions influenced by the Danube River than in Region 1 influenced by the Dnieper, Dniester and Southern Bug rivers. In Regions 4 and 6 the seasonal dynamics of Chl *a* were characterized by a major peak during the winter-early spring blooms, smaller peak in autumn and overall low Chl *a* concentrations in summer, similar to the seasonal patterns of the open sea (Yunev et al., 2002).

Fig. 2. Seasonal variation of Chl *a* in different Black Sea shelf regions during the period of peak eutrophication (1985 – 1992). Values are shown as the mean Chl *a* $\pm$ 1 standard deviation.

PP correlated strongly with Chl *a*, but the relationship varied between summer and other seasons (Fig. 3). The slopes of the two regressions were not significantly different ($F_{1,128}=0.19$; $P=0.6654$), whereas the intercept for summer months (June-August) was significantly higher ($F_{1,128}=44.84$; $P<0.0001$) than for other seasons (September-May), yielding a generally higher PP per unit of Chl *a*. Measured and predicted PP were also in good agreement, justifying the reconstruction approach (Fig. 4). The predicted values could not fully reproduce the lowest and highest PP measurements, since the regressions describe the mean relationships and deviations from these are considered random fluctuations. Thus, the predicted values are suitable for describing monthly means but less suitable for describing specific PP measurements.

The reconstructed values largely reproduced the annual variations of measured PP in all regions (Fig. 5). Although there were obvious differences for certain months in some regions, the effect of these differences became smaller when integrating values across months. For example, in Region 4 PP integrated over the 10 months with measurements resulted in 116 and 120 g C m⁻² using the measured and predicted values, respectively. APP was estimated to vary from 138 g C m⁻² in Region 4 to 318 g C m⁻² in Region 2 (Table 2) when reconstructed monthly means were used to fill the gaps without PP measurements in Fig. 5.

Fig. 3. Relationships between PP and Chl *a* over the entire Black Sea shelf (1980-1995): A) summer (★) and B) autumn (◇), winter (○) and spring (△).

Fig. 4. Comparison of predicted and measured PP values in summer (A) and autumn, winter and spring (B). Both regressions were significant ($P < 0.001$).

Fig. 5 Monthly means of measured (bars) and predicted (symbols in broken line) PP in the Black Sea shelf regions for the peak eutrophication period (1985 – 1992). Measured values are shown as the mean PP $\pm$ 1 standard deviation.

Table 2

Annual integrated primary production (APP_{peak}) in the different shelf regions during the peak eutrophication period (1985-1992).

Shelf regions	1	2	3	4	5	6
APP_{peak} , g C m ⁻² yr ⁻¹	164	318	266	138	190	148

3.3. Reconstructing PP seasonal patterns during early eutrophication period

Chl *a* was measured in all months (except December) during the early eutrophication period only in Region 2 (Table 1) and therefore, in this region, monthly PP values could be predicted from the monthly Chl *a* values (Fig. 6) using the season-specific relationships (Fig. 3). APP was estimated by summing up all monthly PP values, yielding 127 g C m⁻² for the early eutrophication phase, whereas PP aggregated over the four seasons varied from 24 to 48 g C m⁻² (Table 3).

APP in Region 2 increased by factor of 2.5 from the early eutrophication period (1963-1976) to the peak eutrophication period (1985-1992) (Table 3). The increase was largest in spring and decreased towards winter, as also indicated by R. The increase of PP in spring (IF_{spr}) was comparable to the observed increase in winter-early spring nitrate concentrations over time (4.08; Yunev et al. 2011), supporting the use of changes in winter-early spring nitrate concentrations to infer changes in spring PP.

Fig. 6. Region 2 during the early eutrophication period: A) average monthly Chl *a* (mean $\pm$ 1 standard deviation) in the surface layer according to *in situ* data (Bologa, 1977; Skolka, 1968) and B) predicted average monthly primary production using the relationships in Fig. 3.

Table 3

Integrated seasonal and annual primary production ($\text{g C m}^{-2} \text{ season}^{-1}$ or yr^{-1}) in Region 2 during the early (PP_{early}) and peak (PP_{peak}) eutrophication periods with increase factors (IF) for primary production and the ratios (R) of IF_{sum} , IF_{aut} and IF_{win} to IF_{spr} .

Season	PP_{early}	PP_{peak}	IF	R
Spring	30	115	3.83	–
Summer	48	98	2.04	0.53
Autumn	24	60	2.50	0.72
Winter	25	45	1.80	0.47
Annual	127	318	2.50	–

In order to calculate APP values for the early eutrophication period for Regions 1 and 3 we assumed proportionality between IF_{spr} and the increase in winter-early spring nitrate concentrations in these inner shelf regions of the western Black Sea as well, and used the R values obtained for Region 2 (Table 3) to estimate IF values for the other seasons. IF_{spr} values were set to published increases in winter-spring nitrate concentrations: 4.12 for Region 1 (Zaitsev et al., 2006) and 3.60 for Region 3 (Rozhdestvenskiy, 1990). Scaling these IF_{spr} values with R (Table 3) produced increase factors for summer, autumn and winter ranging from 1.94 to 2.68 in Region 1 and from 1.69 to 2.34 in Region 3 (Table 4). Seasonal and annual integrated PP values were compiled for the two regions, producing $\text{APP}_{\text{early}}$ estimates of 67 and $125 \text{ g C m}^{-2} \text{ yr}^{-1}$, respectively.

Table 4

Seasonal and annual integrated primary production ($\text{g C m}^{-2} \text{ season}^{-1}$ or yr^{-1}) in Regions 1 and 3 during the early (PP_{early}) and peak (PP_{peak}) eutrophication periods with the increase factors (IF) used for hindcasting PP during the early eutrophication period.

Season	Region 1			Region 3		
	PP_{peak}	IF	PP_{early}	PP_{peak}	IF	PP_{early}
Spring	30	4.12	7	59	3.60	16
Summer	57	2.18	26	91	1.91	48
Autumn	43	2.68	16	48	2.34	21
Winter	34	1.94	18	68	1.69	40
Annual	164	2.45	67	266	2.13	125

APP_{early} values for the outer shelf regions in the western Black Sea (Region 4 and 5) and for the narrow shelf in the southern and eastern sea (Region 6) were estimated by scaling APP_{peak} values for these regions (Table 2) with AIF = 2.14 for Region 4 and 6 (same value as for the open Black Sea; Yunev, 2011) and AIF = 2.13 for Region 5 (average of the AIF values for the open Black Sea and the neighbouring inner shelf Region 3; Table 4). Hence, the resulting APP_{early} values in Regions 4, 5 and 6 were 64, 89 and 69 g C m⁻² yr⁻¹, respectively.

3.4. Long-term changes in Black Sea APP values

Summarizing the changes in APP over time suggests that all shelf regions as well as the open Black Sea have been exposed to eutrophication, with increases in annual primary production by factors between 2 and 2.5 (Fig. 7). The early phase of eutrophication was characterized by relatively low APP_{early} (<100 g C m⁻² yr⁻¹) in most shelf regions and in the open Black Sea. Higher APP_{early} values were obtained for the inner shelf areas directly influenced by the Danube River (127 and 125 g C m⁻² yr⁻¹ for Regions 2 and 3, respectively). These two regions also experienced the highest APP_{peak} values (318 g C m⁻² yr⁻¹ in Region 2 and 266 g C m⁻² yr⁻¹ in Region 3). APP increased approximately 2.5 times in the northwestern shelves (Regions 1 and 2), as these regions were more strongly influenced by large rivers delivering increasing nutrient inputs. In other areas, including the open sea, APP approximately doubled. APP levels over time in all shelf regions, except the most productive areas (Regions 2 and 3), were close to those of the open Black Sea. Integrating the shelf regions and the open Black Sea by the area they represent resulted in an overall increase in APP for the Black Sea, as a whole, from 68 to 148 g C m⁻² yr⁻¹.

Fig. 7. Changes in APP (g C m⁻² yr⁻¹) for different shelf regions as well as the open Black Sea (Yunev, 2011) from the early (1963-1976) to the peak (1985-1992) eutrophication periods. The change in APP for the entire Black Sea is shown in the center frame.

4. Discussion

4.1. APP estimation methods

The first PP measurements with the ^{14}C method on the Black Sea shelf were carried out (together with measurements from the open sea) in August and October 1960. Based on measurements from these two months only, Sorokin (1962, 1964) provided APP estimates for the entire basin (109 and 112 $\text{g C m}^{-2} \text{ yr}^{-1}$ for the two studies). Later, Sorokin (1982) revised his first APP estimates for the whole Black Sea to 220 $\text{g C m}^{-2} \text{ yr}^{-1}$ after adding two additional data sets from September 1964 (Finenko, 1967) and August 1978 (Kondratyeva, 1979), despite the fact that the new PP data were similar to the values obtained in 1960. More recently, APP estimates for the different shelf regions and the open sea, obtained by integrating PP measurement, were based on data from an extended period (1960 - early/mid 1990s), but the methods of integration did not account for PP trends over time and decadal changes in trophic status were not resolved (Sorokin, 2002; Demidov, 2008). As a consequence, APP estimates were biased towards the more data-rich years during the peak eutrophication period.

Given the large difference among published APP estimates for the 1960s – 1970s (Sorokin, 1962; 1964; 1982) and general lack of PP measurements to describe the real seasonal variation for this period (Table 1), we used other proxy measurements (Chl *a* and winter-early spring nitrate) to reconstruct PP seasonal variations in the early eutrophication period. Similarly, depth-integrated PP is commonly estimated from remote sensing of surface Chl *a* concentrations by means of statistical relationships (e.g. Eppley et al., 1985; Smith and Baker, 1978). Such proxy PP estimates are particularly useful when applied to the regions for which they were derived (Berthelot and Deschamps, 1994; Mantyla et al., 1995; Vinogradov et al., 1999) and to annually averaged data (Harding et al., 2002; Iverson et al., 2000).

We found that the relationships between surface Chl *a* concentration and depth-integrated PP were not significantly different for autumn, winter and spring, and that summer PP was generally higher relative to Chl *a* (Fig. 3). These findings are supported by similar results from the open Black Sea (Yunev et al., 2002; Yunev, 2011), showing that relatively high PP was sustained despite low Chl *a* concentrations. This seasonal change in the PP-Chl *a* relationship is likely due to enhanced light conditions in summer, allowing phytoplankton cells to remain productive with a reduced amount of Chl *a* (Vedernikov, 1976; 1978). Moreover, the phytoplankton community during this time of the year is dominated by small-size species with high affinity to inorganic nutrients, sustaining a high production (Chisholm, 1992).

4.2. APP during the early eutrophication phase

APP estimates for the early eutrophication period can only be obtained by inference from other sources of information due to the lack of complete PP annual or seasonal information. For Region 2 Chl *a* observations were used to proxy PP monthly means, whereas nitrate concentrations were used for the other shelf regions following the approach of Elmgren (1989). Elmgren (1989) estimated APP increases of 30 – 70 % during the 20th century in a coastal area of the northern Baltic proper, and showed that this result was consistent with estimates derived directly from Eppley and Peterson's (1979) relationship between “new” production and primary production. It should be noted, that the Eppley and Peterson's (1979) relationship was derived explicitly for offshore areas, but Wassman (1986) has shown it may apply to coastal areas as well.

The Baltic Sea and Black Sea are both enclosed regional seas that have experienced eutrophication during the 20th century, and since our APP calculations were derived on an approach developed for the Baltic Sea, we found it useful to compare these two systems. Our AIF values for the Black Sea shelf regions (2.0 – 2.5) were higher than in the Baltic Sea (1.3 – 1.7) due to larger increases in winter nitrate concentrations. This implies that the Black Sea has experienced a stronger nutrient enrichment than the Baltic Sea, which is also supported by studies of nitrogen inputs. Gustafsson et al. (2012) reported increases by factor 2-3 for nitrogen inputs to the Baltic Sea, whereas inorganic nitrogen inputs from the Danube River increased by factor 5 (Cociasu et al., 1996; Konovalov et al., 1999; Zaitsev et al., 2006). Moreover, Richardson and Heilmann (1995) compared historical ¹⁴C PP measurements from the 1950s made by Steemann Nielsen with PP monitoring data from the 1980s and found more than 2-fold increase in productivity for the Kattegat at the entrance to the Baltic Sea. For the same area, Carstensen et al. (2003) established significant links between nutrient inputs and productivity. Overall, these results suggest stronger nutrient enrichment and eutrophication in the Black Sea shelf region than in the coastal areas of the Baltic Sea.

It should be emphasized also that our APP values for the early eutrophication period (Fig. 7) differs from Sorokin's studies of the 1960s (Sorokin, 1962; 1964) and, in particular, the later study (Sorokin, 1982). These studies demonstrate too high APP values for 1960s – 1970s, that lead to an incorrect conclusion of no significant increase in PP from the 1960s to the late 1970-1980s (Sorokin, 2002). For similar reasons, Finenko et al. (2011) did not find any positive APP trends from 1950s to the beginning of the 2000s. At the same time, a number of studies in the Black Sea have reported long-term changes in phytoplankton biomass, including Chl *a*, and nutrients, which can be used as supporting evidence of increasing productivity (Wasmund et al., 2001).

For example, Romanian coastal waters (near Constanta) experienced increases from 1960s/1970s to 1980s/early 1990s in phytoplankton biomass from 2 004 to 7 143 mg m⁻³ and winter phosphate and nitrate concentrations from 0.34 to 6.54 and 1.60 to 6.90 µM, respectively (Bodeanu et al., 1998). Similarly, phytoplankton biomass increased from 347 to 4 932 mg m⁻³ in the coastal waters of Bulgaria (Cape Galata) (Bodeanu et al., 1998). In Region 2 phytoplankton biomass increased during the same period from 550 to 3 850 mg m⁻³ (Petranu et al., 1999), surface Chl *a* from 0.66 to 9.0 mg m⁻³, winter-early spring phosphate and nitrate concentrations from 0.11 to 0.30 and 1.31 to 5.30 µM, respectively (Yunev et al., 2007). In the open Black Sea, averaged depth-integrated phytoplankton biomass increased from 3.3 to 19.6 g m⁻² (Mikaelyan et al., 2013), summer Chl *a* in the surface layer from 0.15 to 0.99 mg m⁻³ and in subsurface peak from 0.40 to 3.08 mg m⁻³, annual mean nitrates within the layer of depth maximum from 1.90 to 7.72 µM (Yunev et al., 2002; 2005). This overwhelming evidence of changes during the second half of the 20th century support an increased productivity in the Black Sea.

4.3. Changes of the Black Sea trophic status

Evaluation of trophic status changes is of special interest when aquatic ecosystems are subjected to eutrophication (Wasmund et al., 2001). According to Nixon (1995), eutrophication is defined as “an increase in the rate of supply of organic matter to an ecosystem”. From this definition, it follows that eutrophication is a process and hence, it represents a change. Consequently, eutrophication does not equal the ecosystem trophic status. Secondly, the major point of concern is the change in the amount of organic matter (energy) that is available to support the metabolic demands of the ecosystem. Hence, eutrophication is the change in the ecosystem trophic status. Besides, Nixon (1995) noted that: 1) sources of organic carbon can either be fixation by primary producers (autochthonous carbon) and/or any input of organic matter from outside the system (allochthonous carbon) and 2) the greatest contribution to the increased organic carbon supply in most marine ecosystems during their eutrophication falls on the autochthonous organic carbon, i.e. on primary production.

Comparison of these two sources of organic carbon in the Black Sea (Table 5) confirms Nixon’s presumption that the supply of autochthonous organic carbon exceeds land-based inputs by order of magnitude for both study periods, and most pronounced for the peak eutrophication period. Moreover, approximately 67% of autochthonous organic carbon in the Black Sea is produced in the open sea due to its substantially greater area, and only 11% and 23% come correspondingly from the more productive and the remaining shelf areas. Furthermore, the contribution of phytobenthos to

total primary production in the Black Sea is unimportant. This assertion is based on estimates from the shallow lagoons in the Baltic Sea, where micro- and macrophytobenthos produced only 7% of the total primary production (Wasmund, 1986). In the Baltic Proper, Elmgren (1984) calculated the phytobenthos contribution to 3% of total primary production. Given that the Black Sea has a large deep area, where light cannot support phytobenthic production, the contribution of phytobenthos will be even less. Consequently, trophic status changes on the shelf and in the entire Black Sea can be assessed from the annual primary production of phytoplankton only.

Table 5

Comparison of the two major sources of organic carbon (C_{org}) in the Black Sea: fixation by primary producers (autochthonous carbon) within different regions and the entire basin, and riverine input of organic matter into the Black Sea (allochthonous carbon) during the early and peak eutrophication periods.

Source of organic carbon	Region square, km ^{2***}	$C_{org,}$ 10 ⁶ t C yr ⁻¹	
		early	peak
The most productive shelf (Regions 2 + 3)	21350	2.7	6.5
The remaining shelf (Regions 1, 4 – 6)	89950	6.2	13.9
The open sea*	305960	19.3	41.3
The whole Black Sea	417260	28.2	61.7
Riverine input**		1.9	2.2

(*) Data from (Yunev, 2011), (**) from (Zaitsev et al., 2006), (***) from (GEBCO, 2003).

APP estimates for the regions on the northwestern and western shelf varied substantially. Particularly, Region 1 influenced predominantly by the Dnieper, Dniester and Southern Bug rivers was less productive than Regions 2 and 3 influenced by the Danube River (Fig. 7). The enhanced productivity in Regions 2 and 3 can be explained by higher freshwater discharges and nutrient inputs (Cociasu et al., 1996; Konovalov et al., 1999; Zaitsev et al., 2006). The Danube River freshwater discharge (~210 km³ yr⁻¹) substantially exceeds the collective stock from the Dnieper, Dniester and Southern Bug rivers (~63 km³ yr⁻¹), and inputs of inorganic nitrogen and phosphorus are 4-8 times higher from the Danube River (Table 6) yielding overall higher nutrient concentrations with Danube waters.

Table 6

Riverine inputs of inorganic nutrients (10^3 t yr^{-1}) to the northwestern shelf regions from the Danube River and Dnieper, Dniester, and Southern Bug rivers (DDSB) during two different periods (Cociasu et al., 1996; Konovalov et al., 1999; Zaitsev et al., 2006).

Nutrient	1950-1960		1980-1990	
	Danube	DDSB	Danube	DDSB
Inorganic N	141.8	33.84	756.0	110.3
Phosphate	12.7	2.35	39.6	4.98
Silicate	785.0	188.7	252	77.1

Since the mid-1990s APP (estimated from Chl *a* measurements) in the open Black Sea has decreased approximately 15-20% (Yunev, 2011). The main reason for this oligotrophication (Nixon, 2009) was the reduction of riverine nutrients inputs to the Black Sea caused by the decline of industrial activities in Eastern Europe and marked decrease in fertilizers and P-containing detergents use during the economic recession between 1989 and 1994 (Ragueneau et al., 2002). Unfortunately, more recent estimates of APP from the shelf region are not available due to lack of PP and Chl *a* measurements. However, other indicators of eutrophication suggest reduced productivity in the shelf region as well. Winter nutrient concentrations in the surface layer declined during the late 1990s (Cociasu and Popa, 2005) and changes in summer oxygen concentration above (decrease) and below (increase) the seasonal thermocline in the mid-1990s (Yunev et al., 2007) suggests a reduced photosynthetic activity. Thus, it is likely that the shelf region has experienced a similar decrease in APP as observed for the open Black Sea.

5. Conclusions

The large increase in nutrient inputs to the Black Sea, particularly from the Danube River, has stimulated eutrophication in the shelf region. APP estimates for the major part of the shelf region document a change from oligotrophy ($64\text{-}89 \text{ g C m}^{-2} \text{ yr}^{-1}$) in the early eutrophication phase (1963-1976) to mesotrophy ($138\text{-}190 \text{ g C m}^{-2} \text{ yr}^{-1}$) during the peak eutrophication phase (1985-1992), whereas the shallow shelf waters ($<50 \text{ m}$) off the Romanian and Bulgarian coasts experienced a change from mesotrophic ($125\text{-}127 \text{ g C m}^{-2} \text{ yr}^{-1}$) to eutrophic ($266\text{-}318 \text{ g C m}^{-2} \text{ yr}^{-1}$) conditions. Overall, the trophic level of the entire Black Sea changed from oligotrophic ($\sim 68 \text{ g C m}^{-2} \text{ yr}^{-1}$) to mesotrophic ($\sim 148 \text{ g C m}^{-2} \text{ yr}^{-1}$) during the second half of the 20th century.

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