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Increasing eutrophication in the coastal seas of China from 1970 to 2050

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ABSTRACT

We analyzed the potential for eutrophication in major seas around China: the Bohai Gulf, Yellow Sea and South China Sea. We model the riverine inputs of nitrogen (N), phosphorus (P) and silica (Si) to coastal seas from 1970 to 2050. Between 1970 and 2000 dissolved N and P inputs to the three seas increased by a factor of 2–5. In contrast, inputs of particulate N and P and dissolved Si, decreased due to damming of rivers. Between 2000 and 2050, the total N and P inputs increase further by 30–200%. Sewage is the dominant source of dissolved N and P in the Bohai Gulf, while agriculture is the primary source in the other seas. In the future, the ratios of Si to N and P decrease, which increases the risk of harmful algal blooms. Sewage treatment may reduce this risk in the Bohai Gulf, and agricultural management in the other seas.

1. Introduction

The Chinese coastal waters have been receiving increasing amounts of nutrients from rivers due to the rapid economic development and population growth (Liu et al., 2012; Ma et al., 2012; Qu and Kroeze, 2010,2012; Sutton et al., 2013; Weng, 2007). Currently, approximately 1.3 billion people live in China (Ma et al., 2010), with annual incomes of approximately 3500 US dollars per person (Qu and Kroeze, 2010). The population density increased by 50% between 1970 and 2000, while the per capita income increased by approximately 600% in the large river basins in China (Qu and Kroeze, 2010), these changes generated environmental pressures. The increased availabilities of nitrogen (N) and phosphorus (P) are included among these pressures and are largely associated with trends in agriculture, urbanization and waste management. Increasing the nutrient availability in aquatic systems may lead to eutrophication. Coastal eutrophication is an enrichment of coastal waters by nutrients, such as N and P (Richardson and Jørgensen, 1996). This nutrient enrichment may increase the production of phytoplankton, such as harmful algae (Carstensen et al., 2007), leading to harmful algal blooms (HABs).

Increased food production has increased nutrient inputs to the environment. The production and consumption of animal- (e.g., eggs, meat, milk) and crop-derived (e.g., cereals) products have increased with the growing population and economy (Ma et al., 2012; Riedel et al., 2012). For example, grain production was 70% higher in 2005 than in the 1980s (Ma et al., 2012). After 30 years of rapid economic growth, the living standards have improved. Many people have shifted their dietary preferences toward animal-derived products (Li et al., 2011; Ma et al., 2012). Consequently, meat consumption has more than doubled since 1982 (Qu et al., 2005). These dietary changes are associated with increased nutrient inputs for agriculture, allowing rivers to transport these nutrients further to coastal waters and increasing the risk of harmful algal blooms (Heisler et al., 2008). Food production and consumption in China may continue to increase in the future (Bouwman et al., 2009).

Urbanization is another important source of N and P inputs to the rivers and coastal waters in China (Ma, 2012; Qu and Kroeze, 2010). Sewage systems are urban point sources for the nutrients in rivers. The urban population increased from approximately 100 million people in the 1970s to approximately 400 million people in the 2000s, demonstrating a growth rate twice as fast as the world average during the same period (MMC, 2002-2004; Qu and Kroeze, 2010). In 2008, the urban population reached 590 million (Ma, 2012). Furthermore, animal production seems to move from

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rural areas toward more urban areas due to the increased demand for meat in cities (Ma et al., 2010, 2012). The urban population may continue to increase in the coming years (Ermolieva et al., 2009; Qu and Kroeze, 2010), this increase generates more sewage systems and discharges additional human waste into aquatic systems. However, wastewater treatment may not be able to keep up with the urbanization progress. In 2000–2005, approximately 30–45% of the total amount of wastewater was treated before being discharged into waters. Although wastewater treatment has improved in recent years, the absolute amount of sewage discharge continues to increase dramatically every year as the urbanized areas continue to expand (Liu and Qiu, 2007).

While the riverine inputs of N and P to Chinese seas have increased in recent decades (Qu and Kroeze, 2010), the inputs of dissolved silica (DSi) to coastal seas have continued to decrease worldwide due to the damming of rivers (Billen and Garnier, 2007). This decreases the nutrient ratios (N:P:Si) in aquatic systems, favoring the development of HABs (e.g., cyanobacteria) in estuary systems. These events may be associated with hypoxic events (oxygen depletion) and fish death (Carpenter et al., 1998; Galloway et al., 2008; Smith and Schindler, 2009; Sutton et al., 2013). HABs develop when coastal waters do not contain sufficient silica levels as the N and P loads increase (Billen and Garnier, 2007; Garnier et al., 2010). Some studies (Diaz and Rosenberg, 2008; Selman et al., 2008; Sutton et al., 2013; Wang et al., 2007b; WRI, 2010; Xiao et al., 2007) have reported an increase in areas of harmful algal growth along the Chinese coastal zones. In 2003, 119 algal bloom events were reported for the entire Chinese coast (SOA, 2004).

So far, few studies have linked coastal eutrophication to land-based drivers for the three major seas in China: the Bohai Gulf, Yellow Sea and South China Sea. The riverine inputs of N and P to the coastal waters of China were studied (Qu and Kroeze, 2010, 2012), however, the environmental impacts of these nutrients on coastal waters was poorly addressed, and no sea-specific analyses of nutrient inputs were performed. Various studies have focused on land-based sources of N and P in rivers at the national and/or provincial levels (Ma et al., 2010, 2012; Sutton et al., 2013). Some studies analyzed specific locations, such as the Pearl River estuaries (Ho et al., 2010; Xu et al., 2010), while focusing on the current management of water resources (Cui et al., 2007; Lu et al., 2007; Weng, 2007), others involved the Yangtze River (Li et al., 2012). In addition, eutrophication in selected lakes in China has been studied (Qu et al., 2005). However, none of these studies have addressed eutrophication in the three major seas of China. An integrated analysis of the main drivers and sources of coastal eutrophication in the Bohai Gulf, Yellow Sea and South China Sea is absent. Consequently, sea-specific management strategies to reduce nutrient inputs to rivers and coastal seas have not been explored.

Integrated model, such as Global *NEWS*-2 (Nutrient Export from WaterSheds) may contribute to integrated analyses of causes, effects and solutions. The Global *NEWS*-2 model was developed to understand the relationship between human activities on land and nutrient enrichment in coastal waters (Mayorga et al., 2010). This model has been utilized in many studies to evaluate inputs of N, P, carbon (C), and Si in different forms to coastal seas (Bouwman et al., 2009; Fekete et al., 2010; Seitzinger et al., 2010; Strokal and de Vries, 2012; Strokal and Kroeze, 2013; Suwarno et al., 2013; Thieu et al., 2010; Van der Struijk and Kroeze, 2010; Van Drecht et al., 2009; Yan et al., 2010; Yasin et al., 2010). The model assesses the potential for coastal eutrophication through the ICEP (Indicator for Coastal Eutrophication Potential) approach (Billen and Garnier, 2007; Garnier et al., 2010). This approach has been widely accepted and used in various studies for global (Garnier et al., 2010) and regional (Crosswell et al., 2012; Dauvin et al., 2008; Liu et al., 2012; Romero et al., 2012; Strokal and Kroeze, 2013; Thieu et al., 2011; Wang et al., 2013a) analyses of coastal eutrophication.

The primary objective of this study is to assess the potential eutrophication in the three major seas of China as influenced by riverine inputs of nitrogen, phosphorus and silica in 1970–2050. Toward this purpose, we applied the Global *NEWS*-2 model and ICEP approach. Global *NEWS*-2 can be used to determine the riverine nutrient inputs to coastal seas, which is referred to here as nutrient export by rivers. First, we analyzed the past and future trends in the main drivers for the export of nutrients to coastal seas through rivers (Section 3.1). Second, we analyzed the trends in the river export of N, P and Si in different forms (dissolved inorganic, dissolved organic and particulate), as well as their main sources (Section 3.2). Third, we evaluated the eutrophication potential in the three major seas of China: the Bohai Gulf, Yellow Sea and South China Sea from 1970 to 2050 (Section 3.3). Finally, we discussed future management of eutrophication in these three seas by illustrating some possible sea-specific management options (Section 3.4).

2. Methodology

2.1. Study area

The study area includes 16 rivers that drain into the coastal waters of the Bohai Gulf, Yellow Sea and South China Sea in China (Fig. 1). These rivers are the Global *NEWS*-2 (version 2) rivers with basin areas exceeding 4 grid cells 0.5 longitude by 0.5 latitude in size. We group the selected river basins into three regions that drain into the Bohai Gulf (or Pohai Gulf in Global *NEWS*-2), Yellow Sea and South China Sea (or North-South China Sea in Global *NEWS*-2). The names and delineation of the river basins are taken from the Global *NEWS*-2 model (see Section 2.2).

The river basins draining into the Bohai Gulf cover approximately 35% of the total study area (Fig. 1a). These basins include the Huang He (or the Yellow River, the largest river of this region), Hun (or Liao), Hai Ho (or Yongding), Luan, Daling He and Xiaoqing He (Fig. 1b and c). The river basins draining into the Yellow Sea cover approximately 55% of the study area and include the Chang Jiang (or the Yangtze River, the largest river of China), Huai, Fuchun Jiang (or Qiang Tang), Menjiang (or Minjiang), Yalu and Oujiang. The East China Sea is considered part of the Yellow Sea in this study. The remaining study area includes the river basins of the South China Sea: the Zhujiang, Dongjiang, Hanjiang and Jiulong He (Fig. 1). The Zhujiang and Dongjiang form the Pearl River basin in this study.

2.2. Global NEWS-2 model

2.2.1. Model description

We used the Global *NEWS*-2 (Nutrient Export from WaterSheds, version 2) model to analyze the export of nutrients through the rivers to the coastal waters of the Bohai Gulf, Yellow Sea and South China Sea. The Global *NEWS*-2 model estimates river export of nitrogen (N), phosphorus (P), carbon (C) and silica (Si) at the river mouth in different forms: dissolved inorganic (DIN, DIP, DSi), dissolved organic (DON, DOP, DOC) and particulate (PN, PP, DOC) (Mayorga et al., 2010; Seitzinger et al., 2010). Below, we briefly describe how the river exports of N, P and Si are modeled. Detailed information is provided by Mayorga et al. (2010). The models for the individual nutrient forms are explained by Dumont et al. (2005) for the dissolved inorganic N, Harrison et al. (2010) for the dissolved inorganic P, Harrison et al. (2005) for the dissolved organic N and P, Beusen et al. (2005) for the particulate N and P, and Beusen et al. (2009) for the dissolved Si.