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ORIGINAL ARTICLE

Nitrogen and phosphorus inputs to the Black Sea in 1970–2050

Maryna Strokal · Carolien Kroeze

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Abstract Increased nitrogen (N) and phosphorus (P) inputs are major causes of eutrophication in the coastal waters of the Black Sea. The objective of this study is to analyze the past and future trends in river export of nitrogen and phosphorus to the coastal waters of the Black Sea and to assess the associated potential for coastal eutrophication. The Global *NEWS-2* (Nutrient Export from WaterSheds) model was used for this purpose. Currently, most eutrophication occurs in the North Black Sea and the Azov Sea. In the future, however, this may change. We analyzed trends up to 2050 on the basis of the Millennium Ecosystem Assessment (MEA) scenarios. The results indicate that nutrient loads in rivers draining into the North Black Sea and the Azov Sea may decrease in the coming decades as a result of agricultural trends and environmental policy. However, in these scenarios, the targets of the Black Sea Convention are not met. In the South Black Sea, there is currently little eutrophication. But this may change because of increases in nutrient inputs from sewage in the future.

Keywords River export · Nitrogen · Phosphorus · The Black Sea · Eutrophication

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M. Strokal (✉) · C. Kroeze
Environmental Systems Analysis Group,
Wageningen University, Droevendaalsesteeg 4,
6708 PB Wageningen, The Netherlands
e-mail: strokal84@mail.ru

C. Kroeze
School of Science, Open University of the Netherland,
Valkenburgerweg 177, 6419 AT Heerlen, The Netherlands
e-mail: carolien.kroeze@wur.nl

Introduction

Eutrophication has been a serious problem in the Black Sea since the 1970s (Borysova et al. 2005; Tokarev and Shulman 2007; McGinley 2008; Zaitsev and Mamaev 1997; Yunev et al. 2007; BSC 2008, 2009). This eutrophication is caused by increased nitrogen (N) and phosphorus (P) inputs to the sea, as a result of human activities on the land. In particular, the rapid growth of fertilizer and manure applications in agriculture contributed to this, as well as changes in land use and poor wastewater treatment (Borysova et al. 2005; Yunev et al. 2007; Scheffer 2004). Compared to other European seas, the nutrient inputs to the Black Sea are high. For instance, the total nitrogen (TN) inputs in the 1990s to the North part of the Black Sea alone are six times that to the Baltic Sea and more that twice that to the North Sea. River export of total phosphate (TP) to the coastal waters of the North part of the Black Sea is comparable to those transported to the Baltic Sea, but lower than TP loads exported to the North Sea (Artioli et al. 2008).

The effects of eutrophication in the Black Sea have been considerable. The average phytoplankton biomass increased from 1 g wet weight per m^3 in the 1950s up to 30 g per m^3 in the 1980s (Borysova et al. 2005). In the year 2000, serious eutrophication, leading to hypoxia, caused problems in 14 thousand km^2 of the total area of the Black Sea (mainly the Northwest shelf of the sea). During this episode, the brown algae population (Cystoselra barbata) was minimized and replaced by filamentous green and red algae dominated by cyanobacteria (Borysova et al. 2005). Cyanobacteria are toxic not only for marine organisms, but also for people (Scheffer 2004). Many marine animals and fish are sensitive to oxygen changes. The mussel population, which is responsible for controlling phytoplankton biomass, has been declining since the 1970s (Yunev et al. 2007). Biological losses due to increased nutrient inputs to the Black Sea have been estimated near 60 million tonnes of living marine resources between 1973 and 1990. The associated economic losses for fisheries and tourism have been estimated at 500 million USD per year (Borysova et al. 2005).

In 1992, the Convention on the Protection of the Black Sea Against Pollution (also referred to as Bucharest Convention) was signed by six countries, which directly drain into the Black Sea (Ukraine, Russia, Turkey, Georgia, Romania and Bulgaria). The countries developed Strategic Action Plans to deal with environmental problems in the Black Sea, in particular coastal eutrophication. For instance, the Dnipro Basin Environmental Programme (1996) is an agreement between Belarus, Russia and Ukraine. Different memoranda of understanding were signed between these countries. Since then, a slight decrease in nutrient loads to the Black Sea has been reported (Borysova et al. 2005). However, this decrease is more likely associated with economic decline than with environmental policy measures (Borysova et al. 2005; BSC 2009; EEA 2005; Artioli et al. 2008).

Since eutrophication is a transboundary problem involving multiple actors and multiple sources, there is a clear need to provide decision makers with results of integrated studies in order to help them controlling coastal eutrophication and to minimize the environmental impact of future human activities. So far, integrated studies of N and P pollution of the Black Sea are scarce (EEA 2005). Some studies addressed eutrophication in the Black Sea (Cociasu et al. 1996; Humborg et al. 1997; Dubinina and Kozlitina 2000; Lancelot et al. 2002; Ragueneau et al. 2002; Ludwig et al. 2009). However, their focus has mainly been on the North part of the Black Sea with special attention to the Danube River. Little attention has been paid to the Azov Sea and the Southern Black Sea. A few studies exist on nutrient inputs to the Black Sea along coastal waters of Turkey. These focus on the effects of dams (Isik et al. 2008; Tosun and Seyrek 2010) and land-use change (Sertel et al. 2008). The state of the Black Sea since the 1960s has been reported, including limited overviews of nutrient inputs to the sea (Borysova et al. 2005; TDA 2007; BSC 2008). Unfortunately, no systematic analyses exist of trends in riverine nutrient inputs to the Black Sea that take into account the different forms of N and P such as dissolved inorganic, dissolved organic and particulate. Nutrient sources, indeed, have not been well investigated that makes it difficult to address policy options to manage coastal eutrophication of the Black Sea. Future trends are not well studied either, which hampers developing future environmental strategies.

Here, we take an integrative approach to analyze N and P inputs to the Black Sea, based on the Global *NEWS* model. The Global *NEWS* model (Nutrient Export from WaterSheds) was developed in order to quantify nutrient export by rivers to coastal waters in the past and for the future (Seitzinger et al. 2005). The model considers export of different nutrients such as nitrogen, phosphorus and carbon, in different forms (particulate, dissolved inorganic and organic). The model estimates riverine export of nutrients as a function of human activities on land, hydrology and basin characteristics. Both anthropogenic (point and non-point) and natural (non-point) sources of nutrients are considered (Mayorga et al. 2010; Seitzinger et al. 2010). Global *NEWS-2* models have been used to analyze the past and future nutrient export by rivers at the global scale for dissolved inorganic nitrogen (Dumont et al. 2005) and phosphorus (Harrison et al. 2010), sediments and particulate nutrients (Beusen et al. 2005), organic matter (Harrison et al. 2005) and dissolved silica (Beusen et al. 2009). In addition, Global *NEWS* studies exist at the regional scale, including analyses for Chinese rivers (Qu and Kroeze 2010; Yan et al. 2010), the European Seine and Scheldt rivers (Thieu et al. 2010), rivers in South America (Van der Struijk and Kroeze 2010) and Africa (Yasin et al. 2010). A Global *NEWS* analysis of the Black Sea, however, does not exist.

The objective of this study is, therefore, to analyze the past and future trends in river export of nitrogen and phosphorus to the coastal waters of the Black Sea and to assess the associated potential for coastal eutrophication.

Methodology

Study area

The study area covers sixteen main rivers draining to three Black Sea regions including (1) the North Black Sea, (2) the Azov Sea and (3) the South Black Sea (Fig. 1). These are all rivers from the Global *NEWS-2* model draining into the Black Sea, with a basin area covering more than four 0.5 × 0.5 degree grid cells. Smaller basins are not included because the Global *NEWS-2* model is known to perform best for larger river basins (Mayorga et al. 2010).

Rivers draining to the North part of the Black Sea form the *North Black Sea region* (Fig. 1). These include the Danube River, the Dnepr River, the Dnestr River, the Bug River and two small watersheds, Sasik and Odessa (basins GHAAS1074 and GHAAS1084 in Global *NEWS-2*, respectively). The drainage basin of this region belongs to the European continent. The North Black Sea region is larger than the other two regions and covers almost two-third of the drainage basin of the Black Sea with the

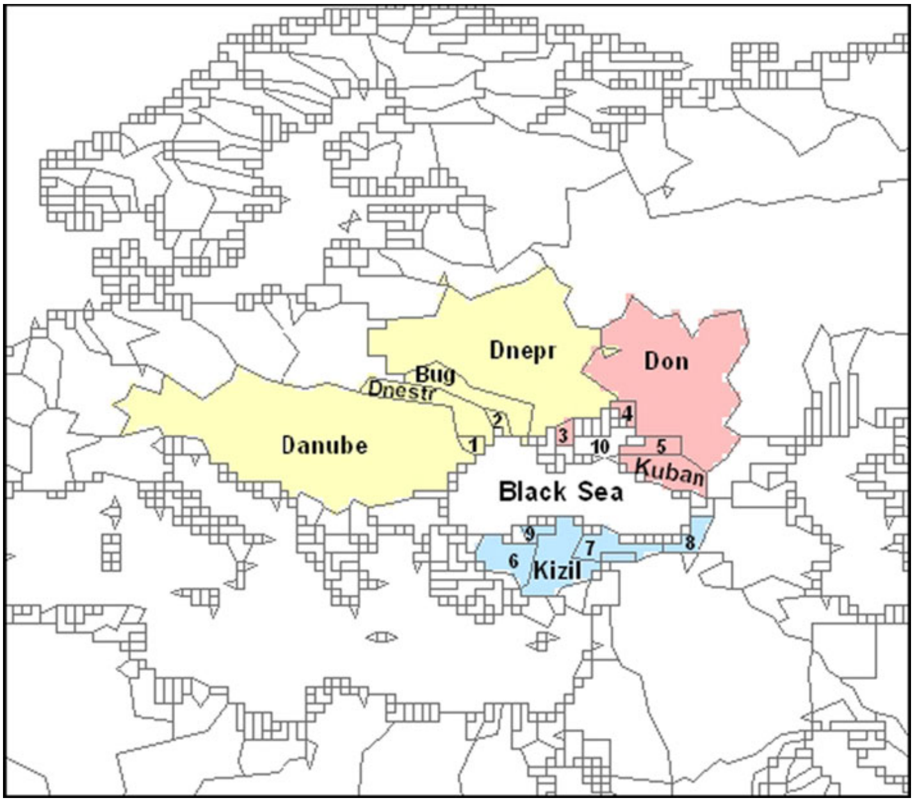

Fig. 1 The study area including three Black Sea regions: the North Black Sea (*yellow*), the Azov Sea (*pink*) and the South Black Sea (*blue*). The North Black Sea region consists of six river basins: the Danube, Dnestr, Bug, Dnepr and two small watersheds, the Sasik (*number 1*) and Odessa (*number 2*). The Azov Sea region includes five river basins that drain to the Azov Sea (*10*): the Don, Kuban and three small watersheds, the Malitopol (*3*) Taganrog (*4*), Akhtarsk (*5*). The South Black Sea region covers five river basins: Sakarya (*6*), Kizil, Yesil (*7*), Coroch (*8*), Filyos (*9*). Small watersheds were named after population centers in the basin areas except for Sasik which is named after a lake. Names of the other river basins are according to the Global *NEWS-2* model. River basins smaller than 4 grid cells are excluded from the analysis

Danube basin covering more than half of the region (Fig. 1).

Rivers draining to the Azov Sea form the *Azov Sea region* (Fig. 1). These include the Don River, the Kuban River and three small watersheds, Akhtarsk, Taganrog and Malitopol (GHAAS565, GHAAS936 and GHAAS1078 in Global *NEWS-2*, respectively). The river basins also belong to the Europe continent, and they cover about 25 % of drainage area of the Black Sea (Fig. 1).

The *South Black Sea region* is formed by Asian rivers that drain into the South part of the Black Sea. These river basins are relatively small compared to other basins and cover around 10 % of the drainage basin of the Black Sea (Fig. 1).

Global *NEWS-2* model

The Global *NEWS* model version 2 (referred to as Global *NEWS*-2) was used in this study to analyze the past and future export of nitrogen and phosphorus by rivers to the three Black Sea regions. The Global *NEWS* model was developed in 2002 and first published in 2005 (Seitzinger et al. 2005). This first version of the model consisted of several sub-models namely sub-models to estimate dissolved inorganic nitrogen (*NEWS*_DIN) and dissolved inorganic phosphorus (*NEWS*_DIP), dissolved organic nitrogen (*NEWS*_DON), dissolved organic phosphorus (*NEWS*_DOP), dissolved organic carbon (*NEWS*_DOC), particulate nitrogen (*NEWS*_PN), particulate phosphorus (*NEWS*_PP) and particulate carbon (*NEWS*_POC) (Seitzinger et al. 2005). In 2009, the Global *NEWS* model has been improved (referred as *NEWS-2* version) combining all multi-forms of nutrients into common model framework, GNE interface (Global *NEWS* Modeling Environment) to facilitate comparison by forms and elements (Mayorga et al. 2010; Seitzinger et al. 2010). The Global *NEWS-2* model has been used to analyze the past and future trends (1970–2050).

The model calculates river export of dissolved inorganic N and P (DIN, DIP), dissolved organic N, P and C (DON, DOP, DOC) and particulate N, P and C (PN, PP, POC). Dissolved inorganic and organic N, P and C are calculated based on a mass-balance approach as a function of socio-economic drivers (for instance, gross domestic product, population density). The model distinguishes between non-point sources (Bouwman et al. 2009) and point sources of nutrients (Van Drecht et al. 2009) under climate and hydrological forcings (Fekete et al. 2010) and other factors (Mayorga et al. 2010; Seitzinger et al. 2010). The model also distinguishes between agricultural and natural areas. *Non-point sources* of N and P include fertilizer and manure applications on land (for all dissolved nutrient forms), nitrogen deposition and fixation on agricultural and natural areas (for DIN), leaching (or export) of dissolved organic N and P from agricultural and natural areas, and weathering of P-contained minerals in soils over agricultural and natural areas (for DIP). The last two sources are considered as additional non-point sources of N and P export from watersheds to rivers. These are calculated on the basis of export-coefficients as a function of annual runoff from land to streams (Mayorga et al. 2010). *Point sources* consist of wastewater discharge to rivers generated from human waste (for all dissolved nutrient forms) and detergents (for dissolved forms of phosphorus) (Van Drecht et al. 2009). Particulate N, P, C are estimated on the basis of linear regressions and relationships between total suspended solid (TSS) and particulate forms of nutrients (Beusen et al. 2005). Detailed information on equations and parameters used in the calculations of nutrient export is provided by Mayorga et al. (2010).

The model includes more than 6,000 river basins and takes into account their geophysical (lithology, land use) and hydrological characteristics (precipitation, runoff from land to streams, aquatic retention within the river system) (Mayorga et al. 2010). The hydrology is based on the Water Balance Plus model (Fekete et al. 2010). Most inputs to Global *NEWS-2* model are on a 0.5 by 0.5 degree grid (Mayorga et al. 2010).

River export of nutrients is estimated for the past (1970, 2000) and future (2030, 2050) and is expressed in yields (kg km^{-2} year^{-1}) and loads (Mg year^{-1}). Future export of nutrients is based on four Millennium Ecosystem Assessment (MEA) scenarios (Alcamo et al. 2005; Carpenter et al. 2006). In the Global *NEWS* project, these MEA scenario storylines have been quantitatively interpreted to produce the required input data for the Global *NEWS-2* model (run 5) (Bouwman et al. 2009; Van Drecht et al. 2009; Fekete et al. 2010). Model inputs have thus been generated for agricultural parameters, sewage and hydrology (Seitzinger et al. 2010). Each of the four MEA scenarios is characterized by assumptions on the socio-economic development (globalization or regionalization) and environmental management (proactive or reactive).

The Global Orchestration (GO) scenario presents a globalized world with a reactive approach toward environmental management focusing on rapid economic growth and low population growth (Seitzinger et al. 2010). Agricultural productivity is assumed to increase leading to higher nutrient inputs to rivers (Bouwman et al. 2009). In contrast, improvements in sewage treatments and full access to improved sanitation facilities are obvious in this scenario (Van Drecht et al. 2009). This may result in lower nutrient inputs to rivers from sewage systems. *The Technogarden* (TG) scenario represents a globalized world with a proactive approach toward environmental management, focusing on environmentally sound technologies (Seitzinger et al. 2010). Population growth is projected to be moderate but with relatively high incomes because global economic markets develop fast. Environmental technologies will improve sewage treatments and sanitation facilities (Bouwman et al. 2009; Van Drecht et al. 2009). However, fertilizer and manure use might be higher in countries with nutrient depletion (Bouwman et al. 2009). *The Order from Strength* (OS) scenario describes a regionalized world with relatively low economic growth and a focus on regional markets, combined with a reactive approach toward environmental management (Seitzinger et al. 2010). The main emphasis is on security and protection of society. Population growth is high, and incomes increase only slowly (Bouwman et al. 2009). Sewage systems will be improved on the basis of available technologies but not as much as in the previous two scenarios (Van Drecht et al. 2009). The efficiency of fertilizer and manure use differs slightly from the past (Bouwman et al. 2009). Finally, *the Adaptive Mosaic* (AM) scenario assumes a regionalized world with a proactive environmental management, resulting in simple and economically feasible environmental technologies at the local and regional level (Seitzinger et al. 2010). High population growth with moderate increasing incomes is projected as well as improvements in sewage systems. However, sewage connection is less well developed compared to the other scenarios (Van Drecht et al. 2009; Bouwman et al. 2009). This scenario assumes a large effort to close nutrient cycles at the local–regional scale, improving manure and fertilizer use efficiency relative to other scenarios. For a detailed description of the MEA scenarios, we refer to Carpenter et al. (2006), Alcamo et al. (2005).

The GO and AM scenarios were used in this study to analyze future trends in N and P export to the coastal waters of the three Black Sea regions. This is because these are two extreme scenarios, representing different views on socio-economic developments and ecosystem management. It has to be mentioned that these scenarios do not project the future. We only can explore possible future trends on the basis of assumptions on changing conditions and future human activities.

Model validation

We validated the Global *NEWS-2* model by comparing measured nutrient yields with modeled yields for rivers draining into the Black Sea. We calculated the coefficient of determination (R^2), which is also referred to as model efficiency (Dumont et al. 2005).

The validation of the model was done on the basis of available measured nutrient yields (kg km^{-2} year^{-1}) for the year 2000. For eight river basins, useful measurement data were available in GEMS-GLORI (Meybeck and Ragu 1995) and other databases (Dumont et al. 2005; Mayorga et al. 2010; Harrison et al. 2005). These eight rivers include the Danube, Dnepr, Don, Dnestr, Bug, Kuban, Sakarya and Yesil. Measured yields for DON, DOP and DIP, expressed in kg km^{-2} year^{-1}, were taken from Mayorga et al. (2010) for up to eight river basins. Measured DIN yields (in kg km^{-2} year^{-1}) were available from Dumont et al. (2005) for four rivers: the Don, Bug, Sakarya and Kuban while for Yesil River, the data were taken from GEMS-GLORI (Meybeck and Ragu 1995) for nitrate and ammonium concentrations (N-NO$_3$; N-NH$_4$ in mg L^{-1}). The sum of nitrate and ammonium was assumed to equal DIN concentrations. Measurements of DOC were taken from Harrison et al. (2005) in the form of concentration (mg L^{-1}) for the Danube, Dnepr, Don and Kuban river basins. The yields of DOC and DIN for these rivers were deduced from these concentrations, taking into account their basin areas and actual discharges. The modeled nutrient yields (kg km^{-2} year^{-1}) for 2000 were derived from the Global *NEWS-2* model (run 5). Measurements of nutrients in rivers for the past decades are scarce. For some nutrient forms, data were available less than 5 rivers draining into the Black Sea, but these cover from 35 % (Danube river basin) to 79 % (the Danube, Dnepr, Don, Kuban river basins) of the total Black Sea drainage basin.

In order to increase our confidence in the Global *NEWS* model for analyses of Southern and Eastern Europe, we also compare model results to five rivers draining into the Mediterranean Sea: the Po, Rhone, Ebro, Evros and Seyhan. Measured data (kg km^{-2} year^{-1}) were available from Mayorga et al. (2010) for DIP for those basins and for DON and DOP for the Po river basin.

Measured and modeled nutrient yields are presented in Fig. 2. Results indicate that the model efficiency for DIN, DIP, DON, DOP and DOC, which are exported by rivers draining into the Black Sea, is 0.76 (R^2) (Fig. 2). When we include rivers that drain into the Mediterranean Sea, the model efficiency is calculated to be 0.77.

Our validation results of Global NEWS are generally in line with other Global *NEWS* studies (Beusen et al. 2005; Dumont et al. 2005; Harrison et al. 2005, 2010; Mayorga et al. 2010; Qu and Kroeze 2010; Van der Struijk and Kroeze 2010; Yasin et al. 2010). Mayorga et al. (2010) concluded that the Global *NEWS* model generally can explain 60–90 % of the observed variation in river export of nutrients. Moreover, the Global *NEWS* model was found to perform well on the continental scale and regional scale, as indicated in the above-mentioned papers. In addition to this, our modeled TN and TP inputs to the Black Sea are close to estimates of the Black Sea Commission (BSC 2002). They reported about 640 kton of TN and 50 ktons of TP in 1998, which are comparable with modeled 620 ktons of TN and 90 ktons of TP in 2000 respectively (see "Past and future trends in river export of nitrogen and phosphorus").

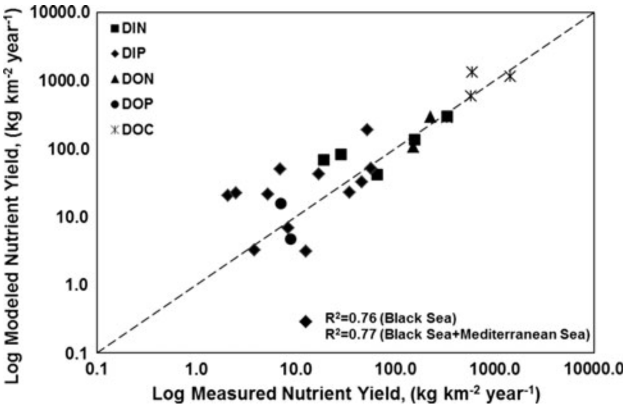

Fig. 2 Measured versus modeled yields (kg km^{-2} year^{-1}) of dissolved organic and inorganic nutrient forms for the selected river basins draining into the Black Sea and Mediterranean Sea. The *dashed line* represents the 1:1 line. See text for sources of information. Modeled yields are from the Global *NEWS* model. DIN and DIP are dissolved inorganic nitrogen and phosphorus, respectively. DON, DOP and DOC are dissolved organic nitrogen, phosphorus and carbon, respectively

The indicator for coastal eutrophication potential (ICEP)

The ICEP approach is used in this study to calculate potentials of the rivers to cause eutrophication along the coastal zones of the Black Sea for the year 2000. This is an indicator for harmful algal blooms rather than for eutrophication in general. The ICEP indicator has been developed by Billen and Garnier (2007) and implemented in Global *NEWS-2* (Garnier et al. 2010). ICEP is expressed in kg carbon per km^2 per day. The calculation of ICEP is based on the Redfield ratio: C:N:P:Si (106:16:1:20). Here, we calculate ICEP for the selected sixteen river basins draining into the Black Sea for 2000 using the Global *NEWS-2* interpretation:

$$\mathrm{ICEP} = [\mathrm{NFlx}/(14 \cdot 16) - \mathrm{SiFlx}/(28 \cdot 20)] \cdot 106 \cdot 12 \tag{1}$$

if N:P < 16 (N is limiting)

$$\mathrm{ICEP} = [\mathrm{PFlx}/31 - \mathrm{SiFlx}/(28 \cdot 20)] \cdot 106 \cdot 12 \tag{2}$$

if N:P > 16 (P is limiting). PFlx, NFlx and SiFlx are the fluxes of total phosphorus, total nitrogen and silica, respectively, delivered at the mouth of rivers, expressed in kg P, N, or Si per km^2 per day. Total nitrogen (TN) and total phosphorus (TP) fluxes of the river basins in kg km^{-2} year^{-1} are from the Global *NEWS-2* model. TN fluxes are calculated as sum of DIN, DON and PN, and TP fluxes as the sum of DIP, DOP and PP. Silica fluxes for the selected river basins are from Beusen et al. (2009).

The N:P ratio is calculated using the following equation (Garnier et al. 2010; the Global *NEWS-2* model source code):

$$\mathrm{N{:}P_{ratio}} = (\mathrm{TNyld}/14)/(\mathrm{TPyld}/31) \quad (3)$$

TNyld and TPyld are total N and total P fluxes in kg km^{-2} year^{-1}.

Positive values of ICEP (ICEP > 0) are calculated when nitrogen and/or phosphorus are present over silica indicating a potential for harmful algal blooms and thus for eutrophication. Negative values of ICEP (ICEP < 0) show that silica is on an annual basis in excess of nutrients indicating on average a low risk for eutrophication. However, an ICEP < 0 should not be interpreted as no risk for eutrophication, since there may still be local or seasonal eutrophication events.

Past and future trends in river export of nitrogen and phosphorus

Drivers of nutrient export

We present the past and future trends in major anthropogenic drivers of nitrogen and phosphorus export by rivers draining into the three Black Sea regions (Fig. 3). Important anthropogenic drivers include economic growth (GDP at purchasing power parity: GDPppp on average in 1995 US$ person^{-1} year^{-1}), population density and population connected to sewage systems (inhabitants per km^2), total nitrogen and phosphorus inputs to watersheds from sewage systems (human waste and detergents, kg km^{-2} year^{-1}) and manure and fertilizer applications in agriculture (kg km^{-2} year^{-1}).

Past trends (1970 and 2000) differ among the North Black Sea, the Azov Sea and the South Black Sea regions. For instance, GDPppp per capita increased by about 40 % in the Black Sea river basins, but it increased faster in the North and South Black Sea regions than in the Azov Sea region (Fig. 3). Population density almost doubled in the South Black Sea region (Fig. 3). These trends illustrate the economic developments in the 1970s in Europe. In addition, people migrated from rural to urban areas, especially in the Asian regions (TDA 2007; BSC 2008).

In 1970, about 50 % of the population was connected to sewage systems. This percentage increased considerably between 1970 and 2000. By 2000, the percentage of the population connected to sewage facilities increased by 60 % in the North Black Sea region, by 7–10 % in the Azov Sea region and tripled in the South Black Sea region (Fig. 3). This is associated with substantial increases in TN and TP inputs to watersheds from human waste and detergents in the South Black Sea region and an slight increase in the North Black Sea region over the period of 1970 and 2000 (Fig. 3). Despite the economic developments, the total N (TN) and P (TP) inputs to land from manure and fertilizer use decreased between 1970 and 2000 in the North Black Sea and the Azov Sea regions (Fig. 3). This could be caused by collapse of Soviet Union in the 1990s (Bouwman et al. 2009; BSC 2008). In contrast, TN and TP inputs from arable land increased in the South Black Sea region (Fig. 3). The rivers in this region are on the Asian continent, where intensive agriculture developed fast in these years (BSC 2008; TDA 2007).

Future trends differ from the past and also among the three Black Sea regions. GDPppp is projected to continue to increase from 2000 to 2050 in all MEA scenarios. Per capita GDPppp increases fastest in the North Black Sea basins (Fig. 3). The GO scenario shows the most rapid growth of GDPppp. This is because the GO scenario focuses on economy rather than on environment (Bouwman et al. 2009). In contrast, population density may decrease in the Black Sea basins except for the basins draining into the South Black Sea region, where urbanization still plays an important role. As a result, the sewage TN and TP inputs are projected to increase considerably in the South Black Sea region (Fig. 3). Likewise, TN and TP inputs from manure and fertilizer application in agriculture are also projected to increase in the Southern basins, except for fertilizer inputs in the AM scenario. The AM scenario also projects lower rates of TN and TP inputs from manure and fertilizer use in the other two regions compare to the GO, OS and TG scenarios (Fig. 3). This is because the AM scenario assumes a more efficient use of manure and fertilizer in agriculture (Seitzinger et al. 2010; Bouwman et al. 2009). TN and TP inputs from manure use in the watersheds of the North Black Sea and the Azov Sea regions continue to decrease between 2000 and 2050 in the scenarios (Fig. 3). However, TN and TP inputs from arable land increase in those two regions (Fig. 3). Sewage connection is projected to increase in the North Black Sea and the Azov Sea regions, but with better wastewater treatment facilities. This explains the lower TP and TN inputs from point sources (human waste and detergent) to watersheds of those regions in the future (Fig. 3).

Nitrogen river export

The export of nitrogen (DIN, DON and PN) by rivers was higher in 2000 than in 1970 for most Black Sea regions and most nutrient forms (Fig. 4). DIN export by rivers draining to the coastal waters of the North Black Sea and the Azov Sea regions decreased slightly (<5 %) in the North Black Sea and increased slightly (5 %) in the Azov Sea between 1970 and 2000. DIN river export increased in the South Black Sea region by approximately 30 % in this period. This is in line with Seitzinger et al. (2010), who estimated an increase of DIN export at the global scale by about 60 % in South Asia between 1970 and 2000. An increase over

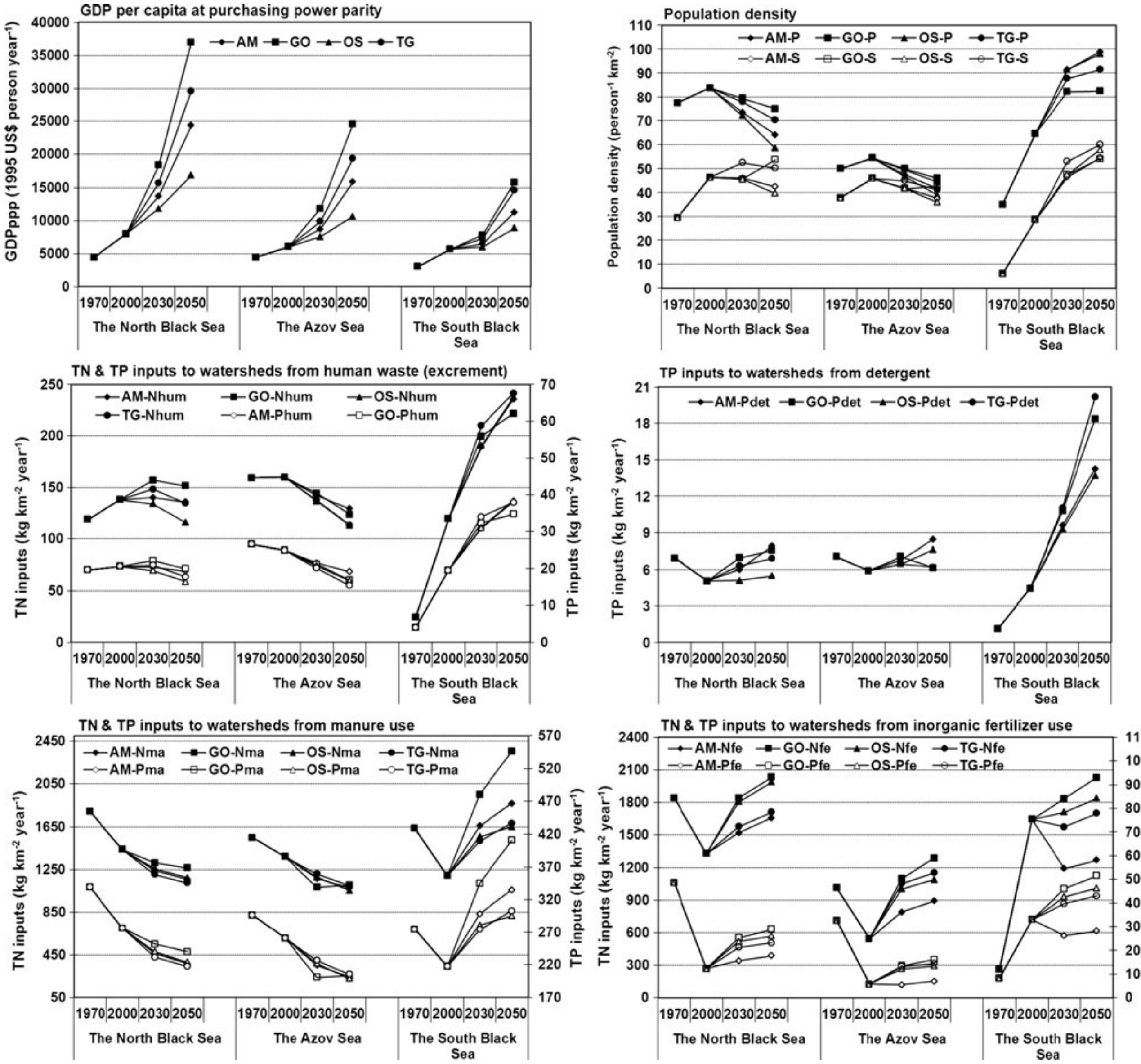

Fig. 3 Major anthropogenic drivers of total nitrogen (*TN*) and total phosphorus (*TP*) export to watersheds of the three Black Sea regions including the North Black Sea, the Azov Sea and the South Black Sea in the past (1970 and 2000) and for the future (2030 and 2050) for the four *MEA* (Millennium Ecosystem Assessment) scenarios: *AM* (Adaptive Mosaic), *GO* (Global Orchestration), *OS* (Order from Straight) and *TG* (TechnoGarden). *P*, population density (inh km^{-2}); *S*, population density connected to sewage systems (inh km^{-2}); *Nma* and *Pma*, total nitrogen and phosphorus inputs to watersheds from manure use in agriculture (kg km^{-2} year^{-1}); *Nfe* and *Pfe*, total nitrogen and phosphorus inputs to watersheds from inorganic fertilizer applications to land (kg km^{-2} year^{-1}); *Nhum* and *Phum*, total nitrogen and phosphorus inputs to watersheds from human waste (excrement) (kg km^{-2} year^{-1}); *Pdet*, total phosphorus inputs to watersheds from detergent use in households (kg km^{-2} year^{-1}). *Source*: Global *NEWS-2* model (Bouwman et al. 2009; Van Drecht et al. 2009)

this period is also calculated for DON and PN export (by up to 25 %) from the three regions, except for PN export from the South Black Sea river basins. The increased export of these nutrients over 30 years can be explained by larger inputs from sewage and fertilizer use (especially in the South Black Sea region, Fig. 3). Synthetic fertilizers and animal manure are the main sources of DIN in rivers, while leaching from agricultural and natural areas, and sewage effluents are major sources of DON.

In the future, nutrient export by rivers may increase or decrease, depending on the nutrient form, Black Sea region and scenario (Fig. 4). An increase is projected for DIN export by rivers to the coastal waters of the Azov Sea (7 %) and the South Black Sea region (around 20 %) between

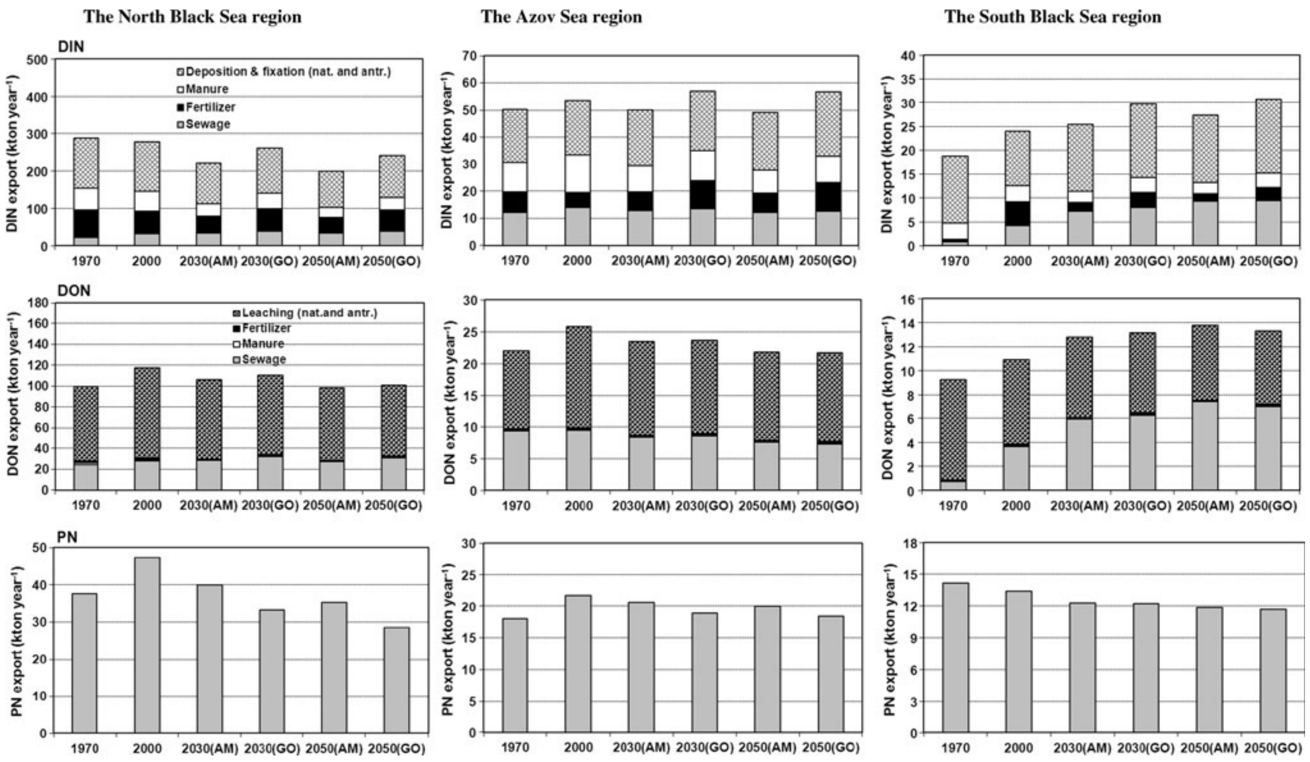

Fig. 4 Modeled export of dissolved inorganic (*DIN*), dissolved organic (*DON*) and particulate (*PN*) nitrogen by rivers that drain to coastal waters of the three Black Sea regions: the North Black Sea, the Azov Sea and the South Black Sea and nitrogen sources. *DIN*, *DON* and *PN* export are calculated for the past (1970 and 2000) and future (2030 and 2050) and expressed in kton per year. Future trends in *DIN*, *DON* and *PN* are based on two Millennium Ecosystem Assessment (*MEA*) scenarios, the Global Orchestration (*GO*) and Adaptive Mosaic (*AM*). The *AM* and *GO* scenarios represent proactive and reactive approaches toward environmental problems, respectively, and a regionalized and globalized world, respectively. *Source*: Global *NEWS-2* (Mayorga et al. 2010; Seitzinger et al. 2010)

2000 and 2050 under the GO scenario. An increase in DON export of 15 % is calculated for the South Black Sea basins in line with increased use of fertilizers and manure and increased sewage effluent to rivers from 2000 to 2050 (see Figs. 3, 4). In 2050, river export of DIN and DON to the coastal waters of the North Black Sea is projected to be about 15 % lower than in 2000 in the GO scenario, and of PN about 40 % lower. Reduced river exports of DON and PN are also calculated for the Azov Sea and the South Black Sea regions between 2000 and 2050. The differences between the two MEA scenarios are most pronounced for DIN. Higher DIN yields are projected for the GO scenario than for AM. This can be explained by different environmental management: the GO scenario assumes a reactive approach toward environmental management, while AM is proactive (Seitzinger et al. 2010). For instance, GO assumes more meat consumption than AM, leading to more fertilizer use and manure excretion, leading to higher DIN export by rivers (Seitzinger et al. 2010). Reducing DIN yields in the AM scenario are also associated with more efficient use of fertilizers in agriculture (Seitzinger et al. 2010; Bouwman et al. 2009). In contrast, the GO scenario projects lower PN loads of the North Black Sea and the Azov Sea regions than in AM. This is associated with dam constructions (increasing sediment trapping in reservoirs) needed for irrigation and hydropower in the Asian basins (Seitzinger et al. 2010; Garnier et al. 2010).

In general, we find that the past and future trends in nitrogen export to the Northern Black Sea and the Azov Sea are similar to other European seas (generally decreasing) while trends to the Southern Black Sea are similar to Asian seas (generally increasing). This reflects the differences in human activities and environmental policies between European and Asian continents (Seitzinger et al. 2010). Additional results for the past and future trends in river export of DIN, DON and PN yields (kg km^{-2} year^{-1}) are given in the Supplementary Materials (Online Resource 1, 2 and 3).

Most Black Sea rivers drain into the Northern Black Sea. About 80 % of DIN, 70 % of DON and 50 % of PN is entering the coastal waters of the North Black Sea. This is in line with the large basin areas of the rivers draining into this region ("Study area"). About 60 % of the nitrogen exported from the rivers flowing to the coastal waters of the three Black Sea regions is in dissolved inorganic form, 25 % of nitrogen is in organic form and 15 % is in particulate form.

Phosphorus river export

The river export of DIP, DOP and PP to the Black Sea was higher in 2000 than in 1970, but not for all forms and Black Sea regions (Fig. 5). DIP export by rivers to the South Black Sea quadrupled between 1970 and 2000. This can be explained by increased inputs of DIP from sewage (see Fig. 3). In contrast, rivers draining into the North Black Sea exported 15–20 % less DIP in 2000 than in 1970. A small decrease in DIP river export occurred in the Azov Sea region (around 10 %). DIP in rivers is mainly from point source (sewage and detergent), with minor contributions from diffuse (manure and fertilizer). River export of DOP increased for rivers of the Azov Sea (>5 %), but hardly changed for the other rivers. Leaching from natural and agricultural areas is the largest source of DOP in rivers (Fig. 5). PP export to the North Black Sea and the Azov Sea coastal waters increased by 25 % and decreased by up to 5 % in the South Black Sea region over this period.

We present future export of DIP, DOP, PP by rivers draining to the coastal waters of the Black Sea (Fig. 5). For DIP, the results differ for the three Black Sea regions. We calculate a large increase in DIP export to the South Black Sea (almost doubling in 2050), while river export of DIP to the North Black Sea may stay at the 2000 level, and to the Azov Sea may decrease. The large increase in the coastal waters of the South Black Sea is caused by high sewage inputs in the future resulting from poor wastewater treatment and an increasing population connected to sewage systems (Fig. 3).

In the GO scenario, river export is in 2050 lower than in 2000 for DOP and PP export to the North Black Sea (20 and 40 % lower, respectively), and to the Azov Sea (up to 15 % lower) and for PP export to the South Black Sea (about 10 % lower). There are some differences between the two GO and AM scenario. River export of DIP is generally higher in AM than in GO. This is because the AM scenario does not assume large improvements in sewage systems (for instance, improved waste water treatments), which are major sources of DIP. Future PP export (2030 and 2050) is projected to be the lower in the GO scenario than in AM, especially for the coastal waters of the North Black Sea and the Azov Sea. This can be

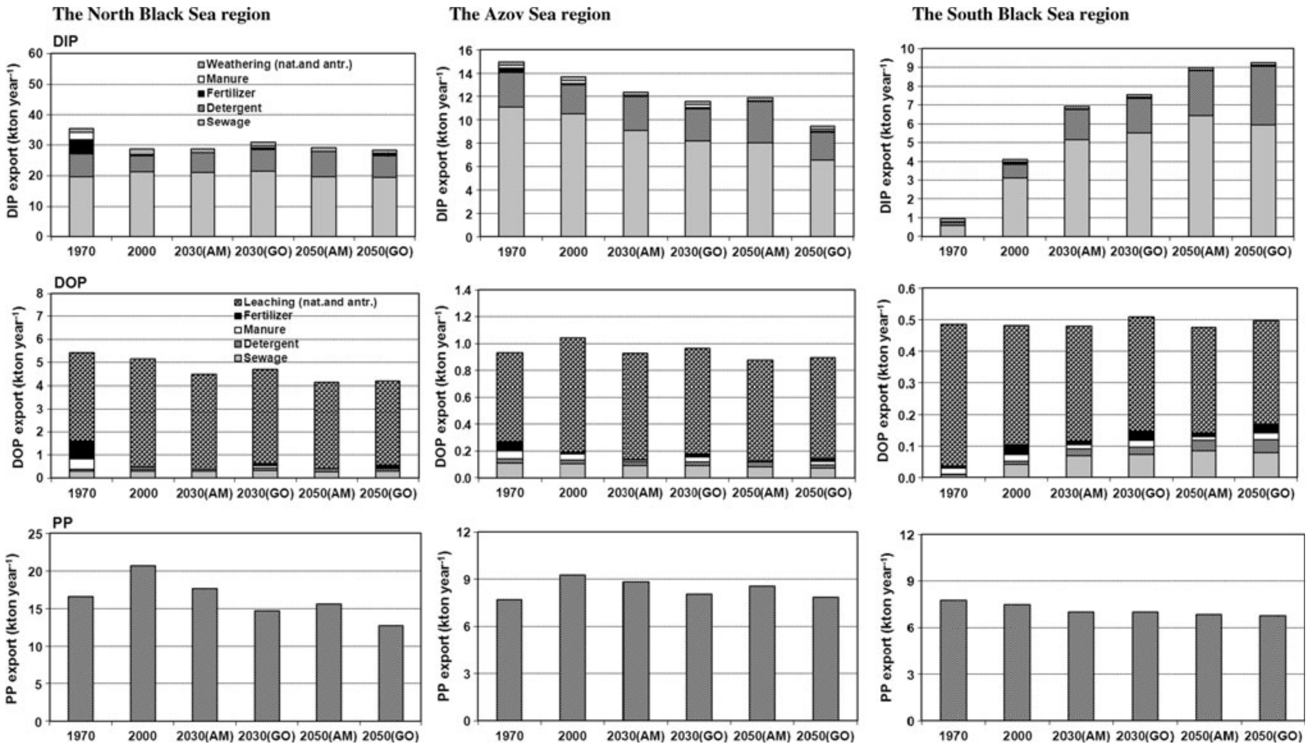

Fig. 5 Modeled export of dissolved inorganic (*DIP*) and dissolved organic (*DOP*) and particulate (*PP*) phosphorus by rivers that drain to coastal waters of the three Black Sea regions: the North Black Sea, the Azov Sea and the South Black Sea and phosphorus sources. River export of *DIP*, *DOP* and *PP* is calculated for the past (1970 and 2000) and future (2030 and 2050) and expressed in kton per year. Future trends in *DIP*, *DOP* and *PP* are based on two Millennium Ecosystem Assessment (*MEA*) scenarios, the Global Orchestration (*GO*) and Adaptive Mosaic (*AM*). The *AM* and *GO* scenarios represent proactive and reactive approaches toward environmental problems, respectively, and a regionalized and globalized world, respectively. Source: Global *NEWS-2* (Mayorga et al. 2010; Seitzinger et al. 2010)

explained by differences in assumed damming (sediment trapping in reservoirs does not allow particulate nutrients to be easily transported to coastal waters). There is more damming assumed in GO in line with globalization trends in this scenario (Seitzinger et al. 2010). Large dams have been built in these two regions since the 1970–1980s for irrigation and hydropower purposes (Borysova et al. 2005; Humborg et al. 1997).

The past and future trends in phosphorus export by rivers to the North part of the Black Sea and to the Azov Sea are comparable to trends in P inputs to other European seas like the Mediterranean Sea and North Sea. This can be explained by similarities in nutrient and environmental management. Trends in the South Black Sea river basins are similar to those in Asian river basins for similar reasons (Seitzinger et al. 2010). Details on calculated trends in river export of DIP, DOP and PP yields (kg km^{-2} year^{-1}) can be found in the Supplementary Materials (Online Resource 4, 5 and 6).

Most P in the Black Sea rivers is exported to the North Black Sea: over 75 % of DOP, 50 % of DIP and 50 % of PP loads drain into this sea region. About 55 % of the phosphorus exported to the Black Sea is in dissolved inorganic form while almost 10 and 35 % are in dissolved organic and particulate forms respectively.

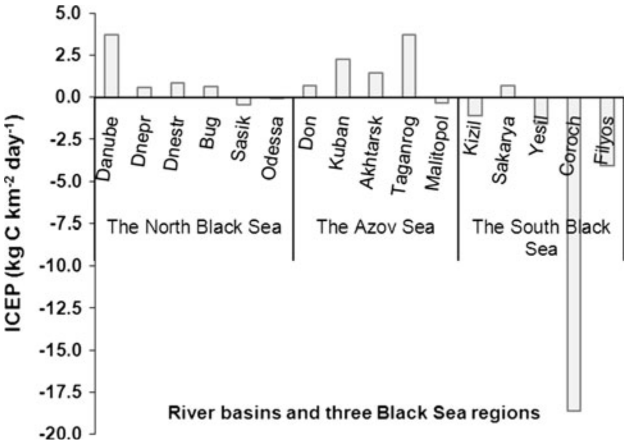

Fig. 6 *ICEP* (indicator for coastal eutrophication potential) values for the selected sixteen rivers draining to the three Black Sea regions: the North Black Sea, the Azov Sea and the South Black Sea. The indicator is calculated for 2000. Calculations were done on the basis of *TN*, total nitrogen, TN = DIN + DON + PN; *TP*, total phosphorus; *TP*, DIP + DOP + PP and *DSi* (dissolved silica) export expressed in kg km^{-2} year^{-1}. They were converted into kg km^{-2} day^{-1}. The indicator reflects N-ICEP or P-ICEP, depending on which nutrient is limiting. P-ICEP was calculated for the Danube, Dnepr, Dnestr and Odessa (N:P ratio >16), and N-ICEP for the other rivers, following Garnier et al. (2010)

ICEP: indicator for coastal eutrophication potential

Nitrogen was estimated to be limiting for almost all rivers of the Black Sea, except for the Danube, Dnepr, Dnestr, and the watershed named Odessa (see "Study area"). These rivers are phosphorus limited, and therefore, the P-ICEP was calculated for these. The N-ICEP was calculated for the N limited river basins [see "The indicator for coastal eutrophication potential (ICEP)"]. In general, P limited rivers have relatively high total N inputs compared to total P inputs. Thus, their N:P ratio is higher indicating potential P limitation.

For a majority of rivers (nine out of sixteen), we calculate ICEP values exceeding zero, indicating a serious potentials for harmful algal blooms and thus for coastal eutrophication (Fig. 6). These nine rivers cover 90 % of the total drainage basin of the Black Sea. Almost all rivers with eutrophication potentials >0 drain to the coastal waters of the North Black Sea and the Azov Sea regions, indicating that 98 % of their drainage basins are at risk for coastal eutrophication. This is in line with observed events of coastal eutrophication in the North Black Sea and Azov Sea, associated with nutrient inputs from the Danube, Dnestr, Bug, Dnepr, Don and Kuban since 1970–1980s (Borysova et al. 2005; BSC 2008; EEA 2005).

For rivers of the South Black Sea region, we do not calculate high potentials for eutrophication in 2000 (ICEP < 0), except for the Sakarya River (Fig. 6). However, this does not mean that there is no local eutrophication or that there will not be any in the future. An increase in ICEP is expected in the future, especially in Asian countries like Turkey (the South Black Sea region) because of urbanization developments (more people will be connected to sewage systems leading to an increase in N and P inputs). A future increase in the river loads of DIN and DIP by up to 20 and 50 % respectively is expected in this region between 2000 and 2050 under the GO (see "Nitrogen river export" and "Phosphorus river export"). This is in line with global analyses, indicating that both DIP and DIN loads may increase by 50 % in South Asia (rivers of the South Black Sea region are in South Asia) from 2000 to 2030 in the GO scenario (Seitzinger et al. 2010).

As any indicator, ICEP has its limitations. The ICEP indicator considers only basin averages ignoring sub-basin variability. Likewise, temporal variability within a year is not included. These aggregations may influence the interpretation of the calculated ICEP values. Nevertheless, this indicator is considered a useful tool to identify coastal waters, which are at risk of eutrophication. It enables us to identify the limiting nutrient in eutrophied areas in the Black Sea, which is important for managing coastal eutrophication. A strength of the indicator is that it integrates information on nitrogen, phosphorus and silica fluxes [see "The indicator for coastal eutrophication potential (ICEP)"].

Reducing N and P loads in rivers

The Black Sea Strategic Action Plan is a policy document to facilitate cooperation between Ukraine, Romania, Bulgaria, Russia, Georgia and Turkey. It is aimed to reduce environmental problems in the Black Sea ecosystems, in particular coastal eutrophication. The policy document resulted from the Bucharest convention and is signed by those six countries in 1992. The main goal of the Convention is to improve the ecological state of the Black Sea to levels of the 1960s. The majority of the targets in the plan are associated with improvements in agricultural systems and wastewater treatment in order to reduce nutrient inputs to the Black Sea. Despite these plans, the nutrient inputs to the Black Sea were in the period 2000–2005 still roughly two times the level of the 1960s (TDA 2007; BSC 2008, 2009). This implies that a reduction of 50 % or more in N and P inputs to the Black Sea is needed in order to meet the aims of the Black Sea policy papers.

In the MEA scenarios, such reductions are not realized (Fig. 7, see also "Nitrogen river export" and "Phosphorus river export"). We analyzed some alternative scenarios assuming further reductions in N and P inputs, while taking two of the MEA scenarios (GO and AM) as a basis. The alternative scenarios GO (ALT) and AM (ALT) assume future reductions in manure plus fertilizer use by 30 % and an increase in nutrient removal through sewage treatment by 50 %. We consider such changes achievable within the coming 40 years.

The target of 50 % reductions in future loads of N and P in the Black Sea is achieved in 2050 in these alternative scenarios in some of the rivers and for some of the nutrients, however, not for all rivers and N and P forms (Fig. 7). We calculate that river export of DIN is reduced by about 20 % on average for the sixteen river basins between 2000 and 2050. For individual rivers, we calculate both increases and decreases. In general, the nutrient export in 2050 is higher than in 2000 for rivers draining into the South Black Sea, and lower for rivers draining into the North Black Sea. River export of DIP can be reduced by 50 % on average, but only in the GO (ALT) scenario (Fig. 7). This can be explained by the fact that the GO scenario already assumes more efficient sewage control in the future than the AM scenario (Seitzinger et al. 2010). As a result, most rivers draining into the North Black Sea and the Azov Sea export 50 % less DIP in 2050 than in 2000 in both alternative scenarios. Rivers draining into the South Black Sea export more DIP in the future, even when assuming a 30 % reduction in manure and fertilizer applications to land and 50 % more nutrient removal through sewage treatment. These reductions are not enough to counterbalance the increase in agricultural production and sewage inputs associated with population growth and urbanization in this region (see also "Phosphorus river export").

River export of DON and DOP is more difficult to reduce. The 50 % reduction targets are not met in 2050 in the GO (ALT) and AM (ALT) scenarios, except for some individual rivers (Fig. 7). The differences in future trends in DON and DOP export among river basins are significant.

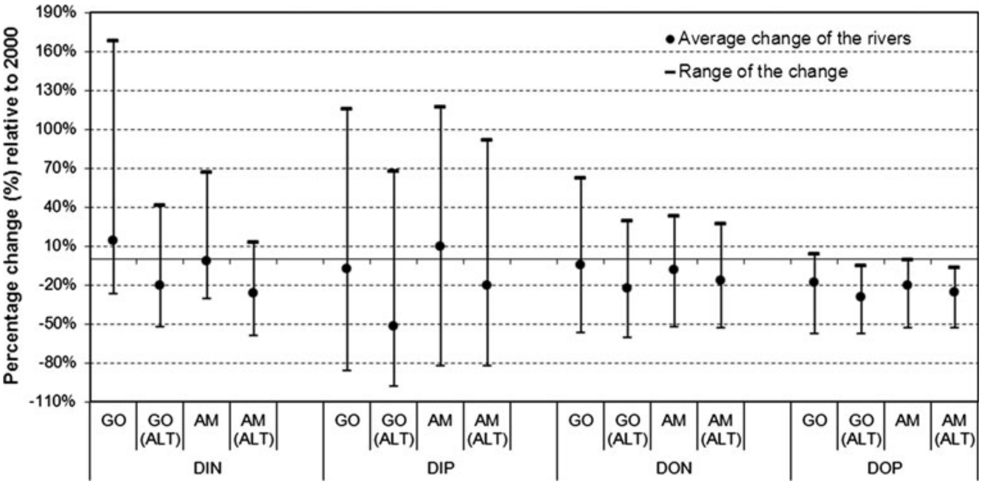

Fig. 7 Percentage change in dissolved inorganic (*DIN*, *DIP*) and organic (*DON*, *DOP*) nitrogen and phosphorus export (load, Mg^{-1} year^{-1}) from 2000 to 2050 by the selected 16 rivers draining to the Black Sea. *GO* (Global Orchestration) and *AM* (Adaptive Mosaic) are the *MEA* (Millennium Ecosystem Assessment) scenarios. *GO* (*ALT*) and *AM* (*ALT*) are two alternative (*ALT*) scenarios for 2050. These alternative scenarios assume 30 % reductions in manure and fertilizer applications to soils and a 50 % increase in N and P removal from sewage. The *graph* presents the average change for the sixteen rivers (*dots*) and the range for these rivers (as *error bar*). Results for *DIP* are for 13 river basins with increases <200 %

Conclusion

Nutrient inputs play an important role in coastal eutrophication in the Black Sea. We analyzed the past and future trends in river export of nutrients to the coastal waters of the Black Sea and identified the potentials of rivers to cause coastal eutrophication.

The European North Black Sea region covers two-thirds of the Black Sea basin area. The coastal waters of this region are suffering from eutrophication. In the past, the situation was worse than today. Between 1970 and 2000, the river export of dissolved inorganic and organic N and P decreased by 20 %, except for DON (which increased). Manure and fertilizers are main source of DIN, leaching of DON and DOP, and sewage of DIP. In the future, river export of these nutrients may continue to decrease by up to 25 %. The decreasing animal numbers in Europe will reduce the relative share of manure as a source of riverine N and P in the future, while the relative share of sewage systems will be increasing. Particulate N and P export increased from 1970 to 2000. This can be explained by increased erosion in the watersheds. In the future, river export of particulates may be decreasing because of increased damming of rivers.

The coastal waters of the Azov Sea region are also receiving high loads of N and P. River export of dissolved inorganic and organic N and P increased from 1970 to 2000 by up to 15 %. For DIP an increase was calculated, in line with increased sewage inputs. Sewage and manure are important sources of dissolved inorganic N and P in the Azov Sea. In the future, river export may decrease by 10–30 %, depending on the scenario. Sewage wastewater will become a more important factor in the future. Particulate N and P export by rivers to the Azov Sea increased by up to 20 % from 1970 to 2000 but will decrease during the coming decades.

We use ICEP, an indicator for potential coastal eutrophication, to analyze the possible effects of N and P inputs to the Black Sea. We calculate relatively high potentials for coastal eutrophication for rivers draining into the North Black Sea and the Azov Sea, indicating a high potential for coastal eutrophication. In the future, however, this may change. Our scenarios for the coming decades show decreasing nutrient loads in rivers potentially leading to decreases in eutrophication along coastal waters of the North Black Sea and the Azov Sea. The MEA trends will, however, not result in meeting the targets of the Black Sea Convention. Additional policies are required.

In the South Black Sea, there is currently little eutrophication (ICEP < 0 for almost all rivers). But this may change in the future because of the projected increases in nutrient inputs from rivers that are difficult to control. So far, nutrient inputs to the South Black Sea have been relatively low. However, river export of dissolved inorganic and organic N and P increased considerably between 1970 and 2000, with DIP export having tripled. Most N and P in these rivers is from agriculture. Sewage and leaching add to this. In the future, the increasing trends in river export continue, except for DOP. Increased sewage inputs associated with population growth and urbanization are causing these trends. In contrast, river export of particulate N and P slightly decreased in the past and will continue to decrease in the future.

Our study adds to the existing literature in that it presents a comprehensive analyses of the past and future trends in nitrogen and phosphorus export to the coastal waters of the Black Sea for different nutrient forms (dissolved inorganic, dissolved organic and particulate). Moreover, the calculated ICEP can help to identify river basins at risk.

We show that an integrated modeling approach may help to understand the past and future trends in coastal eutrophication, and the causes of these trends. Our results indicate trends in N and P export differ largely among river basins, as a result of differences in basin characteristics and human activities on land. Therefore, a basin-specific approach is needed to formulate effective policies to reduce coastal eutrophication in the Black Sea. A generic solution for all basins does not exist. Our study serves as a first step toward identifying basin-specific policies.

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