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The role of technology and policy in mitigating regional nitrogen pollution

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Abstract

Human activity greatly influences nitrogen (N) pollution in urbanized and adjacent areas. We comprehensively studied the N cycling in an urban–rural complex system, the Greater Hangzhou Area (GHA) in southeastern China. Our results indicated that subsurface N accumulation doubled, riverine N export tripled and atmospheric N pollutants increased 2.5 times within the GHA from 1980–2004. Agriculture was the largest N pollution source to air and water before 2000, whereas industry and human living gradually became the primary N pollution sources with the socioeconomic development. Based on the sensitivity analysis, we developed a scenario analysis to quantify the effects of technology and policy on environmental N dynamics. The fertilization reduction scenario suggested that the groundwater N pollution could decrease by 17% with less than a 5% reduction in crop production; the N effluent standard revision scenario led to a surface water N pollution reduction of 45%; the constructed wetlands implementation scenario could reduce surface water pollution by 43%–64%. Lastly, the technological improvement scenario mitigated atmospheric N pollution by 65%. Technologies play a key role in atmospheric N pollution control, policies mainly contribute to groundwater N pollution control, while technology and policy both work on surface water N mitigation within an urban–rural complex.

Keywords: air pollution, constructed wetland, developing country, fertilization, wastewater treatment, water pollution

 Online supplementary data available from stacks.iop.org/ERL/6/014011/mmedia

1. Introduction

Human activities contribute more than 50% of the total reactive nitrogen (N_R) inputs to the global budget for the planet's land surfaces [1, 2]. Natural factors (geomorphology, climate,

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meteorology, etc) may drive temporal and spatial heterogeneity of nitrogen (N) cycling between regions [3, 4]. However, the magnitude and effectiveness caused by human activity are much larger than those driven by natural processing at a specific location [5, 6], especially in an urban–rural complex system (URC), where the city core strongly affects its periphery areas [7]. Differences in environmental N pollution between developed and developing countries indicate that socioeconomic development influences N flux [8]. For example, industrial and domestic point sources of N pollution have been dramatically reduced in developed countries through technology and policy innovation, but remain a serious problem in many developing countries where rapid urbanization is presently occurring [9, 10]. This may result from a lack of environmental awareness, appropriate technology, policy, and management to control the spread of pollution in developing countries [5, 7].

The role of technology and policy in mitigating N pollution has attracted much attention [5, 11], but much of this has focused on cases only in developed countries, such as the Long Island Sound [12] and Chesapeake Bay Program [13], with less attention given to developing countries [5]. Sophisticated environmental technologies and managerial practices in developing countries rely heavily on financial backing [6], making the situation difficult for developing countries. To solve these problems, integrated biogeochemical models based upon real-world cases, such as models applied to some developed countries as they progress [14], are required in developing countries. These models help in systemically analyzing the importance of technological, policy, and economic factors on the temporal and spatial dynamics of N pollution while providing policy makers with a means to achieve optimal regulation.

The southeastern coast, with the fastest economic growth and urbanization, is the most developed as well as polluted region in China [15]. Intensive agriculture and aquaculture in this humid region have a history of several thousand years, and fertilizer over-consumption during the past three decades [16] has led to substantial environmental problems [7]. The Greater Hangzhou Area (GHA) in southeastern China is a typical case of a URC, to illustrate the human mediated N cycling in a highly polluted region (figure 1) [7]. In this study, we: (i) develop a comprehensive N cycling budget (model) for a URC; (ii) quantify the influence of technology and/or policy on environmental N pollution and forecast N pollution dynamics under different scenarios; and (iii) achieve more sustainable N management strategies for developing countries.

2. Methodology

2.1. System dynamics

A URC contains four functional groups based upon mutual services, with humans as the central node: N-processor, N-consumer, N-remover, and N-life-supporter groups [7]. The processor group includes six subsystems: cropland, urban lawn, forest-grassland, livestock, aquaculture (freshwater), and industry. These modules can process the fixed N input into



Figure 1. Geographical location of the Greater Hangzhou Area (GHA) in China, and land use in 2005.

the food chain and biomass products that will then be used by consumers. The consumer group includes both the human and pet subsystems since they are the end of the food chain, as well as the end of the industrial chain. The remover group refers to artificial facilities to treat N_R waste with processes that convert N_R into N_g (nitrogen gas) and includes the wastewater treatment subsystem in this study. The life-supporter group includes the near-surface atmosphere, surface water, and subsurface subsystems that closely relate to all organisms (including humans) within a URC. For the purpose of this study, the simulation timeline dates from 1980 (the point from which rapid economic growth and urbanization occurred in China) to 2050 with a time step of one year (for details see supplementary data available at stacks.iop.org/ERL/6/014011/mmedia).

2.2. System parameterization and calibration

The system parameters can be divided into two types. Type I (available measured data) represents the basic information on the GHA, that is population, cropland area and production, fossil fuel consumption, and wastewater flows. Timeline data from 1980–2004 were obtained directly from statistical documentation (table S1 available at stacks.iop.org/ERL/6/014011/mmedia) while values from 2005–2050 are estimated based upon empirical regression (table S4 available at stacks.iop.org/ERL/6/014011/mmedia) or system assumptions. For example, the value for cropland yield was estimated by the regression equation associated with fertilizer application, while the population growth rate was assumed to be decreased from current rates (0.8%) to 0.3% in 2050 [17]. Two-thirds of the historical data were applied to calibration while the remaining one-third were applied to validation (figure 2). Type II (available coefficient data) represents information developed from coefficients that relate to N, e.g., the excretion per capita livestock, the harvest index of crops, the non-symbiotic N fixation rate of cropland, etc, which were obtained from various published peer-reviewed papers or technical reports

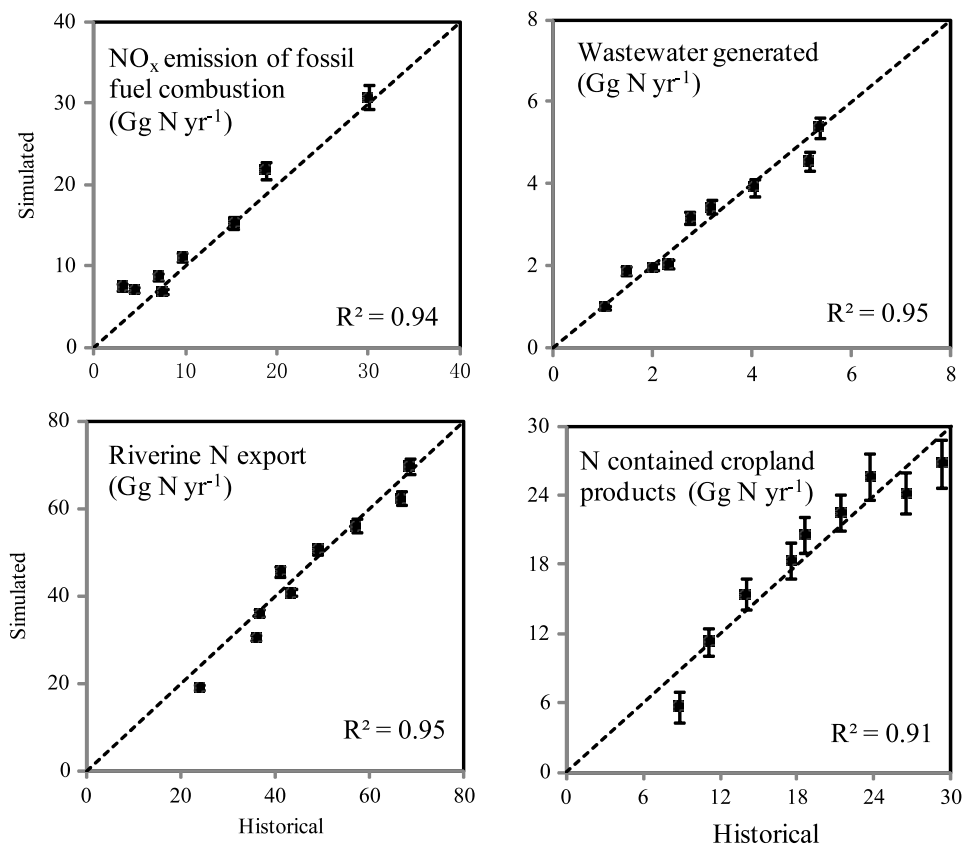


Figure 2. Comparison of historical observations and simulated results from 1980 to 2005 for each consecutive three year period for NO_x emissions due to fossil fuel combustion, wastewater N, riverine N export, and N contained in cropland products within the GHA.

(for details see supplementary data available at stacks.iop.org/ERL/6/014011/mmedia).

2.3. Validation and sensitivity analysis

The simulated results were validated against N flux historical data to test their accuracy (figure 2). Historical data of NO_x emissions, wastewater discharge, riverine N export, and cropland production were used for validation against the simulation results (table S1 available at stacks.iop.org/ERL/6/014011/mmedia). NO_x emissions ($r^2 = 0.94$), wastewater emissions ($r^2 = 0.95$), riverine N exportation ($r^2 = 0.95$), and cropland production ($r^2 = 0.91$) all showed satisfactory agreement between the simulation and historical data ($P < 0.001$, figure 2). Although a system development for this study was used to simulate N dynamics based upon the best available information, the estimations still contained uncertainties due to the input variables, parameters and structure. Based on the Monte Carlo simulation, we found that all output uncertainties are within the mean values $\pm 5\%$ (figure S4 available at stacks.iop.org/ERL/6/014011/mmedia) except for the cropland production, which was under 10% (for details see supplementary data available at stacks.iop.org/ERL/6/014011/mmedia).

Before scenario analysis, sensitivity analysis was conducted by means of changing one variable while keeping all other variables constant in order to identify the key variables driving N pollution. This demonstrated that (table S5 available

at stacks.iop.org/ERL/6/014011/mmedia): (i) the fertilization rate and cropland area had a relatively large effect on subsurface N; (ii) the wastewater treatment plant (WTP) N effluent standard (WNES) and constructed wetlands (CW) were the factors affecting riverine N; while (iii) population growth, fossil fuel consumption, and technological innovation on O_x emission intensity were the main influences on atmospheric N pollution.

2.4. Scenario preparation

Based on sensitivity analysis (table S5 available at stacks.iop.org/ERL/6/014011/mmedia) and the potential changing ranges of different parameters, we developed seven scenarios to quantify the effects of technology and policy on environmental N dynamics (table 1). In scenario 1 (S1), we introduced CW, a novel technology for environmental N pollution control [18, 19], to our system. The effect of CW on N pollution control from agriculture and WTP in a URC (figure S1 available at stacks.iop.org/ERL/6/014011/mmedia) was quantified with a N removal rate in the range $\sim 50\text{--}80\%$ under different engineering design and management [18, 19] (S1.2–1.3). Scenario 2 is technological innovation on NO_x emission intensity, varying across different countries [20], from fossil fuel consumption. The NO_x emission per GDP in China is currently 14.5 kg per 1000 USD (S2.1), much higher than the average level seen in mid-level developed countries (1.9 kg per 1000 USD, S2.2) and developed countries (1.0 kg per 1000 USD, S2.3) [20].

Table 1. Scenario and assumption descriptions since 2005.

Scenarios (S)	References and notes
Technology scenarios	
(1) CW applications for N pollutant removal	
(1.1) NA ^a (BAU ^a)	CWs can remove ~50% of N loading [19]; ~80% can be reached with better engineering design and management [18]
(1.2) with ~50% N removal rate	
(1.3) with ~80% N removal rate	
(2) Technological innovation on NO _x emission intensity	
(2.1) 14.5 kg 10 ⁻³ USD ^a (BAU)	14.5 kg NO _x emission represents China's current technological level; the technological innovation in developed countries reduces it to 1.0–1.9 kg [20]
(2.2) 1.9 kg 10 ⁻³ USD (mid-level)	
(2.3) 1.0 kg 10 ⁻³ USD (high-level)	
Policy scenarios	
(3) Synthetic N fertilizer application rate	
(3.1) 400 kg N ha ⁻¹ yr ⁻¹ (BAU)	Double-cropping system, rice/wheat, considering 150–200 kg N ha ⁻¹ yr ⁻¹ manure input, total N input per crop is 275–300 kg N ha ⁻¹ yr ⁻¹ currently [7]
(3.2) 300 kg N ha ⁻¹ yr ⁻¹	
(3.3) 200 kg N ha ⁻¹ yr ⁻¹	
(4) Cropland area/GHA total area	
(4.1) 10% (BAU)	Keep 10% according to local government long-term perspective plan; may decrease to 5–8% due to urban expansion
(4.2) 8%	
(4.3) 5%	
(5) WTP N effluent standard	
(5.1) 18 mg l ⁻¹ (BAU)	Average value in practice in China is 18 mg l ⁻¹ [35]; 8 mg l ⁻¹ in USA [21]; could be 3 mg l ⁻¹ with advanced technique [21]
(5.2) 8 mg l ⁻¹	
(5.3) 3 mg l ⁻¹	
(6) Population growth rate	
(6.1) Decrease from 0.8% to 0.3% in 2050 (BAU)	Decrease to 0.3% in 2050 following UNPD [17]; zero growth in 2030 if 'one child policy' is kept [30]; keep 0.8% via industrial immigration [36]
(6.2) Zero growth after 2030	
(6.3) Current growth rate (0.8%)	
(7) Fossil fuel consumption	
(7.1) Current increase trend (BAU)	Following Gothenburg Protocol [22], at least 30–50% reduction of increase rate per capita fossil fuel consumption can be achieved
(7.2) Increase rate reduces by 30%	
(7.3) Increase rate reduces by 50%	

^a BAU = Business as usual; NA = not available; USD = United States of America dollars.

Scenario 3 is fertilization reduction (S3.2–3.3), since the N fertilization rate is currently ~50% higher than the optimum value recommended within the GHA [7, 16]. Scenario 4 is cropland area decrease, due to population growth and economic development (S4.2–4.3). Scenario 5 is WNES revision (S5.2–5.3), since the effluents from WTP have been one of the main sources of N pollution to the regional environment [7, 21]. Scenario 6 is the population growth rate changing. It may slow down with a 'one child policy' and natural landscape protection or increase with rapid industrial development that could possibly attract immigration (S6.3). Scenario 7 is fossil fuel consumption rate reduction (S7.2–7.3) according to the Gothenburg Protocol adopted in 1999 to abate acidification and eutrophication [22].

3. Results

3.1. Subsurface N

The subsurface N accumulation rapidly increased from 4.1 ± 0.17 to 7.6 ± 0.25 Gg yr⁻¹ from 1980–1985 with the fertilization rate increasing, then further to 9.0 ± 0.33 Gg yr⁻¹ in 2004. Under the business as usual (BAU) scenario (table 1), the annual subsurface N accumulation within the GHA would increase to 12.2 ± 0.44 Gg yr⁻¹ in 2050. Agricultural N

leaching would contribute more than 50% of pollutants prior to 2015 (figure 3) after which domestic and industrial wastewater will be the largest pollution source.

Under the fertilization reduction scenario (S3.3), with the synthetic fertilizer application rate reduced from 400 to 200 kg N ha⁻¹ yr⁻¹, subsurface N is predicted to decrease by 17% compared to the BAU scenario, while food production would decrease by approximately 4%.

If the cropland area is decreased by ~50% due to urban expansion (S4.3), subsurface N would decrease by ~21% (figure 4). This scenario, however, reduces production by 36%, and weakens the self-sufficiency of the GHA in terms of food production while increasing food importation by 125%.

3.2. Riverine N

Riverine N export rapidly increased from 18.9 ± 0.53 to 69.63 ± 1.8 Gg yr⁻¹ (N concentration from <0.2 to ~0.7 mg l⁻¹) within the GHA from 1980–2004. Under the BAU scenario, riverine N export would increase to 209.3 ± 8.05 Gg yr⁻¹ (N concentration >2 mg l⁻¹) in 2050. N transported from croplands to surface water (the largest pollution source) contributed ~30% of surface water N loading before 2005; after that time, aquaculture and livestock became the largest N sources (figure 3). Industrial and domestic wastewater

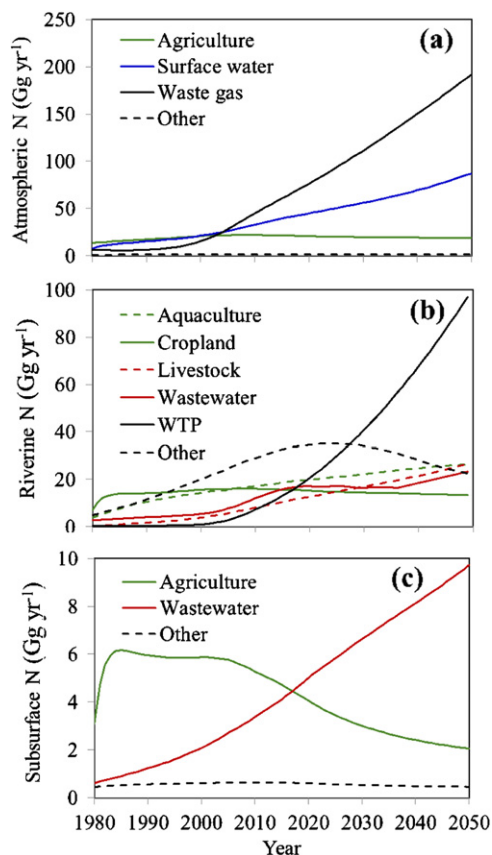


Figure 3. Sources of reactive N (N_R) that contribute to environmental pollution under the business as usual (BAU) scenario (table 1). (a) Atmospheric N export: agriculture primarily refers to cropland while aquaculture and livestock contribute little; other terms include lawn fertilizer vitalization, and straw and garbage burning. (b) Riverine export: other terms include N deposition, upstream inflow, forest-grassland runoff, and landfill filtration. (c) Subsurface N accumulation: agriculture primarily refers to cropland while aquaculture and livestock contribute little; the other term is primarily lawn fertilizer leaching.

emissions will become the largest sources of N pollution by around 2015 (figure 3). The contribution of other N sources, such as N deposition and forest and lawn N runoff, to water bodies remains at $\sim 10\%$.

Under the WNES revision scenarios (S5), effluent N concentration reduced from the current level of 18 to 8 mg l^{-1} or even as low as 3 mg l^{-1} , riverine N export would decrease by 30% or 45% compared to the BAU scenario, respectively (figure 4). If a 3 mg l^{-1} WNES was put into practice (S5.3), the average riverine N concentration would be less than 0.8 mg l^{-1} .

Under the CW application scenarios (S1), CWs intercept N transported from agricultural non-point pollution (cropland and aquaculture), livestock factories, and effluent from WTPs (S1) and reduce riverine N export by $\sim 43\text{--}64\%$ (figure 4). The average riverine N concentration would be less than 0.5 mg l^{-1} if the CW application scenario (S1.3) were enacted.

3.3. Atmospheric N_R

Near-surface atmospheric N_R (including $\text{NH}_3\text{-N}$, $\text{N}_2\text{O-N}$, and $\text{NO}_x\text{-N}$) increased 1.5 times (from 28.4 ± 0.93 to $72.3 \pm$

$2.41 \text{ Gg N yr}^{-1}$) from 1980–2004 within the GHA. Under the BAU scenario, atmospheric N will rapidly increase to $299.7 \pm 11.27 \text{ Gg N yr}^{-1}$ by 2050 (figure 5). Agricultural N volatilization from 1980–2000 was the largest pollution source followed by surface water N volatilization. NO_x emissions from industry and transportation had replaced agriculture as the largest pollution source after 2000 (figure 3).

Under population scenarios, population growth rate changes (S6) contribute less than 10% variation to atmospheric N pollution. Fossil fuel reduction (S7) by 30–50% compared to the BAU scenario would decrease atmospheric N pollution by 21–35%, respectively (figure 5).

Under technology innovation scenarios (S2), the average atmospheric N pollution would decrease by $\sim 60\%$ and $\sim 65\%$, respectively, when the NO_x emission intensity within the GHA would reach the mid- and high-level strata seen in developed countries. In addition, combining the consumption reduction scenario (S7) and technology scenario (S2), average atmospheric N pollution would decrease by $\sim 65\text{--}68\%$ (figure 5).

4. Discussion

4.1. Technological drivers in mitigating N pollution

4.1.1. Coupling WTP and CW. The vast investment in WTP has dramatically reduced the industrial and domestic point-source N pollution in many parts of developed countries [6, 8]. With BAU, WTP effluent within the GHA will contribute more than 50% of the surface water N pollution by 2050; combining the discharge of wastewater that is not being treated, wastewater N will dominate 65% of all surface water N pollution. High levels of precipitation force water cycling to couple with the point of N pollution, ultimately leading to widespread N pollution [7]. By 2005, N pollutants from the GHA emitted to the East China Sea via the Qiantang River, coupled with N pollutants from nearby URCs, have created a polluted coastal area greater than $65\,000 \text{ km}^2$ within the East China Sea ([23], figure S3 available at stacks.iop.org/ERL/6/014011/mmedia). The total polluted coastal area in China reached $139\,000 \text{ km}^2$ in 2005 [24]. If no territorial surface water pollution controls were in existence, the East China Sea would be the next ‘dead zone’ (a condition caused by N pollution transferred from land to ocean that has led to the excess algae bloom seen in the Gulf of Mexico coastal ecosystems [25]).

Fortunately, an emerging low cost and high efficiency ecological technique, CW, may help to solve this problem. The CW technique works well for wastewater N removal by means of microbial nitrification/denitrification, plant uptake, and substrate absorption [19]. CWs have been used for wastewater treatment for several decades and still work well [18]. The average N removal rate of CWs is $\sim 50\%$ in China currently [19], and $\sim 80\%$ N removal rate is observed in other parts of the world due to better design and management [18]. By coupling WTPs and CWs (e.g., CWs are placed the downstream from WTPs), surface water N pollution would decrease by $\sim 25\text{--}40\%$ by 2050 within the

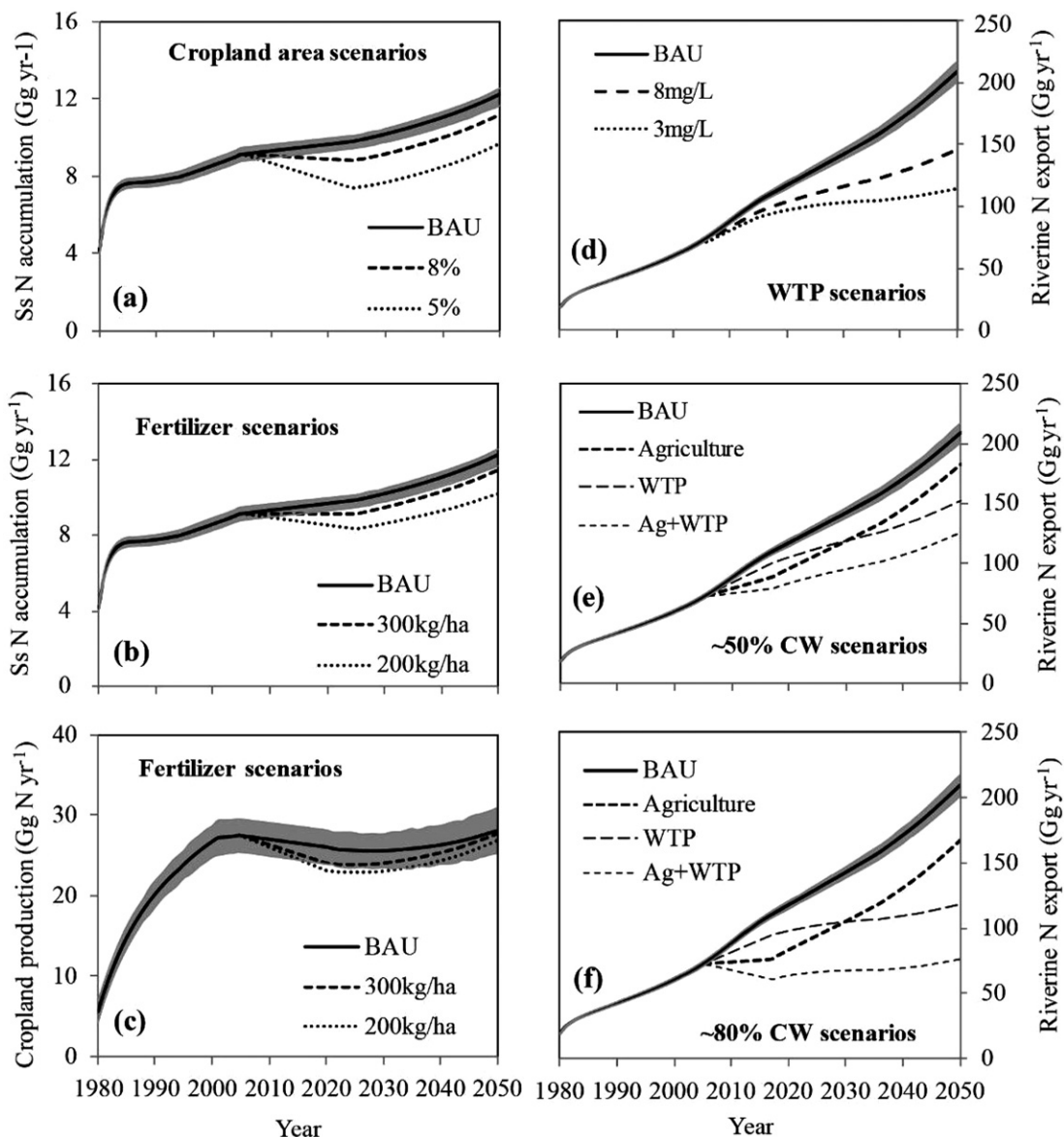


Figure 4. Simulations of subsurface N, N contained in cropland products, and riverine N export changes under the different scenarios. (a) Subsurface N changes under cropland area reduction (S4). (b) Subsurface N changes under fertilizer application reduction (S3). (c) Cropland product N changes under fertilizer application reduction (S3). (d) Riverine N export changes under the WTP N effluent standard revision (S5). (e) Riverine N export changes under the application of constructed wetlands (CWs) with a ~50% N removal rate (S1.2). (f) Riverine N export changes under the application of CWs with a ~80% N removal rate (S1.3) to mitigate agricultural N outflow (including cropland, aquaculture, and livestock), WTP N effluent, or both together. The gray area indicates the 95% confidence interval of simulation under BAU. See table 1 for further scenario details.

GHA (figure 4, S1). Although uncertainties exist (figure S4 available at stacks.iop.org/ERL/6/014011/mmedia), with the technology improvement [18], CWs would play a better role in developing countries where more than half of the wastewater is not being treated [6, 19].

4.1.2. Reducing fuel-N. Atmospheric N pollution in developed countries has been somewhat reduced via technological improvements despite large increases in burning fossil fuels [11, 26]. For instance, the N deposition rate has been reduced from over 10 kg N ha⁻¹ yr⁻¹ in the 1970s to 3.0 kg N ha⁻¹ yr⁻¹ in the United States of America, and 6.8 kg N ha⁻¹ yr⁻¹ in Europe currently [27]. However,

it remains a serious issue in China [15]. The total N deposition rate was as high as 22.6 kg N ha⁻¹ yr⁻¹ in 2004 within the GHA [7], about twice the average in China (12.4 kg N ha⁻¹ yr⁻¹ [28]). Moreover, atmospheric annual average NO₂ concentrations within the GHA amounted to 0.055 mg m⁻³ [7], which is beyond the clean air quality standard (0.04 mg m⁻³) of China [29]. Fossil fuel combustion was the largest source of atmospheric N pollution after 2000 within the GHA (figure 3), and NO_x emissions per GDP were greater by a factor of ~7–15 compared to those seen in developed countries [20]. Reasons for this include: (i) energy consumption per GDP is high [30]; (ii) coal makes up 60–70% of total energy consumption and it emits relatively more NO_x

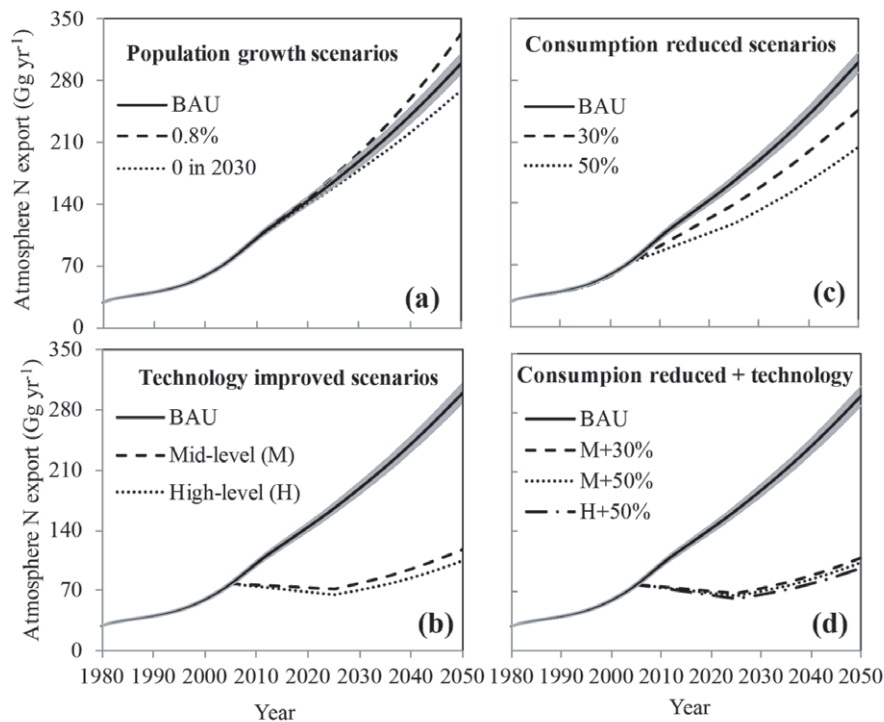


Figure 5. Simulations of atmospheric N export changes under different scenarios. Atmospheric N export under (a) population growth (S6), (b) technological innovation (S2), (c) fossil fuel consumption emission reductions (S7), and (d) both emission reductions and technological innovation. The gray area indicates the 95% confidence interval of simulation under BAU. See table 1 for details.

during combustion [15]; and (iii) techniques of N removal from coal are still less developed [7]. Technology improvement in N removal from coal, coal-burning economy transition, and enhancing the efficiency of energy use [11, 30], should be attained.

4.2. Policy drivers in mitigating N pollution

4.2.1. Precision agriculture. The development of precision agriculture and new crop varieties have resulted in much larger grain harvests with only slight increases, or in some cases a decrease, in the use of synthetic N fertilizer in developed countries since the 1980s [26, 31]. In the case of China with its enormous population and limited farmland, high yields are the first priority. This, in combination with the extra ‘insurance’ of fertilizer application, leads to over-fertilization [16]. In 2004, for example, the intensive double-cropping system within the GHA consumed 400 kg N ha⁻¹ yr⁻¹ synthetic fertilizer and 150–200 kg N ha⁻¹ yr⁻¹ manure (mainly human and livestock excretion). The total applied N reached as high as 275–300 kg N ha⁻¹ per crop, about twice that in Europe and the United States of America (where 150–180 kg N ha⁻¹ per crop is typical [5, 31]). Fertilizer over-consumption was as high as 70% according to the optimal fertilization rate set by Ju *et al* [16], and led to serious non-point source pollution [7].

Although there are still no policies that control over-fertilization in China, as is also true in most of the world, whether developed or developing [5], the national ‘Prescription Filled According to Soil Test Result in Fertilization’ (PSTF) program was implemented from 2005 on [32], supplying basic data and a foundation for policy establishment. Increasing

R&D funding for technology exploitation, reducing or abolishing fertilizer subsidies, and introducing N fertilizer over-consumption taxes [16] based upon the PSTF would all help to achieve the fertilizer reduction scenarios within the GHA (S3). In addition, re-coupling animal and crop production systems can increase the agricultural N use efficiency [11]. Improving local extension services, providing knowledge and training for farmers [16], and providing environmental awareness education for the public [14] would ultimately help to avoid serious environmental degradation.

4.2.2. Feasibility of effluent standards revision and CW applications. As mentioned above, the WTP tertiary treatment is currently unfeasible in China due to its high cost [30]. For instance, the GHA would need to invest 1.7 billion USD, ~15% of the total GDP, to update its WTP system and reach 3 mg l⁻¹ WNES (S5.3) according to the cost budget carried out by the CBF [21]. This is the reason for the current low percentage of wastewater being treated and the low WENS within the GHA. Prompted by the ‘Taihu Lake water pollution incident’ in 2006 and 2007 [33], governments revised the WNES of newly established WTPs from 20 to 15 mg N l⁻¹ in this region. However, even if this standard were followed, the WTP effluent N to surface water would continue to grow and become the primary pollution source in the next two decades (figure 3). Therefore, governments should strictly revise the WNES to a level they can afford, e.g., 8 mg N l⁻¹ (S5.2), which can lighten the burden on surface water.

Constructed wetlands have been highlighted as more economical and feasible than WTPs in China [19]. The cost of building a CW is only one-third to one-half the cost of a WTP

while achieving the same wastewater treatment capacity [19]. Moreover, the costs of operation and maintenance are less than one-tenth of those of WTPs [34]. Although CWs require three to five times larger area than WTPs to remove an equal quantity of N_R (table S4 available at stacks.iop.org/ERL/6/014011/mmedia), they can provide additional ecosystem benefits such as bioenergy resources and habitat conservation zones for birds while providing recreational and amenity usage [19, 34]. Meanwhile, CWs can work well on pollution control through midcourse N interception (i.e., intercept N before it is discharged to small watersheds from agricultural and domestic activities) [18, 19]. The CW application scenario (figure 4; S1) requires 2.8–5.5% of cropland area (0.28–0.55% of the total land area) within the GHA to intercept N runoff from agricultural sources and WTP by 2050. Considering the unused marginal land, it is possible for the GHA to use less than 5% of its cropland area for CW applications.

4.2.3. Clean air act. Atmospheric pollution control in China has shown some initial success, especially concerning SO_2 emission control. However, the recent change in acid rain chemistry from a sulfate-type to nitrate-type indicates an accelerating atmospheric N problem [15]. In 2009, China's central government made atmospheric N control the primary environmental protection goal of the 12th '5-Year Plan' (2011–2015). New atmospheric quality and N emission standards are ongoing as well. These 'top-down' policies will drive the technological improvement (S2) by means of attracting more financial support to upgrade techniques and equipment. Additionally, the management of multi-source N emission is essential [2, 22] since fossil fuel combustion is predicted to contribute only 10% of N air pollution while other sources will contribute more than 80% within the GHA by 2050, after achieving the mid-level technology seen today in developed countries (figure 5).

4.3. Policy and technology collaboration

Our results provide a case study on how technology and policy can work toward pollution control in a URC, where pollution would extend beyond the URC borders and affect nearby regions, e.g. water pollution of an upstream URC affects a downstream URC located in the same watershed. Research results from Chesapeake Bay [12] and other areas in the US [4, 13] supply good examples of policy collaboration between multiple administration units on pollution control at the watershed level. As opposed to regional policy collaboration, technology cooperation usually happens at national and global scales [11]. The poor pollution control technology and deficient financial support in developing countries compared to the advanced technology and sufficient financial support in developed countries reveals that there is enormous potential for international collaboration to protect our environment [22]. A successful example of such a collaboration is the CW technology transfer. The CW system was introduced to China from Europe beginning in 1996, and has been applied in many areas in China [19]. In addition, the environmental impacts would extend beyond national borders

and affect the entire world. For example, GHA's riverine N export greatly contributes to the pollution of the East China Sea [23], air N pollutants are propelled eastwards by prevailing winds, reaching North America [30], contributing to the global change, and regional N_2O emissions lead to global warming [22]. International collaboration, therefore, must be strengthened to combat environmental pollution globally.

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