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2016 Environ. Res. Lett. 11 024014

(http://iopscience.iop.org/1748-9326/11/2/024014)

Environmental Research Letters

LETTER

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CrossMark

OPEN ACCESS

RECEIVED
27 September 2015

REVISED
15 January 2016

ACCEPTED FOR PUBLICATION
18 January 2016

PUBLISHED
19 February 2016

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Keywords: nutrient pollution, rivers, agricultural transitions, China, integrated modeling

Supplementary material for this article is available online

Abstract

Transitions in Chinese agriculture resulted in industrial animal production systems, disconnected from crop production. We analyzed side-effects of these transitions on total dissolved nitrogen (TDN) and phosphorus (TDP) inputs to rivers. In 2000, when transitions were ongoing, 30%–70% of the manure was directly discharged to rivers (range for sub-basins). Before the transition (1970) this was only 5%. Meanwhile, animal numbers more than doubled. As a result, TDN and TDP inputs to rivers increased 2- to 45-fold (range for sub-basins) during 1970–2000. Direct manure discharge accounts for over two-thirds of nutrients in the northern rivers and for 20%–95% of nutrients in the central and southern rivers. Environmental concern is growing in China. However, in the future, direct manure inputs may increase. Animal production is the largest cause of aquatic eutrophication. Our study is a warning signal and an urgent call for action to recycle animal manure in arable farming.

Introduction

Many aquatic systems in China are polluted with nitrogen (N) and phosphorus (P), causing eutrophication and harmful algal blooms [1–4]. Over half of the Chinese lakes are eutrophic today [5]. For example, the water quality in Thaihu Lake, the third largest lake in China, declined from Class I/II (oligotrophic clean water: Class I suitable for drinking and Class II suitable for fishing and bathing) in the 1960s to Class IV (eutrophic polluted water by nutrients, not suitable for drinking or bathing) [5]. Many Chinese rivers show similar trends. Northern rivers, such as the Huang (Yellow River), Hai, Liao and Huai, and river deltas are polluted by nutrients to the extent that their water is not suitable for human contact (Class VI) [6]. Leaching of nutrients from fertilized soils is generally considered the major cause [3, 6–9]. Nutrient leaching from land is increased by inputs from synthetic and organic fertilizers, atmospheric N deposition, and biological N fixation by crops. This leaching of N and P from land is a diffuse source of N and P in rivers.

Here, we argue that nutrient pollution of Chinese rivers is largely associated with manure discharges, i.e., point sources. Chinese agricultural transitions, in particular the recent industrialization of animal production and the disconnection of crop and animal production, result in direct discharges of animal manure to surface waters (figure 1). Existing studies [3, 6–9] generally do not account for these point sources and thus may underestimate actual nutrient loads to rivers (see Results below). Some links between agricultural transitions and water quality were published in studies [10–14] focusing largely at national analyses. China's pollution report [10] indicates that animal production is today responsible for around 20% of nitrogen and

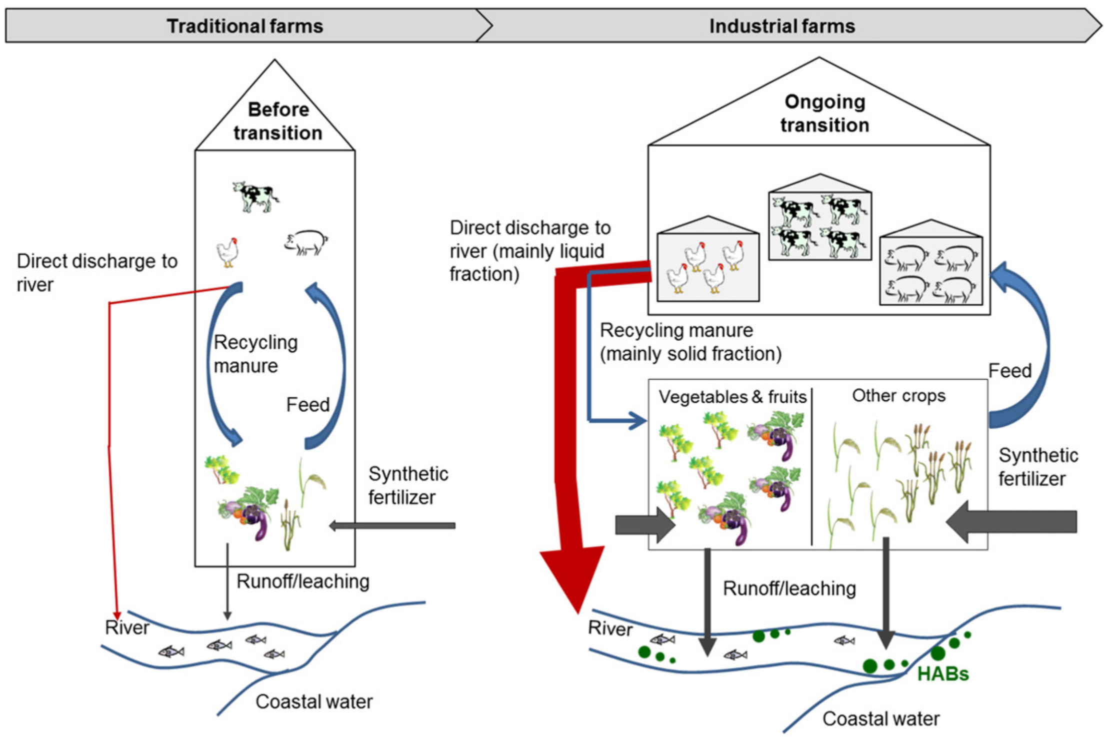

Figure 1. A simplified historical overview of farming systems in China. This overview is shown in relation to direct nutrient losses to rivers, and their environmental impacts [2, 35, 39, 53] including harmful algal blooms (HABs). The transition in Chinese agriculture started in the early-1980s.

40% of phosphorus pollution in aquatic systems. However, none of these studies explicitly account for direct discharges of animal manure to rivers. Clearly, the implications of agricultural transitions on N and P inputs to Chinese rivers are not well known, making it difficult to formulate effective environmental policies. Our analyses fill these gaps.

In our study, we quantify the nutrient pollution of large Chinese rivers associated with direct point discharges of animal manure to the rivers as a result of agricultural transitions. Our analysis includes the following rivers in China: the Huang, Changjiang, Zhujiang (Pearl), Huai, Hai and Liao. The drainage basins of the largest rivers (Huang, Changjiang, Zhujiang) were divided into sub-basins (figure S1). Although a few sub-basin scale analyses of the Changjiang River [9, 15] exist, ours is the first to assess nutrient pollution in Chinese rivers by source while accounting for direct discharges of manure by sub-basin.

Methodology

Model description and inputs

Our study is based on two models: Global *NEWS*-2 (Nutrient Export from WaterSheds) [16, 17] and NUtrient flows in Food chains, Environment and Resources use (NUFER) [18]. Global *NEWS*-2 is a spatially explicit model that has been applied to analyze nutrient-related problems worldwide [19–30] including China [17, 31–33]. This model quantifies river export of different nutrients (nitrogen, phosphorus, carbon, silica) in different forms (dissolved inorganic, dissolved organic, particulate) as a function of human activities on land (e.g., agriculture, sewage) and basin characteristics (e.g., hydrology, land use). This basin-scale model has been used to analyze past (1970, 2000) and future (2030, 2050) trends [16, 34]. NUFER was developed for China to quantify efficiencies of nutrients in the food chain at national [13, 35–37] and provincial [18] scales over time (e.g., the period of 1980–2010 [18, 37]). This model is also used to assess management options for efficient nutrient management in the food chain [38, 39].

We developed a sub-basin version of the Global *NEWS*-2 model in which we included information from NUFER (see extended materials and methods in supporting information). Novel aspects of our modeling approach include (*i*) the sub-basin scale at which we run Global *NEWS*-2 to quantify total dissolved nitrogen (TDN) and phosphorus (TDP) inputs to Chinese rivers by source, and (ii) the coupling of this sub-basin version of Global *NEWS*-2 with NUFER. The latter we did to include direct discharge of animal manure as a point source of nutrients in rivers in our modeling to analyze the consequences of agriculture transitions on river quality in China. This has not been done before. TDN and TDP include both dissolved inorganic and organic forms of N and P.

To assess the consequences of agricultural transition on water quality, we modeled TDN and TDP inputs to rivers for 1970 and 2000. We selected 1970 to reflect the pre-transition period and 2000 to reflect the ongoing transitions in Chinese agriculture. We also modeled TDN and TDP inputs to rivers for 2050 as an illustrative example to show the risks for future river pollution.

Our model includes point ($RSpnt_{F.total.j}$, kg, see equation (1)) and diffuse ($RSdif_{F.total.j}$, kg, see equation (2)) sources of nutrients in rivers. Point sources of the nutrients (F: TDN and TDP) include direct discharges of animal manure to rivers ($RSpnt_{F.ma.j}$, kg) and human sewage ($RSpnt_{F.sew.j}$, kg). Diffuse sources of the nutrients (F: TDN and TDP) include manure ($RSdif_{F.ma.j}$, kg) and synthetic fertilizers ($RSdif_{F.fe.j}$, kg) used in croplands, atmospheric N deposition (only for TDN; $RSdif_{F.dep.j}$, kg), biological N fixation (only for TDN; $RSdif_{F.fix.j}$, kg), leaching of organic matter (for dissolved organic N and P as a function of runoff) ($RSdif_{F.lch.j}$, kg), and P-weathering (only for TDP; $RSdif_{F.wth.j}$, kg)

$$RSpnt_{F.total.j} = RSpnt_{F.ma.j} + RSpnt_{F.sew.j}, \quad (1)$$

$$RSdif_{F.total.\bar{j}} = RSdif_{F.ma.j} + RSdif_{F.fe.j} + RSdif_{F.dep.j} + RSdif_{F.fix.j} + RSdif_{F.lch.j} + RSdif_{F.wth.j}. \quad (2)$$

TDN ($RSpnt_{TDN.ma.j}$, kg) and TDP ($RSpnt_{TDP.ma.j}$, kg) inputs to rivers of sub-basin j from the manure point source were calculated as:

$$RSpnt_{TDN.ma.j} = Nexc_j \cdot frN_{sw.j}, \quad (3)$$

$$RSpnt_{TDP.ma.j} = Pexc_j \cdot frP_{sw.j}. \quad (4)$$

Here $Nexc_j$ and $Pexc_j$ are the N and P animal excretion in each sub-basin (j) (kg), respectively. We used gridded Global *NEWS*-2 information: 0.5 longitude by 0.5 latitude; i.e. cell areas ranging from 2135 to 2868 km^2 for the study area. Gridded information includes animal manure excretion corrected for losses of N during storage and housing (see figure S7) [16]. These values were originally derived from the integrated model to assess the global environment (IMAGE) model [40]. Bouwman *et al* [41] prepared these inputs for Global *NEWS*-2. IMAGE first calculated country-based manure production based on animal stocks and excretion rates, and then spatially allocated this manure over grids using land use maps (see details in [40, 41]). We used this gridded information to calculate animal manure for sub-basins (see figure S8 for values) using ArcGIS functions. We used these values for P excretion ($Pexc_j$). We calculated N excretion ($Nexc_j$) from the available N animal manure from Global *NEWS*-2 while accounting for N losses to the air (these losses were derived from NUFER, see supplementary methods).

$frN_{sw.j}$ and $frP_{sw.j}$ are the fractions (0–1) of N and P in animal excretion that are discharged directly to surface waters (sw) of sub-basin (j), respectively. These fractions were calculated for each sub-basin from provincial data by NUFER [18] (figure S2) using ArcGIS (area-weighted averages). Thus the fraction of manure that is directly discharged to surface waters of a sub-basin is Σ_i (fraction of area covered by province i · fraction of manure directly discharged for province i). Fractions of manure discharged for provinces were taken from NUFER for 1980 and 2005 because NUFER includes those years. We assume that 1980 is close to 1970 and 2005 is close to 2000 in our study. In NUFER discharges of N and P from animal manure to surface waters were calculated from manure excretion by correcting for losses during storage and housing, and for applications to cropland and to grassland (see details in [18]). Manure excretion was calculated based on animal feed from crop and kitchen residues, animal stocks (e.g., pigs, layer and broiler poultry, milk and beef cattle, sheep and goat), and excretion rates for N and P (see 'Model performance' for sources of information in the supplementary methods). In NUFER animal production (see details in [18]) includes two intensities of animal breeding, reflecting traditional and industrial farming systems. The high intensity types of animal breeding are defined for pig systems (>50 heads), dairy cattle (>5 heads), beef cattle (>50 heads), layer poultry (>500 heads), and meat poultry (>2000 heads) (figure S10 as an example).

Nutrient inputs to rivers from sewage and diffuse sources were quantified following the modeling approaches of Global *NEWS*-2 [16] (summarized in the supplementary methods). Most model inputs were derived from gridded global datasets (0.5 longitude × 0.5 latitude) developed for Global *NEWS*-2 [41–43] for 1970, 2000 and 2050, and most of model parameters are also from this model [16] (figure S7). Inputs for 2050 were based on earlier studies [41–43] which are based on interpretations of the storylines of the millennium ecosystem assessment scenarios [34, 44]. In this study we used model inputs that reflect a global orchestration scenario assuming globalized trends towards socio-economic development and reactive management of environmental problems. This scenario was implemented in the sub-basin Global *NEWS*-2 model as a starting point [16, 45]. The total population is assumed to have increased slightly by 2050 because of better education (e.g., low mortality and fertility rates, and high migration). However, urban population is assumed to have increased fast. This reflects migration of people to cities to find better jobs [43]. The demand for animal production will have increased by 2050 and thus agriculture is projected to intensify for food security reasons [41]. This existing scenario assumes that all available manure will be applied on land. However, this may not be likely. Considering the development of industrial farms today and the poor manure management it is more likely that direct discharges of animal manure to rivers will occur in the coming years without efficient manure management. Thus, in this study we assumed that direct discharges of manure to surface waters will still occur in 2050. Therefore, we used for 2050 the same fractions of manure directly discharged to rivers as for

2000 (see details in materials and methods in supporting information).

Model performance

Model uncertainties are associated with model inputs, parameters and approaches. The original Global *NEWS*-2 was validated and calibrated for world rivers [16], indicating an acceptable performance according to the Nash-Sutcliffe model efficiency (R^2_{NSE}: 0.54, 0.51, 0.71, 0.90 for DIN, DIP, DON, DOP, respectively). Strokal *et al* [17] indicated a satisfactory performance of the model for DIN and DIP export by large Chinese rivers for 2000 (Pearson's coefficient of determination ($R_p{}^2$): 0.96; $R_{NSE}{}^2$: 0.42; moldel error (ME): 18%). Yan *et al* [46] validated the model for DIN export by the Changjiang River for 1970–2002 ($R_p{}^2 = 0.93$). Similar conclusions were drawn for application of Global *NEWS*-2 to other world regions (see supplementary methods for references). NUFER was developed based on validated statistical data, field surveys, literature, and has been widely applied in many studies [13, 18, 35–37]. See details in supplementary methods on evaluating the original global *NEWS*-2 and NUFER.

We consider our model appropriate for modeling N and P inputs to the Chinese rivers at the sub-basin scale for three main reasons (see details in supplementary methods for references). First, our modeled nutrient pollution levels in rivers are generally in line with observations. Our model captures the increasing trends in dissolved N and P inputs to the Chinese rivers since 1970, which is in agreement with other studies (e.g., [8, 48–50]). Second, the comparison of model inputs with independent county data (figure S9) convincingly shows that our model inputs for sub-basins are of good quality (e.g., $R_P{}^2$: 0.73–0.98 for studied rivers for N and P synthetic fertilizers and animal manure). Third, we verified relevant model parameters with experts and local information (e.g., nutrient removal during treatment in the Dongjiang basin, fractions of direct manure discharges from NUFER; see supplementary methods).

Results and discussion

Here we first discuss agricultural transitions in China. Next, we show consequences of agricultural transitions on river quality and discuss the risk for future river pollution by nutrients in China. We finish this section by comparing our results with existing studies.

Understanding agricultural transitions in China

Chinese agriculture has been in transitions since the 1980s [11, 12, 51]. These transitions include changes in animal and crop production systems. Pre-1980, Chinese agriculture was dominated by small traditional farms with combined crop and animal production [12, 35, 52] (figure 1 and figure S3). Synthetic fertilizer was not widely used. Instead, farmers used most animal manure collected in confinements or from other places as a fertilizer [52]. Thus direct discharge of manure to surface waters was minimal [52].

Since the 1980s Chinese agriculture has been industrializing to ensure food security (figure 1) [12, 35, 51, 52]. Crop production gradually separated from animal production in large parts of the country. This happened when the centrally planned economy shifted to a market-oriented economy [12, 52]. The human population increased over this period (figure S4, table S1). With the increasing prosperity and urbanization, the human diet shifted towards more meat consumption. This all led to an increasing demand for agricultural products [18]. Synthetic fertilizers are now preferred over animal manure, because of their relatively low prices and low labor demand [52, 53] (figure 1).

Animal production has thus shifted from traditional to industrial, land-less farming systems (figure 1, figures S3 and S10). This allows for a higher production needed to meet the demand for meat in China, but also in the world (e.g., around half of the pork, and 18% of the poultry meat produced worldwide are from China in 2005) [11, 12, 54]. Between 1970 and 2000 the total number of pigs, poultry, cattle, sheep and goats increased 1.5- to 8-fold (range for the different animal categories) in China. By 2000 10%–40% of these animals, and by 2010 over two-thirds of the pigs and poultry were grown in industrial farms in China (figure S3) [18, 35]. Pigs and poultry production accounts for over half of the total manure produced (figure S5). Most of the produced manure is considered waste because industrial farms are largely disconnected from crop production, and often lack facilities to treat or recycle animal manure [18, 35, 52]. Treatment is considered as separation of animal manure into solid and liquid fractions. The solid fraction after composting can be transported and applied to vegetable and fruit farms. The liquid fraction is further treated and then discharged ultimately to water systems. However, the separation and treatment of the liquid fraction is not very effective, and therefore large amounts of N and P are discharged to water systems (figure 1, [52]). For example, treatment ratios for animal waste in industrial farms are reported as [52]: 3% for dairy cows, 10% for chicken and 43% for pigs. Both the treated and untreated manure from these systems are point sources rather than diffuse sources of nutrients in Chinese rivers.

Consequences of agricultural transitions on river quality in China

Our results indicate that manure point sources have a much larger share in total TDN and TDP inputs to rivers than other nutrient sources (figures 2 and 3, figure S6). In 1970 less than 5% of the animal manure

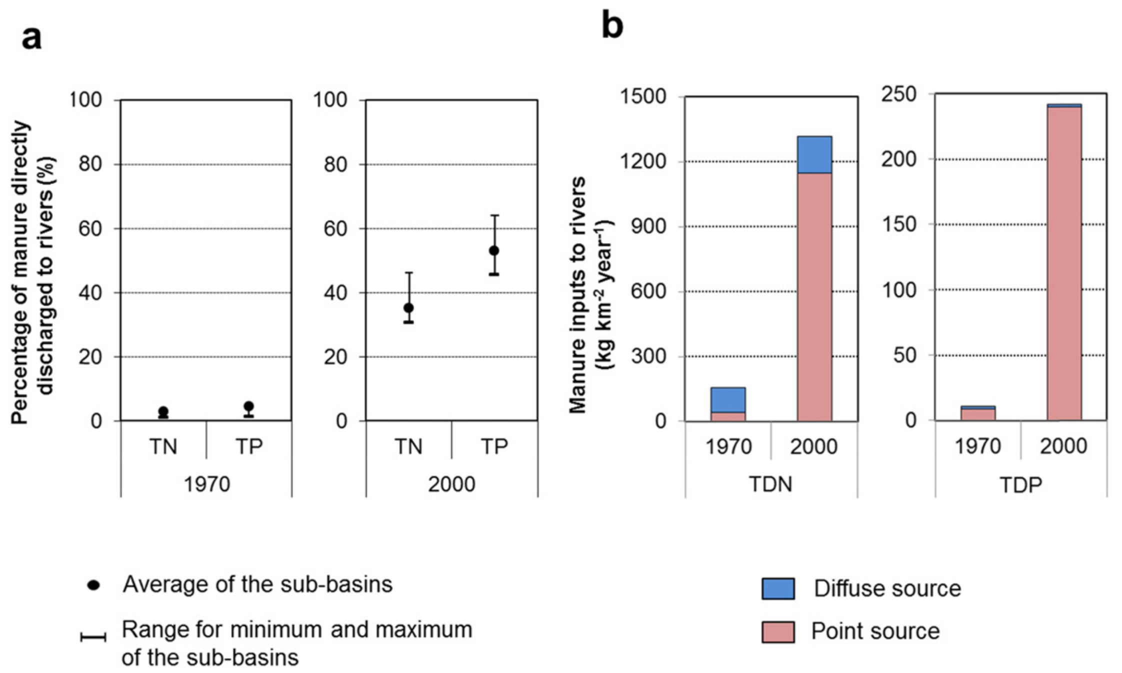

Figure 2. Losses of nitrogen (N) and phosphorus (P) from animal manure to Chinese rivers in 1970 and 2000. (a) Percentage of the total nitrogen (TN) and phosphorus (TP) in animal manure excretion that is discharged directly to rivers in 1970 (the pre-transition period) and in 2000 (reflecting the ongoing transitions in farming systems) (%). (b) The area-weighted averaged inputs of TDN and phosphorus (TDP) from manure to rivers (kg km^{-2} yr^{-1}) in China. Total areas were used to calculate area-weighted averaged inputs. Percentages of direct manure discharges to rivers are calculated from provincial information of NUFER [18, 39]. Animal manure production is from Global *NEWS*-2 [16] (see figure S2 for sub-basin information).

was directly discharged to rivers of the sub-basins as waste. In 2000 this had increased to 30%–70% (figure 2). As a result, the calculated basin area-weighted averaged TDN inputs to rivers from only animal manure (diffuse and point) increased 8-fold, from 156 kg km^{-2} of basin area in 1970 to 1316 kg km^{-2} in 2000. The TDP inputs increased 22-fold, from 11 kg km^{-2} in 1970 to 243 kg km^{-2} in 2000. These inputs are mainly from direct discharges of manure to rivers (point source). These manure point sources are responsible for around half of the total TDN and 80% of TDP inputs to rivers in 2000, which is much higher than in 1970 (around 6% for TDN and 37% for TDP) (table 1).

The increases in TDN and TDP inputs to rivers and the shares of manure point sources differ largely among rivers and their sub-basins (figure 3; table 1). Sources of TDN and TDP in rivers include animal manure, synthetic fertilizers, atmospheric N deposition, biological N fixation, leaching of organic matter, weathering of P-minerals and human waste. Nutrient inputs to rivers have increased by a factor 2 to 45 for sub-basins between 1970 and 2000 (figure 3). These increases are particularly large for the northern rivers, including the Huang, Huai, Hai and Liao (figure S6). For example, the total inputs of TDN to these northern rivers increased 11-fold, from 280 to 3000 kton between 1970 and 2000. TDP inputs increased 20-fold, from 27 to 546 kton (figure S6). The sub-basin areas of these rivers are characterized by low precipitation and runoff [55]. As a result, nutrient inputs from diffuse sources are typically low, and direct discharge of manure thus accounts for at least two-thirds of the TDN and over 80% of TDP inputs to these northern rivers (figure 3). The remainder is from synthetic fertilizers or sewage. Animal manure use in cropland accounts for less than 4% of the nutrients in the northern rivers (figure 3, figure S6). More than half of the total nutrients are concentrated in rivers of the downstream Huang delta, Huai and Hai basins (figure 3).

For the central (Changjiang) and southern (Zhujaing) rivers we calculate an increase in TDN inputs from 2500 to about 7000 kton (a 2.8-fold increase), and in TDP from 62 to almost 600 kton (a 9.5-fold increase) between 1970 and 2000 (figure S6). Manure point sources are responsible for 20%–60% of these TDN and 50%–97% of TDP inputs to rivers in 2000 (range for sub-basins; figure 3). The remainder is mainly from synthetic fertilizers (sub-basin range: 12%–46%), and atmospheric N deposition on land (sub-basin range: 12%–40%). Animal manure as a diffuse source contributes less than 10% to TDN and TDP inputs to rivers. Sewage effluents are important sources of both TDN and TDP inputs particularly in river deltas.

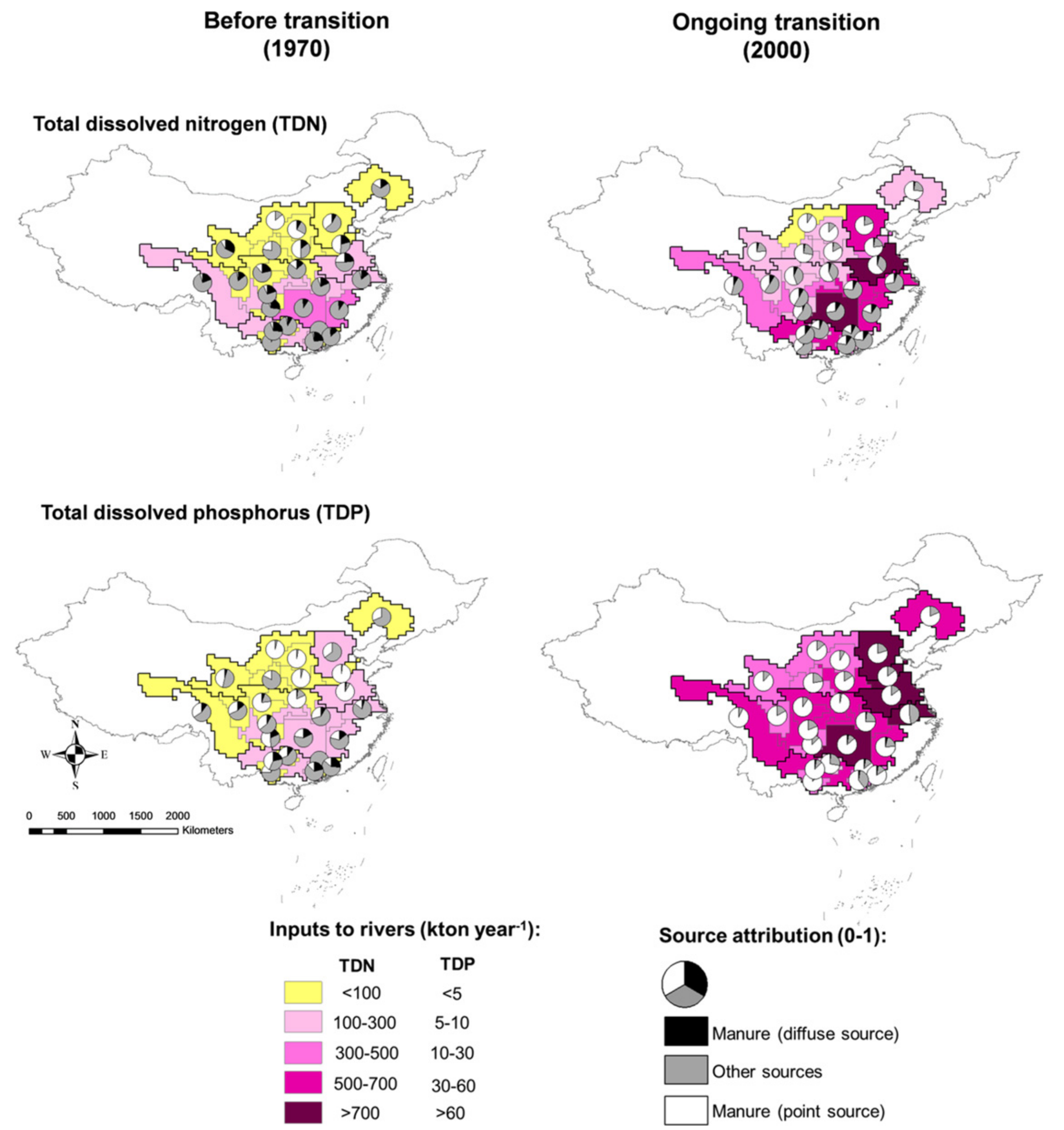

Figure 3. Total dissolved nitrogen (TDN) and phosphorus (TDP) inputs to rivers by sub-basin in China in 1970 and 2000 (kton yr^{-1}). The relative share of sources to these TDN and TDP inputs (source attributions in fractions) are shown in pie charts. Other sources include sewage effluents (TDN, TDP), synthetic fertilizer use (TDN, TDP), biological N_2 fixation by agricultural crops and by natural vegetation, atmospheric N deposition (TDN), leaching of organic matter (TDN, TDP), and weathering of P-contained minerals (TDP) from agricultural and non-agricultural soils (see the supplementary material for model descriptions and sources of model inputs, and figure S6 for details on source attribution).

Risks for future river pollution by nutrients

Nutrient pollution in Chinese rivers may increase in the coming years if future manure management stays as it is during the ongoing transition. Furthermore, the demand for animal products in China will remain high causing further development of industrial farms. We analyzed river pollution in 2050 as an example to illustrate the environmental consequences of future trends without improved manure management. Figure 4 illustrates to what extent TDN and TDP inputs to Chinese rivers may increase in 2050 compared to 2000 (reflect the ongoing transition). In 2050 the total inputs of TDN and TDP to Chinese rivers are calculated to be 8%–325% higher (range for sub-basins) than in 2000, except for one sub-basin in the Zhujaing River (figure 4). Manure point sources are projected to remain the main contributor to river pollution by nutrients in 2050 (22%–91% of the nutrients in rivers from this source, table S2). In our scenario with a rapid economic development, the total area used for agriculture is projected to decrease between 2000 and 2050 in some sub-basins (up to 46%, figure S11); this results from rapid urbanization (table S1). Rivers may also receive nutrients from other sources. These are, for example, use of synthetic fertilizers to grow more crops, and sewage effluents from urbanized areas [17, 43]. However, we calculate a lower contribution of these sources to nutrients in Chinese rivers (up to 40%) compared to manure point source (table S2). Therefore, the risk for future river

Table 1. Area-weighted averaged total dissolved nitrogen (TDN) and phosphorus (TDP) inputs to Chinese rivers in 1970 and 2000 (kg km^{-2} of basin year^{-1}, and share of the animal manure point source in %). The range in brackets is the minimum and maximum values among the sub-basins. See the supplementary material for model description and inputs. Other diffuse sources include biological N fixation, atmospheric N deposition, weathering of P-containing minerals, and N and P leaching from organic matter.

	TDN		TDP	
Nutrient sources in rivers	1970	2000	1970	2000
Animal manure (point)	43 (0–173)	1148 (355–4338)	9 (0–34)	240 (59–952)
Animal manure (diffuse)	113 (0–941)	168 (1–781)	2 (0–33)	3 (0–15)
Synthetic fertilizers (diffuse)	77 (0–903)	547 (1–3529)	1 (0–19)	6 (0–30)
Other diffuse sources for agricultural areas	87 (0–345)	381 (4–1357)	1 (0–5)	4 (0–17)
Other diffuse sources for non-agricultural areas	379 (1–1891)	227 (0.2–1222)	4 (0–21)	2 (0–8)
Sewage effluents (point)	16 (0–172)	121 (0–837)	6 (0–64)	39 (0–272)
Total	715 (10–3921)	2593 (391–7737)	23 (1–156)	294 (68–1113)
The share of point animal manure (%)	*6 (0–86)*	*44 (17–91)*	*37 (0–97)*	*82 (52–97)*

pollution by nutrients will largely depend on how food production will develop, in particular for animal production because of the large contribution of manure to water pollution currently.

Comparison with other studies

Some studies have already quantified N and P transport to waterbodies of the large Chinese rivers [56], in particular of the Changjiang River [9, 15, 46, 57–59]. A few studies exist on sub-basin analyses of the Changjiang River [9, 15, 59]. However, these studies ignore direct discharges of manure to rivers. Therefore, the current nutrient pollution of rivers may be underestimated. For example, our estimates of the total TDN inputs (from all sub-basins) to the Changjiang are comparable with the results of Liu *et al* [9] and Bao *et al* [15] for 1970 when direct discharges of animal manure were small, but higher than the results of Liu *et al* [9] and Xing *et al* [56] for 2000 when direct discharges of manure were considerable. Liu *et al* [9] and Bao *et al* [15] quantified around 2 Tg N transported to waterbodies of the Changjiang River in 1980, which is close to our estimate of 1.7 Tg TDN in 1970. For 2000 Liu *et al* [9] quantified approximately 4.5 Tg of N, of which around 0.4 Tg N is from animal manure used in agriculture. We, however, calculated 5.3 Tg TDN, of which 2.2 Tg TDN from direct discharges of animal manure and 0.4 Tg N from animal manure use (figure S6). We argue that the impact of direct discharges of animal manure from livestock production on river quality is much larger than the impact of over-fertilization of soils by synthetic fertilizers.

Few studies consider direct discharges of manure to rivers, but not at the sub-basin scale [13, 18, 60]. For example, Ma *et al* [13] quantified that 30% of N and 45% of P from manure were discharged to surface waters in 2005 at the national scale. Ti *et al* [60] adopted a 25% value for livestock waste discharged to waterbodies to quantify N export by the Changjiang, Zhujiang and Huang at the basin scale for the 2000s. We, however, demonstrate that this percentage is much higher for 2000 and ranges between 30% and 45% for N, and 46% and 64% for P among sub-basins (figure 2).

Most existing modeling studies on river export of N and P emphasize the importance of managing diffuse agricultural sources of N (e.g., synthetic fertilizer use) and point sewage sources of P to reduce water pollution in China (e.g., [17, 32, 46]). This is because these studies do not account for manure point sources. We show the importance to manage point manure sources for both N and P in the future. Studies on nutrient inputs to surface waters at the national (e.g., [13, 61]) and provincial scales (e.g., [18]) acknowledge the importance of reducing losses of manure. Our study can contribute to such analyses by providing a better spatially explicit understanding of water pollution at the sub-basin scale.

Concluding remarks and future outlook

We consider our study a warning signal because nutrient loads in Chinese rivers are now much higher than previously and will continue to increase. Direct discharge of manure is likely the most important source of unexpected serious nutrient pollution in surface waters of China. This was not recognized in previous studies [6–9, 15, 62]. However, more experimental research is needed to reduce uncertainties (see methods in supplementary material). Industrialization of livestock production is common in other world regions such as Europe and North America (e.g., most of pork and poultry production are from industrial farms) [11, 51]. However, animal manure management outside in those regions is more effective than in China. Examples are permits to discharge manure to water bodies in United States [63] and regulations to recycle manure in grassland and crop fields in Europe [51, 64].

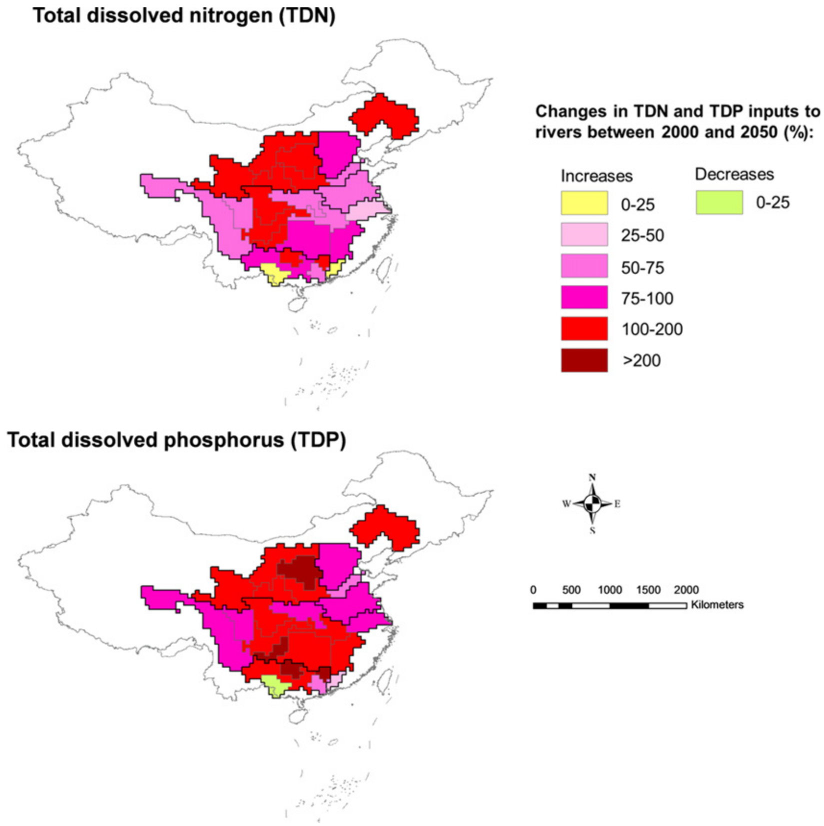

Figure 4. Risk for future river pollution by nutrients in China. The maps show changes in total dissolved nitrogen (TDN) and phosphorus (TDP) inputs to Chinese rivers between 2000 and 2050 (%). High risks for river pollution are indicated by increasing inputs of TDN and TDP to rivers in the future. See the supplementary material for model description, inputs and scenario description for 2050.

The Chinese government started to recognize the side-effects of livestock production, and introduced regulations such as the Discharge Standard of Pollution for Livestock Production, and the Law of Water Pollution Prevention [65]. So far, however, these regulations have not been effective [65]. Thus, the actual level of water pollution by nutrients from direct discharges of animal manure is today likely underestimated in modeling studies. The new 'Environmental Protection Law', 'Zero-growth in Synthetic Fertilizer after 2020 Policy' and the new regulation for livestock production have been recently announced in 2015 with strict regulations for industrial animal production to reduce pollution (http://www.gov.cn). These regulations emphasize in particular recycling of animal manure on land to substitute synthetic fertilizers. However, the effect of these regulations on reducing water pollution will depend on the effectiveness of their implementation.

Meeting the demand for food will remain a challenge in the coming decades. Thus, industrial animal farms will likely continue to grow and increase in numbers. Nutrient pollution of aquatic systems will likely become more serious (see figure 4 as an example), unless manure management will be strongly improved. Besides environmental policies, providing better technologies for manure recycling and treatment, and for fertilizer application, educating farmers, and providing more services (scientific and advisory) to help farmers improve their practices are urgently needed. Future studies of sustainable food production (more food with less environmental impacts) should account for recycling animal manure as fertilizers. This will reduce direct discharges of manure to rivers. Recent experiments [66–69] on integrated soil-crop system management (ISSM: higher crop yields with lower nutrient losses to the environment [69] focused on synthetic fertilizers. Efficient use of animal manure may be a prerequisite for ISSM to effectively reduce nutrient losses to the environment while increasing crop yields [69]. Such changes, however, imply a major shift in farming practices, and until this shift is made the high nutrient loads to Chinese rivers from animal production remain unprecedented in the world.

Acknowledgments

We acknowledge The Netherlands Organisation for Scientific Research (NWO), Wageningen Institute for Environment and Climate Research (WIMEK) and Wageningen University for providing financial support to conduct this research. We also acknowledge the Chinese programs for their support namely the Natural Science Foundation of China (NSFC) (31572210), President's International Fellowship Initiative, PIFI of the Chinese Academy of Science (2015VEA025), and the Hundred Talent Program of the Chinese Academy of Science. We thank Rik Leemans for his constructive comments to the draft of the manuscript. We thank Mengru Wang for helping us to prepare figure S9.

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