Increasing nitrogen use efficiency in agriculture reduces future coastal water pollution in China

Maryna Strokal[1,2], Carolien Kroeze[2], Mengru Wang[2,3], Ang Li[2,3], Lin Ma[3]

[1] Environmental Systems Analysis Group, Wageningen University, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands, https://www.wageningenur.nl/en/Persons/Maryna-M-Maryna-Strokal.htm?subpage=projects, maryna.strokal@wur.nl
[2] Water Systems and Global Change Group, Wageningen University, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands
[3] Key Laboratory of Agricultural Water Resource, Center for Agricultural Resources Research, Institute of Genetic and Developmental Biology, Chinese Academy of Sciences, Huaizhong Road 286, Shijiazhuang, Hebei 050021, China

Abstract
Chinese agriculture has been industrializing since the 1990s to produce enough food. This increased nitrogen (N) in Chinese rivers and coastal waters, resulting in eutrophication-related problems. We analysed three options to reduce future N pollution of coastal waters in China by 2050. We did it using the *MARINA* Nutrient model (a *M*odel to *A*ssess *R*iver *I*nputs of *N*utrients to se*A*s). Two optimistic scenarios (OPT-1 and OPT-2) were developed, taking the Global Orchestration scenario (GO) of the Millennium Ecosystem Assessment as a baseline. These scenarios assume efficient N management in agriculture (OPT-1 and OPT-2) and sewage (OPT-2). We also assessed effects of the "Zero growth in fertilizer use after 2020" policy (the CP scenario). Results show that N management in agriculture is more effective to reduce future N pollution of coastal waters than N management of sewage. In GO, Chinese rivers are projected to export 38-56% more N in 2050 than in 2000 because of poor manure management. The current policy in agriculture (CP) may not be successful to reduce coastal water pollution. In contrast, our more optimistic scenarios project much lower river export of N in 2050 (at around levels of 1970 for northern rivers and 2000 levels for central and southern rivers). This is mainly because OPT-1 assumes high rates of manure recycling, leading to decreased use of synthetic fertilizers. Improved sewage management in OPT-2 can further reduce N export by northern rivers. Our results can serve as a basis for decision makers on N management.

Key Words
coastal waters, industrialized agriculture, manure, nitrogen pollution, optimistic scenarios, sewage

Introduction
Nitrogen (N) is an essential element for society to sustain food production and for ecosystems to support their primary production (Eickhout et al. 2006). However, today's N cycle is largely altered by human activities like agriculture and urbanization (Galloway et al. 2008; Van Drecht et al. 2009). As a result, rivers receive substantial amounts of N and export it further to coastal waters. This has resulted in N pollution of many coastal waters, leading to eutrophication-related problems such as blooms of harmful algae (Diaz et al. 2011).

In this study we focus on N pollution of coastal waters in China, caused largely by industrialization of animal production and urbanization. The Chinese economy developed rapidly and urbanization has been expanding (Liu & Diamond 2005). As a result, urban activities increasingly impact on water quality. Since the 1990s, large industrial animal farms started to emerge as a response to a growing urban population and changes in diets (Ma et al. 2012). However, poor management of animal manure in industrial farms that are often disconnected from crop production led to large discharges of manure to rivers (Strokal et al. 2016b). On the other hand, farmers apply substantial amounts of synthetic fertilizers for crops without considering their nutrient requirements (Li et al. 2013).

This study aims at exploring options in agriculture and sewage management to reduce N pollution of coastal waters in China by 2050. We take an optimistic approach and developed two optimistic scenarios that assume more efficient nutrient management in agriculture and sewage than existing scenarios (Ma et al. 2013b; Qu & Kroeze 2012). We used the *MARINA* (a *M*odel to *A*ssess *R*iver *I*nputs of *N*utrients to se*A*s) model for scenario analyses. We describe the model and scenarios in section 2, discuss the results in section 3 and draw conclusions in section 4.

The *MARINA* Nutrient model and scenarios
The *MARINA* Nutrient model is described in earlier studies (Strokal et al. 2015; Strokal et al. 2016a; Strokal

et al. 2016b). In brief, the model quantifies river export of dissolved inorganic (DIN, DIP) and of dissolved organic (DON, DOP) N and phosphorus (P) export by source for 1970, 2000 and 2050. In this study, we focus on DIN because it is the most biologically available form of N and thus contributes considerably to eutrophication-related problems (Garnier et al. 2010). *MARINA* quantifies nutrient export by six main rivers in China: the Yellow (Huang He in Chinese), Hai, Liao (draining into the Bohai Gulf), Yangtze (Changjiang in Chinese), Huai (draining into the Yellow Sea) and the Pearl river (Zhujiang in Chinese, draining into the South China Sea) (Figure 1). River export of DIN is modelled as a function of human activities on land (e.g., sewage, agriculture) and sub-basin characteristics (e.g., hydrology, land use). The model takes into account in-river retentions (e.g., denitrification, dams) and losses (e.g., water withdrawal) of nutrients and traveling distance of nutrients from sub-basins towards coastal waters (river mouths). Diffuse and point sources of DIN in rivers are distinguished. Diffuse sources include use of synthetic fertilizers, animal manure and human waste in agriculture, atmospheric N deposition and biological N_2-fixation. Point sources include direct discharges of manure and of uncollected human waste (from both rural and urban people) to rivers, and sewage effluents. Details on the model are published in several papers (Strokal et al. 2016a).

We developed two optimistic scenarios (OPT-1 and OPT-2) for 2050 taking the Global Orchestration scenario (GO) of the Millennium Ecosystem Assessment as a baseline. We also developed the CP scenario, to assess the effects of the current policy (CP): "Zero growth in fertilizer use after 2020". This policy aims to cap fertilizer use and to recycle 60% of animal manure. GO is described by Strokal et al. (2016a) for the Chinese rivers. GO is an economy-oriented scenario with globalized trends and a reactive approach for environmental problems. The optimistic scenarios assume full implementation of latest technologies (e.g., (Amann 2012; Burton & Turner 2003; Loyon et al. 2016) to achieve the efficient management of nutrients in agriculture (OPT-1 and OPT-2) and in sewage (OPT-2). For agriculture, efficient nutrient management implies more manure recycling on land (95% of the manure), balanced use of synthetic fertilizers according to crop needs, precision feeding of animals to reduce 20% of N in manure excretion, and improved storage and housing systems that will reduce 50% of ammonia emissions relative to GO (Ma et al. 2013a). For sewage, the efficient nutrient management is realized via implementation of centralized sewage systems for urban people and decentralized sewage systems (Oakley et al. 2010) for rural people with a high efficiency of N removal during treatment (80%) (e.g., Khiewwijit (2016).

Results of scenario analyses

Our results show that efficient nutrient management in agriculture is the most effective in reducing N pollution of Chinese rivers and coastal waters. This is shown in optimistic scenarios (Figure 1). Central and southern rivers (Yangtze, Pearl and Huai) export more N to the coastal waters than northern rivers (Yellow, Liao and Hai). The Yellow, Yangtze and Pearl are rivers with large drainage areas and thus their relative share in the total river export of DIN is large.

In the reference GO scenario, N pollution remains high in 2050. In GO, Chinese rivers are projected to export 3% more DIN in 2050 than in 2000 (Figure 1). The main reason for these increases is poor manure management in industrialized livestock production systems. This holds for all rivers. Direct discharges of animal manure to northern, central and southern rivers may still occur in 2050 under the GO scenario. This is because only part of animal manure is assumed to be recycled on land and the remainder is lost to the air and to rivers, polluting the environment. Another reason for higher future DIN export by the central and southern rivers is increased use of synthetic fertilizers on land. The share of atmospheric N deposition and biological N_2-fixation in DIN export by these rivers is also calculated to increase between 2000 and 2050. This may be associated with expanding agricultural areas for crop production. For northern rivers (the Yellow, Hai and Liao) synthetic fertilizers, atmospheric N deposition and biological N_2-fixation are not important sources of DIN. This is because these rivers have drier drainage areas and thus lower leaching and runoff of N from land-based activities.

Implementing the current policies in agriculture (CP) may not be effective enough to reduce N pollution of the Chinese seas (Figure 1). DIN export by the rivers may continue increasing onwards, but slower than in GO. This can be explained by the fact that rates of manure recycling are slightly higher in CP (60%) than in GO (around 50%). Thus, less N is discharged to rivers in CP, leading to somewhat lower N inputs to coastal waters than in GO. However, the effects of zero growth in synthetic fertilizers after 2020 on river export of DIN are comparable to GO projections also.

In optimistic scenarios (OPT-1 and OPT-2), river export of DIN is much lower in 2050 compared to CP and

GO (Figure 1). In 2050, DIN export by northern rivers (Yellow, Hai, Liao) is projected to be close to levels of 1970. DIN export by central and southern rivers (Yangtze, Pearl, Huai) is projected to be around levels of 2000. OPT-1 assumes that almost all N in animal manure will be used in crop production. As a result, direct discharges of animal manure to rivers are avoided, reducing N inputs to coastal waters considerably. Use of synthetic fertilizers for crops will be lower than in CP and GO. This is because farmers are assumed to apply synthetic fertilizers according to crop needs taking into account manure applications. As a result, in 2050 the relative share of synthetic fertilizers in DIN export by central and southern rivers is lower in OPT-1 than in GO and CP. For northern rivers, this share does not vary considerably between the scenarios because synthetic fertilizers are not dominant contributors of DIN pollution in those rivers. Improving sewage management, as assumed in OPT-2, may further reduce river export DIN by 2050. The effects of improved sanitation are more visible for DIN export by the northern rivers. This is because human waste is an important source of DIN in these rivers.

Conclusion

Coastal waters of China are polluted by N because rivers have exported increasing amounts of N from human activities. Agriculture, and especially livestock production, is the most polluting activity. Sewage contributes to N pollution of aquatic systems in urbanized areas. We explored options to reduce this pollution. Our results show that river export of N is projected to be lower in 2050 than in 2000 only under optimistic scenarios, which assume full implementation of the latest technologies in agriculture and sewage to increase efficiencies of N management. In particular, high rates of manure recycling, as assumed in optimistic scenarios, are most effective to reduce N pollution of rivers and thus of coastal waters in 2050. Use of synthetic N fertilizers according to crop requirements is effective to reduce N export by the central and southern rivers (Yangtze, Pearl, Huai). Full implementation of sewage systems with high removal rates of N during treatment is more effective to reduce N export by the northern rivers (Yellow, Hai, Liao and Huai). However, the current policy aiming at 60% of manure recycling on land and at zero growth in synthetic fertilizer use after 2020 may not be enough to reduce N pollution of the coastal waters in China.

Our study shows clearly that there is a need to improve N use efficiencies in China to avoid water pollution in the future. Our study can help to improve existing and/or formulate new environmental policies to increase N use efficiencies in Chinese agriculture and sewage management. We believe that results of this study can also provide useful insights for other studies focusing on improving N management in China and on exploring options to achieve sustainable development goals for China.

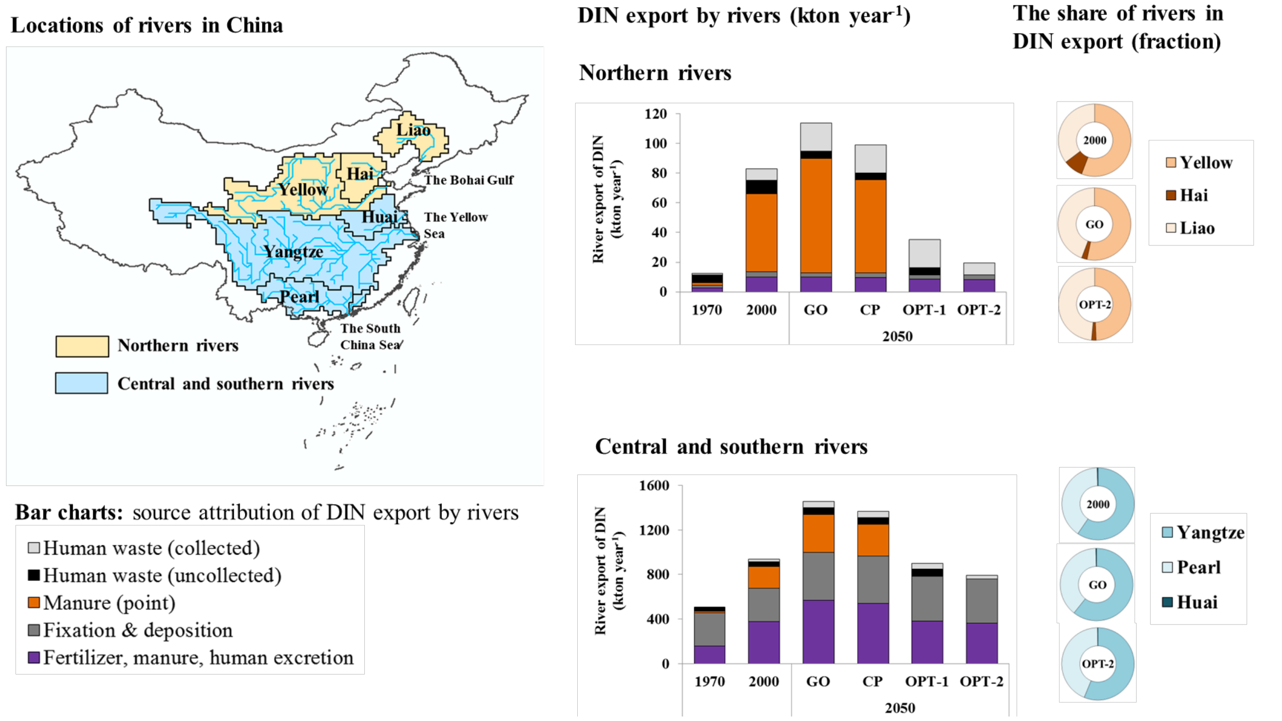

Figure 1. Modelled dissolved inorganic nitrogen (DIN) export by rivers in 1970, 2000 and 2050 according to different scenarios (kton year^{-1}). Colours on the map indicate Chinese rivers draining into the Bohai Gulf, Yellow Sea and South China Sea. CP, OPT-1 and OPT-2 are alternative scenarios, based on Global Orchestration (GO) of the Millennium Ecosystem Assessment (see section on scenario description).

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