Supplementary information files

Urbanization: an increasing source of multiple pollutants to rivers in the 21st century

Maryna Strokal[1]*, Zhaohai Bai[2], Wietse Franssen[1], Nynke Hofstra[1], Albert A. Koelmans[3], Fulco Ludwig[1], Lin Ma[2], Peter van Puijenbroek[4], J. Emiel Spanier[1], Lucie C. Vermeulen[5], Michelle T.H. van Vliet[6], Jikke van Wijnen[7], Carolien Kroeze[1]

[1]Water Systems and Global Change group, Wageningen University & Research, Wageningen, the Netherlands

[2]Key Laboratory of Agricultural Water Resources, Hebei Key Laboratory of Soil Ecology, Center for Agricultural Resources Research, Institute of Genetic and Developmental Biology, The Chinese Academy of Sciences, Hebei, China

[3]Aquatic Ecology and Water Quality Management group, Wageningen University & Research, Wageningen, the Netherlands

[4]PBL Netherlands Environmental Assessment Agency, the Hague, the Netherlands

[5]Centre for Infectious Disease Control, National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands

[6] Department of Physical Geography, Utrecht University, Utrecht, the Netherlands

[7]Open University, Faculty of Science - Environmental Sciences Dept., Heerlen, the Netherlands

*Corresponding author: maryna.strokal@wur.nl

The supplementary information files contain:

Supplementary Tables

Supplementary Figures

Supplementary References

Supplementary Tables

Supplementary Table 1. Description of the global multi-pollutant model to quantify inputs of five pollutants to rivers from point sources simultaneously. Description of the variables is given in Supplementary Table 2. Source: the model takes the sub-basin modelling approach of Strokal, et al. [1] for nutrients[1,2] and integrates existing, evaluated modelling approaches of *Cryptosporidium*[3,4], microplastics[5] and triclosan[6] (details are also in [7]).

Inputs of pollutants to rivers of sub-basins from point sources ($RS_{i.sb}$): open defecation ($RS_{dir.i.j}$) and sewage systems ($RS_{sew.i.j}$)		
$RS_{i.sb} = \sum_{j=n}^{J} RS_{dir.i.j} + \sum_{j=n}^{J} RS_{sew.i.j}$	eq.S1	i = pollutant j = grid of 0.5 degree cell sb = sub-basin n = number of grids of 0.5 degree cell belonging to sub-basin sb
$RS_{dir.i.j} = Pop_{dir.j} \cdot WShw_{cap.i.j}$	eq.S2	
$RS_{sew.i.j} = Pop_{sew.j} \cdot WShw_{cap.i.j} \cdot (1 - hw_{frem.i.j})$	eq.S3	
Quantifying variables for $RS_{dir.i.j}$ *Cryptosporidium* (cry), nitrogen (N) and phosphorus (P)		
$Pop_{dir.j} = Pop_{dir.urb.j} + Pop_{dir.rur.j}$	eq.S4	
$Pop_{dir.urb.j} = Pop_{urb.j} \cdot fr_{pop.dir.urb.j}$	eq.S5	
$Pop_{dir.rur.j} = Pop_{rur.j} \cdot fr_{pop.dir.rur.j}$	eq.S6	
$WShw_{cap.cry.j} = I_{cry.j} \cdot Exc_{cry.j}$ $I_{cry.j}$ is a function of HDI (Supplementary Table 3)	eq.S7	
$WShw_{cap.N.j} = I_{N.j} \cdot 0.365$ $I_{N.j}$ is a function of GDP_{ppp} (Supplementary Table 3)	eq.S8	
$WShw_{cap.P.j} = WShw_{cap.P.sew.j}$	eq.S9	
$WShw_{cap.P.sew.j} = 1/6 \cdot WShw_{cap.N.j}$	eq.S10	
Quantifying variables for $RS_{sew.i.j}$ *Cryptosporidium* (cry), nitrogen (N), phosphorus (P), microplastics (MP) and triclosan (TCS)		
$Pop_{sew.j} = Pop_{sew.urb.j} + Pop_{sew.rur.j}$	eq.S11	
$Pop_{sew.urb.j} = Pop_{urb.j} \cdot fr_{pop.sew.urb.j}$	eq.S12	
$Pop_{sew.rur.j} = Pop_{rur.j} \cdot fr_{pop.sew.rur.j}$	eq.S13	
$WShw_{cap.cry.j}$	see eq.S6	
$WShw_{cap.N.j}$	see eq.S8	
$WShw_{cap.P.j} = WShw_{cap.P.sew.j} + WShw_{cap.P.det.j}$	eq.S14	
$WShw_{cap.P.sew.j}$	see eq.S10	
$WShw_{cap.MP.j} = WShw_{cap.MP.tyres.j} + WShw_{cap.MP.PCP.j} + + WShw_{cap.MP.ldry.j} + WShw_{cap.MP.dust.j}$	eq.S15	
$WShw_{cap.TCS.j}$ Supplementary Table 3		
$hw_{frem.i.j} = (f_{p.j} \cdot RE_{p.j}) + (f_{s.j} \cdot RE_{s.j}) + (f_{t.j} \cdot RE_{t.j}) + (f_{no.j} \cdot RE_{no.j})$ for only cry, N and P	eq.S16	

Supplementary Table 2. Description of the model variables used in Supplementary Table 1.

Supplementary Table 3 gives more details.

Variable	Description	Unit	Equation in Supplementary Table 1	Code in Supplementary Table 3	Source
i = pollutant: Cryptosporidium (cry), nitrogen (N), phosphorus (P), microplastics (MP) and triclosan (TSC) j = grid of 0.5° sb = sub-basin n = number of grids of 0.5° belonging to sub-basin sb					
Inputs of pollutants to rivers					
$RS_{\mathrm{i.sb}}$	Inputs of pollutant i to rivers in sub-basin sb; quantified as the sum of the values over grids of 0.5° belonging to sub-basin sb	kg year^{-1} for N, P, MP; g year^{-1} for TCS; oocysts year^{-1} for cry	eq. S1	-	Figures 2-4, Supplementary Figures 18-29
$RS_{\mathrm{dir.i.j}}$, $RS_{\mathrm{sew.i.j}}$	Inputs of pollutant i to rivers in grid j from open defecation and sewer systems, respectively. Open defecation is a direct discharge of pollutant to rivers. We do not consider open defecation on land (which is a diffuse source of pollutants). We ignore latrines and septic tanks that might be a diffuse source of pollutants in rivers. We focus on point sources.	kg year^{-1} for N, P, MP; g year^{-1} for TCS; oocysts year^{-1} for cry	eq. S2-S3	-	Supplementary Figures 27-29*
$Pop_{\mathrm{dir.j}}$, $Pop_{\mathrm{sew.j}}$	Population in grid j with open defecation and with sewerage connection, respectively	People year^{-1}	eq. S4, S12	-	Supplementary Figures 1-3**
$WShw_{\mathrm{cap.i.j}}$	Excretion or consumption rates of pollutant i per capita in grid j	kg capita^{-1} year^{-1} for N, P, MP; g capita^{-1} year^{-1} for TCS; oocysts capita^{-1} year^{-1} for cry	eq. S7-S10, S14-S15	-	Supplementary Figures 4-8
$hw_{\mathrm{frem.i.j}}$	The fraction of removal of pollutant i during treatment in sewer systems of grid j	0-1	eq. S16	-	Supplementary Figures 9-13
Quantifying variables for $RS_{\mathrm{dir.i.j}}$					
$Pop_{\mathrm{dir.urb.j}}$, $Pop_{\mathrm{dir.rur.j}}$	Urban and rural population in grid j with open defecation, respectively	People year^{-1}	eq. S5, S6	-	Supplementary Figures 1-3**
$Pop_{\mathrm{urb.j}}$, $Pop_{\mathrm{rur.j}}$	Urban and rural population in grid j, respectively	People year^{-1}	-	a	
$fr_{\mathrm{pop.dir.urb.j}}$, $fr_{\mathrm{pop.dir.rur.j}}$	The fraction of urban and rural population with open defecation, respectively	0-1	-	b	
$WShw_{\mathrm{cap.cry.j}}$	Excretion rate of *Cryptosporidium* per capita in grid j	oocysts capita^{-1} year^{-1}	eq. S7	-	Supplementary Figure 8
$I_{\mathrm{cry.j}}$	Infection rates of *Cryptosporidium* in grid j, depends on human development index	0-1	-	c	Supplementary Table 3, Supplementary Figure 14 -
$Exc_{\mathrm{cry.j}}$	Excretion rates of *Cryptosporidium* per ill person in grid j	oocysts ill capita^{-1} year^{-1}	-	d	
$WShw_{\mathrm{cap.N.j}}$	Excretion rate of nitrogen (N) per capita in grid j	kg capita^{-1} year^{-1}	eq. S8	-	Supplementary Figure 4
$I_{\mathrm{N.j}}$	Protein N intake in grid j	g capita^{-1} day^{-1}	-	e	Supplementary Table 3
$GDP_{\mathrm{ppp.j}}$	National Gross Domestic Products at purchasing power parity in grid j	2005 US$ capita^{-1} year^{-1}	-	e	
$WShw_{\mathrm{cap.P.j}}$	Excretion rate of phosphorus (P) per capita in grid j	kg capita^{-1} year^{-1}	eq. S9-S10	-	Supplementary Figure 5
$WShw_{\mathrm{cap.P.sew.j}}$	Excretion rate of phosphorus (P) per capita in grid j associated with human waste	kg capita^{-1} year^{-1}	eq. S10-S11	-	

Quantifying variables for $RS_{\text{sew.i.j}}$					
$Pop_{\text{sew.urb.j}}$, $Pop_{\text{sew.rur.j}}$	Urban and rural population in grid j with sewer connections, respectively	People year^{-1}	eq. S12-S13	-	Supplementary Figures 1-3**
$fr_{\text{pop.sew.urb.j}}$, $fr_{\text{pop.sew.rur.j}}$	Fractions of urban and rural population in grid j with sewer connections, respectively	0-1	-	f	
$WShw_{\text{cap.P.det.j}}$	Consumption rate of phosphorus (P) detergents (laundry and washing) in grid j	kg capita^{-1} year^{-1}	-	g	Supplementary Figure 6
$WShw_{\text{cap.MP.tyres.j}}$, $WShw_{\text{cap.MP.PCP.j}}$, $WShw_{\text{cap.MP.ldry.j}}$, $WShw_{\text{cap.MP.dust.j}}$	Consumption rates of microplastics (MP) associated with the use of car tyres (tyres), personal care products (PCP), and from laundry (ldry) and household dust, respectively	kg capita^{-1} year^{-1}	-	h	Supplementary Figure 7*** Supplementary Table 3
$WShw_{\text{cap.TCS.j}}$	Consumption rate of triclosan (TCS) (from personal care products) in grid j	g capita^{-1} year^{-1}	-	i	Supplementary Table 3
$f_{\text{p.j}}$, $f_{\text{s.j}}$, $f_{\text{t.j}}$, $f_{\text{no.j}}$	Distribution of treatment types in grid j among primary, secondary, tertiary and no treatment, respectively	0-1	-	j	Supplementary Tables 3 and 8
$RE_{\text{p.j}}$, $RE_{\text{s.j}}$, $RE_{\text{t.j}}$, $RE_{\text{no.j}}$	Removal efficiencies of pollutant i in grid j during primary, secondary, tertiary treatment and without treatment, respectively	0-1	-	k	

*These figures provide the share of open defecation in total inputs of nutrients and *Cryptosporidium* to rivers from point sources by sub-basin. **These figures provide the sub-basin specific information for urban, rural, total population that is connected to sewer systems. ***This figure shows the consumption rate associated with the use of care tyres. The consumption rates associated with household dusts, laundry and the use of personal care products are in Supplementary Table 3

Supplementary Table 3. Explanation of how model variables were derived for Supplementary Tables 1 and 2. SSPs are short for the Shared Socio-economic Pathways. HDI is short for Human Development Index. Details on the model inputs for 2010 are in Strokal, et al. [7] and for 2050 and 2100 are in Supplementary Tables 4-6 and Supplementary Figures 1-14.

Code in Table S1.2	Explanation and sources
a	Urban and rural population for 2010, 2050 and 2100 was directly taken from Jones and O'Neill [8]. The data were available at 0.125 degree cell. We aggregated the data to 0.5° grid.
b	The fraction of urban and rural population with open defecation were available by country for 2010 from Hofstra and Vermeulen [4] and based largely on the information from the Joint Monitoring Program (https://washdata.org/) on sanitation types. Strokal, et al. [7] completed the dataset of Hofstra and Vermeulen [4] by adding the fractions for small countries with missing data. Countries with missing data cover <10% of the total study area. Strokal, et al. [7] added the data for those countries using the averaged fractions for the regions covering those countries. The averaged fractions for the regions were estimated using the fractions of the countries for which data were available from Hofstra and Vermeulen [4]. For 2050 and 2100, we made assumptions for countries according to the storylines of SSPs (see Supplementary Tables 4-6). We assigned country values to grids of 0.5° for 2010, 2050 and 2100.
c	Infection rates of *Cryptosporidium* depends on developing and developed countries that are defined based on the HDI index according to Hofstra and Vermeulen [4]. Developed countries are with HDI>0.785 and developing countries are with HDI<0.785. Infection rate was used from Hofstra and Vermeulen [4]: - 5% (or 0.05 fraction) for developed countries; - 10% (or 0.1 fraction) for developing countries. For 2010, HDI was derived from the World Bank database (https://data.worldbank.org/) (see [7]). For 2050 and 2100, we made assumptions for countries according to the storylines of SSPs (see Supplementary Tables 4-6). We assigned country values to grids of 0.5° for 2010, 2050 and 2100.
d	Excretion rates of oocysts of *Cryptosporidium* per ill person is 10^9 according to Hofstra and Vermeulen [4]. We used this value for 2010, 2050 and 2100 for each grid of 0.5° (Supplementary Figure 8).
e	National Gross Domestic Products at purchasing power parity (GDP_{ppp}) was directly derived from Crespo Cuaresma [9] by country for 2010, 2050 and 2100 for the SSPs. First, we quantified $I_{N.k}$ by country using country values of *GDP*ppp for 2010, 2050 and 2100 SSPs. Then, we assigned country values to grids of 0.5° to get $I_{N.j}$. $I_{N.k} = 4 + 17 * (GDP_{ppp.k}/68673)^{0.3}$ according to Strokal, et al. [7] Where $I_{N.k}$ is protein N intake in country k (g N capita^{-1} day^{-1}). $GDP_{ppp.k}$ is national gross domestic product at purchasing power parity (2005 US$ capita^{-1} year^{-1}).
f	The same explanation as for the fractions of the population with open defecation (see point b above).
g	Consumption rates of phosphorus (P) in detergent (laundry and washing) was taken from Van Drecht, et al. [10] for regions. The values are given in the Supplementary Materials of Strokal, et al. [7] (see Supplementary Figure 8 in this manuscript). We assigned regional values to grids of 0.5° for 2010, 2050 and 2100.
h	Consumption rates of microplastics (MP) associated with the use of car tyres (tyres), personal care products (PCP), and from laundry (ldry) and household dust were derived directly from Siegfried, et al. [5] with modification for tyres. Values of Siegfried, et al. [5] for microplastics from personal care products, laundry and household dusts are largely based on literature review. For tyres, Strokal, et al. [7] distinguish between developing and developed countries. Consumption rates are (kg capita^{-1} year^{-1}): - car tyres: 0.18 when HDI>0.785 and 0.018 when HDI<0.785 based on Siegfried, et al. [5] and Strokal, et al. [7] - personal care products: 0.071 from Siegfried, et al. [5] - laundry: 0.12 from Siegfried, et al. [5] - household dust: 0.08 from Siegfried, et al. [5] For 2010, 2050 and 2100, we used these values except for tyres where the values may change depending on HDI. We assigned the values to grids of 0.5° for 2010, 2050 and 2100.
i	Consumption rate of triclosan (TCS) associated with the use of personal care products (PCP was derived directly from van Wijnen, et al. [6]. This rate is 0.5 g capita^{-1} year^{-1}. For 2010, 2050 and 2100, we used this value for all grids of 0.5°. We assumed that people may use the personal care products in the future as today.
j	Distribution of treatment types among primary, secondary, tertiary and no treatment was available by country for 2010 from Hofstra and Vermeulen [4]. Strokal, et al. [7] completed the dataset of 2010 by adding the information for small countries with missing data (occupy <10% of the total study area). For 2050 and 2100, we made assumptions based on the storylines of SSPs. We assigned the values to grids of 0.5° for 2010, 2050 and 2100.
k	Removal efficiencies of pollutant i during primary, secondary, tertiary treatment and without treatment, were directly derived from existing literature for *Cryptosporidium*, nitrogen and phosphorus. The removal fractions are: - For *Cryptosporidium* (Hofstra and Vermeulen [4]): - primary: 0.10 - secondary: 0.55 - tertiary: 0.98 - no treatment: 0 - For nitrogen (Van Drecht, et al. [10] approach adjusted according to Hofstra and Vermeulen [4]):

	- primary: 0.10 - secondary: 0.42 - tertiary: 0.88 - no treatment: 0 - For phosphorus (Van Drecht, et al. [10] approach adjusted according to Hofstra and Vermeulen [4]): - primary: 0.10 - secondary: 0.51 - tertiary: 0.95 - no treatment: 0 The removal rates of different pollutants in wastewater treatment plants depend largely on the type of pollution. In our study, primary treatment implies technologies having the removal efficiencies of the pollutants <10% (see above). Examples for nutrients are screening processes to remove large particles by sedimentation and separation. Secondary treatment is with technologies having the removal efficiencies of the pollutants around 50%[10]. For nutrients, this can be biologically-driven technologies. Examples are aeration by microbes to remove dissolved organic matters, and thus nutrients. Microbes can help chemicals to degrade depending how active microbes are. Tertiary treatment includes advanced technologies and chemicals to clean water further. Examples are efficient ultrafiltration methods can reduce *Cryptosporidium*[11] and microplastics[12], and reverse osmosis can recover nutrients[13] and reduce microplastics[12]. Nature-based solutions can also have high efficiencies of removing pollutants. For example, stabilization ponds and constructed wetlands are largely effective to reduce *Cryptosporidium*[11] and nutrients[14]. Removal efficiencies can also be high in the following technologies: annomox[15] to remove N, calcium precipitation to form struvite and recover P[16], and disinfection by Ultraviolet radiation to inactivate *Cryptosporidium*[11]. We used the known removal rate of phosphorus to assume removal of triclosan and microplastics. To make this assumption, we used data about removal of triclosan and microplastics from literature[17-21]. With the data from these sources, we made an assumption how to relate the average phosphorus removal in a watershed with the triclosan removal. We formulated three classes of triclosan removal (0, 60 or 90 %) and related these to known phosphorus removal in each sub-basin (details are in van Wijnen, et al. [6]). A similar approach was carried out for microplastics. We made four microplastics removal classes and related those to the known average phosphorus removal in each sub-basin[5,22]. These classes represent an average microplastics removal in each sub-basin. Microplastics removal depends on size and density of the microplastics. Therefore, the removal at each individual Waste Water Treatment Plants will be dependent on these and other characteristics. In our study, on a global scale, we chose to assume average removal for each sub-basin. The removal efficiencies per treatment type do not change over time, but the distribution of treatment types do change (see point j above). We assigned the values to grids of 0.5° for 2010, 2050 and 2100. See Supplementary Table 8 for treatment types and efficiencies, Supplementary Figures 9-13 provide the information for sub-basins.

Supplementary Table 4. Storylines of the global scenarios to assess impacts of urbanization on river pollution in the 21st century. SSP is short for Shared Socio-economic Pathways. Proactive environmental approaches indicate that people react on environmental problems such as river pollution when they appear. Proactive environmental approaches indicate that people try to avoid or reduce river pollution. Quantitative interpretation of the storylines for model variables are given in Supplementary Tables 5-6 and in Supplementary Figures 1-14 for 2050 and 2100. The model is described in Supplementary Tables 1-3. GDP is gross domestic product

Storylines	Scenario names and their storylines				
	Low_{urb}-Low_{wwt}	Mod_{urb}-Mod_{wwt}	$High_{urb}$-Low_{wwt}	$High_{urb}$-Mod_{wwt}	$High_{urb}$-$High_{wwt}$
○ Urbanization (urb) ○ Wastewater treatment rates (wwt)	Low Low	Moderate Moderate	High Low	High Moderate	High High
Socio-economic development: ○ GDP growth ○ Total population growth	 Low High	 Moderate Moderate	 Moderate Moderate	 High Low	 High Low
Description of the storylines	○ High socio-economic challenges to mitigation and adaptation ○ Fragmented world with difficulties to control population growth ○ Low economic development ○ Low urbanization rates ○ High population growth ○ No technological development to improve wastewater treatment ○ Reactive environmental management ○ Follow SSP3: a Rocky Road	○ Medium socio-economic challenges to mitigation and adaptation ○ Middle of the road ○ Moderate economic development ○ Moderate urbanization rates ○ Moderate population growth ○ Technological development follows business as usual trends ○ Reactive or proactive environmental management depending on region and its current trends ○ Follow SSP2: Middle of the Road	○ High socio-economic challenges to mitigation and low to adaptation ○ Large gap between urban and rural development ○ Moderate economic development (higher in urban areas) ○ High urbanization rates ○ Moderate population growth ○ Some technological development especially in urban areas ○ Proactive environmental management in urban areas and reactive in rural areas ○ Follow SSP4: Road Divided	○ High socio-economic challenges to mitigate, but low to adapt ○ Economy takes priority ○ High economic development ○ High urbanization rates ○ Low population growth ○ High potential for technological development, but less investments in improving wastewater treatment ○ Reactive environmental management because of the strong focus on economy ○ Follow SSP5: Taking the Highway	○ Low socio-economic challenges for adaptation and mitigation ○ Environment takes priority; high importance of achieving sustainable goals ○ High economic development ○ High urbanization rates ○ Low population growth ○ High technological development leading to considerable investments in improving wastewater treatment and in developing and implementing new sustainable-oriented solutions ○ Proactive environmental management because of the strong focus on economy ○ Follow SSP1: a Green Road

Supplementary Table 5. Quantitative interpretations of the storylines from Supplementary Table 4 for 2050. SSP is short for Shared Socio-economic Pathways. See Supplementary Tables 1-3 for the model description. See Supplementary Figures 1-14 for the sources of the model inputs.

Model variables and units	Equations (eq.) in Supplementary Table 1	Scenario assumptions for 2050				
		Low_{urb}-Low_{wwt}	Mod_{urb}-Mod_{wwt}	$High_{urb}$-Low_{wwt}	$High_{urb}$-Mod_{wwt}	$High_{urb}$-$High_{wwt}$
Model variables to account for urbanization						
Fraction of people connected to sewer (% reduction in a gap)*: ○ Urban ○ Rural	eq. S13-S14	 0% (as in 2010) 0% (as in 2010)	 20% 5%	 30% 0%	 30% 10%	 30% 10%
Fraction of people with open defecation (0-1): ○ Urban ○ Rural	eq. S5-S6	 As in 2010 As in 2010	For urban and rural: the difference between the fractions of people with open defecation in 2010 and with connection to sewer in 2050**	 0 (all connected) As in 2010	 As under Mod_{urb}-Mod_{wwt}	 0 (all connected) 0 (all connected)
Use of detergents	eq. S.14	As in 2010	Forbidden	Forbidden	Forbidden	Forbidden
Model variables to account for wastewater treatment						
Distribution of treatment types (% shift to the next treatment type between 2010 and 2050)***: ○ HDI>0.785 (developed countries) ○ HDI<0.785 (developing countries)	eq. S3, S17	 0% (as in 2010) 0% (as in 2010)	 50% 30%	 50% 0% (as in 2010)	 50% 30%	 All tertiary types ½ secondary and ½ tertiary
Model variables to account for socio-economic development						
Total, urban and rural people (people $year^{-1}$)[23]	eq. S5-S6, S12-S13	SSP3	SSP2	SSP4	SSP5	SSP1
Gross domestic product (2005 US$ $capita^{-1}$ $year^{-1}$)[9]	eq. S8-S10	SSP3	SSP2	SSP4	SSP5	SSP1
Human Development index (HDI, % increase relative to 2010)	eq.S7, S15	0% (as in 2010)	10%	10%	20%	20%

*Example for 2010 and 2050: assuming that 40% of the urban people are connected to sewer systems in 2010. In this case, a gap is 60% (100% - 40%). Suppose we would like to reduce a gap by 20%. 20% of the gap is 12% = (60% gap * 20% reduction)/100%. This 12% reflects the 12% of the people with sewer connections as a result of the reduced gap. The total % of people with sewer connections for 2050 would be the % of the people with sewer connections in 2010 (40%) + the % of people with sewer connections as a result of the reduced gap (12%). This approach with a gap closure for population was implemented also in the interpretation of the Millennium Ecosystem Assessment scenarios for a global model quantifying river export of nutrients[24]. Within the gap, open defecation is included as well as onsite sanitation types (e.g., pit latrines and septic tanks).

**Example for 2010 and 2050: if the fraction of people with open defecation in 2010 exceeds the fraction of people with sewer connections in 2050, then this difference is the fraction of people with open defecation in 2050. This implies that not all people with open defecation may become connected to sewer systems in 2050 and may still continue open defecating. If the fractions of people with open defecation in 2010 are lower than the fractions of people with sewer connections in 2050, then it implies that all people that open defecated in 2010 may become connected to sewer systems in 2050. In this case, the fraction of people with open defecation will be zero for 2050.

***The shift in treatment types is considered in this order: no treatment, primary, secondary and tertiary treatment. The shift starts from no treatment. Example: suppose we would like to have a 30% shift to the next treatment type in a developing country (HDI<0.785 in 2050). In 2010, no treatment was dominant in a country. The next treatment type is a primary treatment. A 30% shift (0.3 in a fraction) to this primary treatment is quantified as: the fraction of primary treatment in 2050 = [the fraction of no treatment in 2010 * 0.3] + [the fraction of primary treatment in 2010 * (1-0.3)]. This implies that the fraction of no treatment in 2050 would be = the fraction of no treatment in 2010 * (1-0.3). The same holds for the other secondary and tertiary treatment. This method was also applied in the interpretation of the Millennium Ecosystem Assessment scenarios for a global model quantifying river export of nutrients[24].

Supplementary Table 6. Quantitative interpretations of the storylines from Supplementary Table 4 for 2100. See Supplementary Table 1 and Supplementary Tables 1-3 for the model description. See Supplementary Figures 1-14 for the sources of the model inputs.

Model variables and units	Equations (eq.) in Supplementary Table 1	Scenario assumptions for 2100				
		Low_{urb}-Low_{wwt}	Mod_{urb}-Mod_{wwt}	$High_{urb}$-Low_{wwt}	$High_{urb}$-Mod_{wwt}	$High_{urb}$-$High_{wwt}$
Model variables to account for urbanization						
Fraction of people connected to sewer systems (% reduction in a gap)*: ○ Urban ○ Rural	eq. S13-S14	20% 5%	50% 2%	60% 5%	60% 30%	60% 30%
Fraction of people with open defecation (0-1): ○ Urban ○ Rural	eq. S5-S6	For urban and rural: the difference between the fractions of people with open defecation in 2050 and with connection to sewer in 2100**	0 (all connected) 0 (all connected)	0 (all connected) As under Low_{urb}-Low_{wwt}	0 (all connected) 0 (all connected)	0 (all connected) 0 (all connected)
Use of detergents	eq. S.14	Forbidden	Forbidden	Forbidden	Forbidden	Forbidden
Model variables to account for wastewater treatment						
Distribution of treatment types (% shift to the next treatment type between 2050 and 2100)***: ○ HDI>0.785 (developed countries) ○ HDI<0.785 (developing countries)	eq. S3, S17	50% 30%	70% 50%	70% 30%	70% 50%	All tertiary types All tertiary types
Model variables to account for socio-economic development						
Total, urban and rural people (people $year^{-1}$)[23]	eq. S5-S6, S12-S13	SSP3	SSP2	SSP4	SSP5	SSP1
Gross domestic product (2005 US$ $capita^{-1}$ $year^{-1}$)[9]	eq. S8-S10	SSP3	SSP2	SSP4	SSP5	SSP1
Human Development index (HDI, % increase relative to 2050)	eq.S7, S15	10%	10%	10%	20%	20%

*Example for 2050 and 2100: assuming that 40% of the urban people are connected to sewer system in 2050. In this case, a gap is 60% (100% - 40%). Suppose we would like to reduce a gap by 20%. 20% of the gap is 12% = (60% gap * 20% reduction)/100%. This 12% reflects the 12% of the people with sewer connections as a result of the reduced gap. The total % of people with sewer connections for 2100 would be the % of the people with sewer connection in 2050 (40%) + the % of people with sewer connections as a result of the reduced gap (12%). Within the gap, open defecation is included as well as onsite sanitation types (e.g., pit latrines and septic tanks).

**Example for 2050 and 2100: if the fraction of people with open defecation in 2050 exceeds the fraction of people with sewer connections in 2100, then this difference is the fraction of people with open defecation in 2100. This implies that not all people with open defecation may become connected to sewer systems in 2100 and may still continue open defecating. If the fractions of people with open defecation in 2050 are lower than the fractions of people with connections to sewer in 2100, then it implies that all people that open defecated in 2050 may become connected to sewer systems in 2100. In this case, the fraction of people with open defecation will be zero for 2100.

***The shift in treatment types is considered in this order: no treatment, primary, secondary and tertiary treatment. The shift starts from no treatment. Example: suppose we would like to have a 70% shift to the next treatment type in a developed country (HDI>0.785 in 2100). All waste is treated. A 70% shift (0.7 in a fraction) from a primary treatment to secondary treatment types is quantified as: the fraction of secondary treatment in 2100 = [the fraction of primary treatment in 2050 * 0.7] + [the fraction of secondary treatment in 2050 * (1-0.7)]. This implies that the fraction of primary treatment in 2100 would be = the fraction of primary treatment in 2050 * (1-0.7).

Supplementary Table 7. Modelled global sewage point source inputs of multiple pollutants to rivers in the world in comparison with other modelling studies. SSPs are short for Shared Socio-economic Pathways. In our study, the SSPs are incorporated in the following five scenarios: Low_{urb}-Low_{wwt} (SSP3), Mod_{urb}-Mod_{wwt} (SSP2), High_{urb}-Low_{wwt} (SSP4), High_{urb}-Mod_{wwt} (SSP5) and High_{urb}-High_{wwt} (SSP1). See details in Supplementary Tables 1-6 and Supplementary Figures 1-14 on the model and scenario descriptions.

References	Past or present	Future	Remark
Nitrogen inputs to rivers from sewage			
This study (Tg year^{-1})	2010: 9.5	2050: 5.4-21.0 2100: 4.8-31.1	10,226 sub-basins Our scenarios with extended SSPs
Van Drecht, et al. [10] (Tg year^{-1})	2000: 6.4	2050: 12.0-15.5	Millennium Ecosystem Assessment scenarios (urbanization is lower than in SSPs) No open defecation; >6000 basins
Morée, et al. [25] (Tg year^{-1})	2000: 7.7	-	Accounts for more sources from urban areas (e.g., open defecation, sewer pipe leakage)
van Puijenbroek, et al. [26] (Tg year^{-1})	2010: 10.4	2050: 13.5-17.9	SSPs
Phosphorus inputs to rivers from sewage			
This study (Tg year^{-1})	2010: 1.6	2050: 0.6-3.5 2100: 0.3-4.9	10,226 sub-basins; Our scenarios with extended SSPs
Van Drecht, et al. [10] (Tg year^{-1})	2000: 1.3	2050: 2.4-3.1	Millennium Ecosystem Assessment scenarios; No open defecation; >6000 basins;
Morée, et al. [25] (Tg year^{-1})	2000: 1.0	-	Accounts for more sources from urban areas (e.g., open defecation, sewer pipe leakage)
van Puijenbroek, et al. [26] (Tg year^{-1})	2010: 1.5	2050: 1.6-2.4	SSPs
Cryptosporidium inputs to rivers from sewage			
This study (10^{17} oocysts year^{-1})	2010: 1.60	2050: 0.40 – 2.92 2100: 0.08 – 4.81 2050 (Low_{urb}-Low_{wwt} based on SSP3): 2.44	10,226 sub-basins; Our scenarios with extended SSPs; Open defecation (OD)
Hofstra, et al. [27] Hofstra and Vermeulen [4] (10^{17} oocysts year^{-1})	2000: 1.10 2010: 1.42	2050 SSP3: 2.28	No open defecation in 2000; Open defecation in 2010; Gridded modeling
Triclosan inputs to rivers from sewage			
This study (kton year^{-1})	2010: 0.72	2050: 0.46 – 1.61 2100: 0.28 – 2.79	10,226 sub-basins; No changes in the consumption rate between the years; Our scenarios with extended SSPs; Ranges for Danube, Zhujiang and Ganges are for their sub-basins
This study (g km^{-2} year^{-1})	2010: 10-50 for Danube 2-50 for Zhujiang and Ganges	-	
van Wijnen, et al. [6] (g km^{-2} year^{-1})	2010: 11.7 for Danube 6.0-18.5 for Zhujiang and Ganges	-	Based on the data from the Millennium Ecosystem Assessment and the Global NEWS model (Nutrient Export from WaterSheds)
Microplastic inputs to rivers from sewage			
This study (Tg year^{-1})	2010: 0.45	2050: 0.15 – 0.99 2100: 0.10 – 1.49	10,226 sub-basins; No changes in the consumption rate between the years; Consumption rate as in Europe; Our scenarios with extended SSPs
Best [28] (g km^{-2} year^{-1})	0.41 – 4.00	-	32 largest rivers worldwide; Plastic (macro and micro) loads to rivers
Avio, et al. [29] (Tg year^{-1})	0.27	-	Inputs of plastic (macro and micro) to oceans based on 24 expeditions during the period of 2007-2013 along the coastal waters of Australia, Bay of Bengal and the Mediterranean Sea

Supplementary Table 8. Comparison of the results of this study for nitrogen (N) and phosphorus (P) with the results of van Puijenbroek, et al. [26]. SSPs are the Shared Socio-economic Pathways. SSPs. In our study, the SSPs are incorporated in the following five scenarios: Low_{urb}-Low_{wwt} (SSP3), Mod_{urb}-Mod_{wwt} (SSP2), $High_{urb}$-Low_{wwt} (SSP4), $High_{urb}$-Mod_{wwt} (SSP5) and $High_{urb}$-$High_{wwt}$ (SSP1). See details in Supplementary Tables 1-6 and Supplementary Figures 1-14 on the model and scenario descriptions. Results of van Puijenbroek, et al. [26] are based on SSPs.

Variables	Units	Year	This study	van Puijenbroek, et al. [26]
Total population	10^9 people	2010	7[a]	7[a]
		2050	8-10	8-10
Population with sewage connection	10^9 people (% of the total, ranges for scenarios)	2010	2 (34)	2 (36)
		2050	3-5 (30-55)	5-7 (55-77)
Distribution of treatment types: primary	Range for countries and scenarios, %	2010	0-63	0-93
		2050	0-63	0-81
Distribution of treatment types: secondary	Range for countries and scenarios, %	2010	0-73	0-66
		2050	0-73	0-97
Distribution of treatment types: tertiary	Range for countries and scenarios, %	2010	0-95	0-97
		2050	0-97	0-100
Distribution of treatment types: no treatment	Range for countries and scenarios, %	2010	1-100	0-100
		2050	0-100	-
Removal efficiency N:*	%	-		
○ Primary			10	10
○ Secondary			41.5	35
○ Tertiary			88.3	80
○ Quaternary			-	95
○ No treatment			0	0
Removal efficiency P:*	%	-		
○ Primary			10	10
○ Secondary			50.5	45
○ Tertiary			95.1	90
○ Quaternary			-	95
○ No treatment			0	0
Wastewater treatment for N and P (calculated using treatment types and removal efficiency N and P)***	Range for countries and scenarios, %	2010	N: 0-86 P: 0-92	NP: 0-87
		2050	N: 0-97 P: 0-95	NP: 0-100
Human excretion rate of N**	Range for scenarios, kg/capita/year	2010	4.7	4.7
		2050	5.4-6.2	5.4-6.2
Human excretion rate of P**	Range for scenarios, kg/capita/year	2010	0.8	0.5
		2050	0.9-1.0	0.5-0.6

* Van Drecht, et al. [10]; **In this study, it is calculated following the approach of Van Drecht, et al. [10] as a function of gross domestic product at purchasing power parity (GDPppp), but corrected for units of GDPppp for US$ 2005 according to Strokal, et al. [7]. ***See equations in Supplementary Table 1.

Supplementary Table 9. The setup of the sensitivity analysis for the multi-pollutant model. The multi-pollutant model quantifies annual inputs of pollutants to rivers from point sources. This includes the three main variables (see Supplementary Table 1): excretion or consumption rates of pollutants ($WShw_{cap.i.j}$, kg or g or oocysts per capita per year depending on pollutant), removal fractions of pollutants during treatment ($hw_{frem.i.j}$, 0-1) and the number of people connected to sewage systems ($Pop_{sew.j}$, people per year) and practicing open defecation ($Pop_{dir.j}$, people per year). Model inputs for quantifying $WShw_{cap.i.j}$ are numbered from 1 to 13, for $hw_{frem.i.j}$ from 14 to 19, and for $Pop_{sew.j}$ and $Pop_{dir.j}$ from 20 to 25. Abbreviations are given in Supplementary Table 1 and their descriptions are in Supplementary Table 2. In the sensitivity analysis, every model input is changed relative to the year 2010. The multi-pollutant model is ran for every change separately. The model results are compared with the original results in Supplementary Tables 10-12 and Supplementary Figure 17.

Model inputs		Original resolution	Affected pollutant (in grey)					Change relative to 2010	
			Cry	N	P	TCS	MP		
1	HDI	Country	■				■	-10%	+10%
2	GDPppp	Country		■	■			-10%	+10%
3	$I_{cry.j}$	Country	■					-10%	+10%
4	$Exc_{cry.j}$	Country	■					-10%	+10%
5	$WShw_{cap.cry.j}$	Country	■					-10%	+10%
6	$WShw_{cap.N.j}$	Country		■				-10%	+10%
7	$WShw_{cap.P.sew.j}$	Country			■			-10%	+10%
8	$WShw_{cap.P.det.j}$	Region			■			-10%	+10%
9	$WShw_{cap.TSC.j}$	Global				■		-10%	+10%
10	$WShw_{cap.MP.tyres.j}$	Country					■	-10%	+10%
11	$WShw_{cap.MP.PCP.j.}$	Global					■	-10%	+10%
12	$WShw_{cap.MP.ldry.j}$	Global					■	-10%	+10%
13	$WShw_{cap.MP.dust}$	Global					■	-10%	+10%
14	$f_{p.j}$#	Country	■	■	■	■	■	-10%	+10%
15	$f_{s.j}$#	Country	■	■	■	■	■	-10%	+10%
16	$f_{t.j}$#	Country	■	■	■	■	■	-10%	+10%
17	$RE_{p.i}$	*	■	■	■	■	■	-10%	+10%
18	$RE_{s.i}$	*	■	■	■	■	■	-10%	+10%
19	$RE_{t.i}$	*	■	■	■	■	■	-10%	+10%
20	$Pop_{urb.j}$	0.5°grid	■	■	■	■	■	-10%	+10%
21	$Pop_{rur.j}$	0.5°grid	■	■	■	■	■	-10%	+10%
22	$Fr_{pop.sew.urb.j}$	Country	■	■	■	■	■	-10%	+10%
23	$Fr_{pop.sew.rur.j}$	Country	■	■	■	■	■	-10%	+10%
24	$Fr_{pop.dir.urb.j}$	Country	■	■	■			-10%	+10%
25	$Fr_{pop.dir.rur.j}$	Country	■	■	■			-10%	+10%

*Pollutant specific;

#Changes in the fraction of treatment type (primary, secondary or tertiary) are assumed to influence the fraction of no treatment. For example, if the fraction of primary treatment is increased by 10%, then the fraction of no treatment will decrease by 10% to maintain the total of 100% for all treatment types in a country (primary, secondary, tertiary and no treatment).

Supplementary Table 10. Results of the sensitivity analysis for 10,226 sub-basins. These results show changes in model outputs as a result of +10% and -10% change in model inputs (% change relative to the original model run of 2010). Model outputs are annual inputs of pollutants to rivers from point sources in 2010. Pollutants are *Cryptosporidium* (Cry), nitrogen (N), phosphorus (P), triclosan (TCS) and microplastics (MP). The numbers outside of the parenthesis are changes in global pollutant inputs to rivers (totals for 10,226 sub-basins). The changes inside of the parenthesis are the ranges for the 10,226 sub-basins. Supplementary Table 1 provides equations with the model inputs and Supplementary Table 2 explains the abbreviations of the model inputs. The changes in the model outputs are higher (in yellow) or lower (in green). In bold, are the changes that are analysed further in Supplementary Tables 11-12. Empty or without colour cells indicate that the model outputs are not affected by the changes in the model inputs.

Changed model inputs (see Supplementary Table 9)		Changes in model outputs: pollutants to rivers from point sources (% change)									
		+10% change in model inputs					-10% change in model inputs				
		Cry	N	P	TCS	MP	Cry	N	P	TCS	MP
1	**HDI**	**15 (0-50)**				**17% (0-72)**	**4 (0-100)**				**5 (0-42)**
2	GDP_{ppp}		2 (1-2)	2 (1-2)				2 (1-2)	2 (1-2)		
3	$I_{cry.j}$	10 (-)					10 (-)				
4	$Exc_{cry.j}$	10 (-)					10 (-)				
5	$WShw_{cap.cry.j}$	10 (-)					10 (-)				
6	$WShw_{cap.N.j}$		10 (-)					10 (-)			
7	$WShw_{cap.P.sew.j}$			9 (7-10)					9 (7-10)		
8	$WShw_{cap.P.det.j}$			1 (0-3)					1 (0-3)		
9	$WShw_{cap.TSC.j}$				10 (-)					10 (-)	
10	$WShw_{cap.MP.tyres.j}$					2 (1-5)					2 (1-5)
11	$WShw_{cap.MP.PCP.j.}$					0.3 (0.2-0.3)					0.3 (0.2-0.3)
12	$WShw_{cap.MP.ldry.j}$					4 (3-5)					4 (3-5)
13	$WShw_{cap.MP.dust}$					3 (2-4)					3 (2-4)
14	$f_{p.j}$	0.1 (0-0.5)	0.1 (0-0.5)	0.2 (0-0.5)	0 (-)	0 (-)	0.1 (0.1-0.5)	0.1 (0.1-0.5)	0.2 (0.1-0.5)	0 (-)	0.2 (0-33)
15	$\boldsymbol{f_{s.j}}$	2 (0-8)	1 (0-5)	2 (0-7)	**0.2 (0-60)**	**0.2 (0-50)**	2 (0-8)	1 (0-5)	2 (0-7)	**0.2 (0-150)**	**3 (0-50)**
16	$\boldsymbol{f_{t.j}}$	**1 (0-99)**	**2 (0-36)**	**3 (0-63)**	**0.4 (0-75)**	**2 (0-80)**	**1 (0-188)**	**2 (0-58)**	**3 (0-118)**	**0.6 (0-300)**	**1 (0-400)**
17	$RE_{p.i}$	0.1 (0-0.5)	0.1 (0-0.5)	0.2 (0-0.5)	0 (-)	0 (-)	0.1 (0-0.5)	0.1 (0-0.5)	0.2 (0-0.5)	0 (-)	0.2 (0-33)
18	$\boldsymbol{RE_{s.i}}$	2 (0-8)	1 (0-5)	2 (0-7)	**0.2 (0-60)**	**0.2 (0-50)**	2 (0-8)	1 (0-5)	2 (0-7)	**0.2 (0-150)**	**3 (0-50)**
19	$\boldsymbol{RE_{t.i}}$	**0.3 (0-43)**	**2 (0-58)**	**1 (0-61)**	**0.3 (0-75)**	**1 (0-80)**	**1 (0-188)**	**2 (0-58)**	**3 (0-118)**	**0.6 (0-300)**	**1 (0-400)**
20	$Pop_{urb.j}$	9 (0-10)	9 (0-10)	9 (0-10)	9 (0-10)	9 (0-10)	9 (0-10)	9 (0-10)	9 (0-10)	9 (0-10)	9 (0-10)
21	$Pop_{rur.j}$	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)
22	$Fr_{pop.sew.urb.j}$	7 (0-10)	7 (0-10)	7 (0-10)	8 (0-10)	7 (0-10)	8 (0-10)	8 (0-10)	8 (0-10)	9 (0-10)	9 (0-10)
23	$Fr_{pop.sew.rur.j}$	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)	1 (0-10)
24	$Fr_{pop.dir.urb.j}$	1 (0-10)	1 (0-10)	1 (0-10)			1 (0-10)	1 (0-10)	1 (0-10)		
25	$Fr_{pop.dir.rur.j}$	0.2 (0-10)	0.1 (0-10)	0.1 (0-10)			0.2 (0-10)	0.1 (0-10)	0.1 (0-10)		

Meaning of the colours

Yellow	Model outputs are increased as a result of changes in model inputs
Green	Model outputs are decreased as a result of changes in model inputs

Supplementary Table 11. Results of the sensitivity analysis with +10% change in model inputs. Table shows percentages of global sub-basin area where model outputs change <5%, 5-10%, 10-15% or >50%. Results are given for the changed model inputs for which changes in model outputs vary among sub-basins (see model inputs in bold in Supplementary Table 10). Model outputs are pollutants entering rivers from point sources: *Cryptosporidium* (Cry), nitrogen (N), phosphorus (P), triclosan (TCS) and microplastics (MP). Green is for decreases and yellow is for increases in model outputs relative to the original model run of 2010 (Supplementary Table 9).

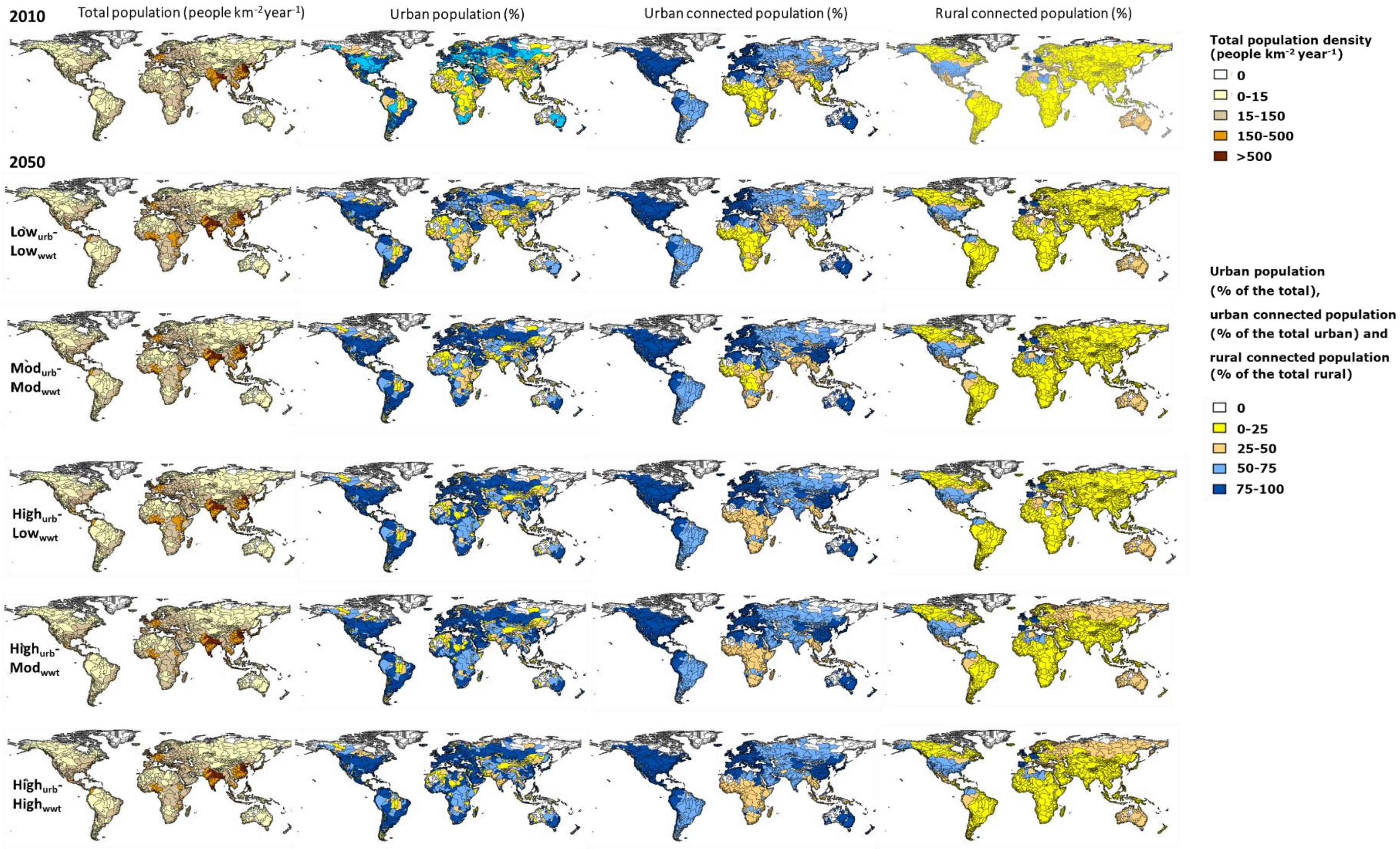
Change in model outputs (%)	Percentage of the sub-basin area with the change in model outputs for the pollutants (%)															
	Cry			N		P		TCS				MP				
	1*	16*	19*	16*	19*	16*	19*	15*	16*	18*	19*	1*	15*	16*	18*	19*
<5	66	85	99	86	86	85	98	99	99	99	99	66	99.6	98	99.6	98
5-10	1	13	0.2	13	13	13	1	0	0.2	0	0.2	2	0	0	0	0
10-50	33	2	0.8	1	1	2	1	<0.1	<0.1	<0.1	0	4	0.4	1	0.4	1
>50	0	0.3	0	0	<0.1	0.1	<0.1	<0.1	0.6	<0.1	0.5	29	0	1	0	1
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

*These changed model inputs are numbered as 1, 15, 16, 18 and 19 in Supplementary Table 9.

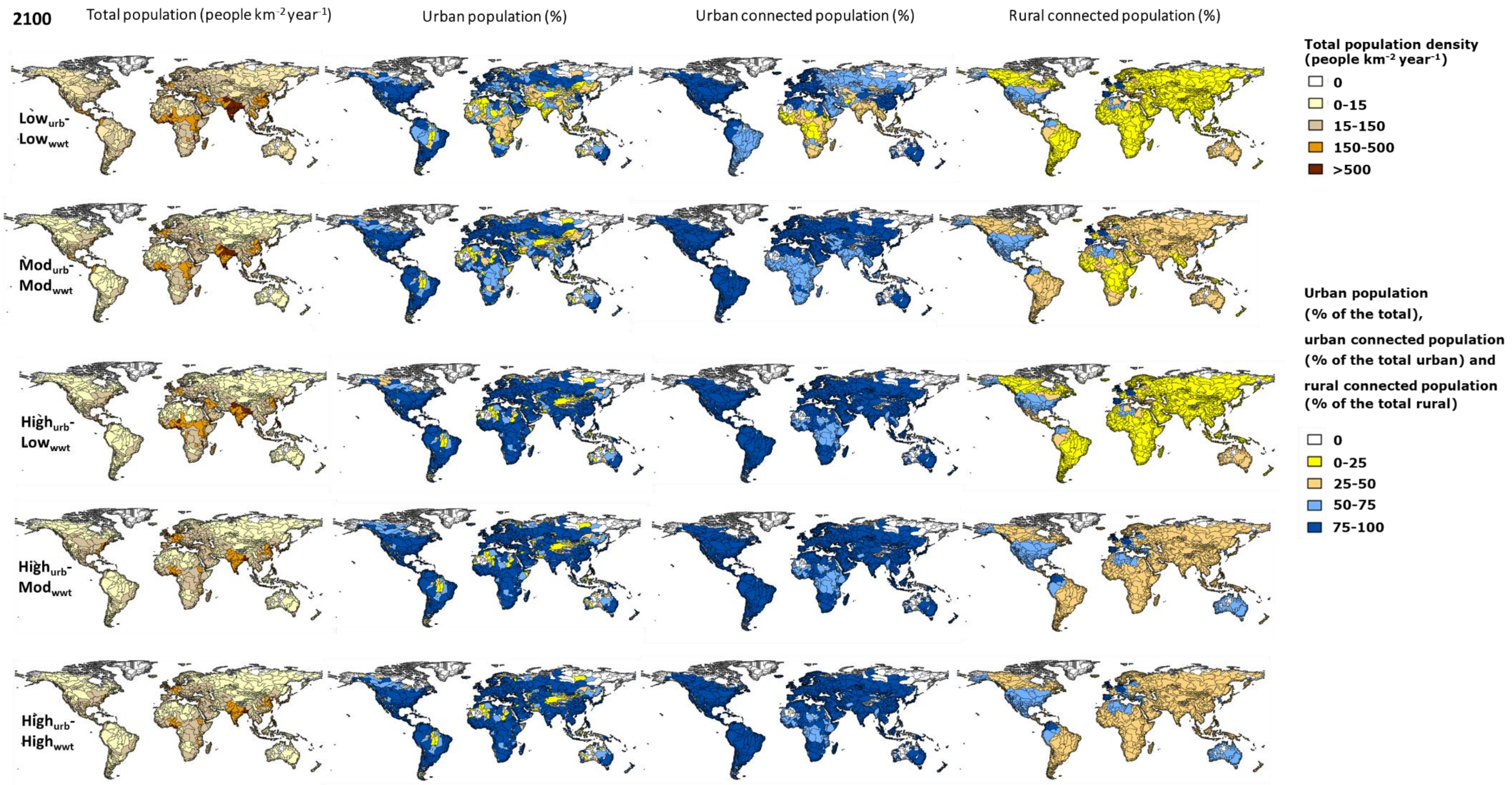
Supplementary Table 12. Results of the sensitivity analysis with -10% change in model inputs. Table shows percentages of global sub-basin area where model outputs change <5%, 5-10%, 10-15% or >50%. Results are given for the changed model inputs for which changes in model outputs vary among sub-basins (see model inputs in bold in Supplementary Table 10). Model outputs are pollutants entering rivers from point sources: *Cryptosporidium* (Cry), nitrogen (N), phosphorus (P), triclosan (TCS) and microplastics (MP). Green is for decreases and yellow is for increases in model outputs relative to the original model run of 2010 (Supplementary Table 9).

Change in model outputs (%)	Percentage of the sub-basin area with the change in model outputs for the pollutants (%)															
	Cry			N		P		TCS				MP				
	1	16	19	16	19	16	19	15	16	18	19	1	15	16	18	19
<5	93	85	85	89	86	85	85	99	99	99	99	93	92	93	92	93
5-10	0.3	13	13	10	13	13	13	0	0	0	0	0.3	0.3	0.5	0.3	0.5
10-50	1	1.5	1.5	1	1	2	2	<0.1	0.2	<0.1	0.2	7	8	7	8	7
>50	6	0.5	0.5	<0.1	<0.1	0.3	0.3	0.2	0.4	0.2	0.4	0	0	0.3	0	0.3
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

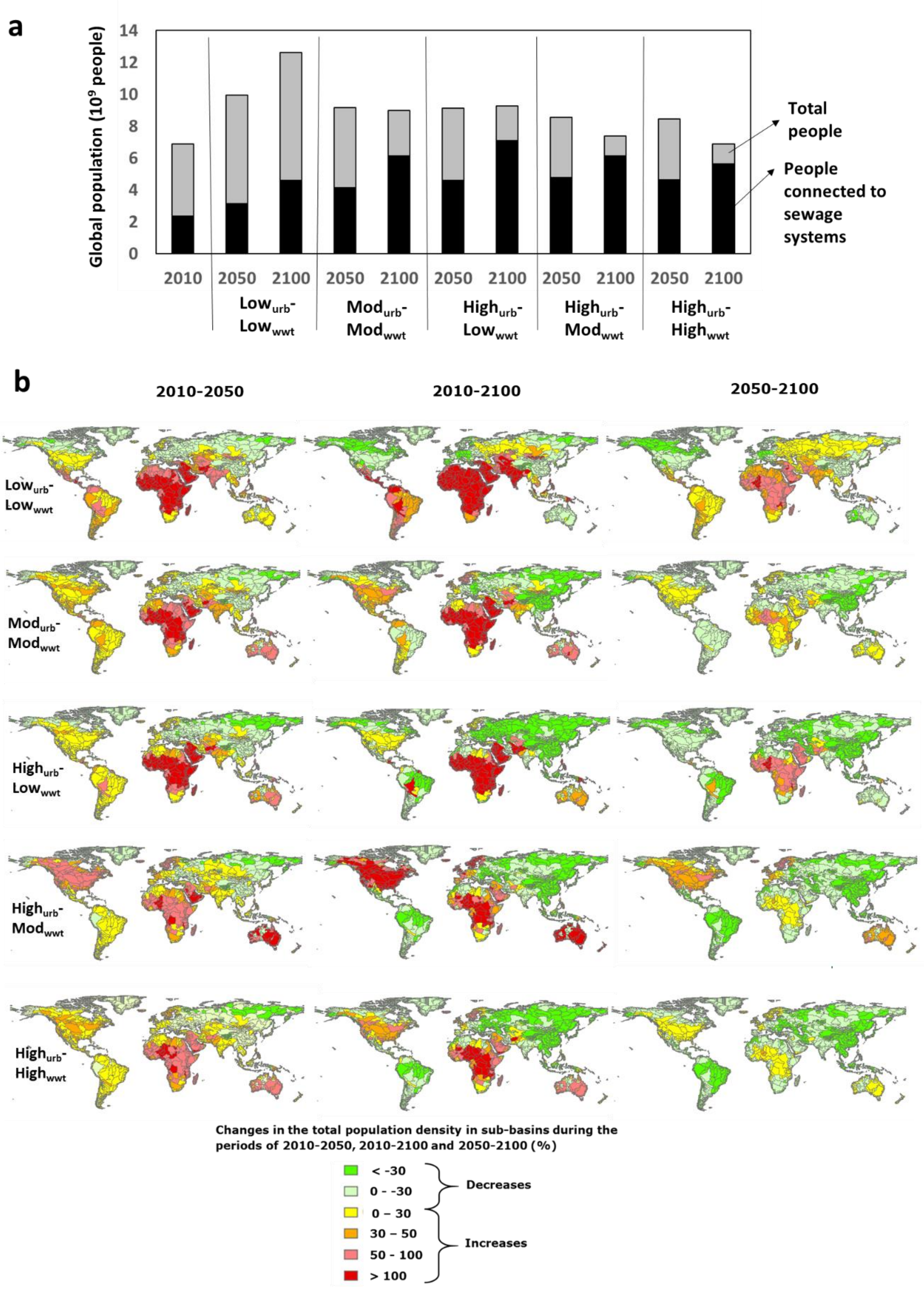
Supplementary Figures



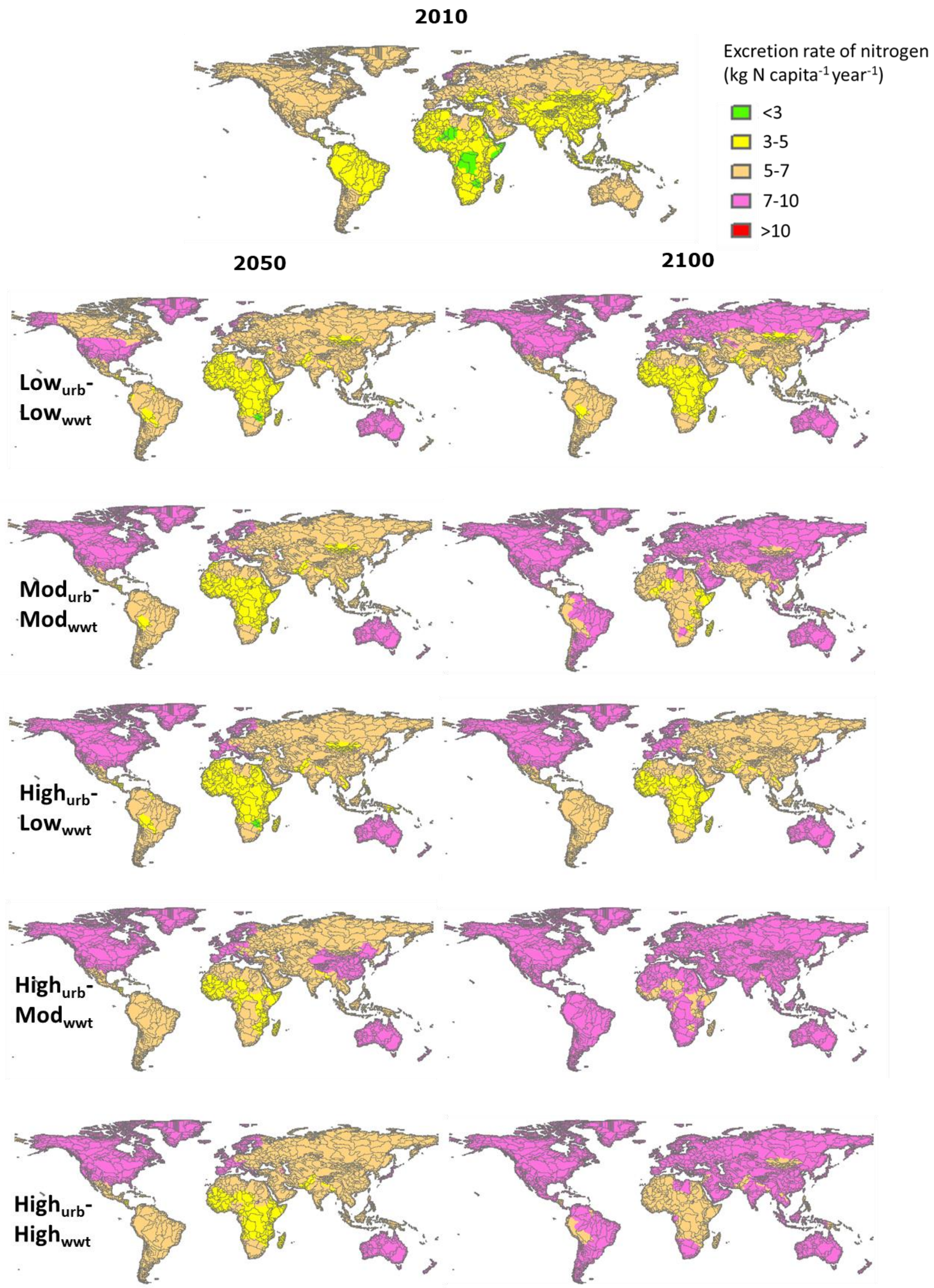
Supplementary Figure 1. Trends in population by sub-basin in 2010 and 2050 according to the five scenarios. See Supplementary Tables 1-6 for the model and scenario descriptions.



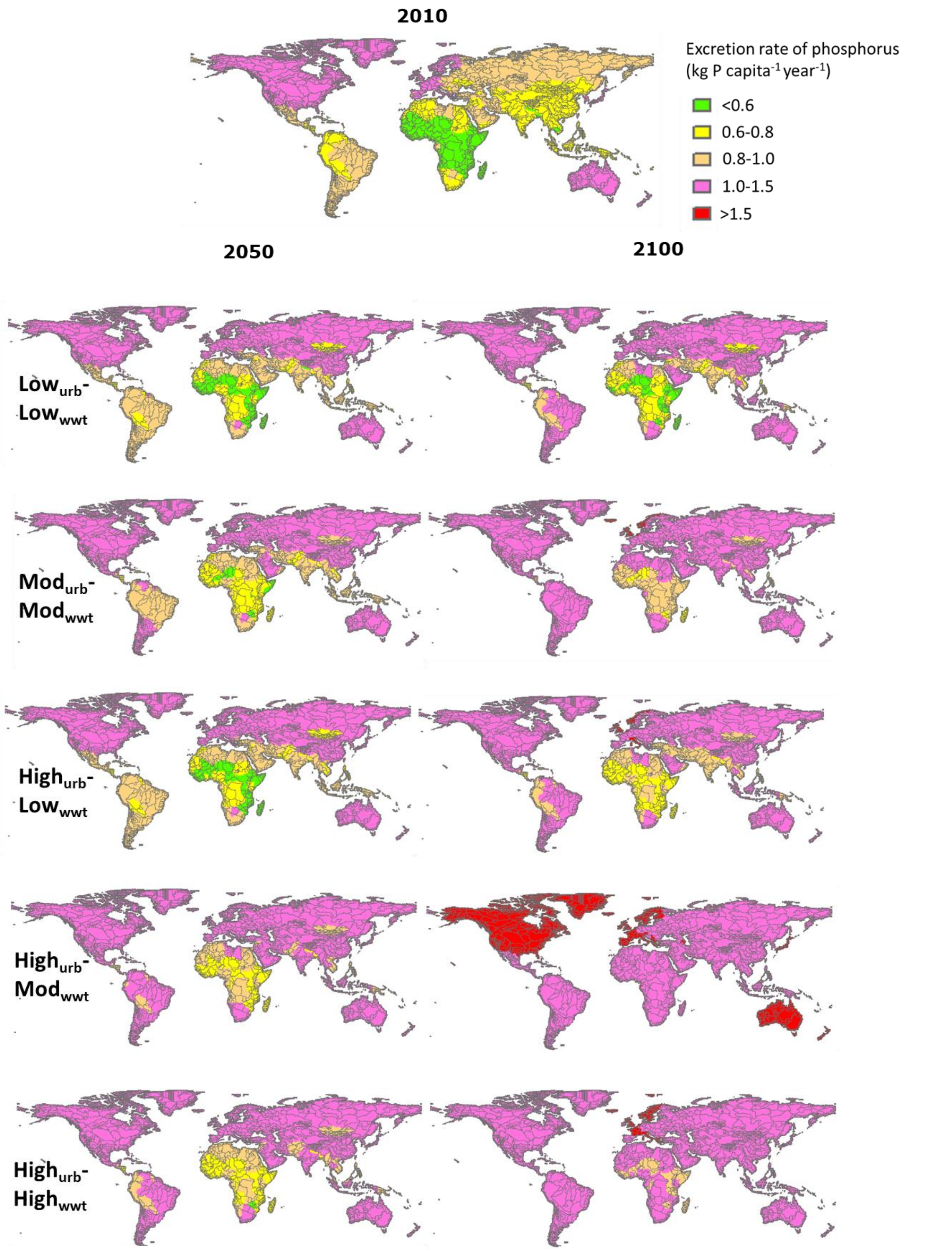
Supplementary Figure 2. Trends in population by sub-basin in 2100 according to the five scenarios. See Supplementary Tables 1-6 for the model and scenario descriptions.



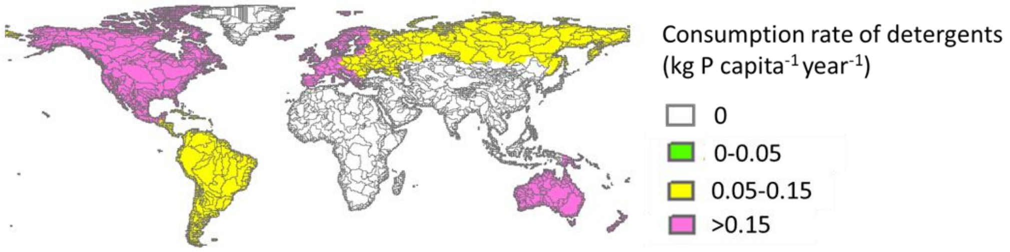
Supplementary Figure 3. Future trends in population. Total population (panel a, 10^9 people) and changes in the total population density in sub-basins during the periods of 2010-2050, 2010-2100 and 2050-2100 (panel b, %) according to the five scenarios. See Supplementary Tables 1-6 for the model and scenario descriptions.



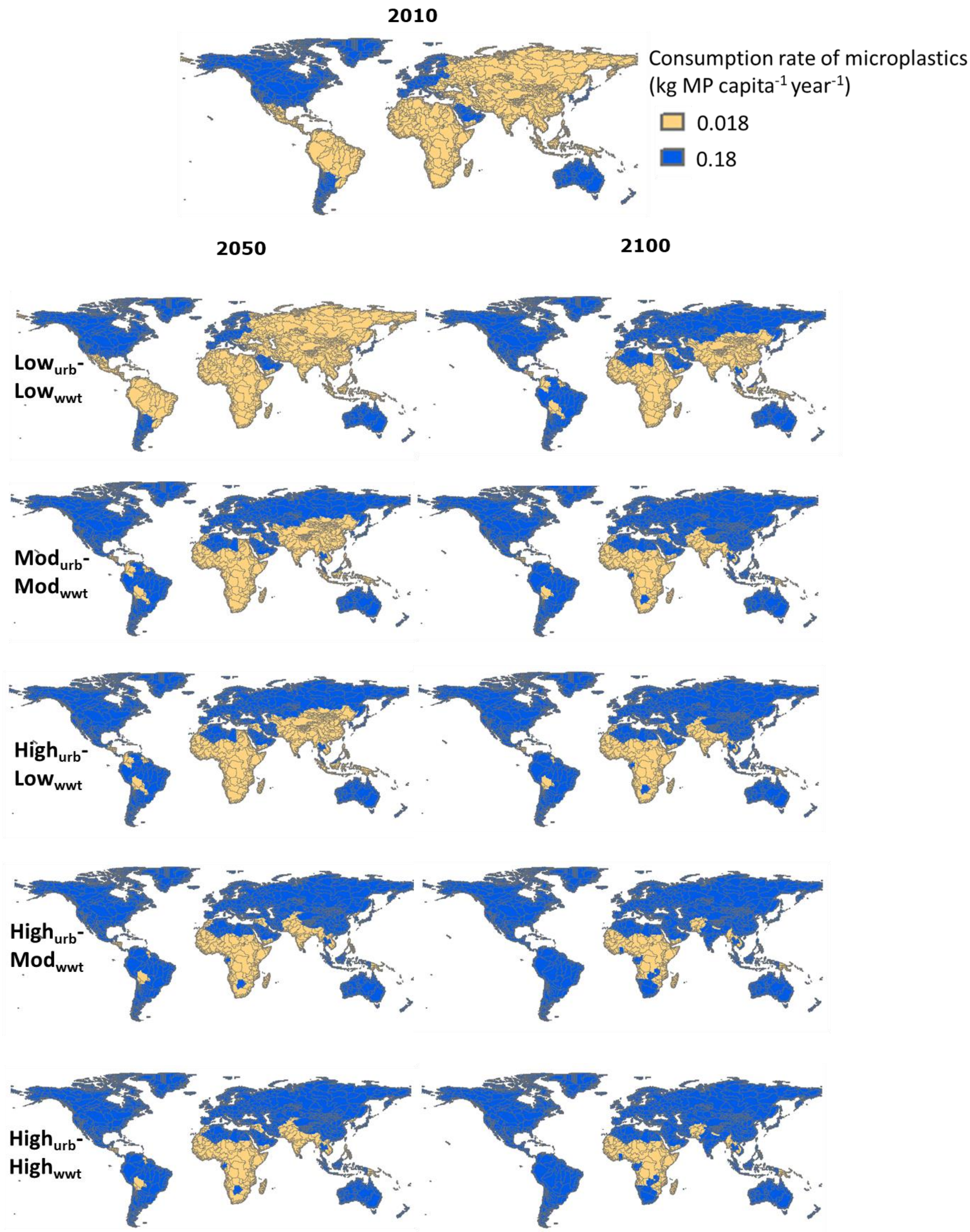
Supplementary Figure 4. Excretion rates of nitrogen in human waste in 2010, 2050 and 2100 by grid according to the five scenarios (kg N capita^{-1} year^{-1}). See Supplementary Tables 1-6 for the model and scenario descriptions.



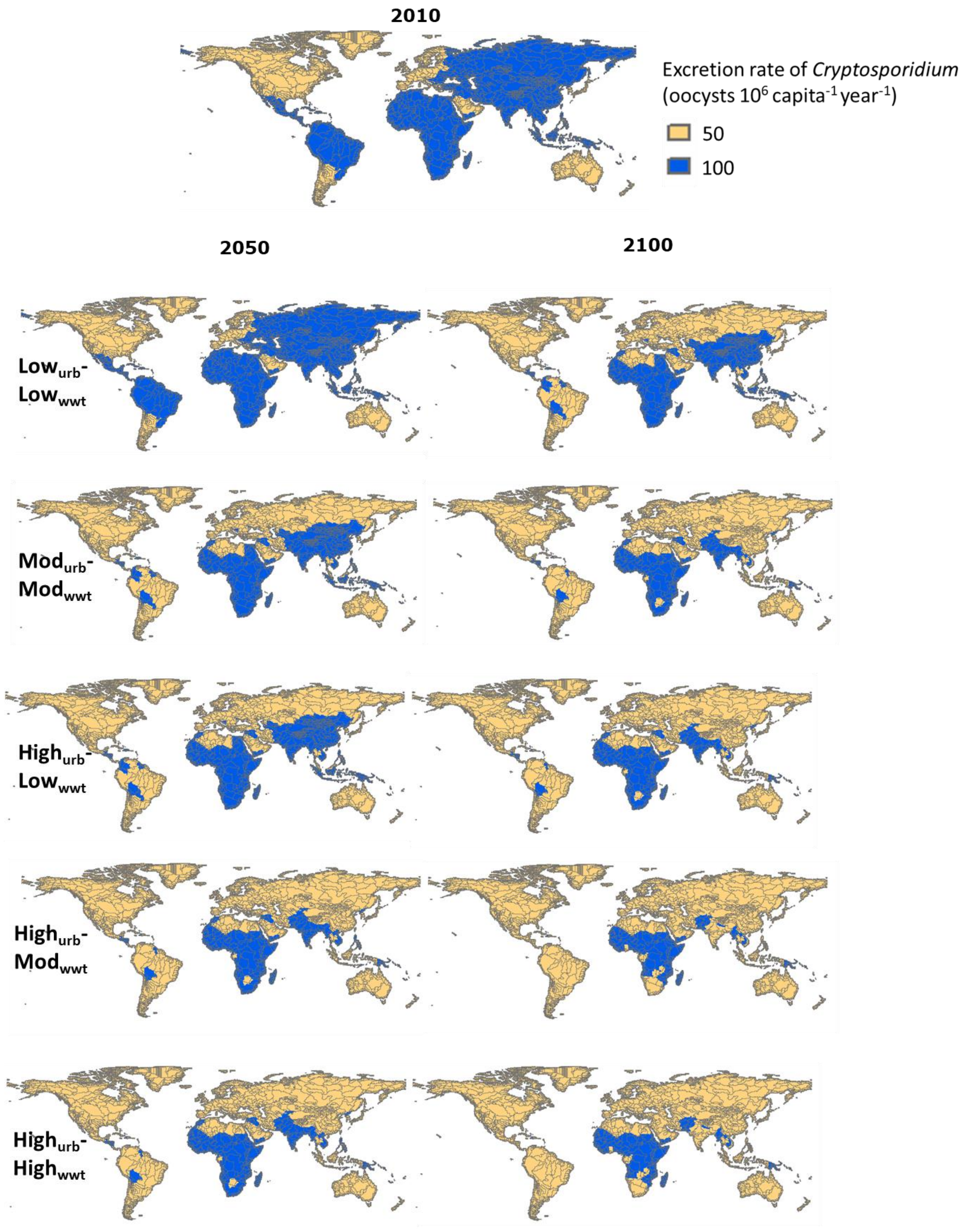
Supplementary Figure 5. Excretion rates of phosphorus in human waste by grid in 2010, 2050 and 2100 according to the five scenarios (kg P capita^{-1} year^{-1}). See Supplementary Tables 1-6 for the model and scenario descriptions.



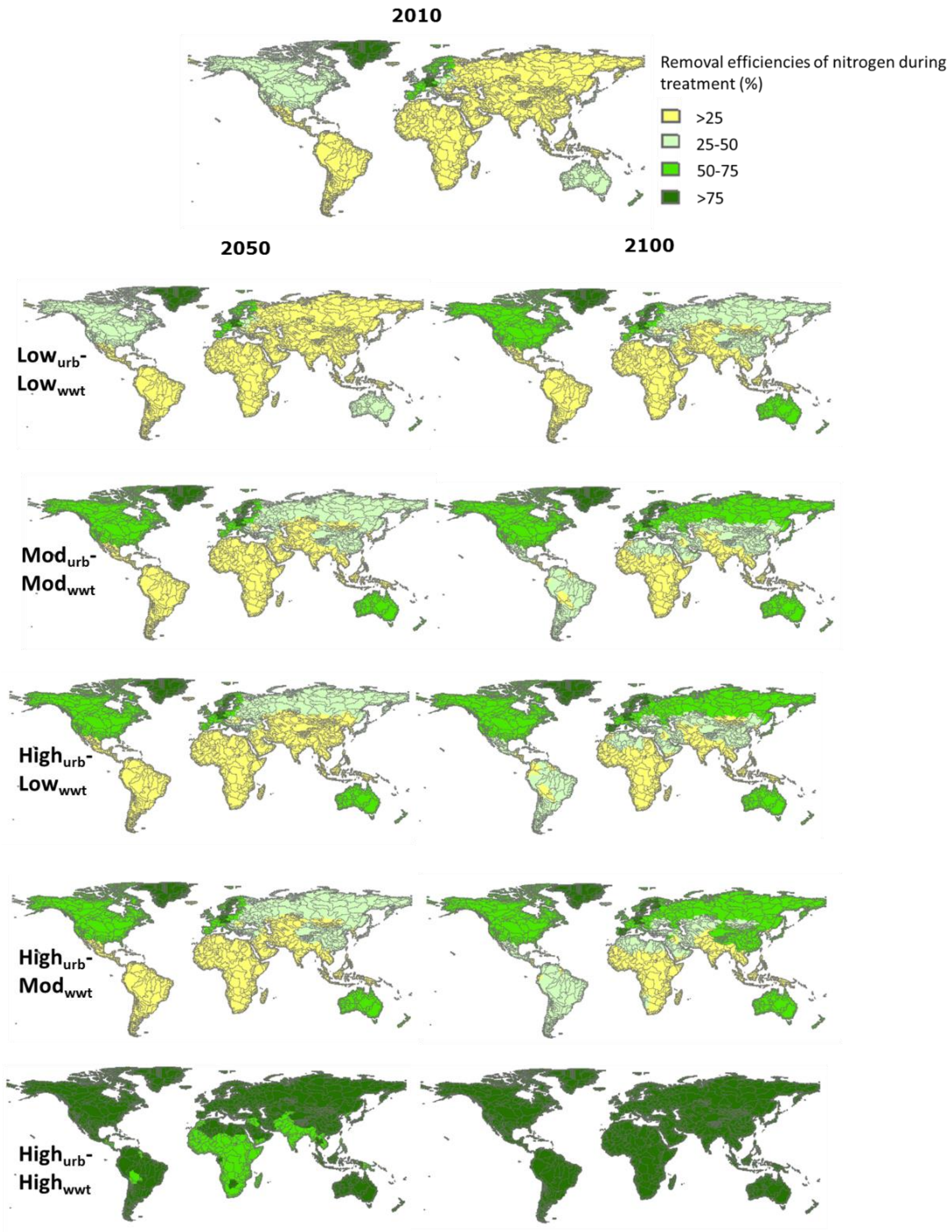
Supplementary Figure 6. Consumption rates of phosphorus detergents by grid in 2010 (kg P capita^{-1} year^{-1}). See Supplementary Tables 1-6 for the model and scenario descriptions.



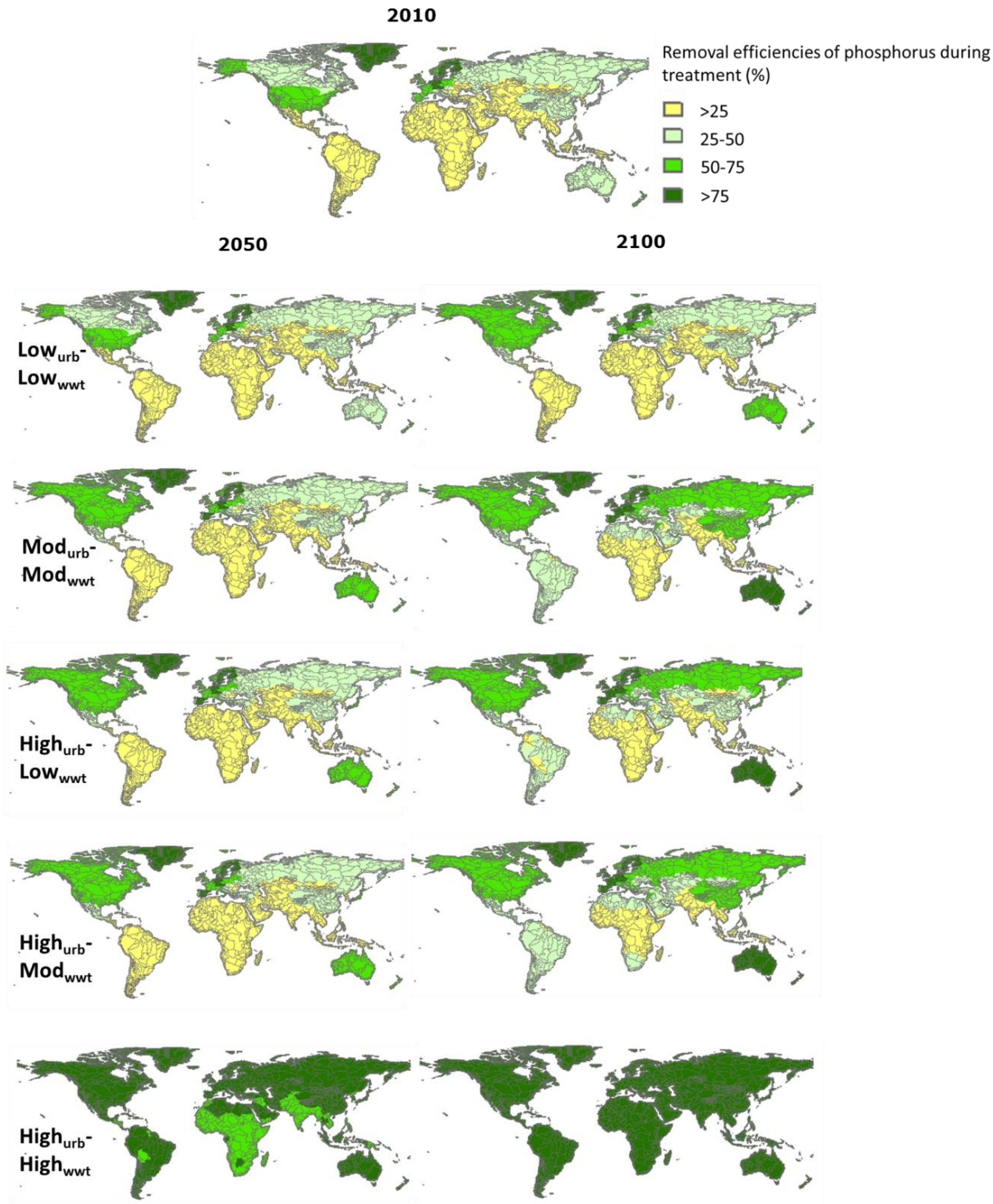
Supplementary Figure 7. Consumption rates of microplastics for care tyres by grid in 2010, 2050 and 2100 according to the five scenarios (kg MP capita^{-1} year^{-1}). See Supplementary Tables 1-6 for the model and scenario descriptions.



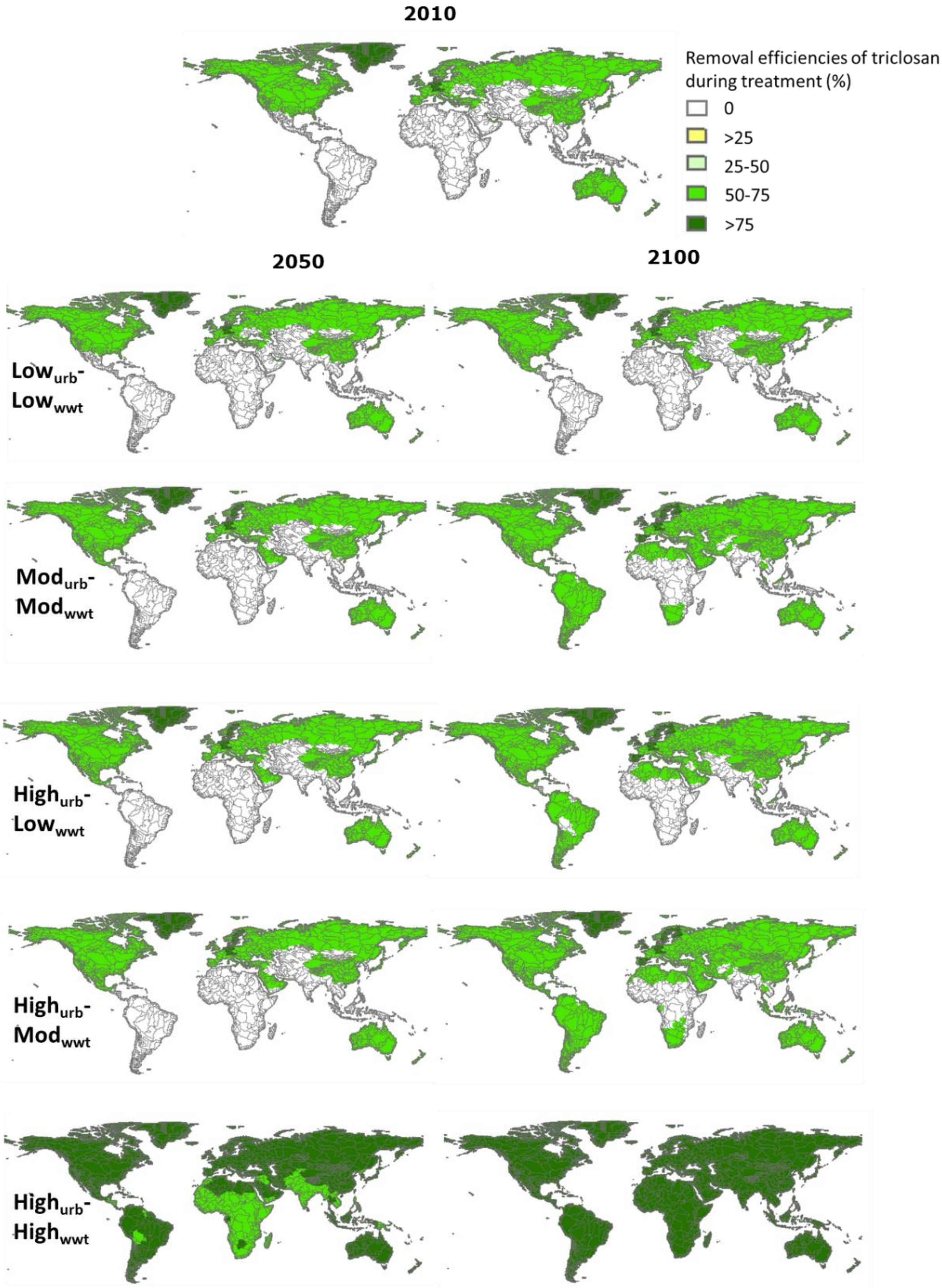
Supplementary Figure 8. Excretion rates of *Cryptosporidium* by grid in 2010, 2050 and 2100 according to the five scenarios (oocysts 10^6 capita^{-1} year^{-1}). See Supplementary Tables 1-6 for the model and scenario descriptions.



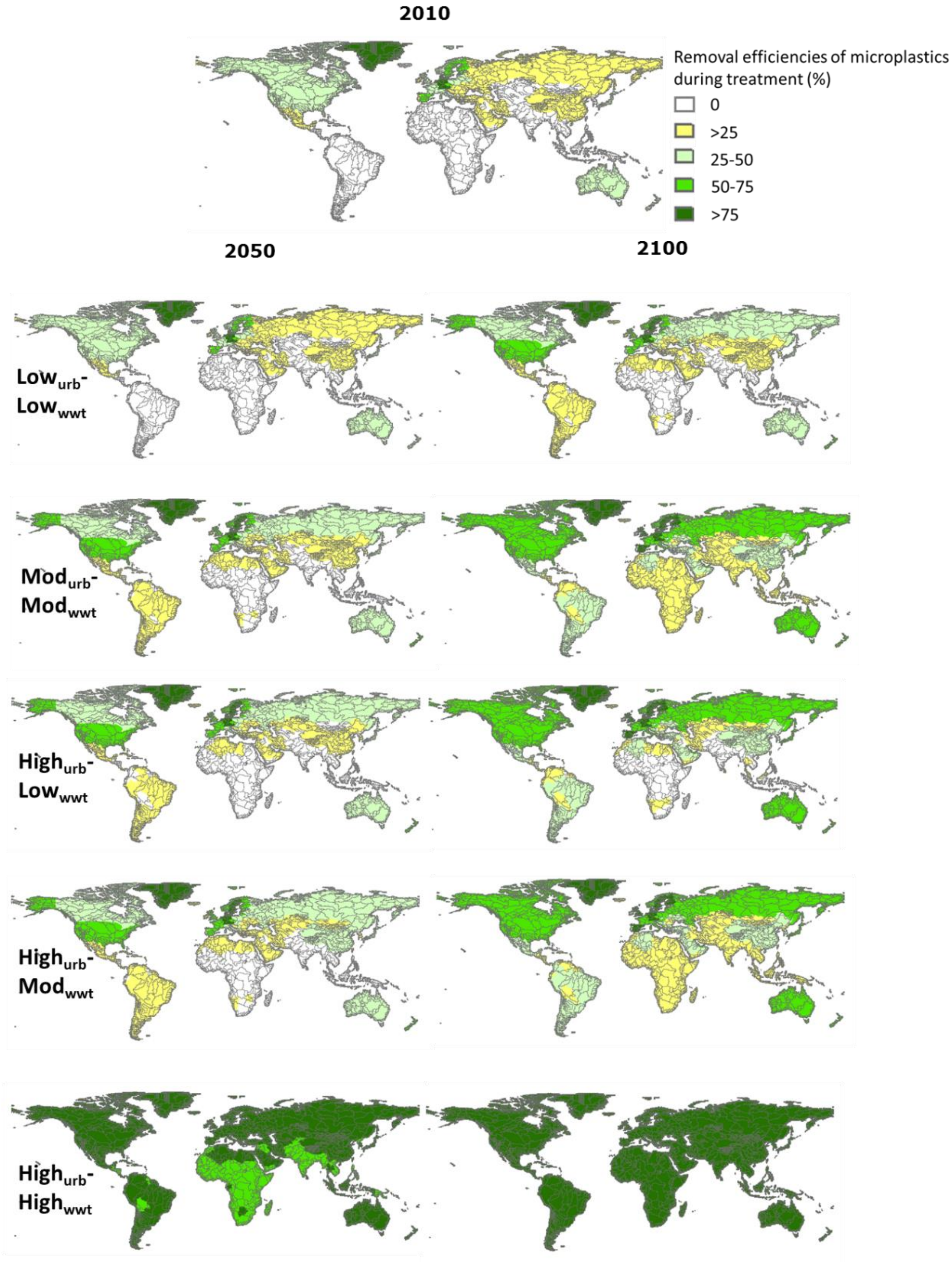
Supplementary Figure 9. Wastewater treatment of nitrogen by grid in 2010, 2050 and 2100 according to the five scenarios (%). See Supplementary Tables 1-6 for the model and scenario descriptions. This wastewater treatment is quantified using the treatment types (primary, secondary, tertiary, no treatment) and their removal efficiencies for each pollutant (see Supplementary Tables 1-2). The difference between the five scenarios is the shift towards a next treatment type: e.g., from primary to secondary to tertiary (Supplementary Tables 4-6).



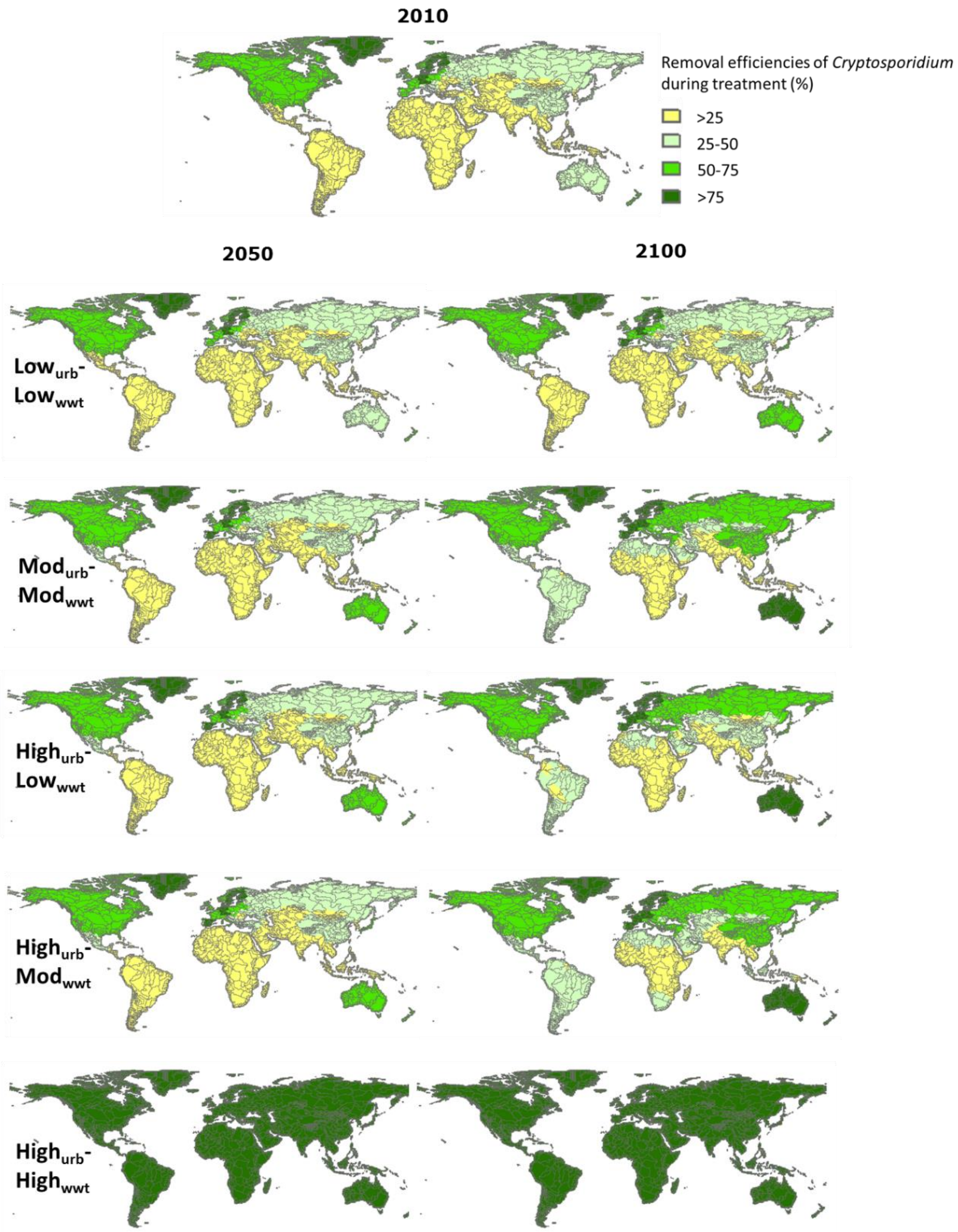
Supplementary Figure 10. Wastewater treatment of phosphorus by grid in 2010, 2050 and 2100 according to the five scenarios (%). See Supplementary Tables 1-6 for the model and scenario descriptions. This wastewater treatment is quantified using the treatment types (primary, secondary, tertiary, no treatment) and their removal efficiencies for each pollutant (see Supplementary Tables 1-2). The difference between the five scenarios is the shift towards a next treatment type: e.g., from primary to secondary to tertiary (Supplementary Tables 4-6).



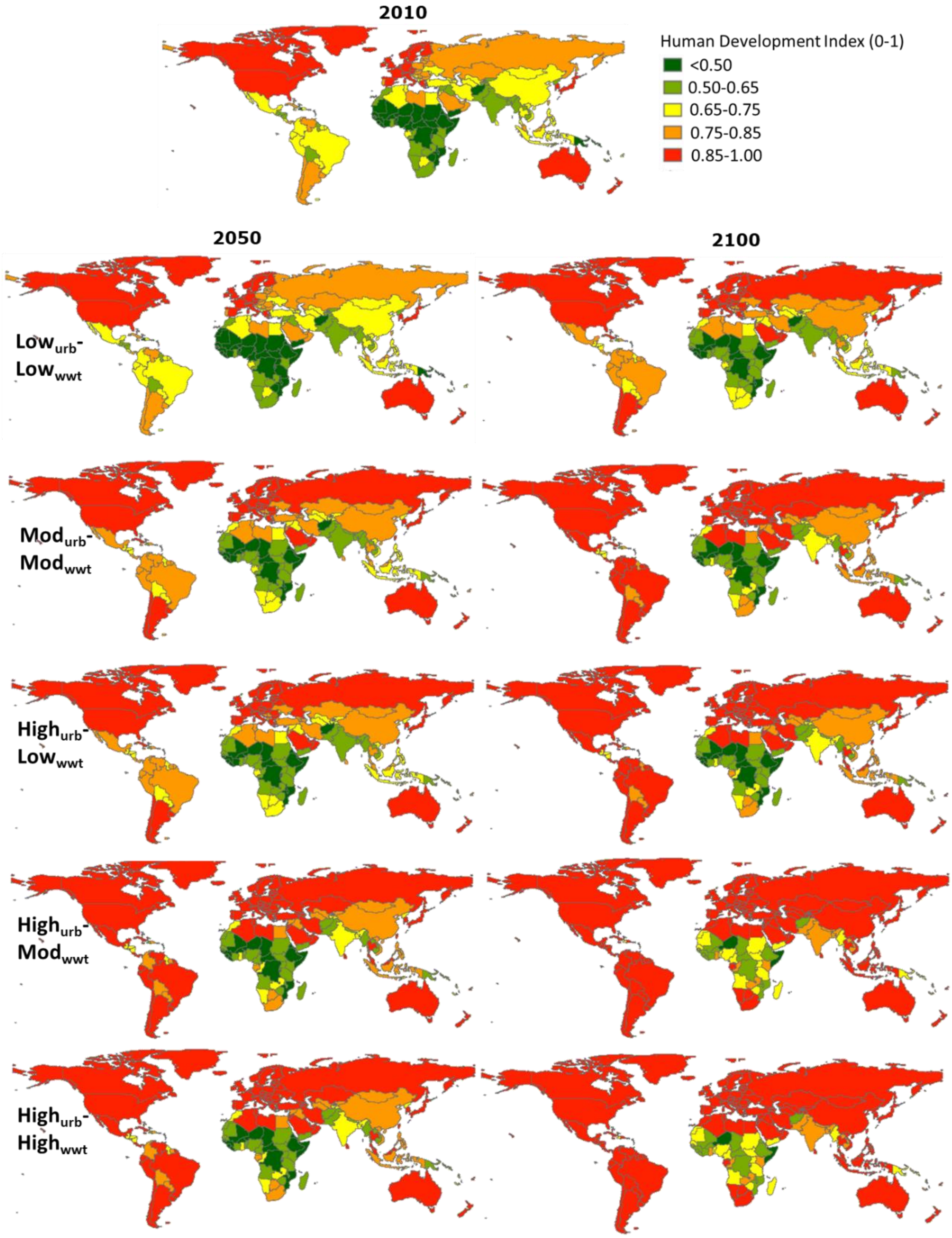
Supplementary Figure 11. Wastewater treatment of triclosan by grid in 2010, 2050 and 2100 according to the five scenarios (%). See Supplementary Tables 1-6 for the model and scenario descriptions.



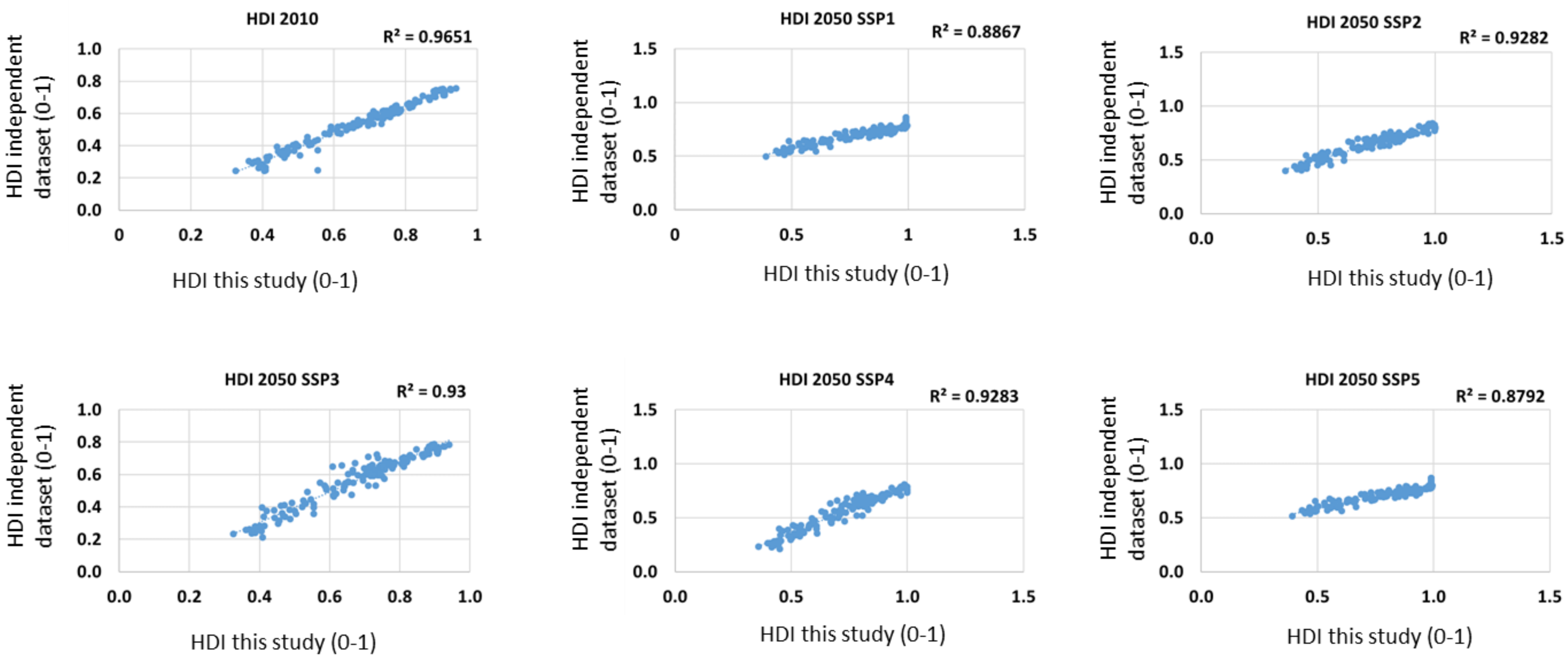
Supplementary Figure 12. Wastewater treatment of microplastics by grid in 2010, 2050 and 2100 according to the five scenarios (%). See Supplementary Tables 1-6 for the model and scenario descriptions.



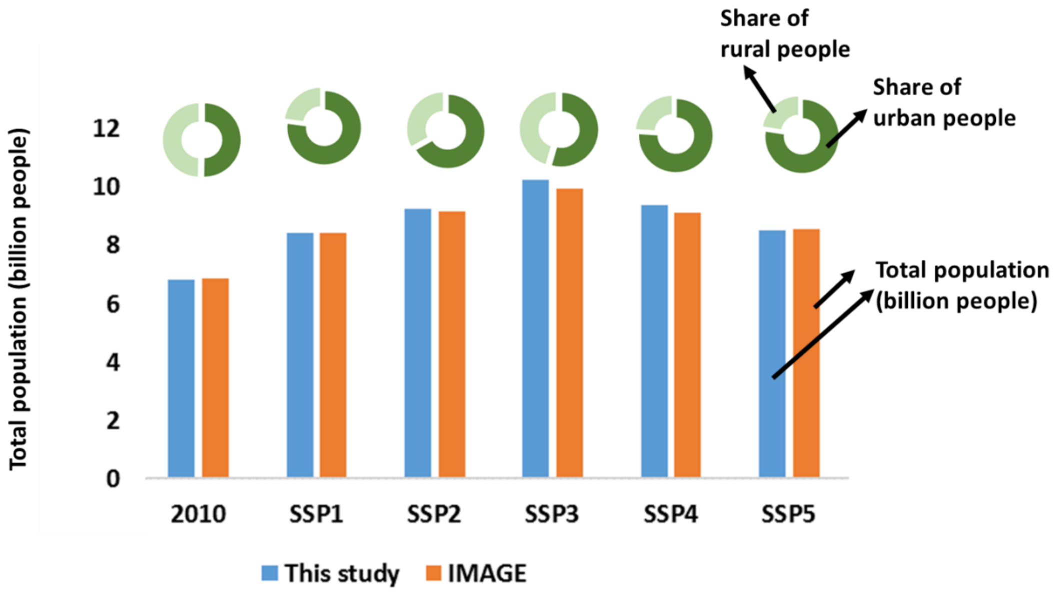
Supplementary Figure 13. Wastewater treatment of *Cryptosporidium* by grid in 2010, 2050 and 2100 according to the five scenarios (%). See Supplementary Tables 1-6 for the model and scenario descriptions.



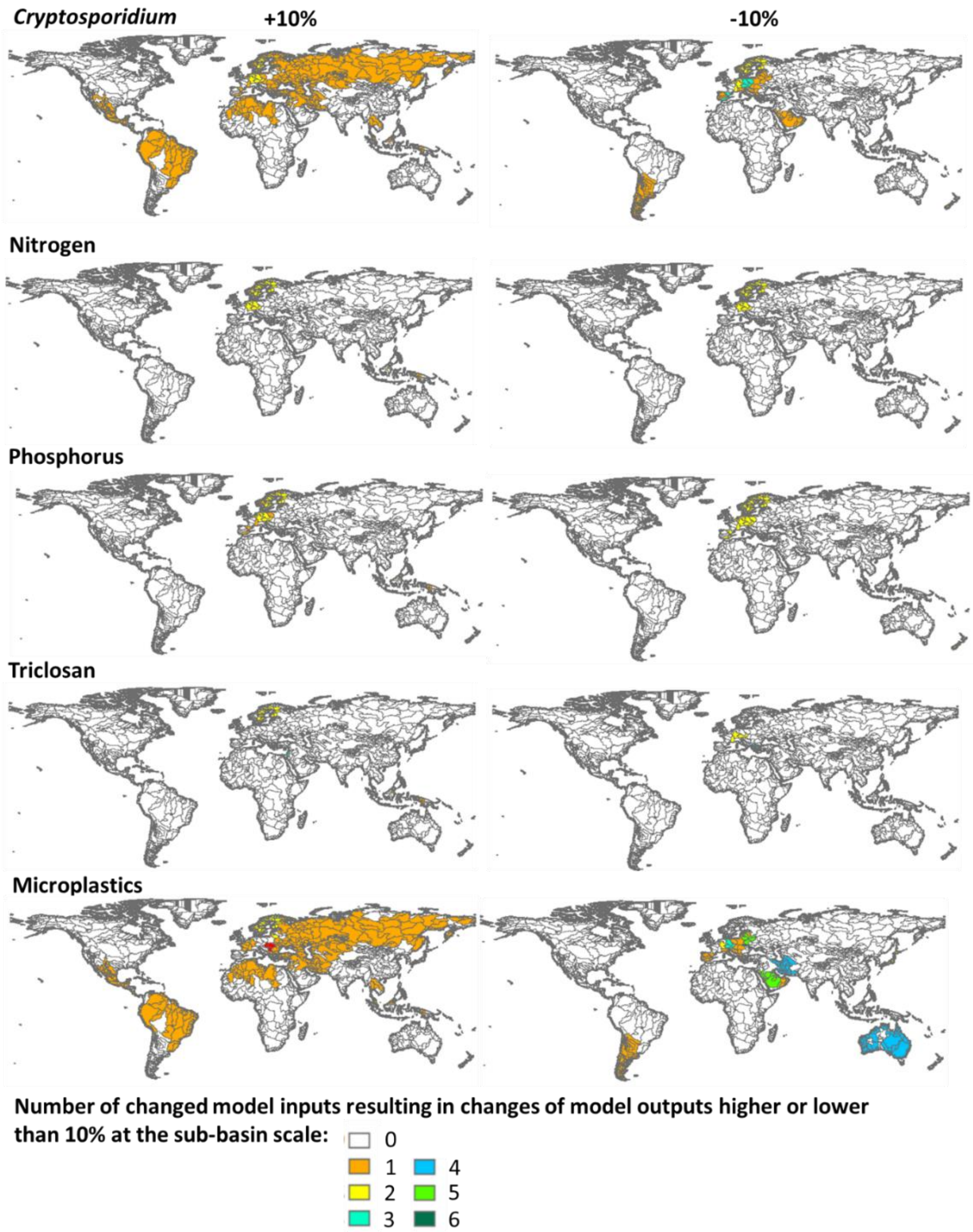
Supplementary Figure 14. Human Development Index by county in 2010, 2050 and 2100 according to the five scenarios. Details on the assumptions for 2050 and 2100 and the scenarios are in Supplementary Tables 4-6.



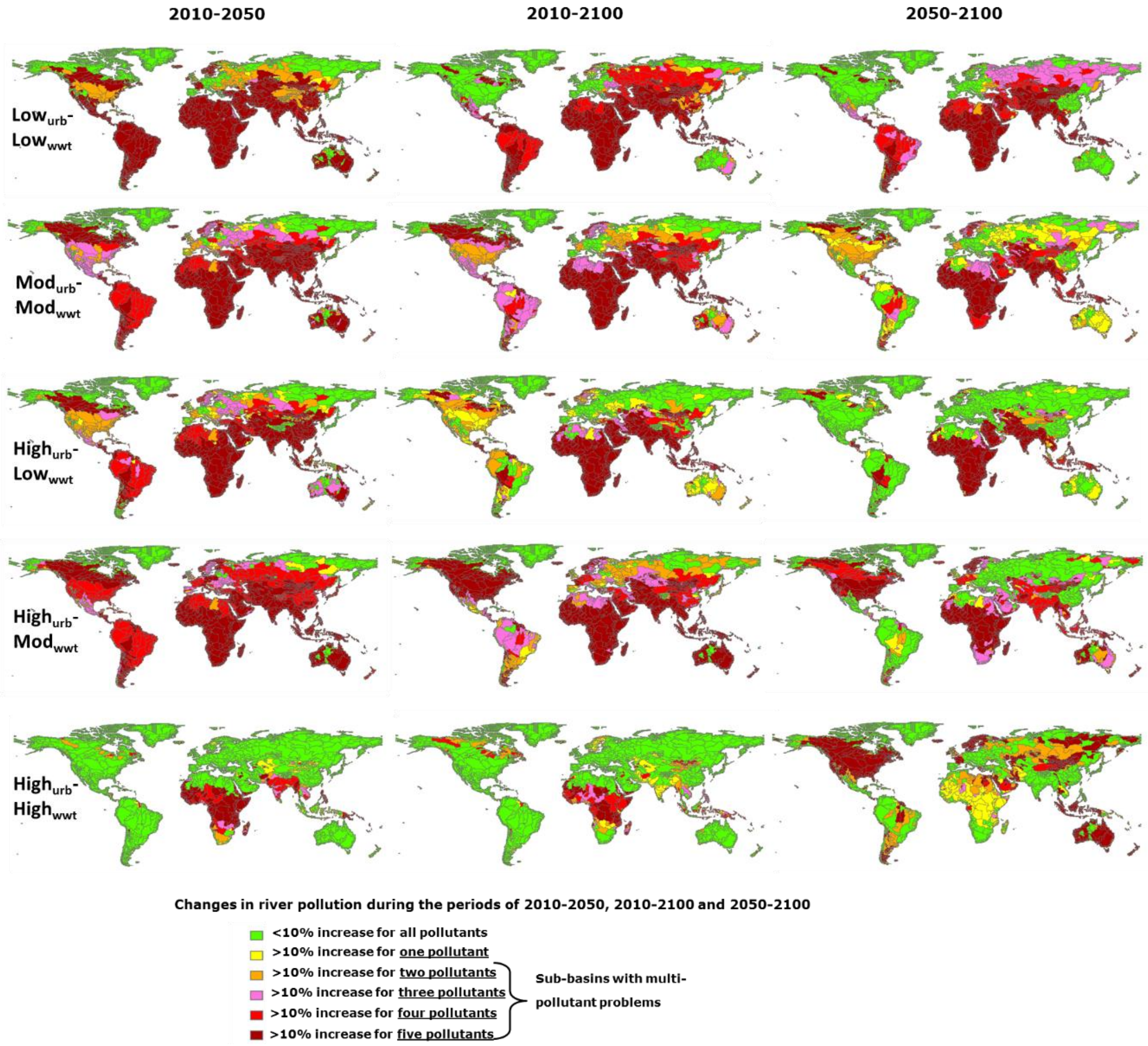
Supplementary Figure 15. Human Development Index (HDI). Graphs show comparison of HDI by country between this study and an independent dataset from Crespo Cuaresma and Lutz [30] for the five Shared Socio-economic Pathways scenarios (SSPs) for 2010 and 2050 (0-1). SSPs. In our study, the SSPs are incorporated in the following five scenarios: Low_{urb}-Low_{wwt} (SSP3), Mod_{urb}-Mod_{wwt} (SSP2), $High_{urb}$-Low_{wwt} (SSP4), $High_{urb}$-Mod_{wwt} (SSP5) and $High_{urb}$-$High_{wwt}$ (SSP1). See details in Supplementary Tables 1-6 on the model and scenario descriptions where HDI is used in our study.



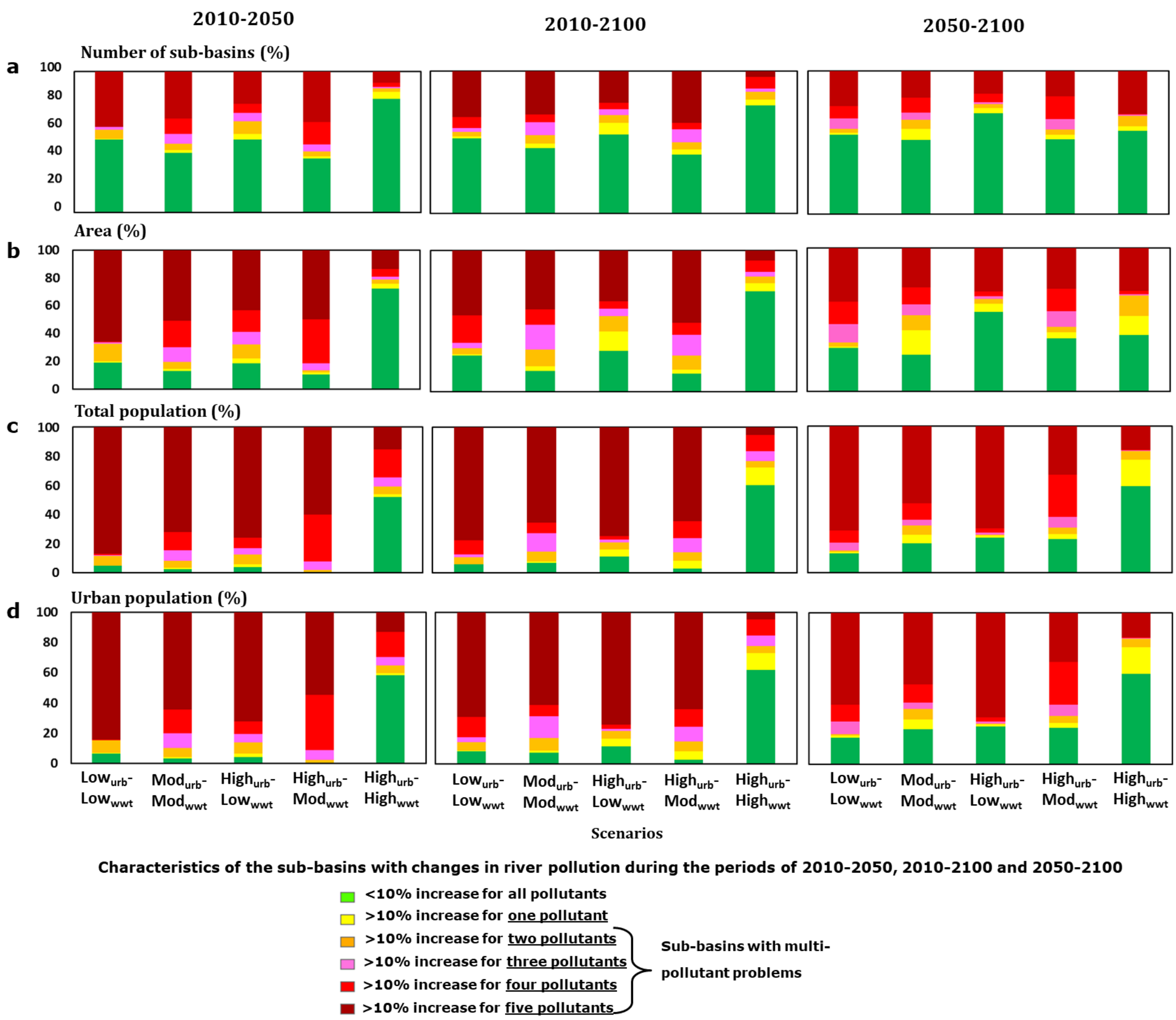
Supplementary Figure 16. Total population (billion people) for the world in 2000, 2010 and 2050 under the Shared Socio-economic Pathways. This study is based on a gridded database of Jones and O'Neill [8]. IMAGE is an independent dataset of the global integrated assessment model that is based on county values[31]. SSPs. In our study, the SSPs are incorporated in the following five scenarios: Low_{urb}-Low_{wwt} (SSP3), Mod_{urb}-Mod_{wwt} (SSP2), $High_{urb}$-Low_{wwt} (SSP4), $High_{urb}$-Mod_{wwt} (SSP5) and $High_{urb}$-$High_{wwt}$ (SSP1). See details in Supplementary Tables 1-6 on the model and scenario descriptions where population from SSPs is used in our study.



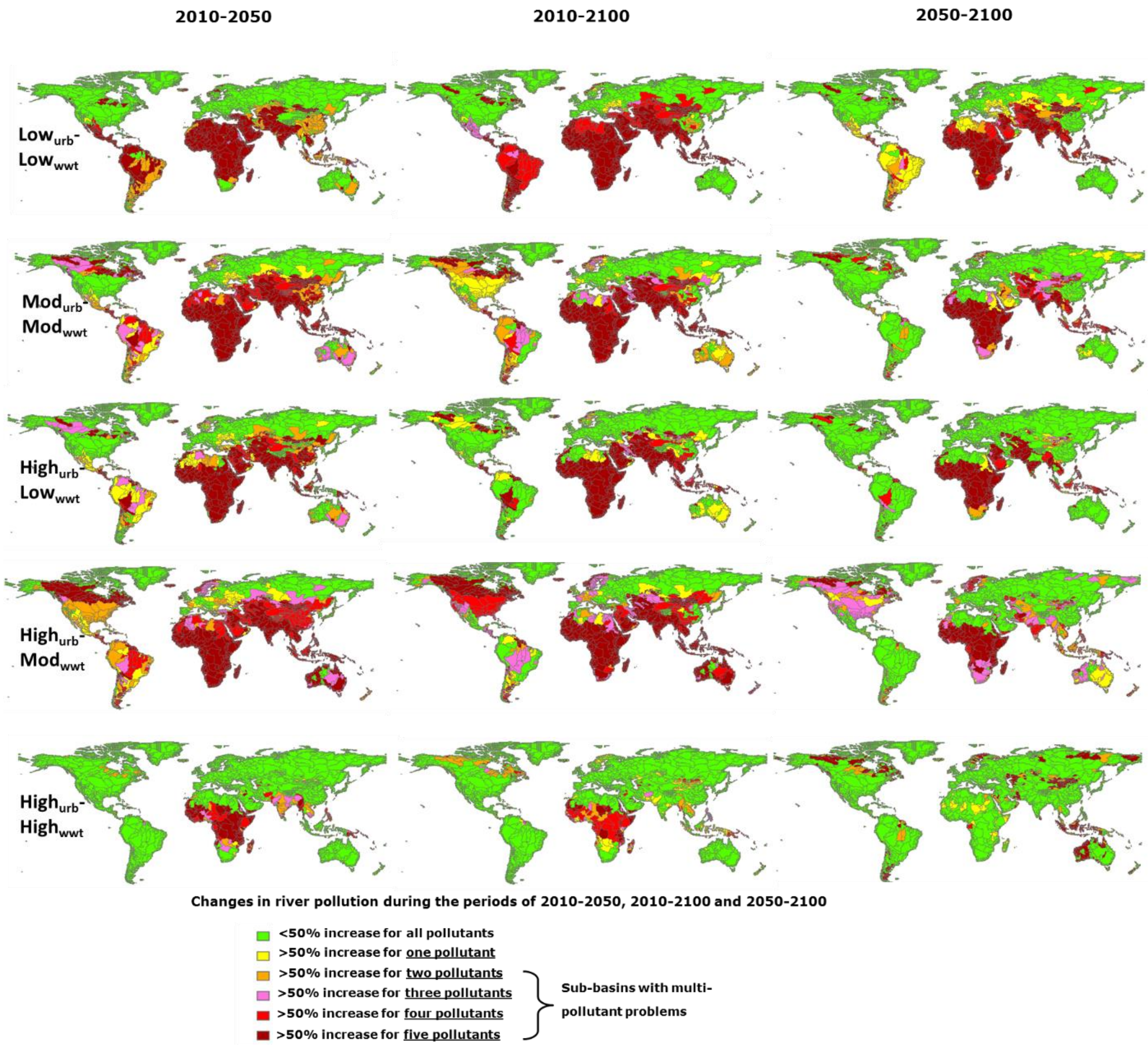
Supplementary Figure 17. Results of the sensitivity analysis. Maps show number of changed model inputs resulting in changes of model outputs higher or lower than 10% relative to the original model run of 2010 at the sub-basin scale. In total, 25 model inputs are changed with +10% and -10%. Details and names of the model inputs are in Supplementary Table 9. Model outputs are annual inputs of pollutants to rivers from point sources. Sub-basins with 0 indicate that none of the 25 changed model inputs has led to changes in model outputs higher or lower than 10% relative to the original model run. Sub-basins with 6 indicate that 6 out of the 25 changed model inputs have led to changes in model outputs higher or lower than 10%. The similar principle is applied to sub-basins with 1, 2, 3, 4 and 5.



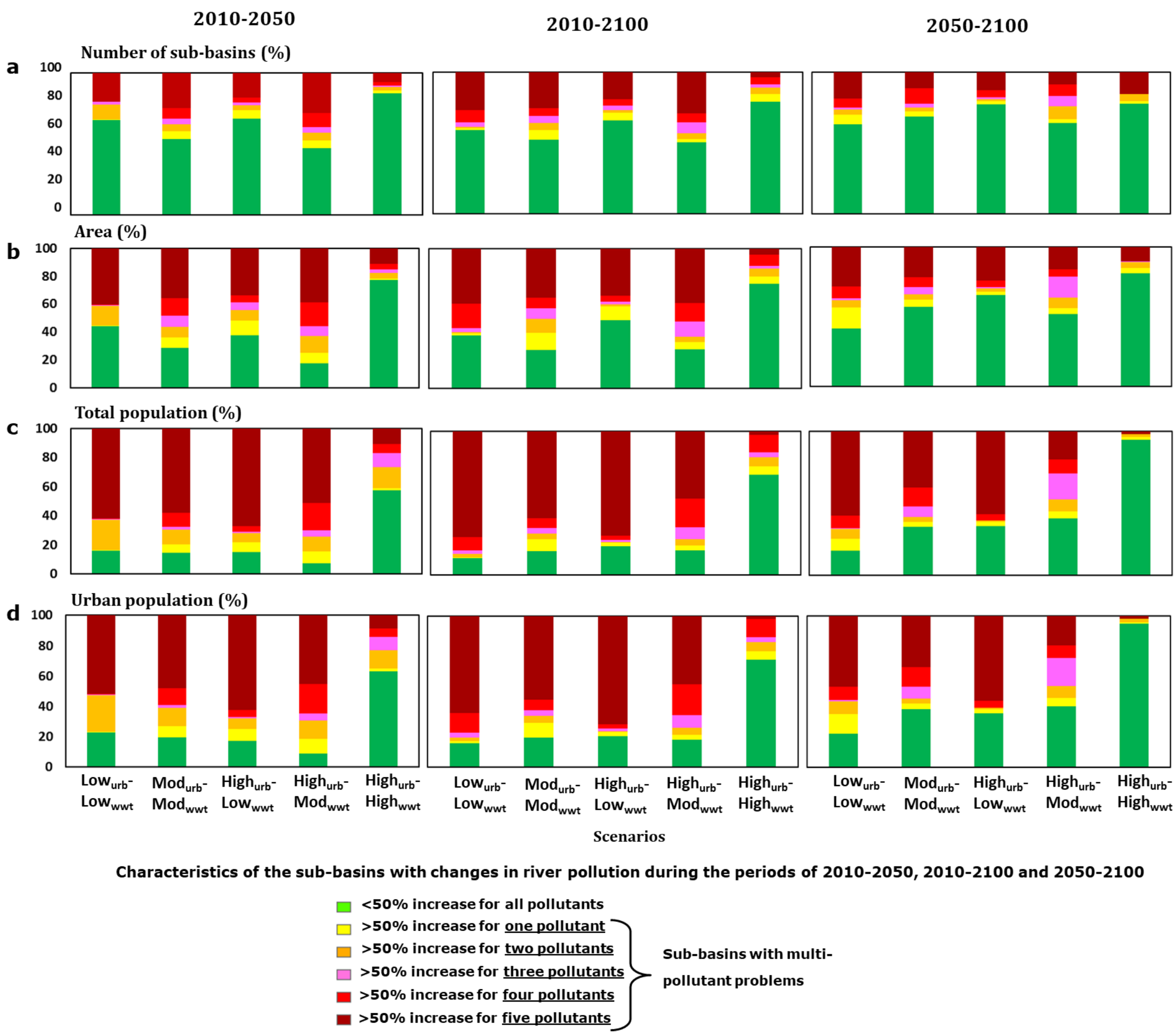
Supplementary Figure 18. River pollution by multiple pollutants in 2050 and 2100 compared to 2010 in 10,226 sub-basins. Maps show at least 10% changes in inputs of pollutants to rivers during the periods of 2010-2050, 2010-2100 and 2050-2100 according to the five scenarios. We classify sub-basins based on the number of pollutants for which the increases are higher or lower than 10% (Note: 10% is arbitrary). The pollutants include *Cryptosporidium,* microplastic, triclosan, nitrogen and phosphorus. More information is available in Supplementary Figures 18-29. The description of the five scenarios is in Figure 2 of the main manuscript, in the Methods and Supplementary Tables 4-6. Results for 2010 are in Figure 3 of the main manuscript. Source: the global multi-pollutant model (model description is provided in the Methods, and in Supplementary Tables 1-6, model inputs are in Supplementary Figures 1-14). Model uncertainties are discussed in the Methods.



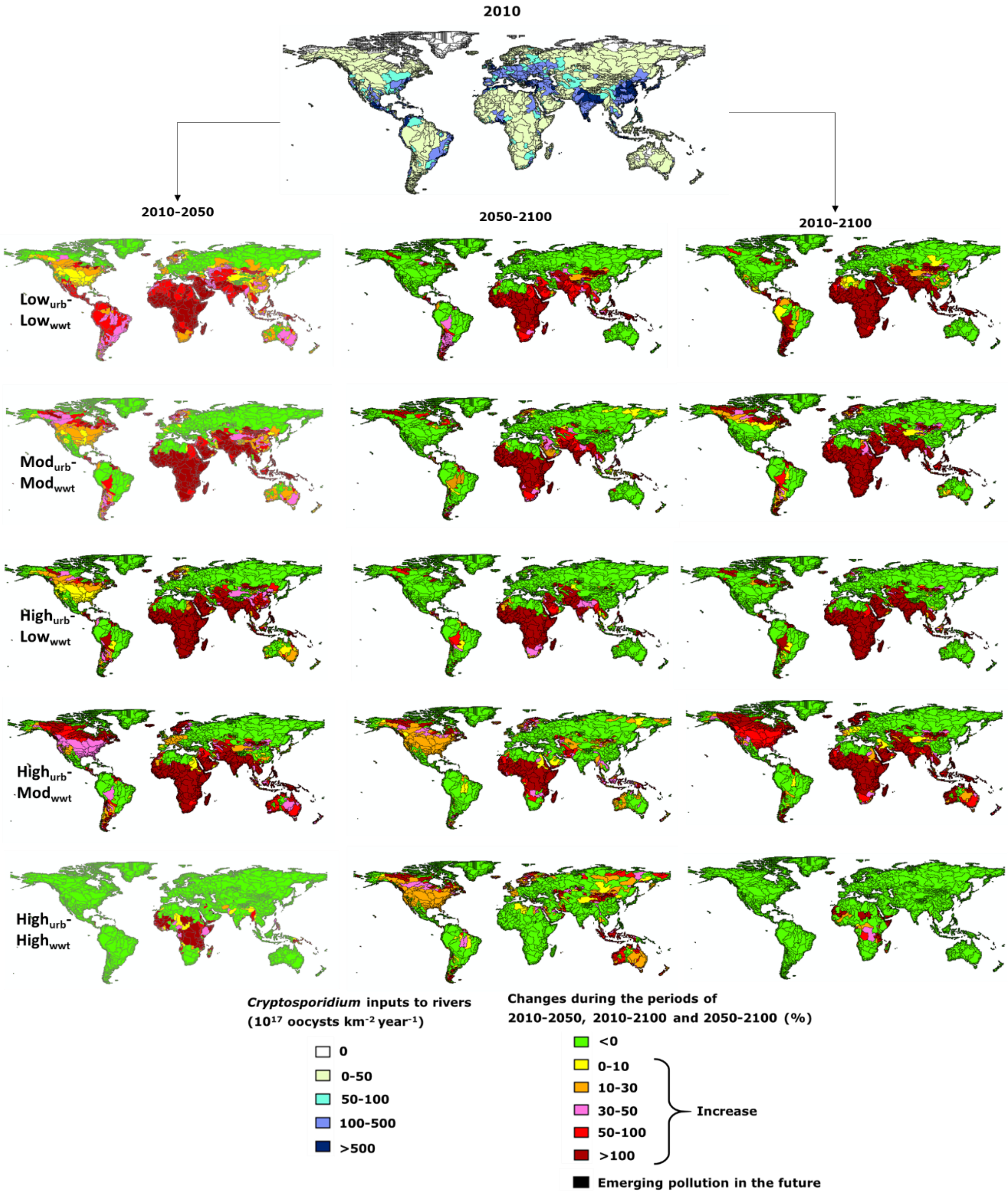
Supplementary Figure 19. Characteristics of the sub-basins with multi-pollutant problems in the future. Sub-basins are classified based on the number of pollutants for which the increases are higher or lower than 10% during the periods of 2010-2050, 2010-2100 and 2050-2100 according to the five scenarios. Graphs show number of sub-basins (a), sub-basin areas (b), total population (c) and urban population (d) for the sub-basins for which the increases of higher or lower than 10% (Note: 10% is arbitrary). More information is available in Supplementary Figures 18-29. See Supplementary Figure 18 for the changes in inputs of pollutants during the periods of 2010-2050, 2010-2100 and 2050-2100. The description of the scenarios is in Figure 2 of the main manuscript, in the Methods and Supplementary Tables 4-6. Results for 2010 are in Figure 3 of the main manuscript. Source: the global multi-pollutant model (model description is provided in the Methods, and in Supplementary Tables 1-6, model inputs are in Supplementary Figures 1-14). Model uncertainties are discussed in the Methods.



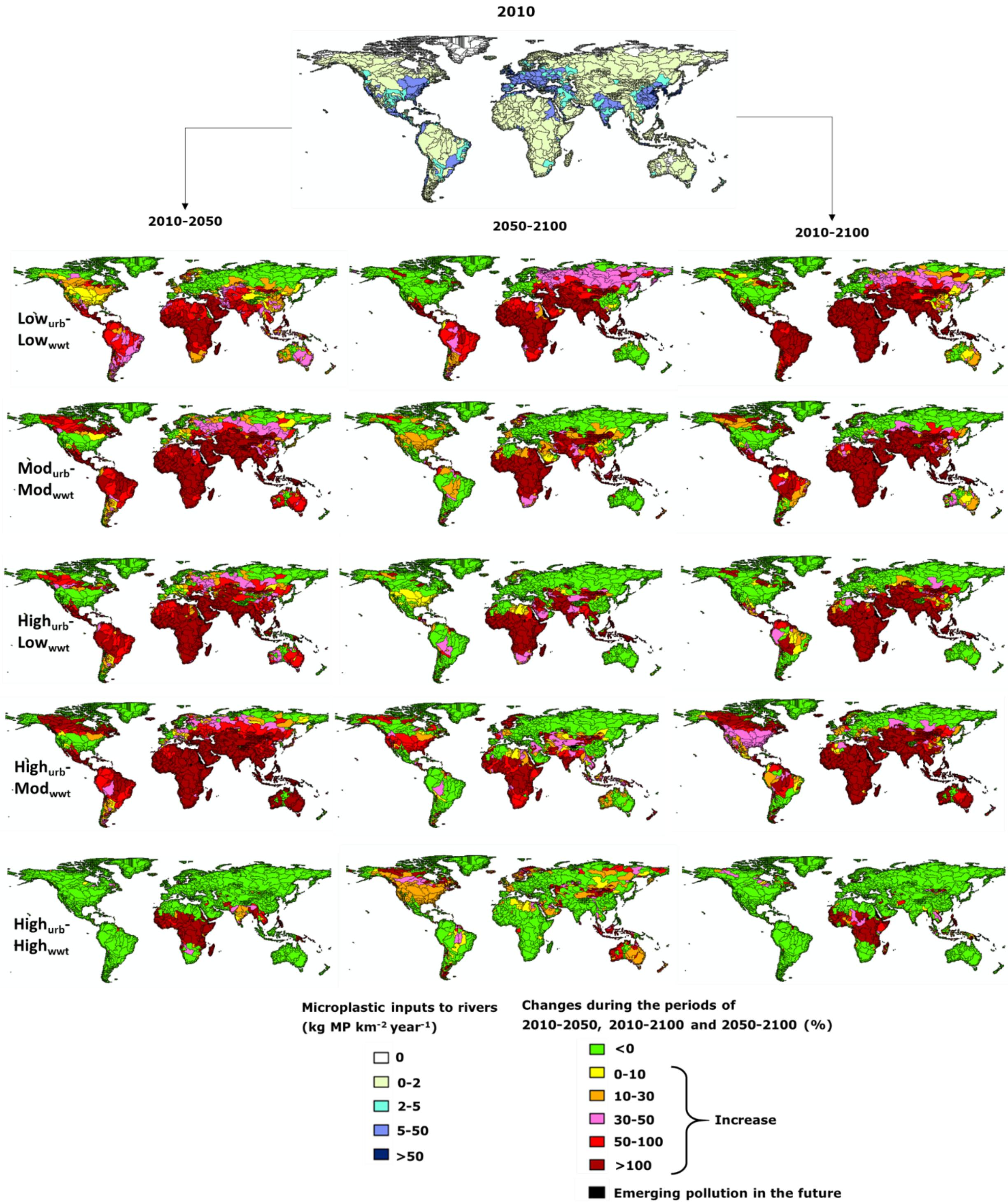
Supplementary Figure 20. River pollution by multiple pollutants in 2050 and 2100 compared to 2010 in 10,226 sub-basins. Maps show at least 50% changes in inputs of pollutants to rivers during the periods of 2010-2050, 2010-2100 and 2050-2100 according to the five scenarios. We classify sub-basins based on the number of pollutants for which the increases are higher or lower than 50% (Note: 50% is arbitrary). The pollutants include *Cryptosporidium,* microplastic, triclosan, nitrogen and phosphorus. More information is available in Supplementary Figures 18-29. The description of the five scenarios is in Figure 2 of the main manuscript, in the Methods and Supplementary Tables 4-6. Results for 2010 are in Figure 3 of the main manuscript. Source: the global multi-pollutant model (model description is provided in the Methods, and in Supplementary Tables 1-6, model inputs are in Supplementary Figures 1-14). Model uncertainties are discussed in the Methods.



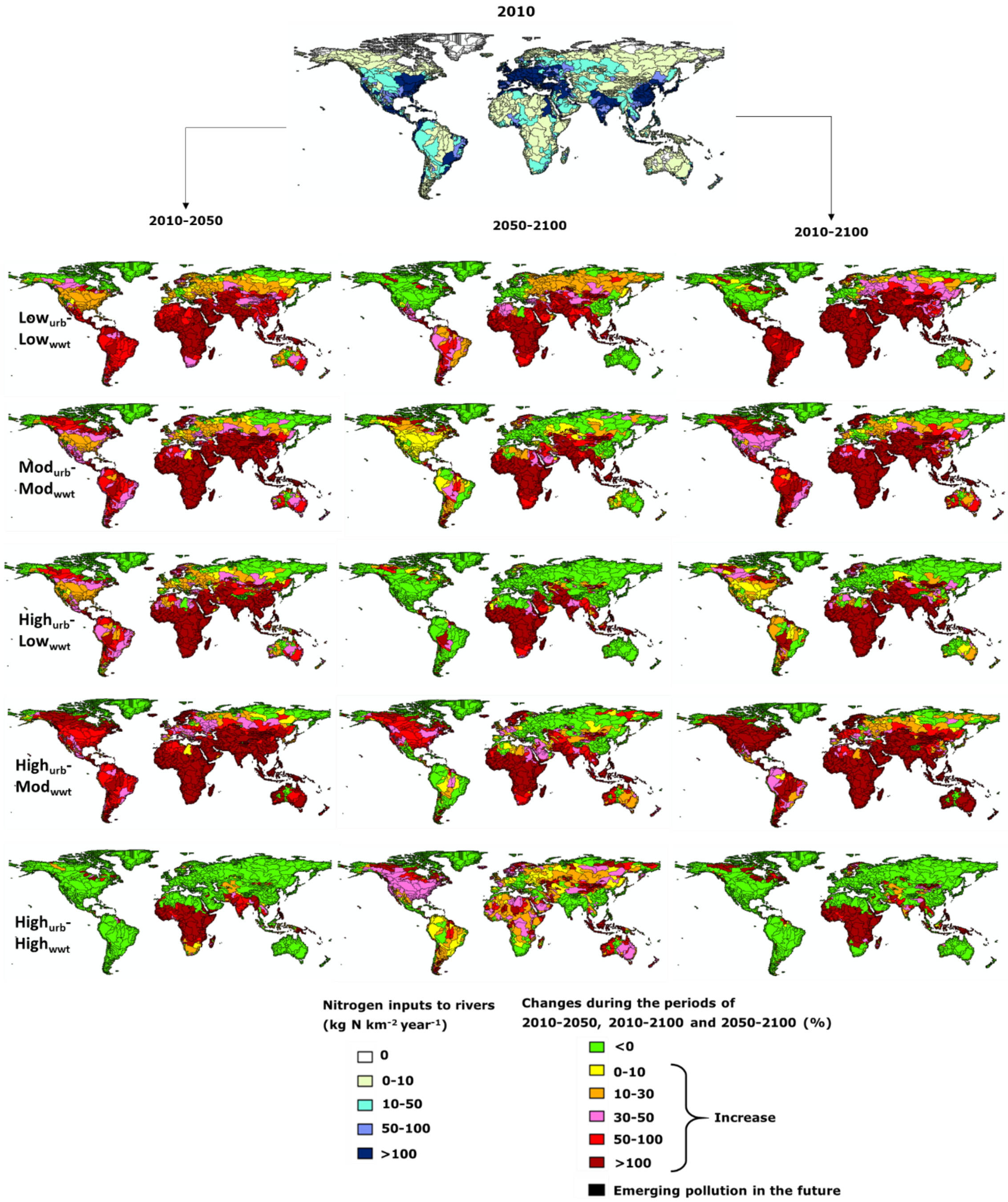
Supplementary Figure 21. Characteristics of the sub-basins with multi-pollutant problems in the future. Sub-basins are classified based on the number of pollutants for which the increases are higher or lower than 50% during the periods of 2010-2050, 2010-2100 and 2050-2100 according to the five scenarios. Graphs show number of sub-basins (a), sub-basin areas (b), total population (c) and urban population (d) for sub-basins for which the increases of higher or lower than 50% (Note: 50% is arbitrary). More information is available in Supplementary Figures 18-29. See Supplementary Figure 20 for the changes in inputs of pollutants during the periods of 2010-2050, 2010-2100 and 2050-2100. The description of the scenarios is in Figure 2 of the main manuscript, in the Methods and Supplementary Tables 4-6. Results for 2010 are in Figure 3 of the main manuscript. Source: the global multi-pollutant model (model description is provided in the Methods, and in Supplementary Tables 1-6, model inputs are in Supplementary Figures 1-14). Model uncertainties are discussed in the Methods.



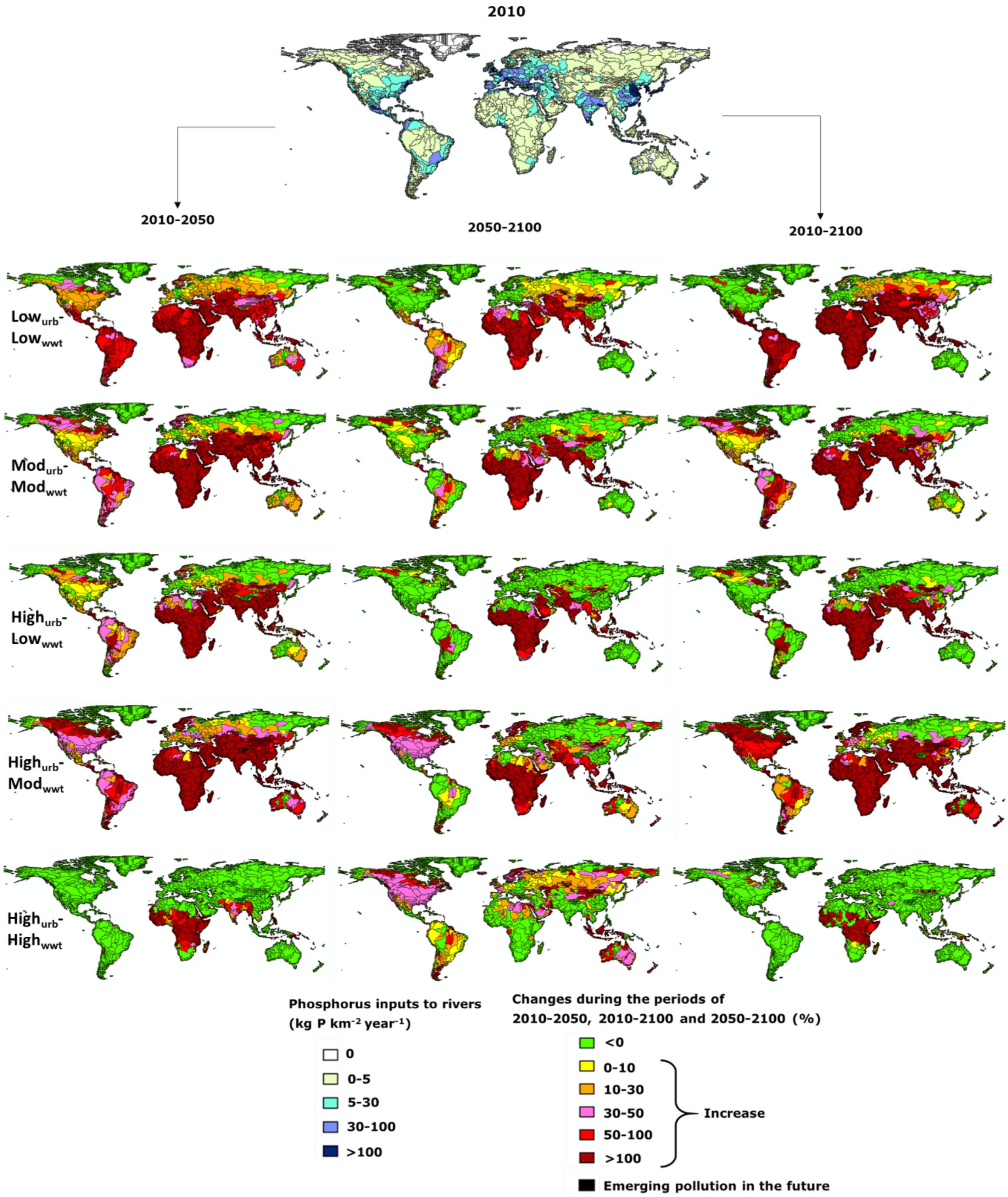
Supplementary Figure 22. River pollution by *Cryptosporidium*. Maps show inputs of *Cryptosporidium* to rivers from point sources in 2010 (10^{17} oocysts km^{-2} year^{-1}) and their changes during the periods of 2010-2050, 2010-2100 and 2050-2100 according to the five scenarios (%). Point sources include sewage effluents and open defecation. See Supplementary Tables 1-6 for the model and scenario descriptions.



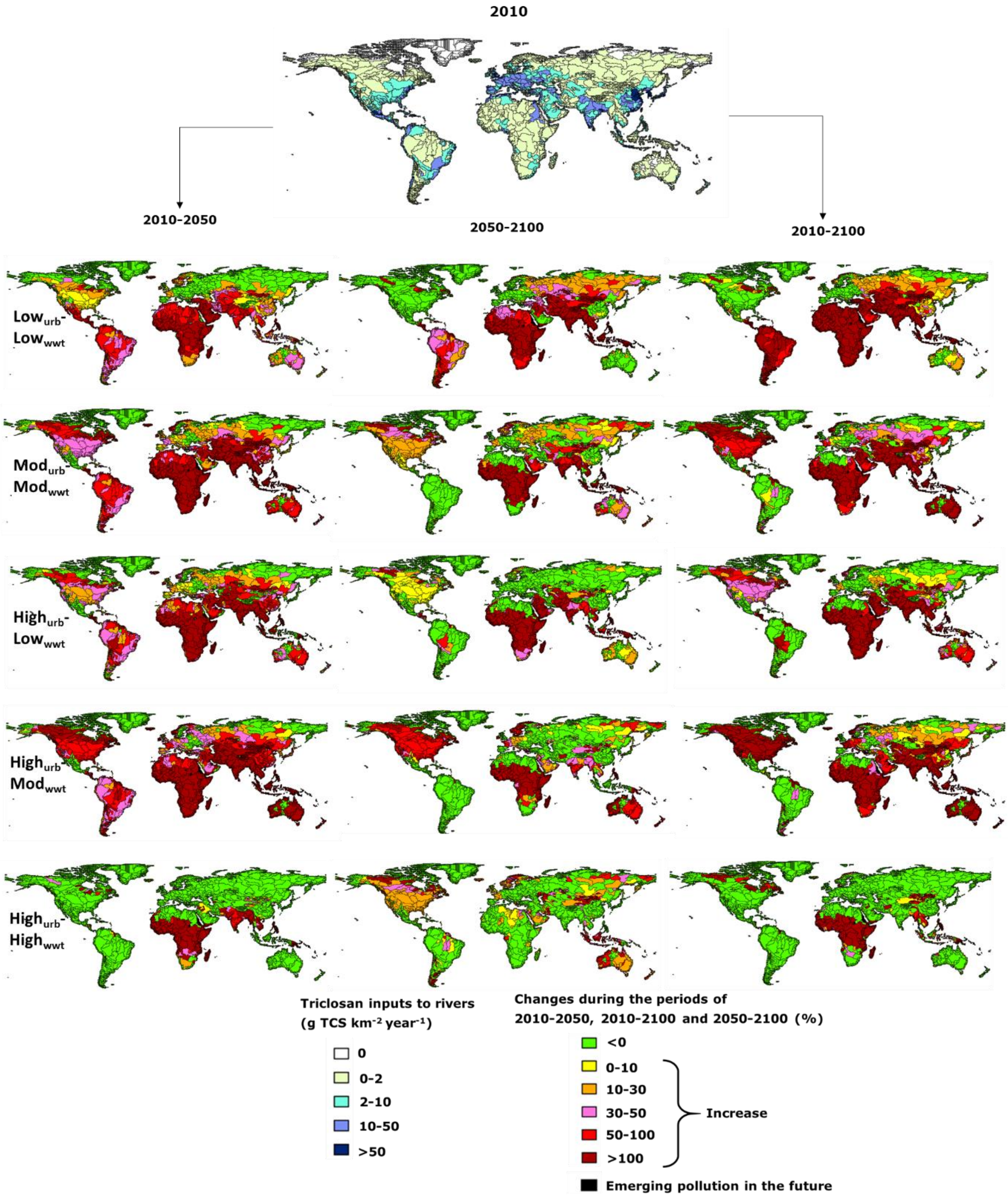
Supplementary Figure 23. River pollution by microplastics. Maps show microplastic inputs to rivers from point sources in 2010 (kg MP km^{-2} $year^{-1}$) and their changes during the periods of 2010-2050, 2010-2100 and 2050-2100 according to the five scenarios (%). Point sources include sewage effluents (human waste and detergents). See Supplementary Tables 1-6 for the model and scenario descriptions.



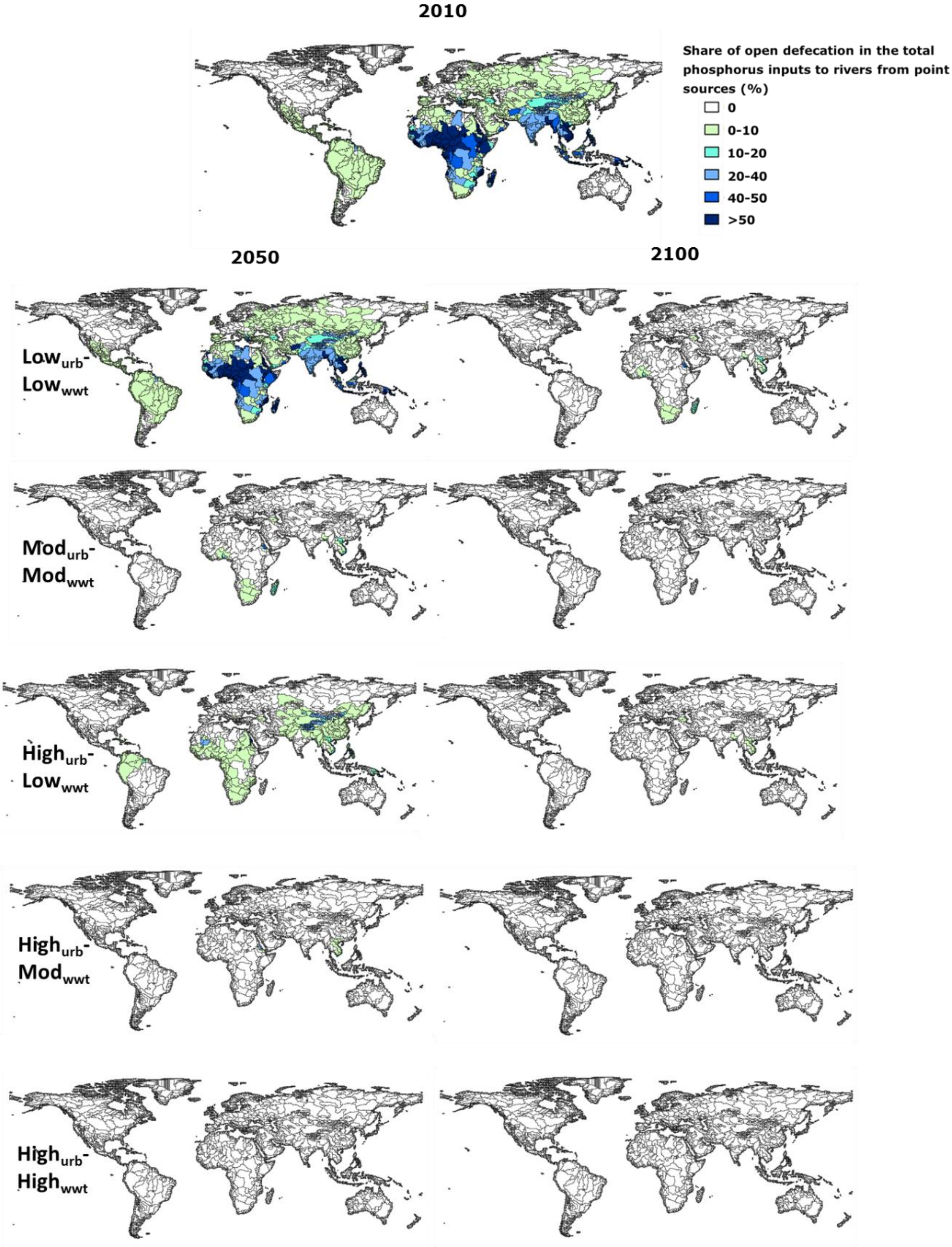
Supplementary Figure 24. River pollution by nitrogen. Maps show nitrogen (N) inputs to rivers from point sources in 2010 (kg N km^{-2} year^{-1}) and their changes during the periods of 2010-2050, 2010-2100 and 2050-2100 according to the five scenarios (%). Point sources include sewage effluents and open defecation. See Supplementary Tables 1-6 for the model and scenario descriptions.



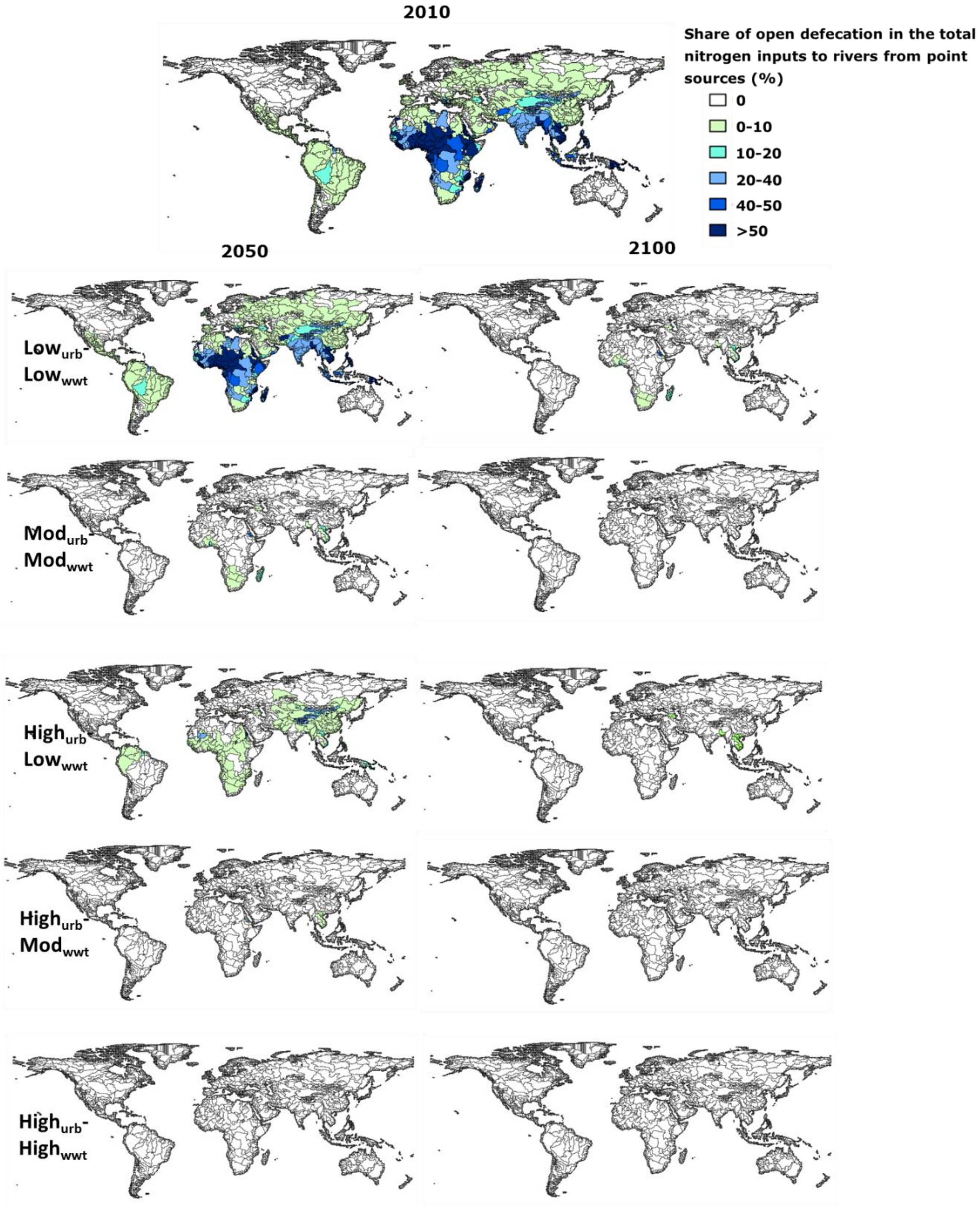
Supplementary Figure 25. River pollution by phosphorus. Maps show phosphorus (P) inputs to rivers from point sources in 2010 (kg P km^{-2} year^{-1}) and their changes during the periods of 2010-2050, 2010-2100 and 2050-2100 according to the five scenarios (%). Point sources include sewage effluents (human waste and detergents) and open defecation. See Supplementary Tables 1-6 for the model and scenario descriptions.



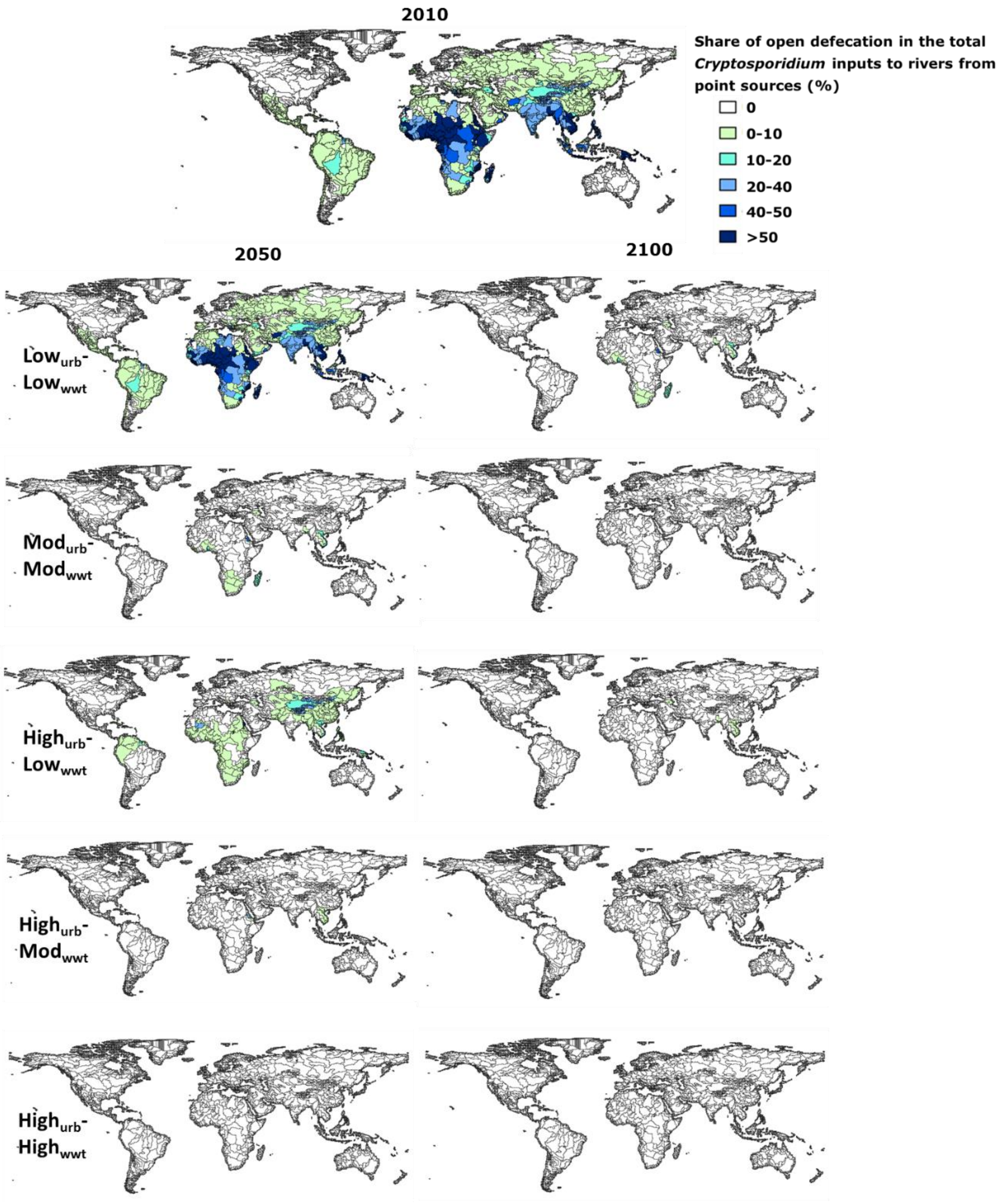
Supplementary Figure 26. River pollution by triclosan. Maps show triclosan (TCS) inputs to rivers from point sources in 2010 (g TCS km^{-2} year^{-1}) and their changes during the periods of 2010-2050, 2010-2100 and 2050-2100 according to the five scenarios (%). Point sources include sewage effluents (human waste and detergents) and open defecation. See Supplementary Tables 1-6 for the model and scenario descriptions.



Supplementary Figure 27. Share of open defecation in the total inputs of phosphorus to rivers from point sources in 2010, 2050 and 2100 according to the five scenarios (%). Point sources include sewage effluents, detergents and open defecation. See Supplementary Tables 1-6 for the model and scenario descriptions.



Supplementary Figure 28. Share of open defecation in the total inputs of nitrogen to rivers from point sources in 2010, 2050 and 2100 according to the five scenarios (%). Point sources include sewage effluents, and open defecation. See Supplementary Tables 1-6 for the model and scenario descriptions.



Supplementary Figure 29. Share of open defecation in the total inputs of *Cryptosporidium* to rivers from point sources in 2010, 2050 and 2100 according to the five scenarios (%). Point sources include sewage effluents, and open defecation. See Supplementary Tables 1-6 for the model and scenario descriptions.

Supplementary References

1 Strokal, M., Kroeze, C., Wang, M., Bai, Z. & Ma, L. The MARINA model (Model to Assess River Inputs of Nutrients to seAs): model description and results for China. *Sci. Total Environ.* 562, 869-888, (2016).

2 Mayorga, E. et al. Global Nutrient Export from WaterSheds 2 (NEWS 2): Model development and implementation. *Environ. Modell. Softw.* 25, 837-853, (2010).

3 Hofstra, N., Bouwman, A. F., Beusen, A. H. W. & Medema, G. J. Exploring global Cryptosporidium emissions to surface water *Sci. Total Environ.* 442, 10-19, (2013).

4 Hofstra, N. & Vermeulen, L. C. Impacts of population growth, urbanisation and sanitation changes on global human Cryptosporidium emissions to surface water. *Int. J. Hyg. Environ. Health* 219, 599-605, (2016).

5 Siegfried, M., Koelmans, A. A., Besseling, E. & Kroeze, C. Export of microplastics from land to sea. A modelling approach. *Water Res.* 127, 249-257, (2017).

6 van Wijnen, J., Ragas, A. & Kroeze, C. River export of triclosan from land to sea: A global modelling approach. *Sci. Total Environ.* 621, 1280-1288, (2017).

7 Strokal, M. et al. Global multi-pollutant modelling of water quality: scientific challenges and future directions. *Curr. Opin. Env. Sust.* 36, 116-125, (2019).

8 Jones, B. & O'Neill, B. Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. *Environ. Res. Lett.* 11, 084003, (2016).

9 Crespo Cuaresma, J. Income projections for climate change research: A framework based on human capital dynamics. *Global Environ. Chang.* 42, 226-236, (2017).

10 Van Drecht, G., Bouwman, A. F., Harrison, J. & Knoop, J. M. Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050. *Global Biogeochem. Cy.* 23, GB0A03, (2009).

11 Nasser, A. M. Removal of Cryptosporidium by wastewater treatment processes: a review. *J. Water Health* 14, 1-13, (2016).

12 Sun, J., Dai, X., Wang, Q., van Loosdrecht, M. C. & Ni, B.-J. Microplastics in wastewater treatment plants: Detection, occurrence and removal. *Water Res.* 152, 21-37, (2019).

13 Mondor, M., Masse, L., Ippersiel, D., Lamarche, F. & Masse, D. Use of electrodialysis and reverse osmosis for the recovery and concentration of ammonia from swine manure. *Bioresour. Technol.* 99, 7363-7368, (2008).

14 Vymazal, J. Removal of nutrients in various types of constructed wetlands. *Sci. Total Environ.* 380, 48-65, (2007).

15 Kartal, B., Kuenen, J. & Van Loosdrecht, M. Sewage treatment with anammox. *Science* 328, 702-703 (2010).

16 Jaffer, Y., Clark, T. A., Pearce, P. & Parsons, S. A. Potential phosphorus recovery by struvite formation. *Water Res*. 36, 1834-1842, (2002).

17 Thompson, A., Griffin, P., Stuetz, R. & Cartmell, E. The fate and removal of triclosan during wastewater treatment. *Water Environ. Res.* 77, 63-67, (2005).

18 Butler, E., Whelan, M. J., Sakrabani, R. & van Egmond, R. Fate of triclosan in field soils receiving sewage sludge. *Environ. Pollut.* 167, 101-109, (2012).

19 Heidler, J. & Halden, R. U. Mass balance assessment of triclosan removal during conventional sewage treatment. *Chemosphere* 66, 362-369, (2007).

20 Von der Ohe, P. C. et al. A new risk assessment approach for the prioritization of 500 classical and emerging organic microcontaminants as potential river basin specific pollutants under the European Water Framework Directive. *Sci. Total Environ.* 409, 2064-2077, (2011).

21 Dann, A. B. & Hontela, A. Triclosan: environmental exposure, toxicity and mechanisms of action. *J Appl. Toxicol.* 31, 285-311, (2011).

22 Van Wijnen, J., Ragas, A. M. J. & Kroeze, C. Modelling global river export of microplastics to the marine environment: Sources and future trends. *Sci. Total Environ.* 673, 392-401, (2019).

23 Jiang, L. & O'Neill, B. C. Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environ. Chang.* 42, 193-199, (2017).

24 Seitzinger, S. P. et al. Global river nutrient export: A scenario analysis of past and future trends. *Global Biogeochem. Cy.* 24, GB0A08, (2010).

25 Morée, A., Beusen, A., Bouwman, A. & Willems, W. Exploring global nitrogen and phosphorus flows in urban wastes during the twentieth century. *Global Biogeochem. Cy.* 27, 1-11, (2013).

26 Van Puijenbroek, P. J. T. M., Beusen, A. H. W. & Bouwman, A. F. Global nitrogen and phosphorus in urban waste water based on the Shared Socio-economic pathways. *J. Environ. Manage.* 231, 446-456, (2019).

27 Hofstra, N., Bouwman, A., Beusen, A. & Medema, G. Exploring global Cryptosporidium emissions to surface water. *Sci. Total Environ.* 442, 10-19, (2013).

28 Best, J. Anthropogenic stresses on the world's big rivers. Nature Geoscience 12, 7-21 (2018).

29 Avio, C. G., Gorbi, S. & Regoli, F. Plastics and microplastics in the oceans: From emerging pollutants to emerged threat. *Mar. Environ. Res.* 128, 2-11, (2017).

30 Crespo Cuaresma, J. & Lutz, W. The demography of human development and climate change vulnerability: A projection exercise. *Vienna Yearbook of Population Research* 1, 241-261 (2016).

31 Kc, S. & Lutz, W. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environ. Chang.* 42, 181-192, (2017).