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The future of Chinese rivers: Increasing plastics, nutrients and *Cryptosporidium* pollution in half of the basins

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ABSTRACT

Many Chinese rivers are polluted with multiple pollutants. Therefore, this study aims to quantify the annual inputs of nutrients, macro-and microplastics, and *Cryptosporidium* (a pathogen) to 395 Chinese rivers from agriculture and urbanization-related sources during 2010–2050 following the storyline of Shared Socio-economic Pathway 3 and Representative Concentration Pathway 8.5. Our model estimates that multiple pollutants in Chinese rivers are projected to increase by 41–88 % between 2010 and 2050. Central, eastern, and southern Chinese sub-basins may be more polluted in the future. In half of the sub-basins, at least two types of pollutants are expected to increase by over 50 % during 2010–2050. By 2050, nutrients and plastics in rivers are projected to increase by 70 % due to urbanization. For nutrients and *Cryptosporidium* in rivers increases of 49–88 % are projected, due to agricultural activities. In contrast, water is expected to get cleaner in some western sub-basins by 2050 because of fewer human activities. Our insights about multiple pollutants in Chinese rivers could help prioritize water pollution reduction strategies for sub-basins.

1. Introduction

China is one of the most water-scarce countries in the world (Ma et al., 2020). Water pollution is one of the contributors to water shortage, which challenges sustainable development in Chinese society and increases competition for water allocation among different sectors (Qin et al., 2019). Urbanization and intensification of agriculture are considered the dominant contributors to water pollution and lead to multiple pollutants in rivers from point and diffuse sources (Evans et al., 2019; Lu and Villa, 2022; Ma et al., 2020; MacDonald et al., 2016; Sinha et al., 2017; Vliet et al., 2021). Point sources of water pollution are, for instance, sewage systems discharging nutrients, chemicals, microplastics, and pathogens to rivers (Hofstra et al., 2013; Strokal et al., 2023; Siegfried et al., 2017, 2023a; Yuan et al., 2022). Pollutants in water from diffuse sources of pollution often result from runoff. For instance, the use of livestock manure on land is often a diffuse source of nutrients and pathogens (e.g., *Cryptosporidium*) in rivers because surface runoff brings these pollutants from fertilized land (Li et al., 2022). Mismanaged solid waste is a diffuse source of plastics in rivers (Lebreton and Andrady, 2019; Zhang et al., 2024). Crop production is also considered a diffuse source of plastics (e.g., mulching and greenhouse) and nutrients (e.g., fertilizer application) in rivers (Wang et al., 2020; Zhang et al., 2021).

Multiple pollutants may be retained in the river network once they enter the rivers (Hayes et al., 2023; Li et al., 2018; Manning et al., 2020; Méndez-Hermida et al., 2007). Some pollutants will be transported and ended up in the coastal waters. The transport of pollutants can be influenced by the anthropogenic (e.g., land use change), hydrodynamic (e.g., water flow), and climate factors (e.g., temperature). All of this may hinder or speed up the movement of pollutants from land to rivers (Haberstroh et al., 2020; Zhang et al., 2023). Studies indicate that many Chinese rivers experience pollution with nutrients, plastics, and *Cryptosporidium* (a pathogen) (Li et al., 2022; Wang et al., 2020, 2019a; Wijnen et al., 2019). These pollutants have diverse impacts on society and nature including harmful algal blooms (nutrient-induced), diarrhea (*Cryptosporidium*–induced), damage infrastructure

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(macroplastics-induced), and accumulation of plastics in the food web (Azeem et al., 2021; Honingh et al., 2020; Ragusa et al., 2021; Wanget al., 2019a; Waring et al., 2018). As a result of river pollution, the availability of clean water decrease for society and nature (Ma et al., 2020; MEE, 2020; Wu, 2020).

Water pollution may increase under global change in the future as a result of increasing urbanization (more wastewater discharge and waste production) (Lebreton and Andrady, 2019; Strokal et al., 2021) and intensifying agriculture (more food production leading to more agricultural inputs) (Evans et al., 2019). Socio-economic development and climate change may influence water pollution. Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways (RCPs) provide potential storylines for understanding the future changes in water pollution (O'Neill et al., 2014; Vuuren et al., 2011). For instance, Beusen et al. (2022) pointed out that central and eastern China are projected to be hotspots of nutrient pollution by 2050 under SSP1 and SSP2. Strokal et al. (2021) applied five SSP storylines to estimate multiple pollutants to rivers from urbanization-related sources in the 21st century for 10,226 sub-basins in the word. Wang et al. (2020) quantified nutrient exports by 12 Chinese rivers to seas with different combinations of SSPs and RCPs in 2050. Their study showed higher river exports of nutrients in 2050 according to SSP3-RCP8.5 compared to the other combinations. So far, scenarios focusing on inputs of multiple pollutants to rivers from both food production and urbanization under climate change and socio-economic developments for China are hardly available, hindering the formulation of effective reduction strategies.

A spatially explicit future assessment of multiple pollutants in Chinese rivers that accounts for urbanization and agricultural drivers is currently lacking. MARINA (Model to Assess River Inputs of pollutaNts to seA) is a large-scale water quality model that quantifies water pollution at the sub-basin scale for multiple pollutants such as nutrients, and plastics. Several versions of MARINA have been developed and applied at different scales and for different purposes across the world (Chen et al., 2022; Li et al., 2022; Strokal et al., 2023, 2021, 2023b, 2022; Wang et al., 2020). The MARINA models differ in pollution sources (sewage systems, and crop and animal production) and scales (e.g., global, Europe, China), and not all versions have future analyses considering the impacts of socio-economic developments and climate change.

Therefore, the aim of this study is to quantify the annual input of nutrients, macro- and microplastics, and *Cryptosporidium* (a pathogen) to 395 Chinese rivers from agriculture and urbanization related sources (sewage systems, mismanaged solid wastes) during 2010–2050. We selected the storyline of combined SSP3 with RCP8.5 as an example to show a "fragmentated world" with high global warming and without any future environmental improvements. The results of our study aim to highlight the urgent need for proactive actions to mitigate future water pollution. Our insights help better understand the changes in future water pollution in China associated with poor environmental management under high global warming. Thus, our insights could be used to explore effective reduction strategies that are targeted at multiple pollutants, sub-basins, and their sources. Moreover, our integrated multi-pollutant modeling approach can be used to assess future water pollution, and inspire policy makers for effective multi-pollutant water management.

2. Materials and methods

2.1. Modeling multiple pollutants in rivers

We developed a new version of the MARINA-Multi (China-1.0) model to quantify future inputs of multiple pollutants to rivers from agriculture and urbanization-related sources. This was done by integrating the modeling approaches of the MARINA-Multi (Global-1.0) (Strokal et al., 2021), MARINA-Multi (Global-2.0) (Li et al., 2022), MARINA-Nutrients (Global-1.0) (Wang et al., 2024) and MARINA-Plastics (China-1.0) (Li et al., 2023) models (Fig. 1). Below, we first briefly describe these four versions of the MARINA models. Then, we describe how we integrate existing MARINA to the MARINA-Multi (China-1.0) model. All detailed equations, data sources and data processing of our intergrated MARINA-Multi (China-1.0) are presented in the Supplementary Information Tables S1–S3.

- **Four existing versions of the MARINA models**

MARINA-Multi (Global-1.0) is a point source-specific model, which is developed based on existing approaches for nitrogen (N), phosphorus (P), microplastics, triclosan, and *Cryptosporidium* for 10,226 sub-basins worldwide (Hofstra et al., 2013; Siegfried et al., 2017; Strokal et al., 2016; Wijnen et al., 2017, 2019). Point-sources input of pollutants are related to urbanization, including sewage systems and open defecation (Fig. 1). Sewage effluent is the result of human waste that is collected by sewage systems and treated in wastewater treatment plants. Open defecation is a direct discharge of human feces and urine into rivers. MARINA-Multi (Global-1.0) calculates the annual inputs of pollutants from sewage systems as a function of the human excretion rates, consumption rates of pollutants per capita, rural and urban population connected to sewage systems, and pollutant removal fractions during wastewater treatment. Pollutants entering rivers from open defecation are calculated as a function of the population practicing open defecation in urban and rural areas, and the per capita human excretion rates.

MARINA-Multi (Global-2.0) mainly focused on multiple pollutants in rivers from livestock production for 10,226 sub-basins, globally (Fig. 1). MARINA-Multi (Global-2.0) is developed based on modeling approaches for nutrients, and *Cryptosporidium* (Chen et al., 2022; Strokal et al., 2016; Vermeulen et al., 2017, 2019). The model quantifies the annual inputs of nutrients and *Cryptosporidium* to rivers *via* the direct discharge of manure and runoff from fertilized land. The model includes manure on land from 11 livestock species and two types of manure management systems (grazing systems and storage systems). Livestock species include camels, cattle, buffalos, chickens, ducks, horses, mules, sheep, goats, donkeys, and pigs. This model calculates Dissolved Inorganic Nitrogen (DIN), Dissolved Organic Nitrogen (DON), Dissolved Inorganic Phosphorus (DIP), Dissolved Organic Phosphorus (DOP), and *Cryptosporidium* entering rivers as a function of livestock number, prevalence, and pollutant excretion rates in livestock manure, manure management, crop uptake, soil-associated retention rates, and surface runoff.

MARINA-Nutrients (Global-2.0) is a nitrogen specific model which is developed by integrating existing studies (Beusen et al., 2015; Li et al., 2022; Mayorga et al., 2010; Strokal et al., 2021, 2016). MARINA-Nutrients (Global-2.0) calculates DIN and DON entering rivers from point and diffuse sources (Fig. 1). Point sources are, sewage systems and open defecation from the total population. The calculation for nutrients from point sources follows the approach of MARINA-Multi (Global-1.0). Moreover, MARINA-Nutrients separates N into DIN and DON based on the approach of Strokal et al. (2023a). Diffuse sources include N inputs to rivers from agriculture and non-agricultural areas. Annual inputs of DIN and DON entering rivers from agriculture as the function of agricultural activities (e.g., fertilizer, manure, crop uptake), land use, atmospheric N deposition on agricultural land, and biological N_2 fixation by crops, and hydrology (e.g., runoff and leaching).

MARINA-Plastics (China-1.0) is a China-specific plastic model, which is developed by integrating existing studies (Siegfried et al., 2017; Strokal et al., 2021, 2022; Wijnen et al., 2019; Zhang et al., 2024). It quantifies the annual inputs of plastics (macro- and microplastics) to 395 rivers at the sub-basin scale from both point and diffuse sources (Fig. 1). Point source inputs of microplastics entering rivers are associated with sewage systems. It is calculated as a function of per capita microplastic consumption rates of personal care products, laundry fiber, household dust, and car tire wear, treatment of microplastics, and the total population connected to sewage systems. Diffuse source inputs of pollutants to rivers are associated with the application of agricultural

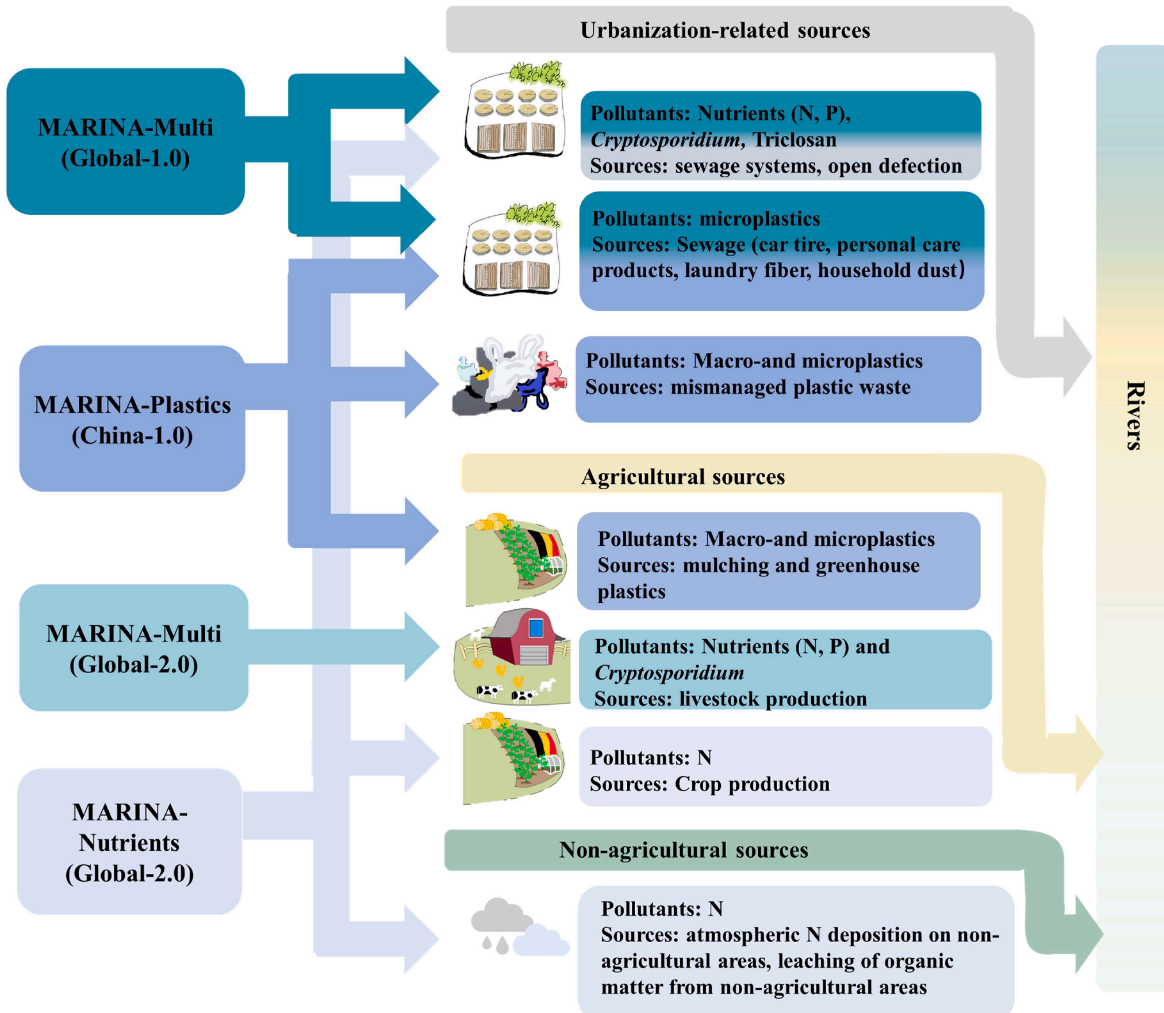

Fig. 1. An overview of integrated four existing MARINA models into a new MARINA-Multi (China-1.0) model to quantify the annual inputs of multiple pollutants to 395 Chinese sub-basins. MARINA is short for Model Assess River Inputs of pollutaNts to seA. Pollutants include nutrients, *Cryptosporidium*, and macro- and microplastics from urbanization and agriculture-related sources, and non-agricultural area. N and P are short for Nitrogen and Phosphorus. The color represent the different versions of the MARINA model and their sources. Source: The MARINA-multi (China-1.0) ("Materials and Methods").

plastic films (mulching and greenhouse plastics) on cropland and the production of mismanaged plastic wastes from the total population. Plastics entering rivers from mismanaged plastic waste is calculated as a function of the total population, the amount of mismanaged plastic waste generated per person, the residence time of macro- and microplastics in the environment, the release rate of microplastics from macroplastics, and the fraction of macroplastics entering the river from surface runoff. Plastics (macro- and microplastics) in rivers from agriculture are calculated as a function of the application amount of agricultural plastic film in crop production, the collection rate of plastic films, the degradation rate of plastics in soil, slope, and surface runoff.

- **New integrated MARINA-Multi (China-1.0)**

We intergrated four aformentioned MARINA models to develop MARINA-Muti (China-1.0). The intergrated MARINA-Multi (China-1.0) is a process-based model, which uses the lumped approach to quantify the annual inputs of dissolved inorganic and dissolved organic nitrogen and phosphorus (DIN, DIP, DON, and DOP), *Cryptosporidium*, and plastics (macroplastics and microplastics) in rivers for 395 Chinese sub-basins in the period of 2010–2050. TDN (Total Dissolved Nitrogen) is the sum of DIN and DON. TDP (Total Dissolved Phosphorus) is the sum of DIP and DOP. Annual inputs of these pollutants to rivers are calculated in mass (Tg/yr for DIN, DON, DIP and DOP, and plastics; oocysts/yr for *Cryptosporidium*). Our intergrated model considers retention and losses of pollutants during their transport from land to rivers (e.g., physical, chemical and biological processes).

This new integrated MARINA-Multi (China-1.0) model differs from the existing four versions of MARINA in the four main aspects. *First*, we calculate DIP and DOP inputs to rivers from agriculture and non-agricultural sources based on the existing studies, which is different from MARINA-Multi (Global-2.0) (Li et al., 2022; Salm et al., 2016; Strokal et al., 2016, 2023a). Agricultural sources include synthetic fertilizer, animal manure, and crop uptake (for DIP and DOP). Non-agricultural sources include weathering of P-contained minerals from non-agricultural areas (for DIP), and leaching of organic matter from non-agricultural areas (for DOP) (details of our approach are in Tables S1–S4). *Second*, we calculate DIP and DOP from urbanization-related sources (sewage systems and open defection) based on the approach of Strokal et al. (2023a) (details in Table S5).

Third, our model accounts for point and diffuse sources input of DIN, DON, DIP, DOP, *Cryptosporidium*, and macro-and microplastics to rivers in China, simultaneously. This is done by intergrating the approaches of MARINA-Multi (Global-1.0) for point sources (for N, P, *Cryptosporidium* from sewage systems and open defecation). MARINA-Multi (Global-2.0) (for N, P and *Cryptosporidium* from livestock production), MARINA-

Nutrients (Global 2.0) (for N from agriculture and non-agriculture sources) and MARINA-Plastics (China-1.0) (for microplastics from sewage systems, macro-and microplastics from mismanaged solid waste and crop production) for diffuse sources (Li et al., 2022; Strokal et al., 2021) (equations and explanations are in Supplementary Tables S1–S3).

Fourth, we interpreted the storyline of SSP3-RCP8.5 to develop a scenario for multiple pollutants. In our scenario, we calculate future inputs of DIN, DON, DIP, DOP, *Cryptosporidium*, and macro- and microplastics to rivers with the high impacts of climate change (e.g., impacts on water discharges) and socio-economic developments (e.g., impacts on urbanization trends). Our model results are presented for the recent past (2010 and 2015) and future (2050) and consistent in the spatial and temporal scales, which makes the comparison of river pollution between pollutants and sub-basins possible (see Fig. 2 for scenario descriptions, Supplementary Table S6 for our assumption).

In our MARINA-Multi (China-1.0), we distinguish pollution sources that are urbanization-related (sewage systems, open defection, mismanaged solid waste), agriculture-related (agricultural plastic films, synthetic fertilizers, aniumal manure), and non agriculture-related (atmospheric N deposition, biological N_2 fixation, P weathering and leaching of organic matetr from non-agricultural areas). Sources of pollutants in rivers that are considered in the intergrated MARINA-Multi (China-1.0) model are presented in Supplementary Information Table S6. We calculate inputs of pollutants to rivers using Eqs. (1)–(26) below (details on equations and data processing are summarized in Supplementary Tables S1–S5, Fig. S1).

Annual inputs of DIN, DON, DIP and DOP, *Cryptosporidium* and microplastics from sewage systems (point sources) are calculated as follows:

$$RSpnt_{sew.cry.j} = Pop_j \times fr_{pop.sew.j} \times WScap_{cry.j} \times \left(1 - hw_{frem.cry.j}\right) \quad (1)$$

$$RSpnt_{sew.mic.j} = Pop_j \times fr_{pop.sew.j} \times WScap_{mic.j} \times \left(1 - hw_{frem.mic.j}\right) \quad (2)$$

$$RSpnt_{sew.DIN.j} = Pop_j \times fr_{pop.sew.j} \times WScap_{N.j} \times \left(1 - hw_{frem.N.j}\right) \times FE_{sew.DIN.j} \quad (3)$$

$$RSpnt_{sew.DON.j} = Pop_j \times fr_{pop.sew.j} \times WScap_{N.j} \times \left(1 - hw_{frem.N.j}\right) \times FE_{sew.DON.j} \quad (4)$$

$$RSpnt_{sew.DIP.j} = Pop_j \times fr_{pop.sew.j} \times WScap_{P.j} \times \left(1 - hw_{frem.P.j}\right) \times FE_{sew.DIP.j} \quad (5)$$

$$RSpnt_{sew.DOP.j} = Pop_j \times fr_{pop.sew.j} \times WScap_{P.j} \times \left(1 - hw_{frem.P.j}\right) \times FE_{sew.DOP.j} \quad (6)$$

where,

$RSpnt_{sew.cry.j}$, $RSpnt_{sew.mic.j}$, $RSpnt_{sew.DIN.j}$, $RSpnt_{sew.DON.j}$, $RSpnt_{sew.DIP.j}$, and $RSpnt_{sew.DOP.j}$, are annual inputs of *Cryptosporidium* (cry), microplastics (mic), dissolved inorganic nitrogen (DIN), dissolved organic nitrogen (DON), dissolved inorganic phosphorus (DIP) and dissolved organic phosphorus (DOP) to rivers from sewage systems (sew) in sub-basin (j), respectively (kg/yr for nutrients and microplastics; oocysts/yr for *Cryptosporidium*);

Pop_j is the total population in sub-basin (j), which includes urban and rural people (people/yr);

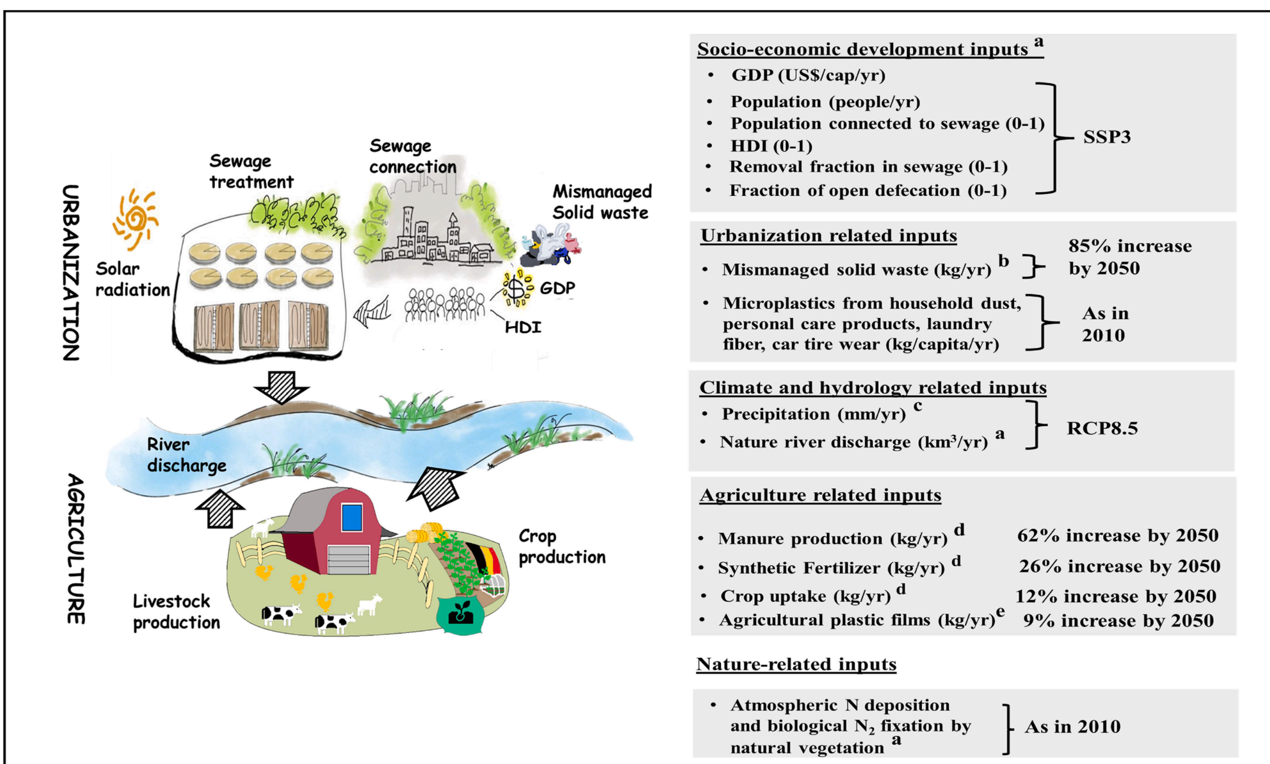

Fig. 2. *Overview of assumptions reflecting the designed future under SSP3-RCP8.5 in China in 2050.* Assumptions are for the national scale. GDP is the gross domestic product at purchasing power parity, HDI is the human development index, and population refers to the total population which includes the urban and rural population. Population connection to sewage systems refers to the total people that are connected to sewage systems in China. SSP3 is the Shared Socio-economic Pathway. RCP8.5 is the Representative Concentrative Pathway 8.5. Values indicate the changes in the annual inputs of pollutants to all Chinese rivers by 2050. Alphabet (a-e) represent references: a is Strokal et al. (2021), b is Lebreton and Andrady (2019), c is NBSC (2021), d is Wang et al. (2017), e is Lange and Büchner (2017). References for our assumptions and how we derived data are presented in the Supplementary Table S7. Source: The MARINA-multi (China-1.0) ("Materials and Methods").

$fr_{pop.sew.j}$ is the fraction of the total population connected to sewage systems (sew) in sub-basin (j) (0-1);

$WScap_{cry.j}$, $WScap_{mic.j}$, $WScap_{N.j}$, and $WScap_{P.j}$ are per capita excretion or consumption rates of *Cryptosporidium* (cry), microplastics (mic), nitrogen (N) and phosphorus (P) in human waste in sub-basin (j), respectively (oocysts/cap/yr for *Cryptosporidium*, kg/cap/yr for nutrients and microplastics). For microplastics, the total per capita concumption rate is the sum of per capita consumption rates for car tires, personal care products, household dust and laundry fiber;

$hw_{frem.N.j}$, $hw_{frem.P.j}$, $hw_{frem.cry.j}$, and$hw_{frem.mic.j}$ are removal fractions of nitrogen (N), phosphorus (P), *Cryptosporidium* (cry), and microplastics (mic) during treatment in wastewater treatment plants in sub-basin (j), respectively (0-1);

$FE_{sew.DIN.j}$, $FE_{sew.DON.j}$, $FE_{sew.DIP.j}$ and $FE_{sew.DOP.j}$ are fractions of nitrogen and phosphorus entering rivers from sewage systems in the forms of dissolved inorganic nitrogen (DIN), dissolved organic nitrogen (DON), dissolved inorganic phosphorus (DIP), and dissolved organic phosphorus (DOP) in sub-basins (j), respectively (0-1) (unitless) (Table S5).

Annual inputs of DIN, DON, DIP, DOP, and *Cryptosporidium* to rivers from open defecation (point sources) are calculated as follows:

$$RSpnt_{dir.cry.j} = Pop_j \times WScap_{cry.j} \times fr_{pop.dir.j} \quad (7)$$

$$RSpnt_{dir.DIN.j} = Pop_j \times WScap_{N.j} \times fr_{pop.dir.j} \times FE_{dir.DIN.j} \quad (8)$$

$$RSpnt_{dir.DON.j} = Pop_j \times WScap_{N.j} \times fr_{pop.dir.j} \times FE_{dir.DON.j} \quad (9)$$

$$RSpnt_{dir.DIP.j} = Pop_j \times WScap_{P.j} \times fr_{pop.dir.j} \times FE_{dir.DIP.j} \quad (10)$$

$$RSpnt_{dir.DOP.j} = Pop_j \times WScap_{P.j} \times fr_{pop.dir.j} \times FE_{dir.DOP.j} \quad (11)$$

where,

$RSpnt_{dir.cry.j}$, $RSpnt_{dir.DIN.j}$, $RSpnt_{dir.DON.j}$, $RSpnt_{dir.DIP.j}$, and $RSpnt_{dir.DOP.j}$ are annual inputs of *Cryptosporidium* (cry), dissolved inorganic nitrogen (DIN), dissolved organic nitrogen (DON), dissolved inorganic phosphorus (DIP), and dissolved organic phosphorus (DOP) to rivers from open defection in sub-basin (j), respectively (oocysts /yr for *Cryptosporidium*, kg /yr for nutrients);

$fr_{pop.dir.j}$ is the fraction of the total population experiencing open defecation in sub-basin (j) (0-1); $FE_{dir.DIN.j}$, $FE_{dir.DON.j}$, $FE_{dir.DIP.j}$, and $FE_{dir.DOP.j}$ are fractions of dissolved inorganic nitrogen (DIN), dissolved organic nitrogen (DON), dissolved inorganic phosphorus (DIP), and dissolved organic phosphorus (DOP) entering rivers from open defecation in sub-basins (j), respectively (unitless).

Annual inputs of DIN, DON, DIP, and DOP to rivers from agricultural and non-agricultural areas (diffuse sources) are calculated as follows (detailed equations and explaination of model parameters are presented in Supplementary Information Tables S1 and S2):

$$RSdif_{DIN.y.j} = WSdif_{N.y.j} \times G_{DIN.j} \times FE_{ws.DIN.j} \quad (12)$$

$$RSdif_{DON.y.j} = WSdif_{N.y.j} \times G_{DON.j} \times FE_{ws.DON.j} \quad (13)$$

$$RSdif_{DIP.y.j} = WSdif_{P.y.j} \times G_{DIP.j} \times FE_{ws.DIP.j} \quad (14)$$

$$RSdif_{DOP.y.j} = WSdif_{P.y.j} \times G_{DOP.j} \times FE_{ws.DOP.j} \quad (15)$$

where,

$RSdif_{DIN.y.j}$, $RSdif_{DON.y.j}$, $RSdif_{DIP.y.j}$ and $RSdif_{DOP.y.j}$ are annual inputs of dissolved inorganic nitrogen (DIN), dissolved organic nitrogen (DON), dissolved inorganic phosphorus (DIP), and dissolved organic phosphorus (DOP) to rivers from diffuse sources (y) in sub-basin (j), respectively (kg/yr). Diffuse sources include sythetic fertilizer, animal manure, atmospheric N deposition on agriculture and non-agricultural areas, biological N_2 fixation by crops and natural vegetation;

$WSdif_{N.y.j}$ and $WSdif_{P.y.j}$ are annual inputs of nitrogen (N) and phosphorus (P) to land from diffuse sources (y) in sub-basin (j), respectively (kg/yr). For agricultural areas, these sources include synthetic fertilizer, animal manure, atmospheric N deposition on agricultural land, biological N_2 fixation by crops. For non-agricultural areas, these sources include atmospheric N deposition and biological N_2 fixation by natural vegetation;

$G_{DIN.j}$, $G_{DON.j}$, $G_{DIP.j}$ and $G_{DOP.j}$ are fractions of dissolved inorganic nitrogen (DIN), dissolved organic nitrogen (DON), dissolved inorganic phosphorus (DIP), and dissolved organic phosphorus (DOP) that are remained in the soil after crop harvesting and livestock grazing in sub-basin (j), respectively (0-1). These fractions are only applied to the diffuse sources from agricultural areas;

$FE_{ws.DIN.j}$, $FE_{ws.DON.j}$, $FE_{ws.DIP.j}$, and $FE_{ws.DOP.j}$ are fractions of dissolved inorganic nitrogen (DIN), dissolved organic nitrogen (DON), dissolved inorganic phosphorus (DIP), and dissolved organic phosphorus (DOP) that are exported from land to rivers *via* surface runoff in sub-basin (j), respectively (0-1). These fractions are estimated using runoff.

Annual inputs of DIN, DON and DIP to rivers from leaching of organic matter and weathering of P-contained minerals from agriculture and non-agricultural areas (diffuse sources) are calculated as follows (detailed equations and explaination of model parameters are presented in Supplementary Information Tables S1 and S2):

$$RSdif_{DON.lchag.\ j} = CL_{DON} \times Rnat_j \times EC_{DON} \times Ag_{fr.j} \quad (16)$$

$$RSdif_{\ DON.lchna.j} = CL_{DON} \times Rnat_j \times EC_{DON} \times (1 - Ag_{fr.j}) \quad (17)$$

$$RSdif_{\ DOP.lchag.j} = CL_{DOP} \times Rnat_j \times EC_{DOP} \times Ag_{fr.j} \quad (18)$$

$$RSdif_{\ DOP.lchna.j} = CL_{DOP} \times Rnat_j \times EC_{DOP} \times \left(1 - Ag_{fr.j}\right) \quad (19)$$

$$RSdif_{\ DIP.wthag.j} = CW_{DIP} \times Rnat_j \times EC_{DIP} \times Ag_{fr.j} \quad (20)$$

$$RSdif_{\ DIP.wthna.j} = CW_{DIP} \times Rnat_j \times EC_{DIP} \times \left(1 - Ag_{fr.j}\right) \quad (21)$$

where, $RSdif_{DON.lchag.\ j}$, $RSdif_{\ DOP.lchag.j}$ are annual inputs of dissolved organic nitrogen (DON and dissolved organic phosphorus (DOP) to rivers from leaching of organic matters from agricultural areas in sub-basin (j), respectively (kg/yr). $RSdif_{\ DON.lchna.j}$, $RSdif_{\ DOP.lchna.j}$ are annual inputs of dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) to rivers from leaching of organic matters from non-agricultural area in sub-basin (j), respectively (kg/yr). $RSdif_{\ DIP.wthag.j}$ and $RSdif_{\ DIP.wthna.j}$ are annual inputs of dissolved inorganic phosphorus (DIP) to rivers from weathering of P-contained minerals from agricultural and non-agricultural areas in sub-basin (j), respectively (kg/yr). $Rnat_j$ is the annual runoff from land to rivers in sub-basin (j) (m). CL_{DON} and CL_{DOP} are export coefficients for leaching (CL) of dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) to rivers (0-1) (see Tables S2 and S4). CW_{DIP} is the export coefficient for weathering (CW) of dissolved inorganic phosphorus from land to rivers (0-1) (see Tables S2 and S4). EC_{DON}, EC_{DIP}, EC_{DOP} are the coefficients for leaching of organic matter leaching (for DON and DOP) and weathering of P-contained minerals for DIP (kg/km^2) (see Table S2). $Ag_{fr.j}$ is the fraction of agricultural area in sub-basin (j) (0-1).

Annual input of *Cryptosporidium* to rivers from agriculture (diffuse sources) are calculated as follows (detailed equations and explaination of model parameters are presented in Supplementary Information Tables S1 and S2):

$$RSdif_{cry.j} = \sum_{m=12}^{m} WSdif_{cry.m.j} \times FE_{ws.cry.j} \tag{22}$$

where,

$RSdif_{cry.j}$ is the annual inputs of oocysts of *Cryptosporidium* to rivers from land in sub-basin (j) (oocysts/yr);
$WSdif_{cry.m.j}$ is the monthly inputs of oocysts of *Cryptosporidium* to land from animal manure in sub-basin (j) (oocysts/month);
$FE_{ws.cry.j}$ is the fraction of oocysts of *Cryptosoridium* that reach rivers from land *via* surface runoff in sub-basins (j) (0-1). This fraction considers oocyst decay in the soil.

Annual inputs of macro- and microplastics to rivers from mismanaged solid waste (diffuse sources) are calculated as follows (detailed equations and explaination of model parameters are presented in Supplementary Information Tables S1and S2):

$$RSdif_{mac.mpw.j} = WS_j - RSdif_{mic.mpw.j} \tag{23}$$

$$RSdif_{mic.mpw.j} = \left(WS_{f.j} \times t_{res.f.j} + WS_{s.j} \times t_{res.f.j}\right) \times F_{mac} \tag{24}$$

where,

$RSdif_{mac.mpw.j}$ and $RSdif_{mic.mpw.j}$ are annual inputs of macroplastics (mac) and microplastics (mic) in rivers from mismanaged solid waste (mpw) in sub-basin (j), respectively (kg/yr);
WS_j is the annual inputs of mismanaged solid waste to sub-basin (j) resulting from the total population (kg/yr);
$WS_{f.j}$ and $WS_{f.j}$ are annual inputs of macroplastics into the fast and slow fractions in sub-basin (j), respectively (kg/yr);
$t_{res.f.j}$ and $t_{res.s.j}$ are residence times of macroplastics in the fast and slow fractions in sub-basin (j), respectively (yr);
F_{mac} is the release rate of microplsatics from macroplastics (0-1).

Annual inputs of macro- and microplastics to rivers from crop production (diffuse sources) are calculated as follows (detailed equations and explaination of model parameters are presented in Supplementary Information Tables S1 and S2):

$$RSdif_{mic.\ apf.j} = WSdif_{mic.apf.j} \times \left(1 - fr_{deg.j}\right) \times FE_{sr.j} \tag{25}$$

$$RSdif_{mac.\ apf.j} = WSdif_{mac.apf.j} \times \left(1 - fr_{deg.j}\right) \times FE_{sr.j} \tag{26}$$

where,

$RSdif_{mic.\ apf.j}$ and $RSdif_{mac.\ apf.j}$ are annual inputs of microplastics (mic) and macroplastics (mac) to rivers from crop mulching and greenhouses in crop production in sub-basin (j), respectively (kg/yr);
$WSdif_{mic.apf.j}$ and $WSdif_{mac.apf.j}$ are annual inputs of microplastics (mic) and macroplastics (mac) to agricultural areas from agricultural plastic films in sub-basin (j), respectively (kg/yr);
$fr_{deg.j}$ is the fraction of macro-and microplastics that are degraded in the soil in sub-basin (j) (0-1);
$FE_{sr.j}$ is the fraction of macro-and microplastics entering rivers by surface runoff in sub-basin (j) (0-1).

2.2. Scenario description

We develop a scenario to estimate annual inputs of multiple pollutants to rivers in 395 Chinese sub-basins (details see Fig. 2 and Table S7). This is done by taking the storyline of the existing Shared Socio-economic Pathway 3 (SSP3, O'Neill et al. 2014) in combination with the Representative Concentrative Pathway 8.5 (RCP8.5) as the basis (Vuuren et al., 2011). This combination is limited in environmental policies and assumes high global warming. The future is described as a "fragmental world", which is characterized by low priority for environmental issues, and high priority for energy and food security. The economy slowly grows leading to less focus on education and environmental protection. Public awareness of environmental protection is relatively low (O'Neill et al., 2014). At the same time, inadequate technological progress and limited environmental policies cause more environmental problems. Along with this, human activities accelerate high concentrations of greenhouse emissions (RCP8.5) (Vuuren et al., 2011).

We incorporated quantitatively the storylines of how agriculture, sanitation, and urbanization might be developed in China under the SSP3-RCP8.5 combination (Fig. 2). We used existing studies (Lange and Büchner, 2017; Lebreton and Andrady, 2019; NBSC, 2021; Strokal et al., 2021; Wang et al., 2017) for our assumptions and explain how we derived the data in the Supplementary Table S7. In our scenario, 1.33 billion people lived in the drainage area in the year 2010 (Fig. S2). By 2050, more people are assumed to move to urban areas. As a result, the urban population will increase by around 20 % at the national scale by 2050, the total population is projected to have slightly decreased by 3 % at the national scale (Fig. S2). Along with socio-economic development, people's living standards are expected to have slowly improved between 2010 and 2050. GDP (Gross Domestic Product) is expected to increase by 422 % from 2010 to 2050 (Strokal et al., 2021). This implies that economy will grow. However, improving sanitation will not be a priority mainly because of a reactive approach towards the environmental issues. By 2050, society will not invest in expanding wastewater treatment facilities and improving treatment. This implies that the fraction of people with sewage connections and the removal fraction of pollutants during treatment in 2050 will stay at the level of 2010. The urban expansion will challenge waste management, especially in urban areas. The production of mismanaged plastic waste will largely increase in the future and it is projected to have increased by 85 % at the national scale by 2050 (Lebreton and Andrady, 2019). However, inadequate technological progress may not reduce per capita microplastic-related consumptions of personal care products, laundry fiber, household dust, and car tire wear in 2050 and they will stay at the level of 2015. Climate and hydrology-related inputs will follow the trend of RCP8.5 (Lange and Büchner, 2017; Strokal et al., 2021) (Fig. 2). Intensive agricultural activities along with the increase of agricultural materials inputs in crop production for the year 2050, agricultural plastic films are expected to have increased by 9 % from 2015 to 2050 at the national scale (NBSC, 2021). During the same period, manure production, application of synthetic fertilizers, and crop uptake are projected to increase by 62 %, 26 %, and 12 %, respectively, at the national level (Wang et al., 2017). The atmospheric N deposition and biological N_2 fixation rates are expected to be at the level of 2010 in 2050 (Wang et al., 2017).

3. Results

3.1. Multiple pollutants in rivers in the recent past

We calculated inputs of nutrients, *Cryptosporidium*, and plastics in rivers of 395 Chinese sub-basins for the period of 2010 to 2015 (Fig. 3). We categorized sub-basins based on pollution levels. We did this by considering five groups, based on pollutants inputs to rivers per km^2 of the sub-basin area per year: 0–20 % (lowest inputs to rivers), 20–40 %, 40–60 %, 60–80 %, and 80–100 % (highest inputs to rivers).

In the recent past, the Chinese rivers received around 21 Tg of TDN, 2 Tg of TDP, 2×10^{20} oocysts of *Cryptosporidium*, and 0.7 Tg of macro- and microplastics in rivers (Fig. 3). For nutrient forms, it was around 18 Tg for DIN, 3 Tg for DON, 1.5 Tg for DIP, and 0.5 Tg for DOP (Fig. 3). Generally, nutrients and *Cryptosporidium* were largely from agricultural sources and the remainder were mainly from urbanization-related sources (sewage systems and open defection). Agricultural sources contributed around 77 % of TDN, 83 % of TDP, and 99 % of oocysts of *Cryptosporidium* in rivers (Fig. 3). These amounts were mainly from

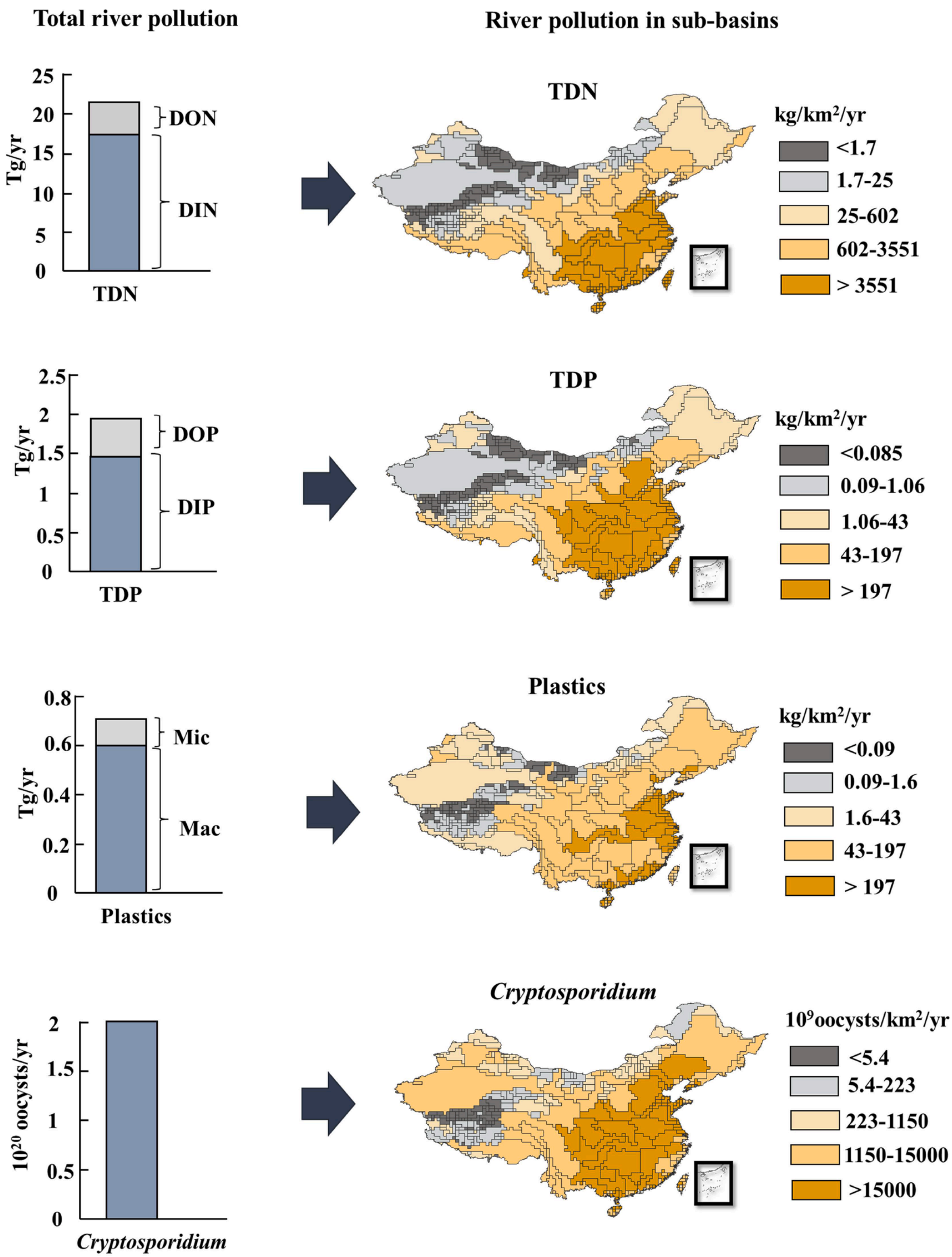

Fig. 3. River pollution in 395 Chinese sub-basins in the recent past (2010–2015). Graphs show the annual inputs of pollutants to rivers (Tg/yr for nutrients, plastics and 10^{20}oocysts/yr for *Cryptosporidium*). Maps show the annual inputs of pollutants to rivers per km^2 of sub-basin areas (kg/km^2/yr for nutrients, plastics and 10^9 oocysts/km^2/yr for *Cryptosporidium*). Pollutants include Total Dissolved Nitrogen (TDN), Dissolved Inorganic Nitrogen (DIN), Dissolved Organic Nitrogen (DON), Total Dissolved Phosphorus (TDP), Dissolved Inorganic Phosphorus (DIP), Dissolved Organic Phosphorus (DOP), macroplastics (mac), microplastics (mic) and *Cryptosporidium.* TDN is the sum of dissolved inorganic and organic nitrogen. TDP is the sum of dissolved inorganic and organic phosphorus. Source: MARINA-Multi (China-1.0) ("Materials and Methods").

livestock production and crop production. Plastics in rivers were mainly from mismanaged solid waste and sewage systems. Macroplastics were dominant in the total plastic pollution (Fig. 2). Plastics from urbanization-related sources (sewage systems and mismanaged solid waste) were responsible for around 80 % of plastics in rivers, the remainder was from applied agricultural plastic films in crop production (Fig. 3).

There was a large spatial variability in river pollution among the 395 Chinese sub-basins (Fig. 3). Many central and eastern sub-basins received over 3551 kg of TDN, 197 kg of TDP, 197 kg of plastics, and

1.5×10^{13} oocysts per km^2 of their basin area per year (Fig. 3, sub-basins belonging to the interval 80–100 %). The southern sub-basins had generally higher inputs of nutrients and *Cryptosporidium* compared to plastics. River pollution in the northern and western sub-basins (Fig. 3, sub-basins belonging to the intervals of 0–20 % and 20–40 %) was lower compared to the central, eastern, and southern sub-basins in China. The high pollution in central, southern, and eastern sub-basins can be explained by the fact that these sub-basins were densely populated with intensive agricultural activities.

3.2. Multiple pollutants in rivers in the future

In the year 2050, the 395 Chinese sub-basins are projected to receive around 29 Tg of TDN, 3 Tg of TDP, 1.1 Tg of plastics, and 3.76×10^{20} oocysts of *Cryptosporidium* in total (Fig. 4). This is an increase of 41 %, 50 %, 57 %, and 88 % in the national inputs of TDN, TDP, plastics, and *Cryptosporidium* to rivers between the recent past (2010–2015) and 2050, respectively. These increases differ among sub-basins (Fig. 5). By 2050, river pollution with TDN is expected to change from −84 % (decrease) to +130 % (increase) among sub-basins. For TDP, this range is projected to be from −92 % (decrease) to +577 % (increase). For plastics, this range is projected to be from −40 % (decrease) to 204 % (increase). The range for *Cryptosporidium* is from −100 % (decrease) to +304 % (increase, Fig. 4). These results are the net effects of urbanization related activities (e.g., more urban people), and intensive livestock production.

Most Chinese sub-basins may get more polluted in 2050, but a few western sub-basins may get cleaner because of fewer human activities (Fig. 5). For a few western sub-basins, changes in river pollution will be lower than 50 % for all pollutants between the recent past and 2050. For some western sub-basins, increase in river pollution are projected to over 50 % for one pollutant in 2050 (Figs. 5 and 6). For sub-basins which we estimate a lower than 50 % increase for one pollutant accommodates approximately 6 % of the total population. These sub-basins account for 27 % of total sub-basin areas (Fig. 6). For most central, eastern, and southern sub-basins, inputs of at least two pollutants to rivers are projected to increase by over 50 % by the year 2050. As a consequence, in around half of the sub-basins, river pollution is projected to have increased by 50 % for at least two types of pollutants (Fig. 6). For these sub-basins which have increase by 50 % for at least two types of pollutant will accommodate 94 % of the total population, and the polluted areas account for 73 % of totalsub-basin areas (Fig. 6). Reasons are largely associated with urbanization and agricultural activities as explained below.

- **Urbanization is an increasing source of future river pollution**

By 2050, increases of 70 % are projected for nutrients and plastics in rivers from urbanization (Fig. 4). Sewage systems are projected to be dominant contributors to microplastic pollution. Mismanaged solid waste from municipal households is projected to be the dominant contributor to plastic pollution (Figs. 6 and S3). A relatively small increase is projected for oocysts of *Cryptosporidium* inputs to rivers from urbanization-related sources during recent past and future (Fig. 4). Urbanization-related sources will contribute 2 Tg TDN, 0.45 Tg TDP, 0.97 Tg of plastics, and 4×10^{16} oocysts of *Cryptosporidium* in rivers by 2050 (Fig. 4). DIN and DIP will be the dominant forms of TDN and TDP from urbanization-related sources (80 % for DIN, and 98 % for DIP, Fig. 4). Most central, eastern, and southern sub-basins will be affected by nutrients and plastic pollution (over 50 % increase for inputs of nutrients and plastics to rivers, Fig. 5). These pollution trends are the net effects of increasing GDP, urbanization, unimproved sanitation conditions (e.g., increased waste production, more open defecation), and sewage treatment efficiencies in these sub-basins. Lower increasing trends are projected for *Cryptosporidium* in the most central eastern and southern sub-basins during 2010–2050 (lower than 25 % increase of *Cryptosporidium* in rivers for 2050). Moreover, the decreasing trends of *Cryptosporidium* are projected for many western and northern sub-basins between the recent past and 2050. This is because of relatively high HDI in urbanized sub-basins (central, eastern, and southern) with densely populated areas leading to a low infection rate of *Cryptosporidium*.

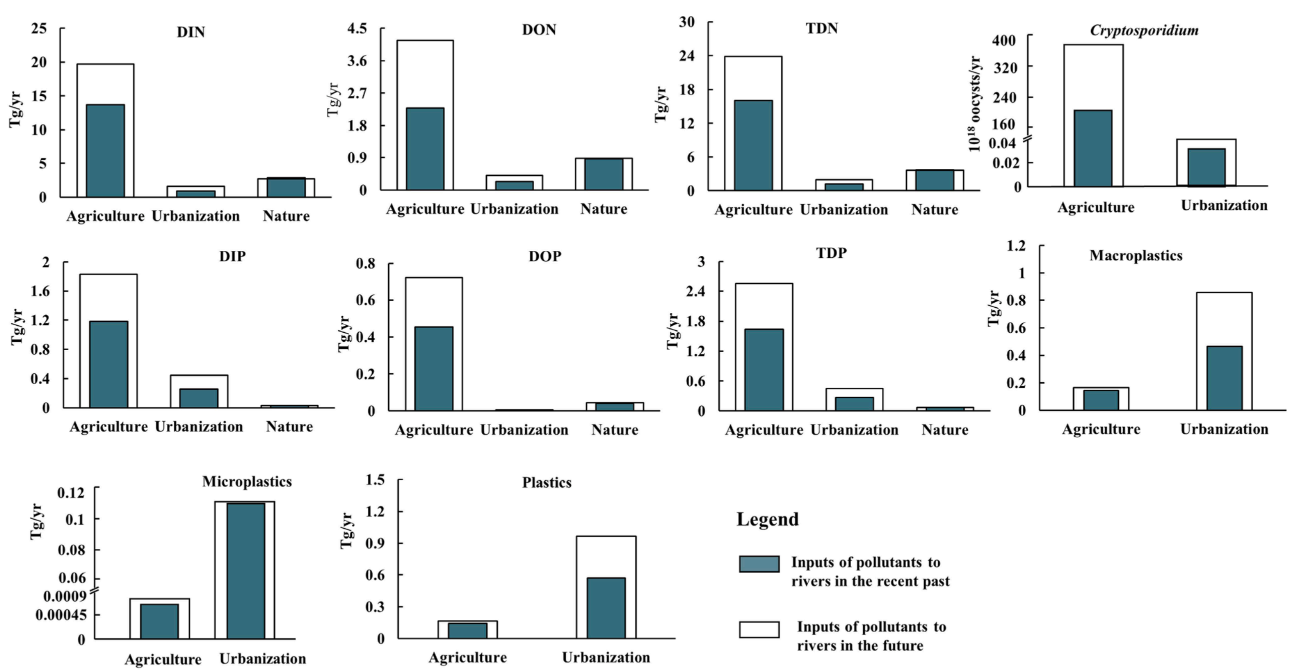

Fig. 4. Annual inputs of pollutants to rivers (Tg/yr for nutrients and plastics, oocysts/yr for *Cryptosporidium*) and changes from the recent past to 2050 (%). The recent past is represented by the period 2010–2015. TDN is short for Total Dissolved Nitrogen. TDP is short for Dissolved Inorganic Nitrogen. DON is short for Dissolved Organic Nitrogen. TDP is short for Total Dissolved Phosphorus. DIP is short for Dissolved Inorganic Phosphorus. DOP is short for Dissolved Organic Phosphorus. TDN is the sum of DIN and DON. TDP is the sum of DIP and DOP. Source: MARINA-Multi (China-1.0) ("Material & Methods").

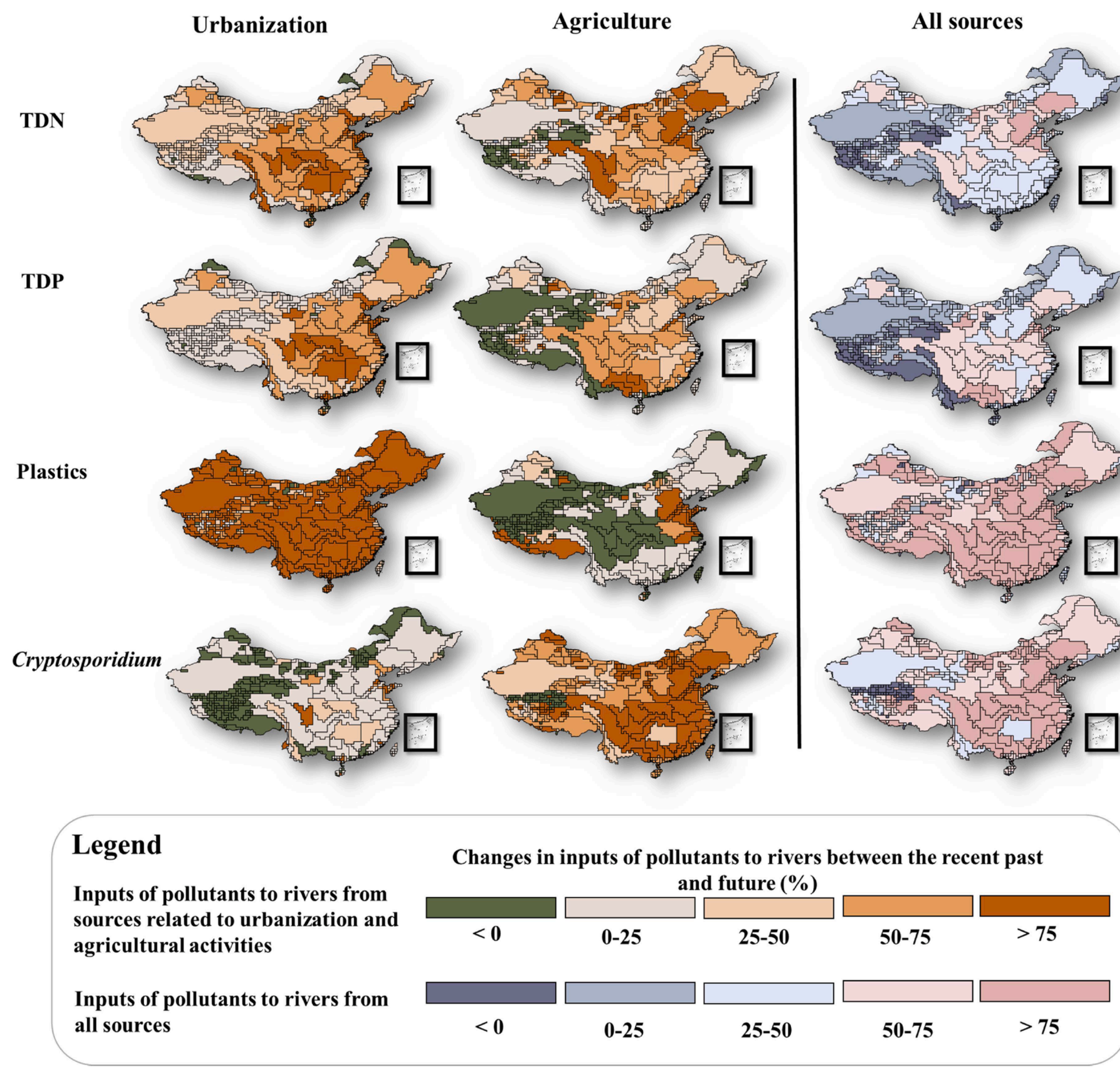

Fig. 5. Changes in river pollution in 395 Chinese sub-basins from the recent past to 2050 (%). Changes are shown for annual inputs of pollutants from sources that are related to urbanization and agricultural activities as well as from all sources (including pollutants from non-agricultural areas). Urbanization-related sources are sewage systems, open defection, and mismanaged solid waste. Agricultural-related sources are agricultural plastic films, animal manure, synthetic fertilizer, atmospheric N deposition, biological N_2 fixation by crops, weathering of P-contained minerals from agricultural areas. Sources from non-agricultural area are atmospheric N deposition on non-agricultural areas (for DIN) and biological N_2 fixation by natural vegetation (for DIN), weathering of P-contained minerals from non-agricultural areas. Source: MARINA-Multi (China-1.0) ("Materials & Methods").

- **Agriculture is an increasing source of future river pollution**

By 2050, 49–88 % increase are projected for nutrients and *Cryptosporidium* in rivers from agriculture. These increases are 49 % for TDN, 56 % for TDP, and 88 % for *Cryptosporidium*. DIN and DIP are the dominant forms of TDN and TDP, respectively. A 16 % increase is projected for inputs of plastics to rivers from crop production during 2010–2050. Approximately 24 Tg TDN, 2.6 Tg TDP, and 3.76×10^{20} oocysts of *Cryptosporidium* and 0.17 Tg plastics are expected to enter rivers from agricultural sources by 2050 (Fig. 4). Synthetic fertilizers and animal manure are the dominant contributors to nutrient and *Cryptosporidium* pollution from agriculture (Fig. 6). Synthetic fertilizer is expected to contribute by 26 % to inputs of TDN to rivers and 10 % to inputs of TDP to rivers. Animal manure is expected to contribute by 45 % toTDN, 71 % to TDP and 99 % to oocysts of *Cryptosporidium* in rivers, largely because of direct discharges of animal manure to rivers (Fig. 6). Pollutants in rivers in some western sub-basins are expected to decrease, because of projected limited agricultural activities. However, the central, southern, and eastern sub-basins are expected to receive more nutrients in rivers in 2050 than in 2010 (over 50 % increase, Fig. 5). For almost all sub-basins across China, *Cryptosporidium* in rivers is projected to increase by over 50 %, except for fewer western sub-basins during recent past and 2050. These are the net effects of intensive crop production, livestock production, limited manure treatment and increasing food demand. Lower plastic inputs to rivers from agriculture are expected in the year 2050 compared to the recent past (Fig. 4). This is largely the net effect of the application amount of agricultural plastic films and climate change. It is different from nutrient and *Cryptosporidium* pollution, in central sub-basins that are expected to receive less plastics in rivers (Fig. 5), largely because of decreased runoff (Fig. S4). Macroplastics are expected to be the dominate contributors of the total plastics in rivers from agriculture in 2050 (Fig. 4). The important reason is the limited recycling of agricultural plastic films.

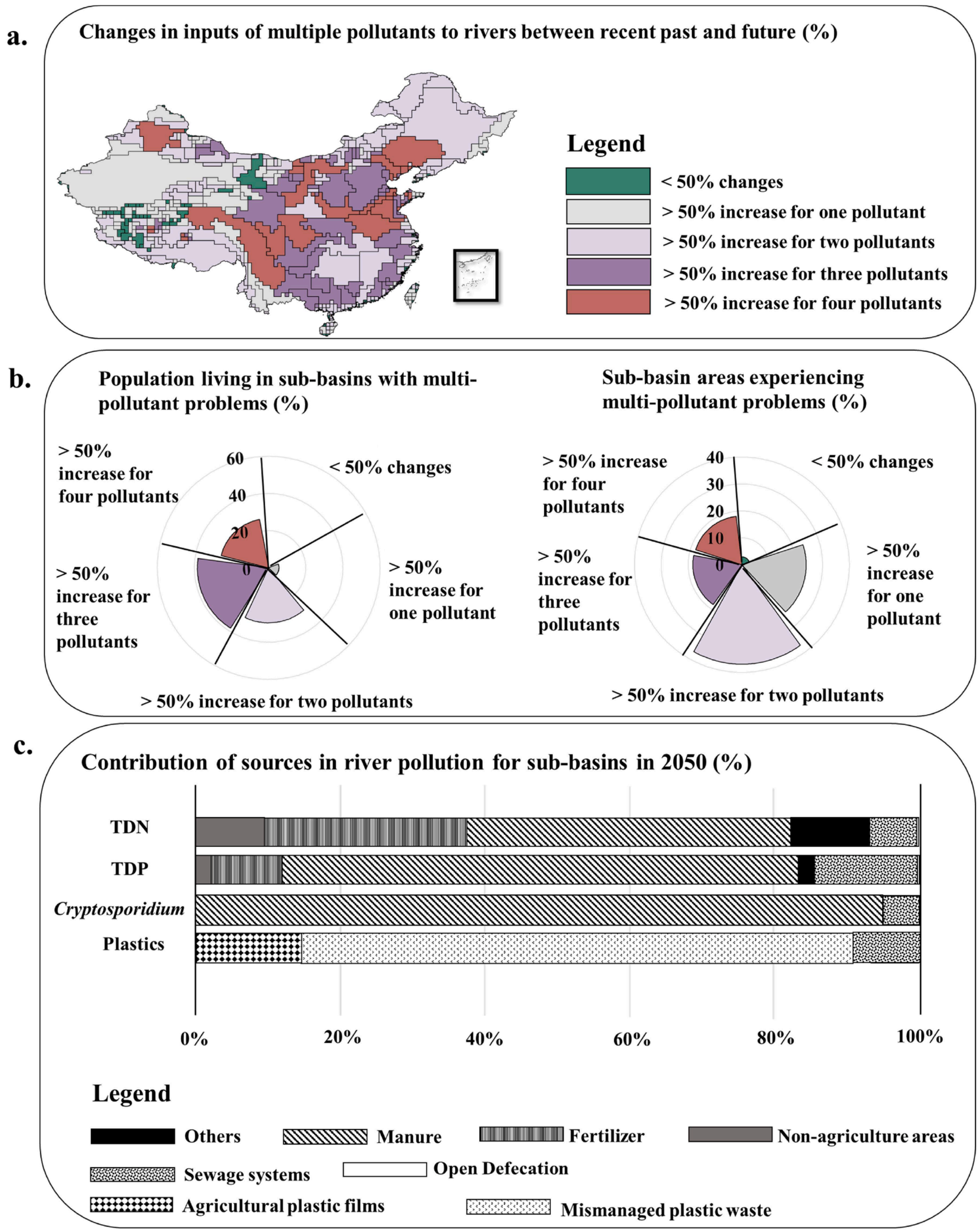

Fig. 6. Future changes in river pollution in China. (a) A map shows the changes in annual inputs of multiple pollutants to rivers between the recent past (around 2010–2015) and future (2050) (%). We calculate changes in river pollution higher or lower than 50 % for inputs of one or more studied pollutants. (b) Figures show the proportion of total population (left figure) and sub-basin areas (right figure) that are affected by multi-pollutant problems in 2050 (%). (c) A Figure shows the contribution of sources in national river pollution in 2050 (%). TDN and TDP are short for Total Dissolved Nitrogen and Total Dissolved Phosphorus, respectively. Source: MARINA-Multi (China-1.0) ("Materials & Methods").

4. Discussion

4.1. Model evaluation and uncertainties

We developed a new version of MARINA-Multi (China-1.0) for multiple pollutants in 395 Chinese sub-basins by integrating four existing MARINA modeling approaches for *Cryptosporidium* (Li et al., 2022; Strokal et al., 2021), plastics (Li et al., 2023), and nutrients (Strokal et al., 2021; Wang et al., 2024) (Section 2). These approaches have been evaluated in previous studies (Chen et al., 2019; Li et al., 2022; Strokal et al., 2021, 2016; Wang et al., 2020). For example, the modeled results of one of the MARINA models for nutrients show good performance for DIN and DIP export by rivers in China (R^2= 0.84; R^2_{NSE} 0.78) (Strokal et al., 2016). Two other model versions of MARINA-Multi (Global-1.0 and Global-2.0) have been evaluated for inputs of nutrients and *Cryptosporidium* to rivers globally *via* a sensitivity analysis (Li et al., 2022; Strokal et al., 2021). The model version of MARINA-Plastics (China-1.0) has been evaluated *via* evaluation with soil empirical data and sensitivity analyses for micro-, and macroplastics in rivers of China.

Uncertainties exist in the model structure and are related to a lumped, process-based approach to estimating annual inputs of multiple pollutants to rivers. Our approach focuses on pollutants entering rivers *via* surface runoff but ignores soil erosion and leaching to groundwater (Mayorga et al., 2010; Ren et al., 2021). We mainly focus on agriculture and urbanization-related sources of pollutants in rivers but ignore more specific sources such as aquaculture (Chen et al., 2021; Golomazou et al., 2021; Lyu et al., 2020; Wang et al., 2019a), sludge (Jasmin et al., 2020; Rezaei et al., 2022; Yuan et al., 2022; Zhang and Chen, 2020), wind erosion (Rezaei et al., 2022, 2019), microplastic deposition (Sun et al., 2022; Wright et al., 2020), vessels (Kaptan et al., 2020; Wang et al., 2019a). We also do not account for diffuse sources of human waste that stay in soil and/or used as fertilizer in agriculture (Wang et al., 2020). As a result, our modeled pollution levels might be underestimated for specific locations where these sources are important (e.g., aquaculture along the coast Wang et al. 2019a).

Another source of uncertainties is related to scenario assumptions (Fig. 2 and Table S7). We largely followed the storyline of SSP3-RCP8.5 to build up our scenario for China and multiple pollutants, which does not consider explicitly technological development and effects of existing policies in China. Our scenario should not be interpreted as a "likely" scenario for future water pollution in China. Our scenario should be interpreted assuming that the removal fraction of pollutants during treatment and the fraction of the population with sewage connections will stay in 2050 at the level of the recent past. However, future development may, in reality, bring opportunities to build more sewage systems and improve wastewater treatment. It may influence water pollution. For example, more sewage systems may result in more pollutants in rivers if treatment is not improved. Thus, future studies that may focus on expanding sewage systems may consider that. We believe that more sewage systems may help to improve sanitation, especially in urban areas, but it should come together with better treatment to avoid more pollutants in water.

Our scenario differs from existing scenarios (Kanter et al., 2020; Wang et al., 2022) in connecting agricultural and urbanization activities for multiple pollutants, which is hardly done for 395 Chinese sub-basins. Thus, our study serve as the first step to better understand the future sources, locations of pollution hotspots and changes in inputs of multiple pollutants to rivers in China. Future studies could take our study as the basis and expand to scenarios with different measures and policies to explore the synergetic solutions for reduction of multiple pollutants in rivers in the future (Wang et al., 2023; Wu et al., 2023; Zhang et al., 2023). More combinations of SSPs-RCPs can be applied to better understand the future effects of climate change and socio-economic developments on water pollution (Li et al., 2019; Strokal et al., 2023; Zhang et al., 2021, 2020).

4.2. Comparisons with other studies

We compared our modeled results with other modeling studies for the Yangtze, Pearl, and Yellow Rivers in China. Our estimate for TDN inputs to the Pearl River in 2010 (2.2 Tg) is lower than the estimate of Chen et al. (2019) (3 Tg TDN), but higher than the estimate of Ti and Yan (2013) and Xu et al. (2017) (0.7 Tg for TN). We calculate 7 Tg of DIN entering the Yangtze River in 2010, which is comparable with the modeling study of Chen et al. (2022) in 2012, Liu et al. (2019), and Liu et al. (2018) in 2010. Our modeled TDP inputs to the Pearl and Yellow rivers (0.2 Tg) are in line with the estimate of Chen et al. (2019). We estimated 0.2 Tg of TDP entering the Yellow Rivers for 2010, which is lower than the estimate of Han et al. (2006) for TP in 2005 (0.5 Tg). For *Cryptosporidium*, studies reported that the prevalence of *Cryptosporidium* in eastern China is higher than in other regions (Chen et al., 2011; Wang et al., 2018, 2010; Zou et al., 2017). It implies that eastern China may have more *Cryptosporidium* pollution in rivers. Our study coincides with this result for eastern areas and also estimates more *Cryptosporidium* in central and southern China. For plastics, existing studies estimate that Asian rivers are large contributors to global plastic pollution (Lebreton and Andrady, 2019; Meijer et al., 2021). We show the spatial variability in plastic pollution among sub-basins (Figs. 4 and 5). Our results are from the process-based MARINA-Multi model, which differs from existing studies in modeling approaches (Beusen et al., 2015; Vermeulen et al., 2017, 2019; Wijnen et al., 2019), spatial (e.g., grid Vermeulen et al. 2017, 2019), basins (Wijnen et al., 2019)) and temporal (e.g., 2005, 2010, 2050) resolutions. This can explain the differences between our results and existing studies mentioned above.

We used the input data of the MARINA-Multi models (Global-1.0 (Strokal et al., 2021), Global 2.0 (Li et al., 2022), and the MARINA-Plastics model (China-1.0) (Li et al., 2023). Model inputs have been evaluated by comparing them with existing studies and datasets. For instance, Strokal et al. (2021) reported that model inputs of urban and rural populations connected to sewage systems, removal fractions of pollutants, and human excretion rates are comparable with Puijenbroek et al. (2019) for 2010 and 2050. Li et al. (2022) also reported comparable results for N excretion in individual livestock species with FAO datasets (Food and Agriculture Organization of the United States) (FAOSTAT, 2010). Li et al. (2022) also showed a good comparison of livestock excretion in China with the results of Bai et al. (2016). Furthermore, our previous study of Li et al. (2023) concluded the spatial distribution of plastics in agriculture are comparable with the second soil census (Zhang et al., 2022).

4.3. Implications for future green development

Green Development promotes economic growth with low environmental degradation to achieve sustainable development in China (Hu, 2014a; Hu and Zhou, 2014b). It implies "urban greening expansion", increasing the productivity of agriculture, and reducing environmental pollution (Hammer et al., 2011). Our study provides insights into the impact of intensified agriculture under high economic growth and expanded urbanization on multiple pollutants in rivers (Figs. 3 and 4). For example, our study shows that agriculture is expected to be an important source of nutrients and a pathogen (*Cryptosporidium*) in many Chinese rivers in the future. This implies that improving the sustainability of agriculture under green development may not only improve the efficiency of crop production but also may reduce nutrients and pathogen pollution in rivers, which will reduce impacts on nature (less blooms of harmful algae) and for people (less diarrhea that is caused by pathogens). Our results also show that urbanization activities are projected to increase inputs of nutrients and plastics in rivers in the future (Figs. 3 and 4). This implies that improving wastewater treatment and management of solid waste under the green development missions may co-benefit in reducing nutrients and plastics in the rivers of China. These insights give directions for green development programs to find synergetic solutions for high agricultural efficiencies and sustainable cities with low water pollution. Furthermore, the insights of our model can also be considered for the other countries. It is helpful for policymakers to prioritize relevant environmental policies for different pollutants and sources from urban, rural areas and agriculture.

Our results also provide insights into spatial variability in multi-pollutant problems. We estimate that in half of sub-basins, river pollution with nutrients, plastics, and a pathogen (*Cryptosporidium*) will be increased over 50 % during 2010–2050. This is especially relevant for some parts of China. For example, upstream and middle stream sub-basins of the Yangtze rivers are expected to experience more pollutants in the future (e.g., over 50 % increase for three pollutants between the recent past and 2050, Fig. 6). Sub-basins located in the central, eastern, and southern parts of China are projected to become more polluted with nutrients, plastics, and a pathogen (*Cryptosporidium*, Fig. 5). These insights can help prioritize green development solutions in sub-basins that are expected to be highly polluted in the future.

5. Conclusions

We analyze future changes in nutrients, *Cryptosporidium*, and plastics to 395 Chinese rivers by 2050. Our results indicate that multiple pollutants in rivers are expected to increase. These increases range from 41 to 88 % between 2010 and 2050. In particular rivers in sub-basins located in central, eastern, and southern China are projected to be more polluted in 2050. For around half of the sub-basins we project increases by at least 50 % for at least two types of pollutants in rivers by 2050. Due to urbanization, an increase of 70 % is estimated for inputs of nutrients and plastics in rivers by 2050. Agricultural activities is the main reason for a 49–88 % increase in nutrients and *Cryptosporidium* in rivers by 2050. Our study serves as the first step to identify the changes in inputs of multiple pollutants to rivers between the recent past and the future. This information could be used to explore the synergetic strategies that can reduce simultaneously multiple pollutants in rivers in the future. We argue for a need to develop multi-pollutant management strategies for agriculture and urban waste if we want to reduce river pollution in the future. Our results could help to prioritize sub-basins for which in-depth research is needed on river pollutant control in the future. This will in turn support green development in China.

CRediT authorship contribution statement

Yanan Li: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Mengru Wang:** Writing – review & editing, Methodology, Conceptualization. **Qi Zhang:** Writing – review & editing, Writing – original draft, Methodology. **Carolien Kroeze:** Writing – review & editing, Supervision. **Wen Xu:** Writing – review & editing, Supervision, Conceptualization. **Lin Ma:** Writing – review & editing, Supervision. **Fusuo Zhang:** Project administration. **Maryna Strokal:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107553.

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