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Modelling phosphorus loading to the largest shallow lake in northern China in different shared socioeconomic pathways

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Excessive nutrients inputs cause anthropogenic lake eutrophication worldwide. It is thus crucial to provide information on future trends of nutrient loading and its implications for the lake's trophic state. Here we quantified total phosphorus (TP) loading to the Lake Baiyangdian (BYD), the largest shallow lake in northern China, and assessed their future trend and the trophic state of the lake. The TP loading to the Lake BYD by rivers in 2015 was 276 ton, which was in a relatively low level in lakes from China. Based on the five shared socioeconomic pathways (SSPs), the TP loading to the Lake BYD in 2050 will increase only at the fragmentation scenario (SSP3) by an increment of 34.4%, in which the directly discharged animal manure become the main source. The lowest TP loading in 2050 is observed at the sustainability scenario (SSP1), in which sewage system will be the dominant contributor. At the sub-basin scale, compositions of river exported TP in rural areas will be more influenced by future socioeconomic developments than those in urban areas. The twenty years nutrient dynamics from clear or turbid state in the Lake BYD were simulated by the PCLake model to calculate the critical P loading (CPL). The results indicated that the CPL in the Lake BYD was 2.06 mg P m^{-2} d^{-1} for eutrophication and 0.84 mg P m^{-2} d^{-1} for oligotrophication. The only scenario in which Lake BYD will become eutrophic is SSP3, which should be avoided in the future development. To restore the lake water to the oligotrophic state, more efforts are necessary to reduce direct discharge of animal manure and increase the TP removal rates, especially in rural areas.

1. Introduction

Anthropogenic lake eutrophication is one of the key environmental problems worldwide. It is caused by excessive inputs of human-induced nutrients, leading to the rapid production of phytoplankton and other micro-organisms in lakes, and the deterioration of water quality (Carpenter, 2008; Smith and Schindler, 2009). Phosphorus (P) has been reported to be the primary limiting nutrient in most lakes (Conley et al., 2009; Li et al., 2019; Yi et al., 2020). Once crossing the critical P loading, eutrophication may cause an abrupt shift from clear to turbid state in shallow lakes (Janse et al., 2008; Kong et al., 2017a, 2017b). Lake ecosystem services, such as freshwater provision, climate regulation, and aquaculture, can be negatively affected by eutrophication (Schindler et al., 2016). Thus, quantification of P loading is essential first step to improving eutrophication management (Macintosh et al., 2018; Schindler et al., 2016).

Many models and methods, such as the Export Coefficient Model (ECM) (Kronvang et al., 2005), Soil and Water Assessment Tool (SWAT) (Gassman et al., 2014), Global Nutrient Export from Watersheds 2 (Global-NEWS2) (Mayorga et al., 2010), and Model to Assess River Inputs of Nutrient to seAs (MARINA) (Strokal et al., 2016b), have been developed to quantify the P input to water systems. Among them, MARINA is a downscaled version for China of the Global-NEWS2, with an improved approach for nutrient losses from animal production and population (Strokal et al., 2016b). It calculates river export of P by source at the sub-basin scale, which can help to identify locations of sources contributing largely to the nutrient pollution. It has been applied in nutrient estimation for the six large river basins in China (Strokal et al., 2016b), Haihe Basin

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(Yang et al., 2019), and Indus River (Wang et al., 2019a). However, most of studies using this model focused on coastal areas (Strokal et al., 2016b; Chen et al., 2019; Wang et al., 2019a), only a few studies have explored the impact of future socioeconomic development on the nutrient loadings to lakes (Yang et al., 2019; Ma et al., 2020). Looking ahead, human-induced nutrient will continue to increasing as a result of socio-economic development, causing more severe anthropogenic lake eutrophication (Yang et al., 2019; Wang et al., 2019a, 2019b; Xiong et al., 2020). It is thus critical to understand the characteristics of future nutrient loads to lakes based on MARINA model. This will contribute to formulate effective policies for improving water quality of lakes. In addition, knowing the difference between nutrient loads and critical nutrient loading will be helpful to identify opportunities to reduce the gap (Wang et al., 2019b). PCLake model, a dynamic model of nutrient cycling and biota for shallow lake ecosystem, can be used to calculated the critical nutrient loading for both eutrophication and oligotrophication (Janse et al., 2008). Integrating MARINA and PCLake make it possible to provide information on future trends of nutrient loading and its implications for the lake's trophic state (Li et al., 2019). So far, this model combination has not been used for future scenarios.

Scenario analyses are effective methods for exploring uncertainty in future societal conditions, assessing the environmental response to human activities, and evaluating the approaches to reduce pollution (O'Neill et al., 2014; Yang et al., 2019; Zandersen et al., 2019). The shared socioeconomic pathways (SSPs) is one of the most important and widely used environmental scenario frameworks (Kanter et al., 2020; O'Neill et al., 2017; van Puijenbroek et al., 2019; Wang et al., 2017). It describes five future societal pathways, characterized by the sustainability (SSP1), middle of the road (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil-fueled development (SSP5), respectively (O'Neill et al., 2017). SSPs provide a unified framework for future scenarios, and the results are comparable across different regions (Zhang et al., 2017). These scenarios have been used to assess the influence of human income on the household discharge of nitrogen (N) and P (van Puijenbroek et al., 2019), the effect of food production and consumption on the N loss from China's food system (Wang et al., 2017), and the impact of sewage system on N loading to surface waters (Wang et al., 2019a). Based on these scenarios, the key determinants of future socioeconomic challenges can be identified.

Lake Baiyangdian (BYD) is the largest shallow lake in northern China. This lake has been suffering from eutrophication as a result of highly disturbed human activities (Tang et al., 2019). For example, Zhao et al. (2011) reported that the monthly average P concentration in the lake water was 0.1–0.6 mg L^{-1} at the periods of 2000–2009, higher than the Chinese environmental quality grade III standards for surface water (0.05 mg L^{-1} for P) (China EPA, 2002). Zhang et al. (2010) reported that the P concentration in the lake water was influenced mainly by river fluxes and population sizes around the lake. Han et al. (2020) analyzed 11 water quality parameters (such as P, N and dissolved oxygen) in the lake from 2006 to 2016, and suggested that Fu River was the dominant pollution contributor for the western part of the lake, and poultry farming, aquaculture, and domestic wastewater from scattered villages were the important pollution source for the eastern part. However, current studies mainly focused on the assessments of historical nutrient conditions in this lake. Little data on future trends in P loading into the lake are available (Yang et al., 2019). Furthermore, the Lake BYD has been recently listed as the key water body of Xiong'an New Area, a state-level new area in the Hebei (HBPC, 2018). According to the government plan, the population size in this new area is projected to increase by 77–121% between 2015 and 2035 (HBPC, 2018). The food production and consumption, and human waste are consequently expected to increase in this region, which may lead to the increase in nutrient exports to the surface waters. Therefore, assessing the future nutrient loading for different socio-economic development scenarios is of significance for the lake's sustainable development.

Therefore, the objective of this study was: 1) to quantify the P loading to the Lake BYD via rivers by the MARINA-lake model; 2) to assess the future trend in P loading based on SSPs; 3) to quantify the critical P loading for the Lake BYD. Linking the results from MARINA-lake model to the PCLake model to analyze to what extent future P loading exceeds critical level. This study will support the understanding of the influence of human activities on P loading into lakes, and provide effective environmental strategies for lake managers.

2. Materials and methods

2.1. Study area

The Lake BYD (115°38′–116°07′ E, 38°43′–39°02′ N) is located at about 100 km southwest of Beijing (Fig. 1a), with an area of 366 km^2 and an average depth of 2 m. This region is a typical temperate semi-arid continental monsoon climate, with average annually temperature, precipitation, and evaporation of 12 °C, 550 mm, and 1637 mm, respectively (Zhao et al., 2011). The BYD basin is consists of eight sub-basins (Fig. 1c). Today most of the rivers have dried up, and Fu River in sub-basin 5 is the only natural inflowing river, which receives wastewater from Baoding City (Table S1, Han et al., 2020; Yang et al., 2016). To maintain the minimum environmental flows, the lake receives water allocations from Yuecheng Reservoir and the Yellow River, with a multi-year (2000–2015) average flux of 2.4×10^8 m^3, which were transferred mainly through Baigouyin River in sub-basin 1 and Xiaoyi River in sub-basin 7 (Tang et al., 2018; Yang et al., 2016; Yi et al., 2020).

2.2. Model implementation

Our study was performed as two main steps (Fig. 2). First, we quantified total phosphorus (TP) loading to the Lake BYD by rivers using the MARINA-Lake model for 2015 and 2050 in five SSPs scenarios. Second, we predicted the critical phosphorus loading (CPL) using PCLake model, and identified the trophic state in different SSPs by comparing the output from the MARINA-Lake model with the critical loads from the PCLake model.

2.2.1. The MARINA-Lake model for river export of phosphorus loading to the lake

2.2.1.1. Model description. In this study, the TP loading to the Lake BYD by rivers at the sub-basin scale were quantified based on the MARINA-Lake model (Fig. 3) (Li et al., 2019; Wang et al., 2019a; Yang et al., 2019). This model is a version of the MARINA 1.0 model specifically focusing on river export of nutrients to lakes (Wang et al., 2019a). The amount of nutrients exported by rivers depend on human activities on land (e.g., agriculture, animal production), hydrology, and basin characteristics (e.g. land use) (Strokal et al., 2016b). Important factors are retention and losses of nutrients in rivers (Strokal et al., 2016b). Rivers export of TP loading to the lake by the sub-basin j (TP_j) was obtained by the follow equation (Fig. 3) (Strokal et al., 2016b):

$$TP_j = RS_j \cdot FE_{riv,j} \tag{1}$$

where RSj is inputs of TP to rivers by point and diffuse sources from sub-basin j (kg $year^{-1}$), $FE_{riv,j}$ is the fraction of TP exported to the river mouth of the sub-basin.

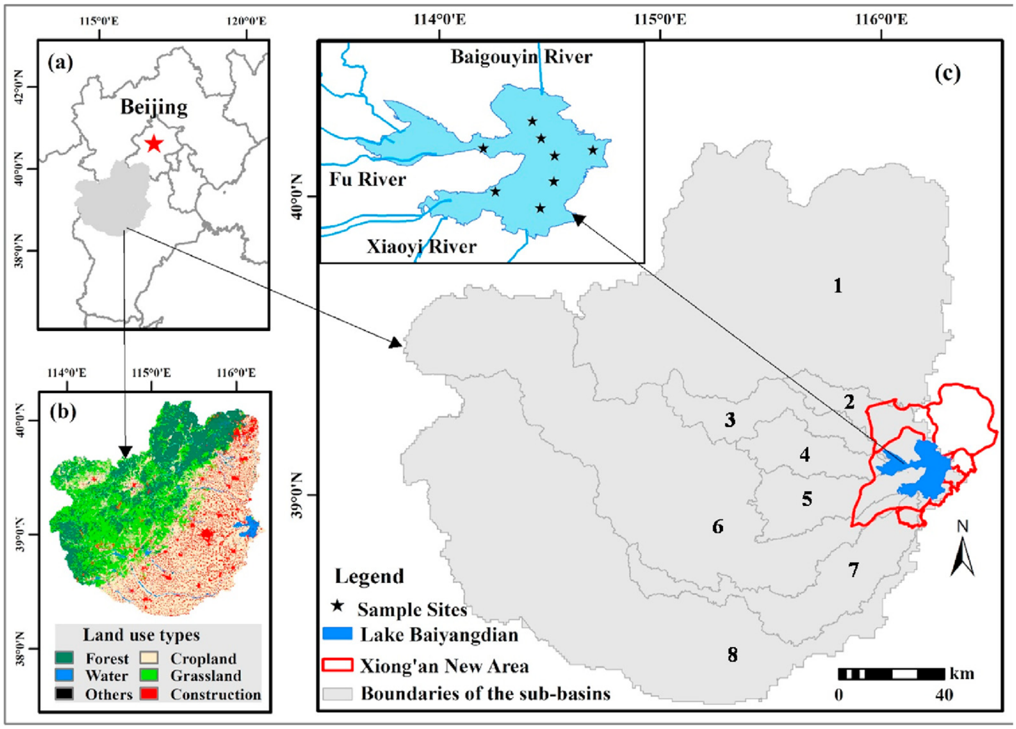

Fig. 1. Location of the study area (a), its land use type (b), and its watershed classification and sample sites in the lake (c).

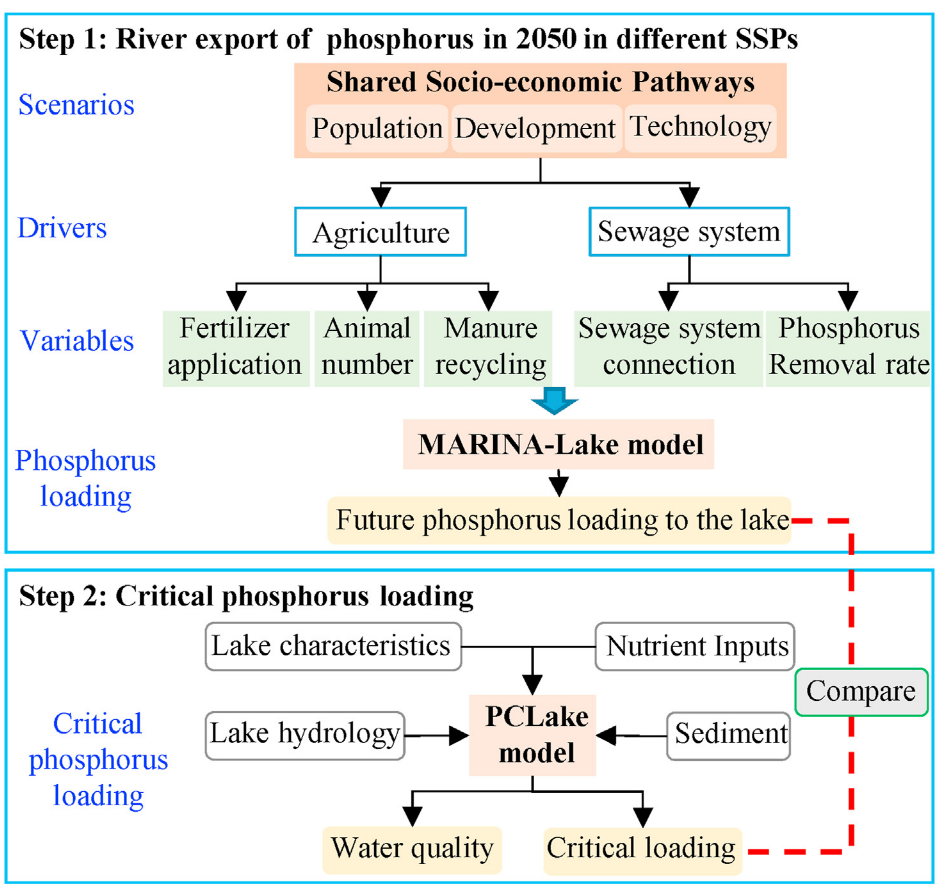

Fig. 2. Integrated analysis diagram of this study.

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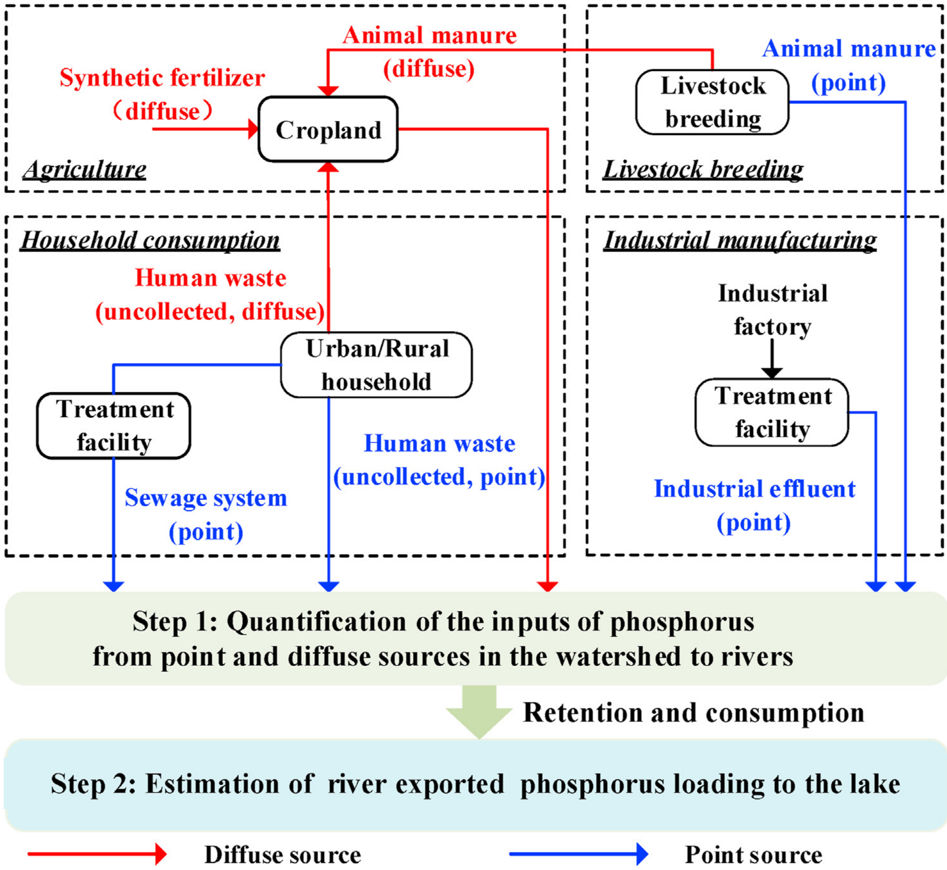

Fig. 3. Estimation of phosphorus loadings from rivers to Lake Baiyangdian, China.

In first step, RS_j was calculated by the following equation:

$$RS_j = (P_{S,j} + P_{H,j} + P_{A,j} + P_{I,j}) + (D_{H,j} + D_{A,j} + D_{S,j}) \tag{2}$$

where $P_{S,j}$, $P_{H,j}$, $P_{A,j}$, and $P_{I,j}$ are the TP inputs from point sources of human waste from sewage system, directly discharged human waste, direct discharges of animal manure, and industrial effluent from sewage system in the sub-basin j to rivers, respectively (kg year^{-1}); $D_{H,j}$, $D_{A,j}$, and $D_{S,j}$ are the TP inputs from diffuse sources of human waste from urban and rural household as a fertilizer without treatment facilities connections, use of animal manure in cropland, and use of synthetic fertilizer in cropland in the sub-basin j to rivers, respectively (kg year^{-1}). It should be noted that atmospheric P deposition and soil leaching were not included as a part of the diffuse source due to their low contribution in the Baiyangdian catchment (Zhang et al., 2020). The detailed calculation processes are given in Supporting Information.

In second step, $FE_{riv,j}$ was quantified as:

$$FE_{riv,j} = (1 - D_j) \cdot (1 - L_j) \cdot (1 - FQrem_j) \tag{3}$$

where D_j and L_j are the fractions of TP retained in dammed reservoirs and in the river system, respectively, and were defined derived from the MARINA model for the Haihe Baisn (Strokal et al., 2016b); FQ_{remj} is the fraction of TP removed from the river system by water consumption (Table S1, Li et al., 2019; Strokal et al., 2016b).

2.2.1.2. Data source. The county-level data sets such as population, fertilizer application, animal numbers, sown area, industrial production were obtained from local statistical yearbooks and national economic and social statistical bulletins. In order to change model inputs from county-level to sub-basin scale, an area-weighted method was used: weighting by the area of the county lying within each sub-basin (Zhang et al., 2015). The fraction of connected to sewage systems and P remove efficiency of sewage systems were derived from MEP (2013) and (Morée et al., 2013). The river discharge data were obtained from Baoding Hydrology Bureau. Other parameters were referred to the NUFER model, MARINA model, and ECM model, etc. (Li et al., 2019; Wang et al., 2019b; Yang et al., 2019; Zhang et al., 2020). Details of model parameters are shown in Table S2-S6.

2.2.2. The shared socio-economic pathways for prediction of phosphorus loading

The Lake BYD has been listed as the core water body for the development of the state-level Xiong'an New Area. Urbanization and food production in this new area are expected to continue to change fast, which will likely affect nutrient inputs to water systems (Wang et al., 2019a). According to Wang et al. (2017), we adopted the five SSPs to analyze the future trends of the TP loading to the Lake BYD, with a focus on agriculture and sewage system. The five SSP storylines for China were developed by Wang et al. (2017), in which the SSP1, SSP2, SSP3, SSP4, and SSP5 assume socio-economic development in the sustainable, moderate, fragmentize, unequal, and conventional ways, respectively. SSP1 assumes a slowly population growth, a more sustainable food production with low meat-diets, and improved in technologies and environmental policies. SSP2 assumes a moderate population growth, a moderate consumption of meat, and some improvements in technologies for recycling of animal manure and human waste. SSP3 assumes a fast population growth, an increasing preference for meat-diets, and limited effectiveness of technologies and environmental policies. SSP4 assumes inequalities in different regions. People in low, and high-income regions will have a high, and low preference for meat diets, respectively. SSP5 assumes a low population growth but a fast urbanization, an increasing preference for meat-rich diets, and a relatively high technologies and strict environmental policies. Based on these characters, model variables were defined (Table 1). In line with the establishment of Xiong'an new area, the model variables (such as animal and people numbers) were adjusted based on “Outline of Plan for Xiong'an New Area of Hebei Province” (HBPC, 2018).

2.2.3. The PCLake model for critical phosphorus loading

2.2.3.1. Model description. The CPL in the Lake BYD was estimated by the PCLake model (Kong et al., 2017a). This model has been designed to simulate the main nutrient dynamics of shallow lakes in response to eutrophication, and has been used to calculate the CPL for a number of lakes, such as Loosdrecht Lakes, the Netherland (Janse et al., 2008), Lake Dianchi (Li et al., 2019), and Lake Chaohu, China (Kong et al., 2017b). The CPL is lake specific and depend on lake characteristics, such as water depth and flux (Li et al., 2019). In general, dynamic simulations at a period of 20 years are sufficient for the model to reach the equilibrium situation (Janse et al., 2008). To determine the CPL for eutrophication and oligotrophication in the Lake BYD, we run the PCLake model from initial states of both turbid and clear lake. Based on the output results reached equilibrium, the CPL in the Lake BYD can be determined by the loading-response curve, which is defined as the response of phytoplankton (i.e. chlorophyll-a) to a range of P loadings (Janssen et al., 2017; Li et al., 2019). There are three types of loading-response curve: linear, non-linear, and non-linear with hysteresis. Lakes characterized by the third type have two switchpoints in terms of CPLs, one for eutrophication and one for oligotrophication. (Janssen et al., 2017).

2.2.3.2. Model calibration. In this study, the PCLake model was calibrated based on a seven-year (2004–2010) TP observation

Table 1
Model variables for MARINA-Lake for 2015 and 2050 in five SSPs scenarios. P refers to phosphorus. The percentages refer to the growth rates between 2015 and 2050.

Model variables			2015[a]		Scenario assumption[a]				
					SSP1	SSP2	SSP3	SSP4	SSP5
					Sustainability development	Middle of the road	Fragmentation	Inequality	Conventional development
Agriculture	Animal number (10^4 individuals)[b]	Sheep and goat	472	Other counties	+17%	+35%	+62%	+44%	+44%
				Xiong'an	halve the growth rate of three counties for Xiong'an				
		Pig	1199	Other counties	+17%	+35%	+62%	+44%	+44%
				Xiong'an	halve the growth rate of three counties for Xiong'an				
		Horse and cows	108	Other counties	+16%	+32%	+58%	+42%	+42%
				Xiong'an	halve the growth rate of three counties for Xiong'an				
		Poultry	14971	Other counties	+17%	+35%	+62%	+44%	+44%
				Xiong'an	halve the growth rate of three counties for Xiong'an				
	P in manure excretion (kg ind^{-1} yr^{-1})	Sheep and goat	1.36		−30%	−20%	0%	−10%	−20%
		Pig	0.34		−30%	−20%	0%	−10%	−20%
		Horse and cows	8.16		−30%	−20%	0%	−10%	−20%
		Poultry	1.46		−100%	−100%	0%	−10%	−100%
	Manure discharge to water (%)	Sheep and goat	60		−100%	−57%	+14%	0%	−37%
		Pig	35		−100%	−57%	+14%	0%	−37%
		Horse and cows	25		−100%	−57%	+14%	0%	−37%
		Poultry	45		−100%	−57%	+14%	0%	−37%
	Synthetic fertilizer application (kton)[b]		370	Other counties	−100%	−49%	+26%	−10%	−28%
				Xiong'an	−100%	halve the growth rate of three counties for Xiong'an			
Sewage system (SS)	Urban	Population (10^4 person)	1540	Other counties	+48%	+32%	+14%	+43%	+48%
				Xiong'an	total population increase 5 times, urban population ratio is 100% for Xiong'an				
		Population connected to SS (%)[c]	54		90 (100 for Xiong'an)	78	62	82	90 (100 for Xiong'an)
		P removal rate (%)[c]	45		80	72	45	76	80 (90 for Xiong'an)
	Rural	Population (10^4 person)	723	Other counties	−65%	−43%	−19%	−66%	−65%
				Xiong'an	rural population ratio is 0% for Xiong'an				
		Population connected to SS (%)[c]	4		20 (60 for Xiong'an)	10	4	4	20 (60 for Xiong'an)
		P removal rate (%)[c]	10		45	30	19	32	53

[a] The datasets on agriculture and sewage system are available for 2015 according to the statistic yearbooks, some current food production and environmental policies, and related references (BDESB, 2016; MDRC and MOHURD, 2016; MEP and MOF, 2017; Wang et al., 2017; Yang et al., 2019). The growth rates between 2015 and 2050 on food system, and urban and rural populations were set according to the SSPs for the China's food system (Wang et al., 2017).

[b] We assumed that would be a rapid urbanization in line with the establishment of Xiong'an new area. Based on the storylines of SSPs, we assumed the animal numbers and the synthetic fertilizer application would be reduced half (Wang et al., 2017; Yang et al., 2019).

[c] The percentage of urban and rural populations connected to SS, and P remote rates in SSP1 were set referring to National urban sewage treatment and recycling planning in 13th Five-Year (2015–2020)” (MDRC and MOHURD, 2016) and the comprehensive improvement of the national rural environmental planning of 13th Five-Year” (MEP and MOF, 2017). Combined with the SSPs for the China's sewage system (van Puijenbroek et al., 2019), the connection rates and removal rates in other four SSPs were set. Considering rapid urbanization of Xiong'an, the percentage of the population connected to SS and P removal rate would be increased in SSP1 and SSP5, the numbers were set according to Yang et al. (2019).

dataset. This period of time was selected because the lake level was stabilized at approximate 7 m from 2004 to 2020 (Yi et al., 2020). The monthly TP concentration levels at eight water sampling sites of Lake BYD (Fig. 1c) were provided by the Research Institute of Environmental Protection of Baoding City (China). Other forcing functions, such as water temperature, flux, and wind, were detailed in Table S7. The observation dataset in 2004 was used and duplicated for the first fourteen year of simulation (Kong et al., 2017a). And the observation dataset in 2005–2010 were used for the last six years of the model simulation. The model outputs of the last seven years were considered as the simulation results, which were compared with the field data for the model calibration. Calibration results were evaluated by correlation coefficient (R_p^2), Nash coefficient (R_{NSE}^2), and normalized root mean square error (RSR) (Moriasi et al., 2007). The R_p^2, R_{NSE}^2, and RSR of TP were 0.34, 0.25, and 0.30, respectively (Fig. 4). These evaluation indicators were all within acceptable ranges, indicating that PCLake can be used to predict the CPL of the Lake BYD.

3. Results

3.1. TP loading to the lake BYD in 2015

In the basin, only the rivers in sub-basins 1, 5, and 7 have an flow to the Lake BYD (Han et al., 2020; Tang et al., 2018; Yi et al., 2020). Thus, these three sub-basins were importantly studied (Fig. 1). The TP loading from three sub-basins to the Lake BYD was 276 ton in 2015 (Fig. 5a). In detail, sub-basins 1, 5, and 7 contributed to 23%, 45%, and 32% of the TP loading, respectively, suggesting that sub-basin 5 was the dominant contributor. On the whole, the TP loading was derived mainly from point sources in rivers, including directly discharged human waste (27%), direct discharges of animal manure (36%), and sewage system (29%) (Fig. 5b). In terms of spatial distribution, the sub-basin 5 was characterized by the high contribution of the sewage system (45.9%) to its TP loading (Fig. 6), which is different from the TP composition in the sub-basins 1 and 7.

3.2. Future TP loading to the lake BYD

Here five SSPs with a focus on agriculture and sewage system were used to analyze the characteristics of the TP loading to the Lake BYD in 2050. The river export of TP to the Lake BYD in the scenarios of SSP1, SSP2, SSP3, SSP4, and SSP5 are 121, 179, 371, 272, and 169 ton, respectively (Fig. 5a). Compared with the baseline scenario (2015), the TP loading is increased only at the SSP3 scenario, and decreased highest at the SSP1 scenario. The TP loading in the SSP2 scenario is closed to that in the SSP5 scenario. For these five scenarios, the sub-basin 5 is still the dominant contributor for the TP loading to the Lake BYD.

On the whole, point sources will still be the dominant contributor for the river export of TP to the Lake BYD in 2050 (Fig. 5b). Compared with the baseline scenario, the source composition is changed highly in the SSP1 scenario, in which sewage system contributes to 72% of the TP loading. The sewage system will be the dominant contributor to the TP loading in the scenarios of SSP2 and SSP5, and the directly discharged animal manure will be the major contributor in the scenarios of SSP3 (40%) and SSP4 (46%). These results indicated that the composition of the TP loading to the Lake BYD will be changed by the future socioeconomic pathways.

The spatial distribution of the TP source composition was analyzed at the sub-basin scale (Fig. 6). The TP export of the sub-basin 5 in the five SSPs will still be derived mainly from the sewage system. For the sub-basins 1 and 7, the main source of TP export will change from the directly discharged animal manure in 2015 to the sewage system in the scenarios of SSP1, SSP2 and SSP5. It has been observed from the land-use types that the sub-basin 5 was flowing through the urban areas, and the sub-basins 1 and 7 were flowing through the rural areas (Fig. 1b). These results indicate that the composition of river exported TP in rural areas will more influenced by the future socioeconomic development than those in urban areas.

3.3. Critical P loading in the lake BYD

The response of phytoplankton (denoted by chlorophyll-a concentration) to the TP loading in the Lake BYD was characterized by the non-linear curve with hysteresis (Fig. 7). Due to the abrupt character of the regime shifts, the CPL in the Lake BYD defined as the switch points between eutrophic and oligotrophic states (Janssen et al., 2017). Moreover, the CPL depends on the previous state in which the lake was either 'clear' or 'turbid'. As shown in Fig. 7, the CPL for the Lake BYD was 2.06 mg P m^{-2} d^{-1} (as measured per lake area) for eutrophication and 0.84 mg P m^{-2} d^{-1} for oligotrophication. If the Lake BYD was initially in the oligotrophic state, it would change into the eutrophic state when the TP loading of higher than 2.06 mg P m^{-2} d^{-1} (denoted by the dashed black line). Otherwise, if the Lake BYD was initially in the eutrophic state, it would change into the oligotrophic state when the TP load of lower than 0.84 mg P m^{-2} d^{-1} (denoted by the solid black line). The Lake BYD would be characterized by the transition state at the TP loadings of 0.84–2.06 mg P m^{-2} d^{-1}.

Based on the above section results, river export of TP loading to the Lake BYD in 2015 was 2.09 P m^{-2} d^{-1}, which just exceeded the CPL for eutrophication. The TP loadings to the Lake BYD were corresponding to 0.91, 1.34, 2.78, 2.03, and 1.26 P m^{-2} d^{-1} in the scenarios of SSP1, SSP2, SSP3, SSP4, and SSP5, respectively. This indicated that the Lake BYD would be characterized by the eutrophic state in the SSP3 scenario, and by the transition state in the scenarios of SSP1, SSP2, SSP4 and SSP5.

4. Discussion

4.1. Strengths and uncertainties

This study provides a quantitative assessment on the TP loading to the Lake BYD and its implication for the lake's trophic state based on combination of the MARINA model and PCLake model, for current situation and for future scenarios. Such information is vital for identifying eutrophication issues, and formulating specific policies for lake restoration (Li et al., 2019; Wang et al., 2019b). Our results

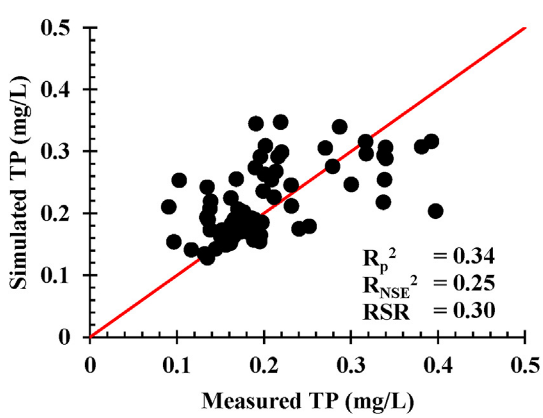

Fig. 4. Correlation between the simulated and measured concentrations of total phosphorus (TP) in Lake Baiyangdian, China.

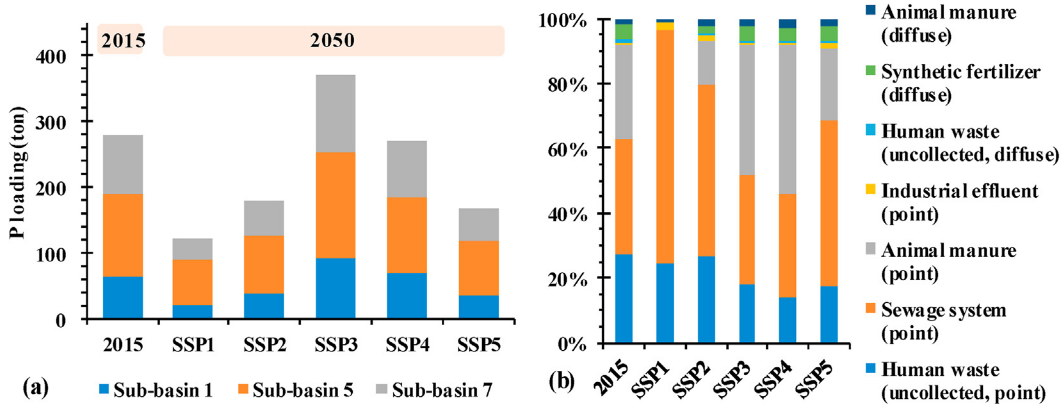

Fig. 5. River export of total phosphorus (a) and its composition by source (b) to the Lake Baiyangdian in 2015 and 2050 with five SSPs scenarios.

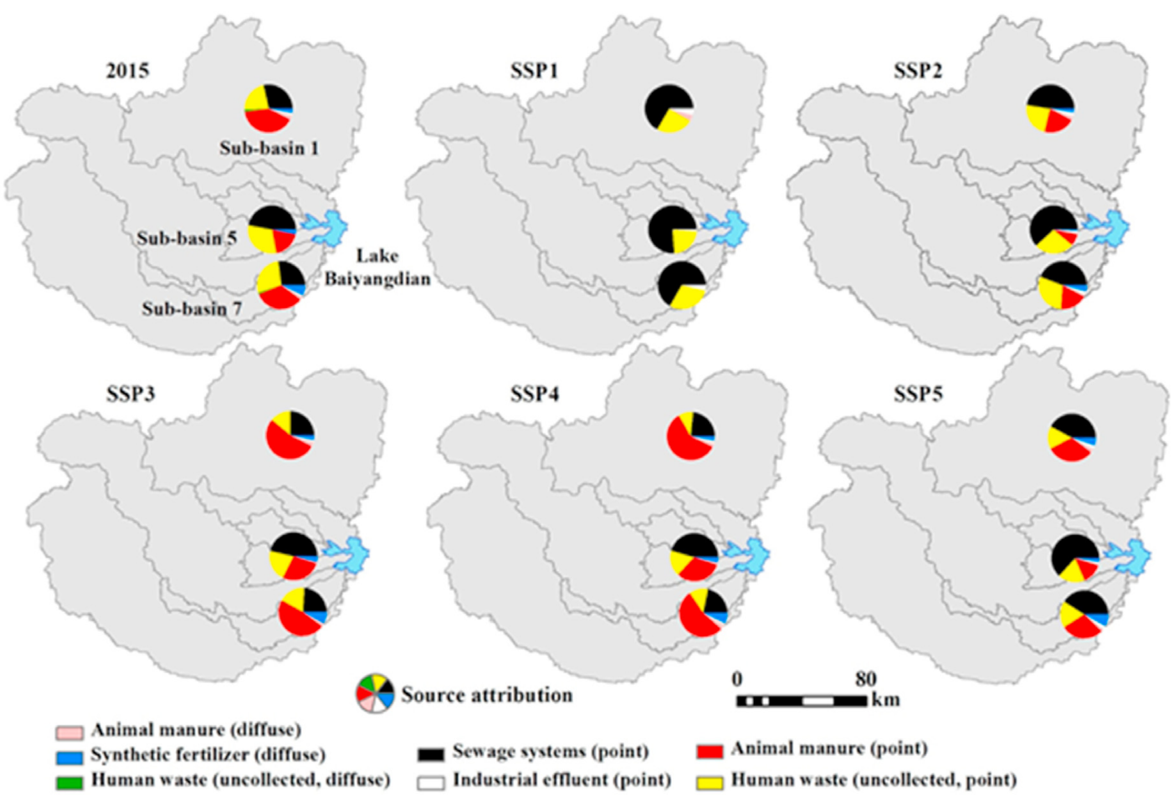

Fig. 6. Spatial distribution of the phosphorus sources in the three sub-basins of the Baiyangdian Catchment in 2015 and 2050.

showed that the TP loading to the Lake BYD by rivers in 2015 was 276 ton. That was comparable with the measured TP loading (268 ton) (Table S8), but was lower than that (405 ton) in 2007 (Zhu, 2011). This may be related with the operation of wastewater treatment plants (WWTPs). It has been reported that 27 WWTPs were starting to run in the Baiyangdian Basin since 2008, decreasing the TP concentrations in the rivers (MEP, 2013). Compared with the main lakes in China (Fig. 8 and Table S9), the river export of TP to the Lake BYD was in a relatively low level in China. Besides, the river export of TP to the northern China lakes were lower than those to the southern China lakes (Fig. 8). This may be related with the lower river flux in the northern China. Thus, the river flux may be one of important factors for influencing the river export of TP to the lake.

As for the source composition, the sub-basin 5 was the dominant contributor for the TP loading to the Lake BYD. It has been reported that the multi-year (2006–2016) water quality index (including TP) in monitoring stations of the sub-basin 5 were about three times higher than those in the sub-basins 1 and 7 (Han et al., 2020), showing the long-term higher concentrations of TP in river waters of the sub-basin 5. Therefore, the sub-basin 5 should be listed as the important sources for the TP loading. Compared with the sub-basins 1 and 7, the sub-basin 5 has a higher contribution of the sewage system to the TP loading. This may be related with the discharge of domestic wastewater from Baoding City, with annually fluxes of 1.2×10^8 m^3 (Yang et al., 2014). It has been reported that households are the dominant point source for TP in urban areas (van Puijenbroek et al., 2019).

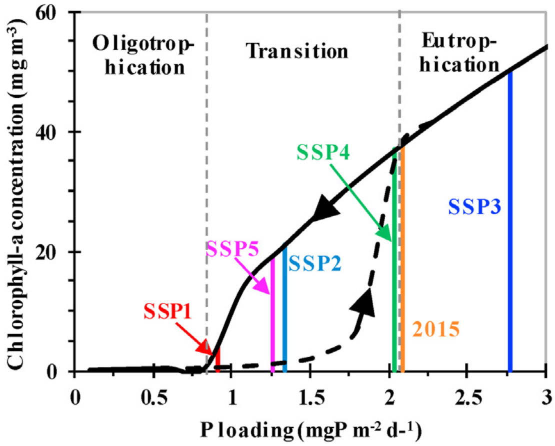

Fig. 7. Response of phytoplankton (i.e., the chlorophyll-a concentration) to a range of phosphorus loadings in Lake Baiyangdian, China. Dashed black line indicates eutrophication process (starting from an oligotrophic state with increasing P loadings); solid black line indicates oligotrophication process (starting from a eutrophic state with decreasing P loadings).

This study is also the first study to analyze the critical nutrient loads in the Lake BYD. According to the loading-response curve (Fig. 7), the Lake BYD has two CPLs: 2.06 mg P m^{-2} d^{-1} for eutrophication (CPLE) and 0.84 mg P m^{-2} d^{-1} for oligotrophication (CPLO). The CPLs in the Lake BYD were comparable with those in shallow lakes in the Netherlands (CPLE: 2.0–5.0 mg P m^{-2} d^{-1}; CPLO: 0.6–1.0 mg P m^{-2} d^{-1}) (Janse et al., 2008), Lake Chaohu (CPLE: 2.33 mg P m^{-2} d^{-1}; CPLO: 1.1 mg P m^{-2} d^{-1}) (Kong et al., 2017a), and Lake Caohai (northern Lake Dianchi), China (CPLE: 2.02 mg P m^{-2} d^{-1}; CPLO: 0.34 mg P m^{-2} d^{-1}) (Li et al., 2019). The TP loading to the Lake BYD in 2015 was 2.09 mg P m^{-2} d^{-1}, which was close to the CPLE, indicating that Lake BYD was near the eutrophic state. This result was consistent with previous field study in 2015 and 2016, in which 69.1% of the Lake BYD area was in a slight eutrophic state, and 29.3% was in a mesotrophic state (Tang et al., 2019).

Inevitably, all model studies have their uncertainties. These uncertainties often related to model inputs and parameters. Most of the inputs in MARINA-Lake model were derived from statistics (e.g., animal number, synthetic fertilizer application), peer-reviewed papers, as well as published models (e.g., GLOBAL-NEWS2, MARINA, and ECM), which have widely used in multiple regions and watersheds (Mayorga et al., 2010; Li et al., 2019; Zhang et al., 2020). We analyzed the sensitivity of the MARINA-Lake model outputs to changes in several important model inputs and parameters (Fig. S1). The modeled river export of TP was relatively sensitive to urban population, manure P excretion, and animal number. Most of these inputs were derived from statistical yearbooks and published papers, which were regarded as the most reliable data source (Wang et al., 2018). There may be some uncertainty for river discharge because we assumed no changes in future river fluxes. This is because water volume of the Lake BYD mainly depends on the inflow of Fu River in sub-basin 5 and the external water replenishment, which were transferred mainly though rivers in sub-basin 1 and sub-basin 7 (Yang et al., 2014; Tang et al., 2018; Xu et al., 2020). The Fu River contains a large quantity of domestic sewage from upstream cities, and its future change is considered in the scenario analysis. Moreover, the multi-year averaged water discharge of ecological water replenishment stays relatively stable since 2004 (Yang et al., 2018). About 2.55×10^8 m^3 and 1×10^8 m^3 of water would be transferred from the Yellow River and the South-to-North Water Diversion Project into the lake, respectively (Yi et al., 2020). With respect to the uncertainties in PCLake model,

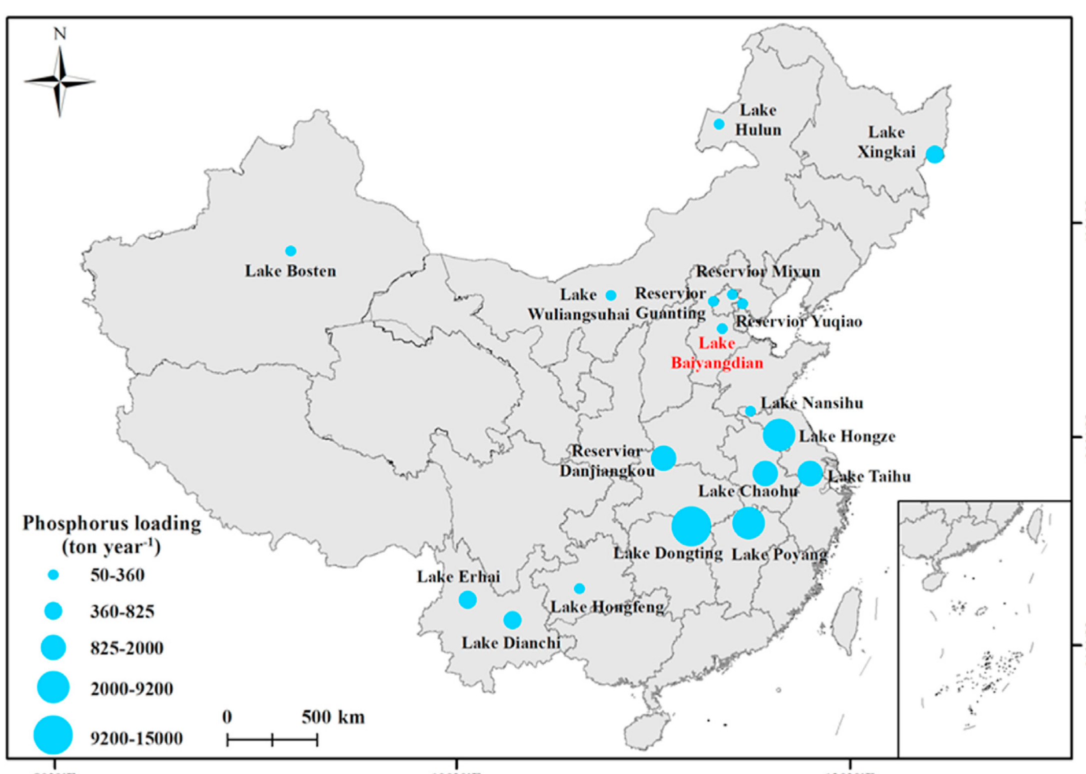

Fig. 8. Spatial distribution of phosphorus loadings to the main lakes of China (the detailed loadings were given in Table S7).

most of model inputs and parameters were derived from statistical datasets, published papers, and default parameters. This model is developed mainly used to predict CPL and has been calibrated for 43 lakes in the Netherlands (Janse et al., 2008; Kong et al., 2017a). Thus, we believed that these uncertainties will not have a great influence on the core information of the research results.

4.2. Implication for future nutrient management

We combined the MARINA-Lake model with PCLake model to know the gap between future TP loadings and CPL. This comparison would provide a better understanding of the effects of socio-economic development on nutrient loads and identify opportunities to reduce the gap. Compared with the baseline scenario, the TP loading to the Lake BYD was increased by 34.4% in the SSP3 scenario, which secure the food supply at the expense of environmental degradation (O'Neill et al., 2017; Wang et al., 2017). In this scenario, people have a high preference for meats, and animal production increases faster than in the other scenarios (Table 1), which will emit more animal manure (Bai et al., 2018; Zhang et al., 2020). This leads to the increased TP export to the rivers, and finally to the lake. The lowest TP loading was observed in the SSP1 scenario, which assumes a sustainable way for the food system development (Wang et al., 2017). In this case, vegetables, fruits, and bean products will take place of meats in the food system, decreasing the meat demand and thus the amount of animal manure. The above scenario results, therefore, indicated that animal manure would affect the TP export to the surface waters. In China, more than two-thirds of nutrients in the northern rivers and 20–95% of nutrients in central and southern rivers were contributed by animal manure (Strokal et al., 2016a).

The TP loading was characterized by the similar level at the scenarios of SSP2 and SSP5 (Fig. 5a), which represent the moderate and high growth rates of urban population, respectively (O'Neill et al., 2017). To meet the food demand, animal production develops in a moderate rate at the SSP2, and in a high rate at the SSP5, in both of which animal manure will be recycled effectively (Table 1). Thus the contribution of the directly discharged animal manure to the TP loading was decreased about half at these scenarios compared to the baseline scenario. This result indicated the importance of collecting animal manure. Similarly, the prohibition in direct discharge of animal manure was reported to be the most effective measure to decrease the TP emission in the Haihe Basin, China (Zhao et al., 2019).

The TP loading in the baseline scenario was comparable with that in the SSP4 scenario, which is characterized by the inequality pathway (Wang et al., 2017). In this scenario, the small scale of animal farms will be widely distributed in the rural regions, and the animal manure will be discharged directly to surface waters, which will be a significant source for the TP loading (Wang et al., 2018). Therefore, the animal manure discharged especially from rural areas should be effectively collected.

At the sub-basin scale, the main source for river exported TP from rural areas may be changed from the directly discharged animal manure to the sewage system in the scenarios of SSP1, SSP2, and SSP5. This may be related with the low-moderate demand of animal products in the scenarios of SSP2 and SSP5 (Bai et al., 2018), and the high collection rates of animal manure in SSP5 scenario (Wang et al., 2017).

The future trends of trophic state in the Lake BYD were also analyzed (Fig. 7). Due to the relatively high P loadings in the SSP3 and SS4 scenarios, the Lake BYD would be in or close to the eutrophic state. It has been observed that the directly discharged animal manure were their dominant source (Fig. 5b). In these scenarios, the animal manure should be collected or recycled effectively to recovery the lake water to the oligotrophic state. The Lake BYD would be in the transitional state in the scenarios of SSP1, SSP2, and SSP5, in all of which sewage systems were their major source. To restore the lake water to the oligotrophic state, the P remove rates should be further increased, especially in the rural areas.

Noting that the directly discharged animal manure and sewage system are the significant source for the TP loading to the Lake BYD. Therefore, more efforts were necessary to 1) recycle manure and reduce direct discharge of animal manure, 2) improve connection rate with sewage systems and nutrient treatment technologies.

5. Conclusions

The TP loading to the Lake BYD by rivers in 2015 was 276 ton, which was in a relatively low level in lakes from China. These nutrients were derived mainly from the point sources, including direct discharge of human waste and animal manure, and sewage system. The TP loading in 2050 will be 121, 179, 371, 272, and 169 ton in the scenarios of SSP1, SSP2, SSP3, SSP4, and SSP5, respectively. Sewage system would be the dominant contributor to the TP loading in the scenarios of SSP1, SSP2, and SSP5, and direct discharge of animal would be the major contributor in the scenarios of SSP3 and SSP4. Thus point sources will remain the main source for the TP loading to the Lake BYD, and should be importantly considered in the future nutrient management.

The response of phytoplankton to the TP loading in the Lake BYD was characterized by the non-linear curve with hysteresis. The Lake BYD have two CPLs: 2.06 mg P m^{-2} d^{-1} for eutrophication and 0.84 mg P m^{-2} d^{-1} for oligotrophication. In future, the Lake BYD would be in the eutrophic state only in the scenarios of SSP3. Therefore, the SSP3 should be avoided in the future development pathways.

CRediT authorship contribution statement

Xiaoxin Zhang: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Yujun Yi:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Ying Yang:** Conceptualization, Investigation, Writing – review & editing. **Hongxi Liu:** Conceptualization, Writing – review & editing. **Zhifeng Yang:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126537.

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