



Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050

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[1] This paper presents estimates for global N and P emissions from sewage for the period 1970–2050 for the four Millennium Ecosystem Assessment scenarios. Using country-specific projections for population and economic growth, urbanization, development of sewage systems, and wastewater treatment installations, a rapid increase in global sewage emissions is predicted, from 6.4 Tg of N and 1.3 Tg of P per year in 2000 to 12.0–15.5 Tg of N and 2.4–3.1 Tg of P per year in 2050. While North America (strong increase), Oceania (moderate increase), Europe (decrease), and North Asia (decrease) show contrasting developments, in the developing countries, sewage N and P discharge will likely increase by a factor of 2.5 to 3.5 between 2000 and 2050. This is a combined effect of increasing population, urbanization, and development of sewage systems. Even in optimistic scenarios for the development of wastewater treatment systems, global N and P flows are not likely to decline.

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1. Introduction

[2] Sewage emissions of nitrogen (N) and phosphorus (P) constitute an important source of nutrients in freshwater and coastal marine ecosystems at local, regional, and even global scales [Dumont *et al.*, 2005; Harrison *et al.*, 2005]. In aquatic ecosystems, nutrient overenrichment or eutrophication may lead to algal blooms, algal scum, enhanced benthic algal growth, massive growth of submerged and floating macrophytes, and aquatic hypoxia and anoxia leading to fish kills [Diaz and Rosenberg, 2008; European Environment Agency (EEA), 2001; Hallegraeff, 1993; National Land and Water Resources Audit, 2001; Turner and Rabalais, 1994; Vollenweider *et al.*, 1992]. This process has degraded lakes, reservoirs, and estuarine and coastal marine waters in many places, with large-scale implications for biodiversity, water quality, fisheries, and recreation [Anderson *et al.*, 2002; Cloern, 2001; Li and Zhang, 1999].

[3] In the past 4 to 5 decades, there have been important changes in sewage N and P emissions to surface water in many countries. N emissions from sewage have changed because of increasing population and economic growth leading to changes in diet, urbanization, and construction of sewerage and wastewater treatment systems. P emissions from sewage have changed for the same reasons, but also

because of changes in patterns of use of P-based detergents in laundry washing machines and dishwashing machines. P-free detergents based on zeolites were introduced in Europe in the mid-1980s and progressively replaced the detergents that were based on sodium tripolyphosphate ($\text{Na}_5\text{P}_3\text{O}_{10}$) (STPP) through to the mid-1990s, when the markets stabilized [Risk and Policy Analysts (RPA), 2006]. At present, P-free detergents based on zeolites make up 80 to 100% of all laundry detergent used in northern and western Europe. However, at the same time, the use of automatic dishwashers is increasing in European households, and no restrictions have yet been placed on the use of P-based detergents for these appliances.

[4] Future continued population and economic growth in developing countries will almost certainly lead to further increasing sewage N and P emissions in the coming decades. With increasing numbers of households being connected to sewerage systems and the lagging installation of wastewater treatment systems, this may lead to severe eutrophication [Bouwman *et al.*, 2005].

[5] Here we present an approach for calculating sewage N and P emissions, developed as part of an international interdisciplinary effort to model river export of multiple bioactive elements (C, N, and P) and their elemental forms (dissolved/particulate and inorganic/organic) by the Global Nutrient Export from Watersheds (Global NEWS) work group of the UNESCO Intergovernmental Oceanographic Commission [Seitzinger *et al.*, 2005]. A continuation of this work involves the use of the Global NEWS models to assess past and future nutrient loading of coastal ecosystems.

[6] This paper is an update of the earlier work on global sewage N emissions [Bouwman *et al.*, 2005; Van Drecht *et al.*, 2003], this time with explicit representation of both N and P emissions. We examine the global development of

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sewage N and P emissions to surface water for the past 3 decades and develop scenarios for the future. Our future scenarios are those used in Global NEWS, i.e., the four scenarios of the Millennium Ecosystem Assessment (MEA) [Alcamo *et al.*, 2006]. These scenarios describe contrasting pathways of the development of human society and ecosystems. A brief summary of the storylines is provided in Table 1.

[7] We will first discuss the approach for N and P emissions to surface water from sewerage systems. On the basis of the trends seen in the past and MEA projections for population growth, urbanization, and economic growth, we constructed scenarios for these effluents (section 2.2). Section 3 discusses the results, and section 4 summarizes our main conclusions. The model sensitivity and uncertainties of the data as well as our approach are presented in Text S1 and Figure S1.¹

2. Methods and Data Used

2.1. N and P Emissions to Surface Water

2.1.1. Overall Approach

[8] Human N emission is the N emitted in wastewater by households and industries that are connected to the same sewerage system. The overall approach for calculating human N emission that is actually discharged to surface water is as follows (Figure 1):

$$E_{sw}^N = E_{hum}^N D(1 - R^N) \quad (1)$$

where E_{sw}^N is the N emission to surface water (kg person⁻¹ a⁻¹), E_{hum}^N is the human N emission (kg person⁻¹ a⁻¹), D is the fraction of the total population that is connected to public sewerage systems (no dimension), and R^N is the overall removal of N through wastewater treatment (no dimension). The total P emission to surface water is calculated as

$$E_{sw}^P = \left(E_{hum}^P + E_{Ldet}^P + \frac{E_{Ddet}^P}{D} \right) D(1 - R^P) \quad (2)$$

where E_{sw}^P is the P emission to surface water (kg person⁻¹ a⁻¹), E_{hum}^P is the human P emission (kg person⁻¹ a⁻¹), E_{Ldet}^P is the P emission from laundry detergents (kg person⁻¹ a⁻¹), E_{Ddet}^P the P emission from dishwasher detergents (kg person⁻¹ a⁻¹), and R^P is the overall removal of P through wastewater treatment (no dimension). E_{Ddet}^P is calculated for the population connected to sewerage systems (equation (10)). Dividing by D results in a value that applies to the total population.

2.1.2. Human N and P Emissions

[9] We assume that the human N emission varies with income. The purchasing power is generally considered to provide a better relationship with food (protein) consumption and associated human N emission than the market exchange rate [Union Bank of Switzerland, 2006]. Therefore, we modified an earlier approach which used per capita GDP based on market exchange rates [Bouwman *et al.*,

2005; Van Drecht *et al.*, 2003]. Our approach is based on estimates of dietary per capita protein consumption per country over the period from 1970 to 2000, from *Food and Agriculture Organization (FAO)* [2007]. Assuming an average 16% N content in protein, the resulting relationship is as follows (Figure 2):

$$I_{hum}^N = 4 + 14 \left[\frac{GDP_{PPP}}{33,000} \right]^{0.3} \quad (3)$$

where I_{hum}^N is the protein N intake in g person⁻¹ d⁻¹ and GDP_{PPP} is the national per capita gross domestic product (purchasing power parity or ppp-based GDP in 1995 U.S. dollars person⁻¹ a⁻¹). For low-income countries, where income is less than 730 1995 U.S. dollars person⁻¹ a⁻¹, I_{hum}^N calculated thus is <8.4 g person⁻¹ d⁻¹ or <3 kg person⁻¹ a⁻¹, and in industrialized countries this is about 16 g person⁻¹ d⁻¹ or 6 kg person⁻¹ a⁻¹. The latter values compare very well with reported western European average human N emission (equation (1)), on the basis of measurements of influent sewage to wastewater treatment plants [EEA, 2005; Kristensen *et al.*, 2004; Zessner *et al.*, 2005], data for a number of eastern European countries [Kroiss, 2005], and data from the *Organisation for Economic Co-operation and Development (OECD)* [2007]. These data include part of the emissions from industrial sources such as food processing. So we can use equation (4) for estimating human N emission:

$$E_{hum}^N \approx 0.365 I_{hum}^N \quad (4)$$

[10] There is a strong relationship between human N and P emissions [Zessner *et al.*, 2005]:

$$E_{hum}^P = f_N^P E_{hum}^N \quad (5)$$

where f_N^P is the ratio between human P and human N emission (no dimension). We use the standard value of 1/6 derived from measurements of 27 wastewater treatment plants in Austria [Zessner *et al.*, 2005]. For low-income countries, this yields P emissions of <1.4 g person⁻¹ d⁻¹ which is close to the physiological emission of 1 to 1.5 g person⁻¹ d⁻¹ [Billen *et al.*, 1999], which corresponds to data found for a country like Vietnam [Quynh *et al.*, 2005]. Equation (5) predicts values close to those observed for Europe [Kristensen *et al.*, 2004].

2.1.3. P Emission From Laundry Detergents

[11] The current P emission from laundry and dishwasher (L&D) detergents in the EU25 is 0.4 kg person⁻¹ a⁻¹, which is about 40% of the total P emission of 0.9 to 1.0 kg person⁻¹ a⁻¹ [Kristensen *et al.*, 2004]. Most of the P emission from L&D detergents is from laundry detergent (72%). However, there are large differences between European countries. At present, laundry detergents containing P are completely banned in some countries (Austria, Belgium, Germany, Ireland, Italy, Luxemburg, and the Netherlands), while in countries such as Poland and the Baltic States only 15 to 20% of laundry detergents are P free [RPA, 2006].

¹Auxiliary materials are available in the HTML. doi:10.1029/2009GB003458.

Table 1. Summary of the Storylines of the Four MEA Scenarios

Scenario	Storyline
Global Orchestration (GO)	<p>General: Globally connected society that focuses on global trade and economic liberalization and takes a reactive approach to ecosystem problems, but also takes strong steps to reduce poverty and inequality and to invest in public goods such as infrastructure and education.</p> <p>Sewage: Efforts to improve health situations and environmental problems associated with sewage are considerable: Most of the gap between the situation in 2000 and full access to improved sanitation and sewerage connection will be closed between 2000 and 2050; sewerage water treatment systems are expanded at the same rate, and with more advanced systems than those available in 2000; parallel to this, existing treatment systems will be replaced with more advanced ones.</p>
Order from Strength (OS)	<p>General: Regionalized and fragmented world, concerned with security and protection, emphasizing primarily regional markets, paying little attention to public goods, and taking a reactive approach to ecosystem problems.</p> <p>Sewage: Efforts of improving health situations and environmental problems associated with sewage keep up with urbanization: Connection to sewerage systems is proportional to urbanization and improved sanitation, sewerage water treatment systems are expanded at the same rate and with more advanced systems than those available in 2000, and existing treatment systems will be replaced with more advanced ones.</p>
Technogarden (TG)	<p>General: Globally connected world relying strongly on environmentally sound technology, using highly managed, often engineered, ecosystems to deliver ecosystem services, and taking a proactive approach to the management of ecosystems in an effort to avoid problems.</p> <p>Sewage: as in GO</p>
Adapting Mosaic (AM)	<p>General: Regional watershed-scale ecosystems are the focus of political and economic activity. Local institutions are strengthened and local ecosystem management strategies are common; societies develop a strongly proactive approach to the management of ecosystems based on simple technologies</p> <p>Sewage: as in OS; human N and P from inhabitants with access to improved sanitation but without a sewerage connection is recycled in this scenario and used to substitute N and P fertilizers in another paper (A. F. Bouwman et al., submitted manuscript, 2009).</p>

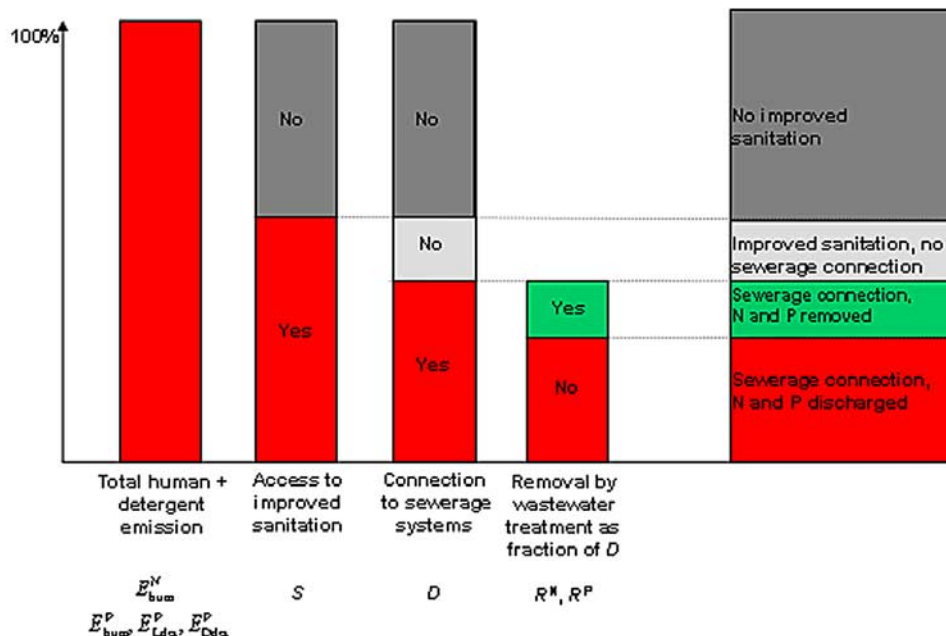


Figure 1. Scheme presenting the calculation of the fate of human N and P emissions.

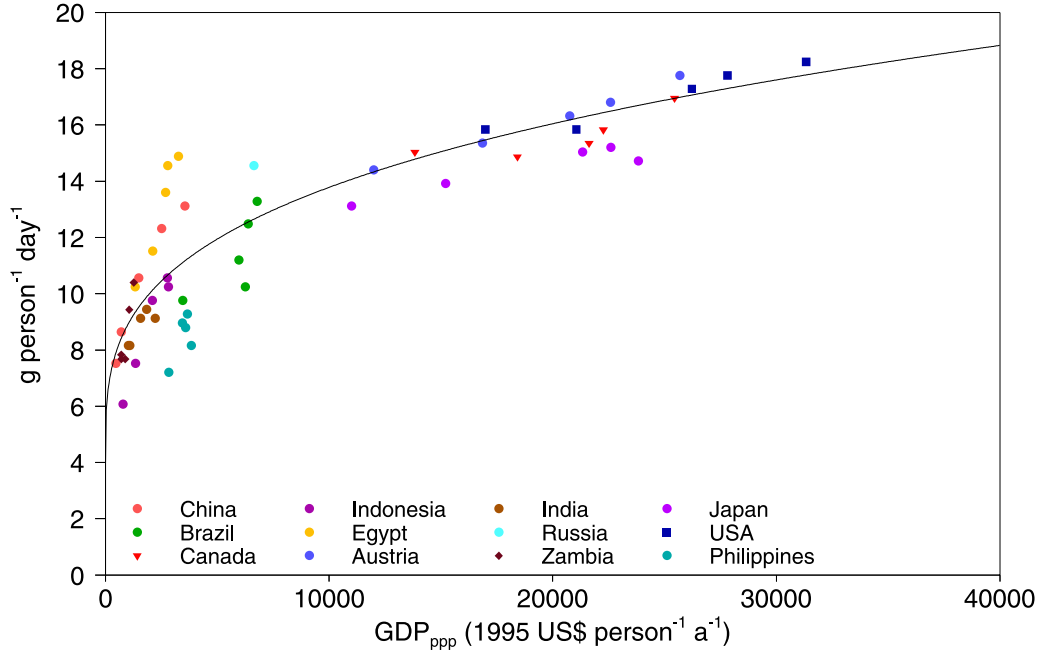


Figure 2. Relationship between per capita GDP_{ppp} and protein N consumption for selected countries. Data from *FAO* [2007].

[12] The P emission from laundry detergents is calculated as follows:

$$E_{Ldet}^P = E_{Ldet} f_{Ldet}^P (1 - f_{Ldet}^{Pfree}) \quad (6)$$

where E_{Ldet} is the use of laundry detergent ($kg\ person^{-1}\ a^{-1}$), f_{Ldet}^P is the P content of laundry detergents (kg/kg), and f_{Ldet}^{Pfree} is the fraction of P-free laundry detergents (no dimension).

[13] The laundry detergent use E_{Ldet} varies between 5 and 7 $kg\ person^{-1}\ a^{-1}$ in countries such as Austria, Denmark, Germany, and the Netherlands, while in Italy, the United Kingdom, Slovenia, and Poland it is typically $>9\ kg\ person^{-1}\ a^{-1}$ [RPA, 2006] (Figure 3). In Vietnam, it is 4.8 kg (including all care products) [Quynh *et al.*, 2005], and in China it is 3 $kg\ person^{-1}\ a^{-1}$ [Zhiming Wang, 1998]. We use reported data for the year 2000 where available. For other countries, E_{Ldet} is a function of per capita GDP_{mer} found by fitting EU country data on laundry detergent use (Figure 3):

$$E_{Ldet} = 10 - 10 \left[\frac{GDP_{mer}}{20,000} - 1 \right]^2 \quad (7)$$

where GDP_{mer} is the national per capita gross domestic product (market exchange rate based GDP expressed in 1995 U.S. dollars $person^{-1}\ a^{-1}$). GDP_{mer} yields a better fit to reported data than GDP_{ppp} . This contrasts with the approach used to fit protein N intake where GDP_{ppp} was used (equation (3)). For E_{Ldet} we assume a minimum value of 3 and a maximum value of 10 $kg\ person^{-1}\ a^{-1}$, on the basis of European data (Figure 3). Reported data on E_{Ldet} represent the mean use for the population as a whole. In western European countries, the degree of urbanization is

high, and the percentage of the population with a connection to public sewerage and access to laundry washing machines is even higher. In the absence of data on the population with access to laundry washing machines, we apply the modeled E_{Ldet} and E_{Ldet}^P exclusively to the population with a connection to public sewerage, D (equation (2)).

[14] The P content in P-based laundry detergent f_{Ldet}^P was calculated from 25% STPP content in laundry detergents and 25% P in STPP [Water Research Centre, 2002]. The P-free fraction f_{Ldet}^{Pfree} is 1 for EU countries such as Austria, Belgium, Germany, Ireland, Italy, Luxembourg, and the Netherlands, and less than 0.50 for the Baltic states, the Czech Republic, Hungary, Poland, Portugal, and Spain. We use reported f_{Ldet}^{Pfree} where available. We recognize that f_{Ldet}^{Pfree} is driven by legislation and regulation rather than by income, but it is difficult to find such information for countries outside Europe. Therefore, we use a calibrated function of GDP_{mer} for the year 2000 for those countries where no information on P-based laundry detergent use is available and for years after 2000 for all countries as follows:

$$f_{Ldet}^{Pfree} = \frac{GDP_{mer}}{33,000} \quad (8)$$

[15] For countries with a per capita GDP exceeding 33,000 U.S. dollars, we assume that $f_{Ldet}^{Pfree} = 1$. We use a trend function with time t for the period from 1970 to 2000 starting from the reported data for the year 2000 (Figure 4):

$$f_{Ldet}^{Pfree, <2000} = f_{Ldet}^{Pfree, 2000} \left(1 + \frac{1}{e^{a(2000-b)}} \right) \left(1 + \frac{1}{1 + e^{a(t-b)}} \right) \quad (9)$$

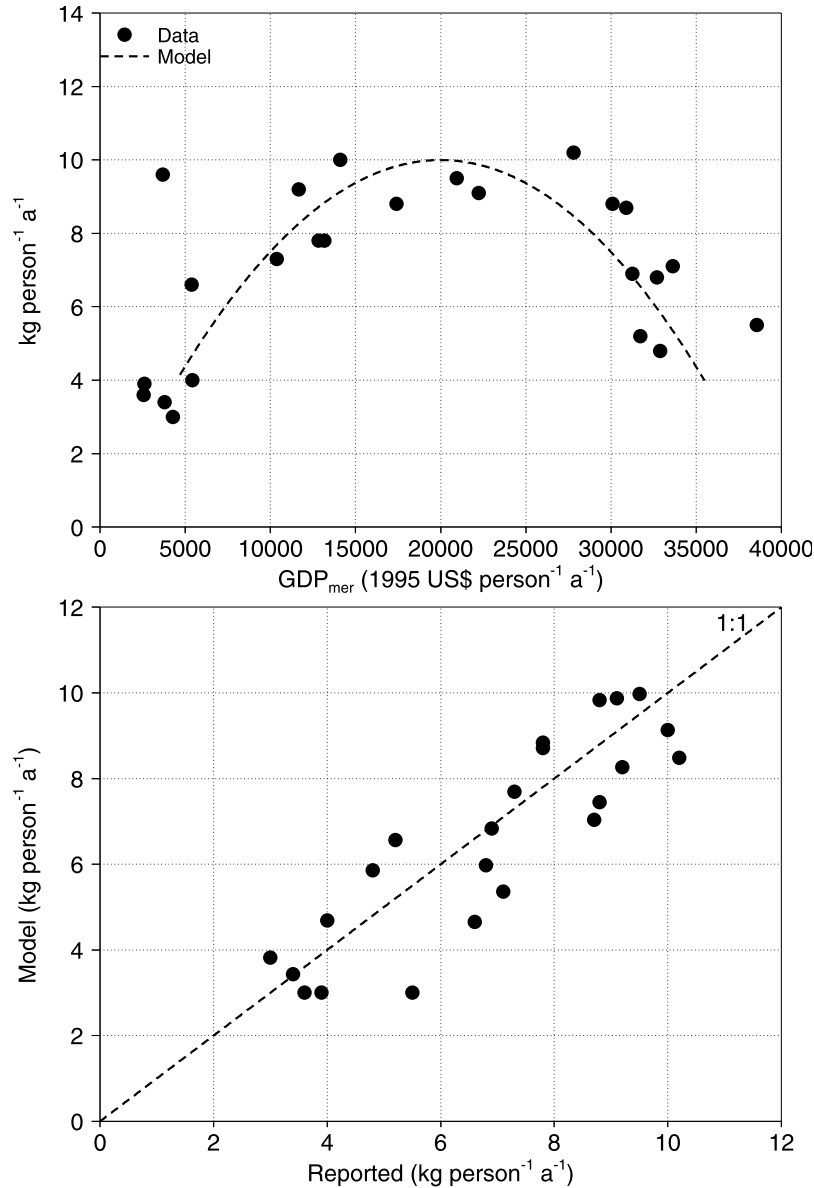


Figure 3. (top) Use of laundry detergents as a function of GDP (equation (6)) and (bottom) comparison of calculated use of laundry detergent with reported data for the EU25 obtained from *RPA* [2006]. Outliers in the data (Luxemburg and Poland) are not shown in Figure 3 (bottom).

where a and b are parameters with values of 0.2 and 1990, respectively, and t is the year between 1970 and 2000. These parameter values fit the situation in the Netherlands. Results of equation (9) agree fairly well with data for the United States [Revelle and Revelle, 1988].

2.1.4. P Emission From Dishwasher Detergents

[16] Similar to equation (6), the P emission from dishwasher detergents is calculated as follows:

$$E_{\text{Ddet}}^{\text{P}} = E_{\text{Ddet}} f_{\text{Ddet}}^{\text{P}} (1 - f_{\text{Ddet}}^{\text{Pfree}}) \quad (10)$$

where E_{Ddet} is the use of dishwasher detergent consumption (kg person⁻¹ a⁻¹), $f_{\text{Ddet}}^{\text{P}}$ is the P content of dishwasher detergents (kg/kg), and $f_{\text{Ddet}}^{\text{Pfree}}$ is the fraction of P-free

dishwasher detergents used (no dimension). E_{Ddet} is calculated according to

$$E_{\text{Ddet}} = 0.365 f_{\text{use}} \frac{\text{dose}}{\text{pphh}} \text{COV}_{\text{DW}} \quad (11)$$

where E_{Ddet} is the use of dishwasher detergent (kg person⁻¹ a⁻¹), f_{use} is the frequency of the use of automatic dishwashers (d⁻¹), dose is the weight of the tablets used in automatic dishwashers (g), pphh is the average number of persons per household, and COV_{DW} is the fraction of a population with access to an automatic dishwasher. E_{Ddet} represents the mean use for the population as a whole. The coverage of dishwashers is generally smaller than of access to

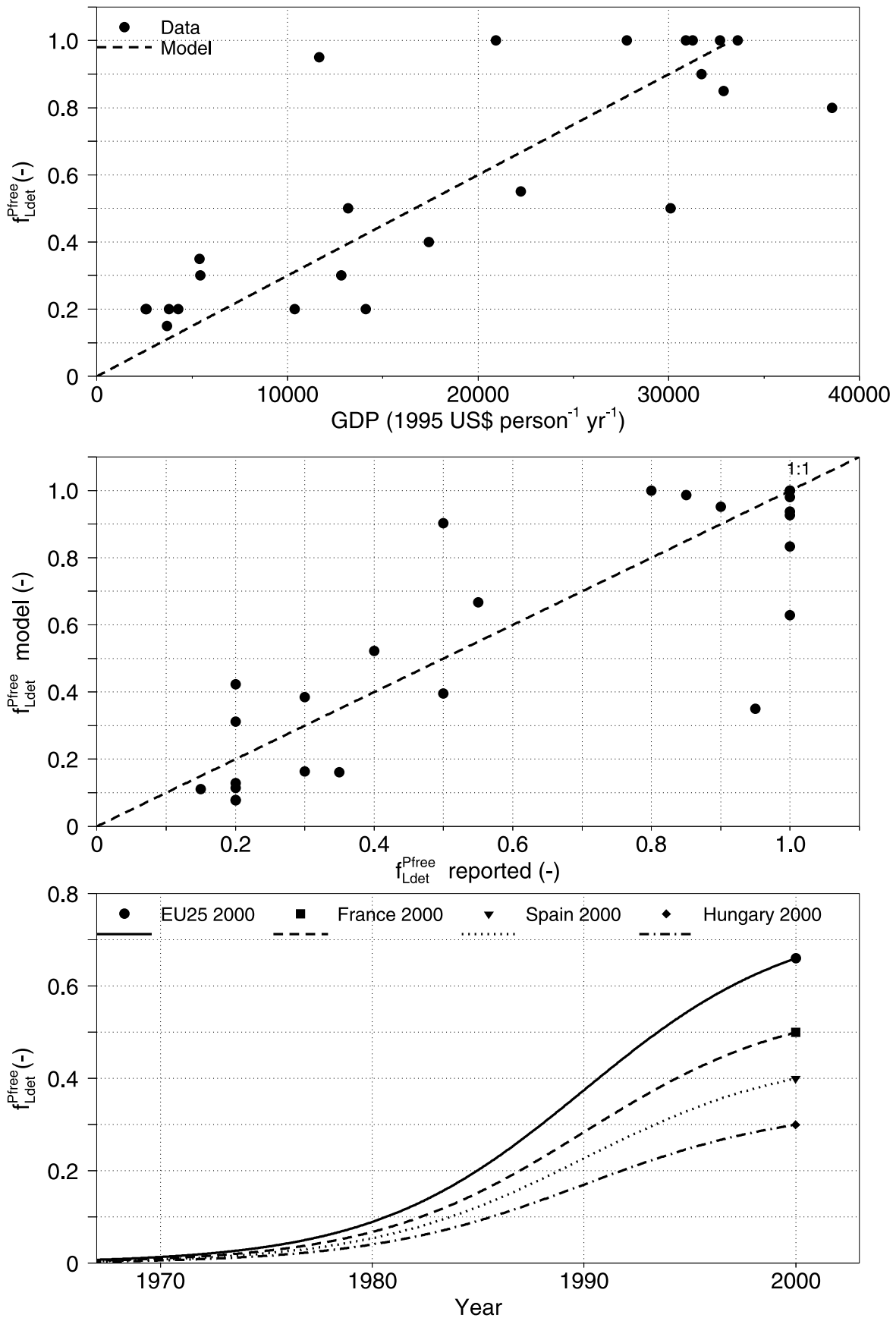


Figure 4

public sewerage. We assume that the population with access to an automatic dishwasher is evenly distributed among the population with a sewerage connection, D (equation (13)). Therefore, we apply E_{Ddet} exclusively to the population with a sewerage connection, with a concentration factor $1/D$ (equation (2)). For f_{use} we use a value of 0.64 d^{-1} based on *RPA* [2006]. The average number of persons per household in Europe is 2.5, and we assume that the detergent used per cycle equals the weight of one tablet of dishwasher detergent of 20–40 g (average 30 g). The P content of dishwasher detergent f_{Ddet}^P is assumed to be 0.117, on the basis of 30% PO_4^{3-} content and 39% P in PO_4^{3-} [*RPA*, 2006].

[17] COV_{DW} is an empirical function of per capita GDP_{mer} , found by fitting reported data for EU25 countries [*RPA*, 2006] (Figure 5):

$$COV_{DW} = 0.25 + 0.07 \frac{GDP_{mer}}{10,000} \quad (12)$$

The value of COV_{DW} is not allowed to exceed 0.80 on the basis of European data, and it is assumed to be negligible for low to moderate income countries ($GDP_{mer} < 10,000 \text{ U.S. dollars person}^{-1} \text{ a}^{-1}$). For historical years, we apply the trend curve from *Statistics Netherlands* [2008] for the coverage in the Netherlands to all countries (Figure 5). Although P-free dishwasher detergents are already available, we have no data on their actual consumption. In addition, manufacturers claim that the main “substitute” combinations of chemicals used in P-free laundry detergents cannot be used in dishwasher detergents because they are insoluble and would coat tableware and glasses [*Centre Européen d’Etudes des Polyphosphates*, 2008]. At present, there is no policy regarding the use of P-free detergents for dishwashers and we assume that this will not change in the period from 2000 to 2050. The effect of such legislation will have only a minor effect on P effluents in many industrialized countries because of the efficient P removal in wastewater treatment.

2.1.5. Connection to Public Sewerage Systems

[18] *Van Drecht et al.* [2003] and *Bouwman et al.* [2005] used regional estimates of D from *World Health Organization/United Nations Children’s Fund (WHO/UNICEF)* [2000]. Here we use available data for D for the period between 1970 and 2000 taken from various reports from World Health Organization/United Nations Children’s Fund (WHO/UNICEF), European Environment Agency (EEA), and Organisation for Economic Co-operation and Development (OECD) (Text S2). For other countries where D is not known, we use data on the population with access to “improved sanitation” [*WHO/UNICEF*, 2000]. This includes connection to public sewerage, but also to other systems such as septic systems, simple pit latrines, pour-flush, and ventilated improved pit latrines. In such cases, D

is calculated from the empirical relation with urbanization and improved sanitation of the urban population:

$$D = c U S_u \quad (13)$$

where c is a calibrated factor (no dimension), U is the fraction of the total population living in urban areas (no dimension), and S_u is the fraction of urban population with access to improved sanitation (no dimension). The factor c is used as follows: for countries where D , U , and S_u are known for the year 2000, c is calculated from equation (13) and used for other years to compute D from U and S_u . If no data on D are available, we use regional estimates for c .

[19] The access to improved sanitation is different for rural and urban populations. For industrialized countries, the access may be 100% for both rural and urban populations. D is the fraction of the total population with a sewerage connection and may exceed U . Therefore, in such cases, equation (13) yields values for $c > 1$ and the correct influent N and P in sewerage. In transitional and developing countries the access to improved sanitation is much lower for the rural than for the urban population. For example, *WHO/UNICEF* [2000] reports that in Romania, 86% of the urban and only 10% of the rural population had access to improved sanitation in the mid-1990s. Particularly in the rural areas of many developing countries, the human waste is commonly collected in latrines or septic tanks, and we assume that this does not enter surface water.

2.1.6. N and P Removal Through Wastewater Treatment Systems

[20] We distinguish four types of wastewater treatment with differing treatment efficiencies, expressed by the N and P removal fractions (equations (1) and (2) and Table 2). The overall values for these removal fractions for a country are calculated as the weighted average of the classes: no treatment, mechanical (primary) treatment, biological (secondary) treatment, and advanced (tertiary) treatment. Data on the distribution of the different types of treatment are available for most European countries from *EEA* [1998] and the European Commission (Eurostat, Environment and Energy, Environment, Water theme, 2007, available at <http://epp.eurostat.ec.europa.eu>). Data for many other countries are obtained from various sources (Text S2). For countries for which no data were found, we use regional estimates, primarily on the basis of *WHO/UNICEF* [2001]. In most developing countries, the overall N and P removal fractions are low because installations with advanced and biological treatment are not widespread. Errors in the estimated N and P discharges from sewerage systems are therefore likely to be small. We use a maximum removal fraction of 0.8 for N and 0.9 for P based on the current treatment technology (Table 2). Nutrient removal fractions have substantially increased during the past decades because of optimized management. With respect to primary

Figure 4. (top) Use of P-free detergents for laundry as a function of GDP (equation (8)), (middle) comparison of calculated use of P-free detergents for the year 2000 with reported use for the EU25, and (bottom) data for 2000 and trend in the P-free laundry detergent use assumed for the EU25, France, Spain, and Hungary between 1970 and 2000 (equation (9)). Data are from *RPA* [2006].

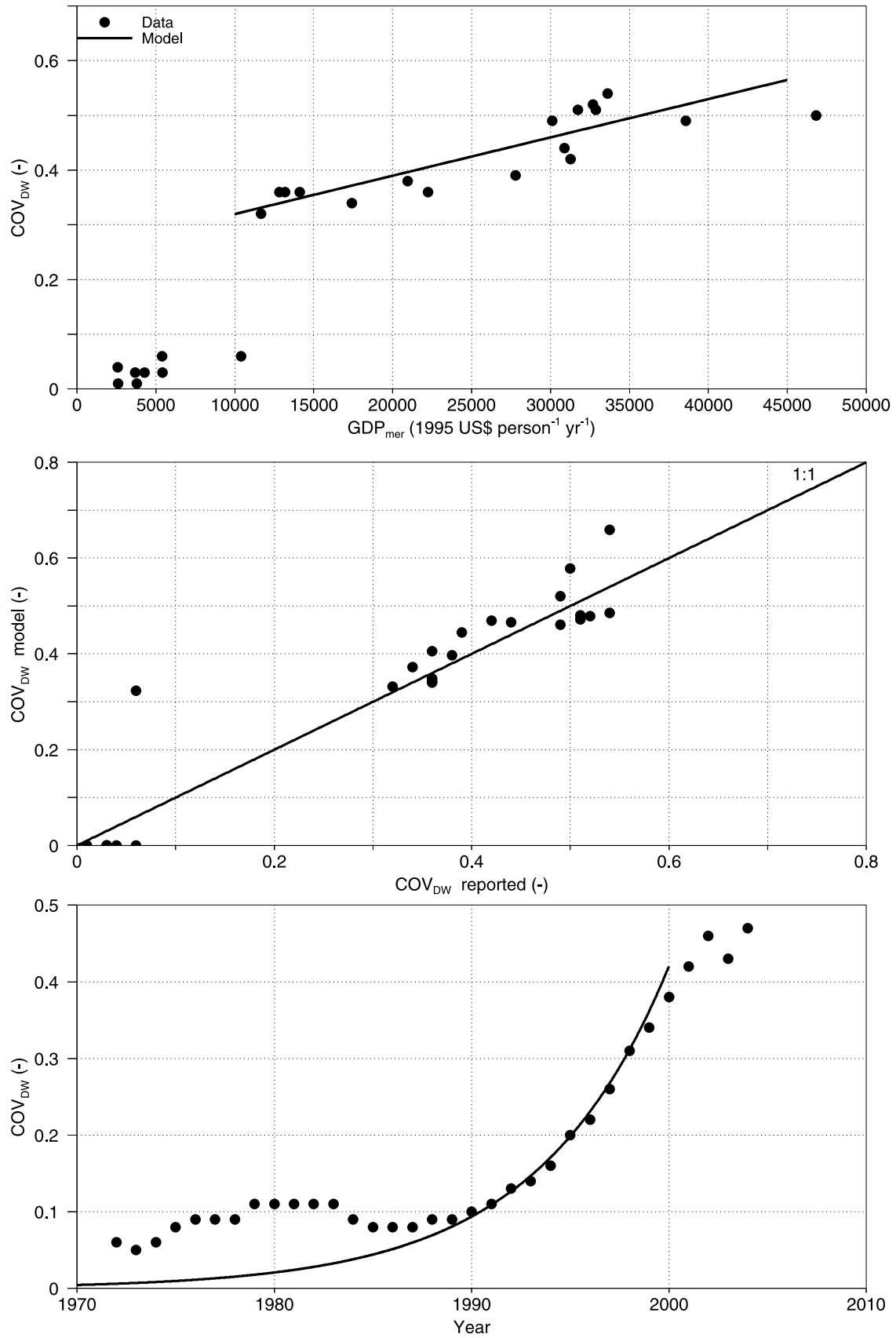


Figure 5

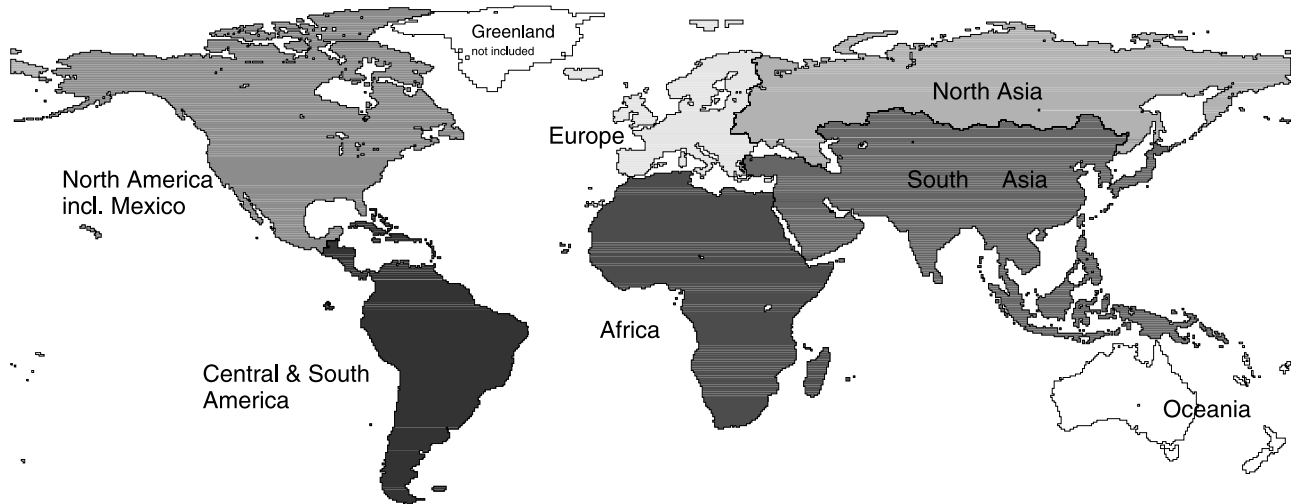


Figure 6. Regions used in the aggregation of the results.

and biological treatment, our assumed removal fractions for (mostly developing) countries with no data are lower than those recorded for most high-income countries, as for example presented by *Kristensen et al.* [2004] for northern Europe (Table 1). These lower fractions reflect assumed suboptimal management.

2.2. Scenario Construction

[21] For the construction of scenarios on the basis of the MEA storylines (Table 1), first the per capita human N and P emissions are calculated as a function of per capita GDP for each year, country, and scenario from equations (3) and (4) (Table 3). Laundry and dishwasher P emissions are calculated from GDP (equations (6) and (10)). As the MEA scenarios for GDP and population are quite contrasting, this results in a range of estimates for the future.

[22] For constructing scenarios we use the calibration factor c (equation (13)) to compute the fraction of the population with access to public sewerage systems from scenario data for the fraction of the population in urban areas (U) and the fraction of the urban population with access to improved sanitation (S_u). Combined with the population scenario, this yields the N and P emissions in raw (untreated) wastewater per country, and equation (1) and (2) provide the total N and P emissions to surface waters.

[23] Scenarios for urbanization are taken from *Grübler et al.* [2006], who developed scenarios for the storylines of the IPCC Special Report on Emission Scenarios (SRES) [*Nakicenovic et al.*, 2000]. Since the MEA and SRES scenarios have similar storylines, we used the A1 scenario to represent Global Orchestration (GO), the A2 scenario for Order from Strength (OS), the B1 scenario for Technogarden (TG), and the B2 scenario for Adapting Mosaic (AM) (Table 3).

[24] For OS and AM, we assume a constant fraction of the population with access to improved sanitation, while the fraction of the population with a connection to sewerage systems is assumed to be proportional to the product of U and S_u (equation (13)) (Table 3). Hence, the calibration factor c is constant. The regional orientation of OS and AM implies that in these scenarios, less technical cooperation will take place between countries than in GO and TG, while with slower economic development in OS and AM, the investment capacity is lacking to develop sewerage systems at a rate that keeps up with population growth and urbanization. For OS and AM this means that despite the constant fraction of the population with access to improved sanitation, considerable investments are needed to keep up with the increasing population and urbanization, particularly in OS with its fast population growth.

[25] For OS and AM we assume that 25% of the share of each treatment type (Table 2) shifts toward the next in line (more advanced) in both the period between 2000 and 2030 and between 2030 and 2050. This implies that 25% of the share of “no treatment” is replaced by mechanical installations, 25% of the share of mechanical treatment is replaced by biological treatment plants, and 25% of the share of biological treatment capacity is replaced by advanced treatment systems. The capacity of existing treatment systems will therefore need to increase, and at the same time there is a slow improvement with modern treatment types replacing less efficient ones. Hence, considerable investments will be needed to increase the capacity of the treatment systems to keep up with population growth and urbanization and to replace part of existing installations. Technological and management improvement, resulting in higher N and P

Figure 5. (top) Coverage of dishwashers for EU25 countries as a function of GDP (equation (12)), (middle) comparison of calculated dishwasher coverage with reported data from *RPA* [2006] for EU25 countries for the year 2000, and (bottom) trend in the coverage of dishwashers in the Netherlands for the time period 1970–2000. Data are from *Statistics Netherlands* [2008].

Table 2. Wastewater Treatment Systems Distinguished in This Study and Corresponding N and P Removal Fractions, Compared With Ranges Reported for a Number of Northern European Countries

Treatment Type	N Removal ^a (R^N)		P Removal ^a (R^P)	
	A (%)	B (%)	A (%)	B (%)
No treatment	0	0	0	0
Primary ^b (mechanical)	10	20–25	10	28–30
Secondary ^b (biological)	35	36–55	45	51–90
Tertiary ^b (advanced)	80	45–83	90	88–95

^aA, estimates for R^N from Van Drecht et al. [2003], for R^P from this study; B, Kristensen et al. [2004].

^bSee section A4 in Text S1.

removal efficiencies per treatment type, are not taken into account.

[26] In the GO and TG scenarios the situation will improve. The proportion of people without sustainable access to improved sanitation (S_u) will be reduced by half between the year 2000 and 2030. In the period between 2030 and 2050 we assume that another 50% of the gap will be bridged between the situation in 2030 and that of 100% access.

[27] We also assume that sewerage systems are the preferred means for better control of wastewater and that there are adequate economic resources available. To achieve this in GO and TG, the calibration factor c (equation (13)) increases, which means that the fraction of the population with a sewerage connection is growing faster than in OS and AM. For countries with $c(2000) < 1$ we consider $c = 1$ as the Millennium Development Goal [United Nations (UN), 2000] with respect to sanitation for the year 2050 (MDG-2050). We therefore reduce the gap between $c(2000)$ and $c = 1$ in the year 2030; for between 2030 and 2050 we assume no further increase of c . For industrialized countries with $c(2000) > 1$ there is no need for this extra effort, and c remains unchanged.

[28] For GO and TG we assume that 50% of the share of each treatment type shifts toward the next in line in both the period between 2000 and 2030 and between 2030 and 2050 (Table 3). Hence, the capacity of existing treatment systems will need to increase, and at the same time there is a rapid improvement with modern treatment types replacing less efficient ones. The motivation for these investments differs, however, between the GO and TG scenarios (Table 1).

2.3. Spatial Allocation

[29] For allocating the N and P emissions we use LandScan population density data with a 30 by 30 min resolution (Oak Ridge National Laboratory, LandScan Global Population 1998 Database, 2002, available at http://www.ornl.gov/sci/gist/projects/LandScan/landscan_doc.htm). Definitions of urban area and population within United Nations (UN) projections [UN, 2005] show a wide variation depending on the methodology applied by countries [Hilderink, 2006]. To avoid these definition problems, we count the people starting from the grid cells with highest population density within each country by means of ranking, up to the number

of persons equals the number of people with a sewage connection. Areas with high population density most logically have the highest degree of connection to sewerage systems, and rural areas with low population density have the lowest degree of connection. We scaled the population density map with the population projection for 2030 and 2050 for each country and each scenario, with a maximum population density within a grid cell.

3. Results and Discussion

3.1. Overview

[30] Using country-specific projections for population and economic growth, urbanization, development of sewerage systems, and wastewater treatment installations, we predict a rapid increase in global sewage emissions from 6.4 Tg of N and 1.3 Tg of P a^{-1} in 2000 to 12.0–15.5 Tg of N and 2.4–3.1 Tg of P a^{-1} in 2050. North America (strong increase), Oceania (moderate increase), Europe (decrease), and North Asia (decrease) show contrasting developments of N and P sewage emissions. In the developing countries, sewage N and P discharge will likely increase by a factor of 2.5 to 5.5 between 2000 and 2050. Especially rapid (4–6-fold) increases in sewage N and P emissions are projected to occur in southern and eastern Asia. Projected patterns occur because of a combined effect of increasing population, urbanization, and development of sewage systems, leading to increased concentrations of N and P in sewage water. Even in optimistic scenarios for the development of wastewater treatment systems, global N and P flows are not likely to decline.

3.2. Regional Analyses

[31] The sewage N and P emissions are calculated on the country scale. Here we discuss our results on the scale of seven world regions (Figure 6). For each region, we present the changes in sewage N and P emissions for the period between 1970 and 2000 and for the period between 2000 and 2050 for the four MEA scenarios.

3.2.1. North America

[32] The population of North America (Canada, United States, and Mexico) increased from 282 to 415 million inhabitants (+47%) between 1970 and 2000 (Table 4), while at the same time the per capita GDP_{mer} increased by 75%. As a result, the per capita human N and P emissions increased by 12%, while the detergent P emission decreased by close to 50% (Figure 7). Total human N and P emissions increased by 65% between 1970 and 2000. N and P removal increased from 34 to 54% (Figure S2), while the population with a sewerage connection increased from almost 60 to 70%. The consequence of all these simultaneous developments was an increase of N discharge after treatment to surface water from 686 to 957 Gg a^{-1} (+39%), while P discharge increased by only 1% from 166 to 168 Gg a^{-1} (Figure 7).

[33] The scenarios show a wide range of possible population and economical developments. Both OS and AM show rapid population growth of 30% to 540 million persons between 2000 and 2030 and a further 11% increase to close to 600 million persons by 2050. In GO and TG scenarios, the population increases by 40% between 2000 and 2050. Per capita GDP

Table 3. Approach for Scenario Development for the Main Drivers of Sewage N and P Emission to Surface Water in Each of the Millennium Assessment Scenarios

Scenario Driver	Scenario			
	Global Orchestration (GO)	Order From Strength (OS)	Technogarden (TG)	Adapting Mosaic (AM)
Population	MEA regional scenarios [Alcamo <i>et al.</i> , 2006] downscaled to countries based on country UN [2006] projections according to Van Vuuren <i>et al.</i> [2007]	As in GO	As in GO	As in GO
Per capita GDP	MEA regional scenarios from Alcamo <i>et al.</i> [2006] downscaled to countries according to Van Vuuren <i>et al.</i> [2007] based on country data from World Bank [2001] and United Nations Statistics Division (UNSTAT National accounts main aggregates database, 2005, United Nations Statistics Division, New York, available at http://unstats.un.org/). Income growth rates range from 1.3% to 3.0% and increase in sequence of OS, AM, TG, GO. Per capita purchasing power, GDP_{ppp} , was calculated under the assumption that the ratio GDP_{ppp}/GDP_{mer} is decreasing with GDP_{mer} and converging to 1.	As in GO	As in GO	As in GO
Urbanization	Downscaling to country scale is from Grübler <i>et al.</i> [2006]; B1 is used to represent GO (low urbanization rate), A2r is used for OS (rapid urbanization), B1 for TG (low urbanization rate) and B2 for AM (medium rate).	As in GO	As in GO	As in GO
S_u , fraction of population with access to improved sanitation	Increase, 2030: reduce 50% of the gap between $S_u(2000)$ and 100% improved sanitation; 2050: reduce 50% of the gap between $S_u(2030)$ and 100% improved sanitation.	Constant, $S_u(2000)$	Increase, As in GO	Constant, As in OS
D , fraction of population connected to public sewerage: The share of sewerage connection in the population with access to improved sanitation depends on the value of c in equation (13)	Increase, 50% of the gap between $c(2000)$ and $c = 1$ is closed in the period 2000–2030 and constant afterwards, except for countries with $c(2000) > 1$ where c remains constant	Constant, $c(2000)$	Increase, As in GO	Increase, As in OS
Detergent use	Laundry detergent use (E_{Ldet}) and fraction of P-free laundry detergents (f_{Ldet}^{Pfree}) and automatic dishwasher detergent use (E_{Ddet}) and fraction P-free dishwasher detergents (f_{Ddet}^{Pfree}) are entirely based on GDP	As in GO	As in GO	As in GO
R^N and R^P , removal of N and P through wastewater treatment plants: Removal of N and P through wastewater treatment plants will increase by a gradual shift to higher technological treatment classes. The removal efficiency per class remains constant	50% of each treatment class shifts toward the next in line in the period 2000–2030 and another 50% in 2030–2050 ^a	25% of each treatment class shifts toward the next in line in the period 2000–2030 and another 25% in 2030–2050 ^a	As in GO	As in OS

^a25% (OS and AM) or 50% (GO and TG) of “no treatment” is replaced by mechanical; 25% or 50% of mechanical treatment is replaced by biological; 25% or 50% of biological is replaced by advanced treatment.

Table 4. Population, GDP_{mer}, Human N and P Emission, Detergent P Emission, Population Connected to Sewerage Systems, and N and P Removal From Sewage Water for 1970, 2000, 2030, and 2050 for Selected World Regions and for the Four MEA Scenarios

Year	Scenario	Region ^a								
		North America	Central and South America	Europe	Africa	North Asia	South Asia	Southern Asia	Eastern Asia	Oceania
		<i>Population (Million Inhabitants)</i>								
1970		282	234	466	357	143	2,206	721	850	17
1990		367	358	507	622	164	3,239	1,118	1,184	22
2000		415	421	519	796	162	3,750	1,363	1,307	26
2030	GO	525	554	533	1,239	155	4,685	1,874	1,404	33
2050	GO	575	602	541	1,443	147	4,826	1,993	1,315	38
2030	OS	540	642	463	1,496	145	5,242	2,203	1,520	30
2050	OS	599	763	385	2,014	124	5,754	2,568	1,489	31
2030	TG	531	598	513	1,364	153	4,966	2,027	1,465	32
2050	TG	579	673	484	1,717	141	5,281	2,262	1,394	35
2030	AM	539	640	473	1,472	147	5,215	2,182	1,515	31
2050	AM	599	754	429	1,927	132	5,748	2,532	1,499	33
		<i>GDP_{mer} (1995 US Dollars Person⁻¹ a⁻¹)</i>								
1970		13,945	2,648	10,000	695	1,709	1,333	309	162	12,874
1990		20,408	3,360	17,336	766	4,061	2,304	774	516	16,725
2000		24,419	3,948	20,810	746	2,704	2,685	1,010	1,129	20,730
2030	GO	49,196	10,073	43,884	1,254	9,171	7,405	6,100	7,885	42,677
2050	GO	70,138	23,050	64,116	2,993	23,002	16,599	17,254	22,604	62,456
2030	OS	39,995	6,578	36,281	949	5,885	4,148	2,982	3,704	36,834
2050	OS	48,338	10,010	44,789	1,488	10,018	5,502	5,260	5,932	45,750
2030	TG	44,190	8,566	39,960	1,150	7,658	5,838	4,663	5,862	39,718
2050	TG	60,445	18,636	56,307	2,659	18,075	11,932	12,386	15,547	56,700
2030	AM	39,760	7,377	36,173	1,019	6,800	4,936	3,919	4,998	36,632
2050	AM	52,187	13,170	48,741	1,905	14,935	9,002	9,639	11,729	49,954
		<i>Human N Emission (E_{hum}^N in kg Person⁻¹ a⁻¹)</i>								
1970		5.4	4.1	4.8	3.4	4.3	3.3	3.3	2.9	5.3
1990		5.9	4.4	5.5	3.5	4.9	3.7	3.5	3.5	5.6
2000		6.1	4.5	5.7	3.5	4.5	4.0	3.7	4.1	5.9
2030	GO	7.2	5.6	6.8	3.8	5.2	5.0	4.5	5.6	6.9
2050	GO	8.0	6.8	7.5	4.4	6.1	6.1	5.5	6.8	7.6
2030	OS	6.8	5.0	6.4	3.6	4.7	4.4	4.0	4.7	6.7
2050	OS	7.2	5.5	6.8	3.8	5.0	4.7	4.3	5.0	7.0
2030	TG	7.0	5.4	6.6	3.7	5.0	4.8	4.3	5.2	6.8
2050	TG	7.7	6.4	7.3	4.3	5.7	5.7	5.2	6.3	7.4
2030	AM	6.8	5.2	6.5	3.6	4.9	4.6	4.2	5.1	6.7
2050	AM	7.3	5.9	7.0	4.0	5.5	5.3	4.8	5.9	7.2
		<i>Human P Emission (E_{hum}^P in kg Person⁻¹ a⁻¹)</i>								
1970		0.9	0.7	0.8	0.6	0.7	0.5	0.5	0.5	0.9
1990		1.0	0.7	0.9	0.6	0.8	0.6	0.6	0.6	0.9
2000		1.0	0.8	1.0	0.6	0.8	0.7	0.6	0.7	1.0
2030	GO	1.2	0.9	1.1	0.6	0.9	0.8	0.7	0.9	1.2
2050	GO	1.3	1.1	1.3	0.7	1.0	1.0	0.9	1.1	1.3
2030	OS	1.1	0.8	1.1	0.6	0.8	0.7	0.7	0.8	1.1
2050	OS	1.2	0.9	1.1	0.6	0.8	0.8	0.7	0.8	1.2
2030	TG	1.2	0.9	1.1	0.6	0.8	0.8	0.7	0.9	1.1
2050	TG	1.3	1.1	1.2	0.7	1.0	0.9	0.9	1.0	1.2
2030	AM	1.1	0.9	1.1	0.6	0.8	0.8	0.7	0.8	1.1
2050	AM	1.2	1.0	1.2	0.7	0.9	0.9	0.8	1.0	1.2
		<i>Detergent P Emission (E_{Ldet}^P + E_{Ddet}^P in kg Person⁻¹ a⁻¹)</i>								
1970		0.3	0.1	0.3	0.0	0.1	0.0	0.0	0.0	0.4
1990		0.2	0.1	0.2	0.0	0.1	0.0	0.0	0.0	0.3
2000		0.2	0.1	0.2	0.0	0.1	0.0	0.0	0.0	0.3
2030	GO	0.2	0.3	0.2	0.1	0.2	0.1	0.0	0.1	0.2
2050	GO	0.3	0.3	0.3	0.1	0.3	0.2	0.1	0.2	0.2
2030	OS	0.2	0.1	0.2	0.0	0.2	0.1	0.0	0.1	0.2
2050	OS	0.3	0.2	0.2	0.0	0.3	0.1	0.0	0.1	0.2
2030	TG	0.2	0.3	0.2	0.1	0.2	0.1	0.0	0.1	0.2
2050	TG	0.3	0.3	0.3	0.1	0.3	0.2	0.1	0.3	0.2
2030	AM	0.2	0.2	0.2	0.0	0.2	0.1	0.0	0.1	0.2
2050	AM	0.3	0.2	0.2	0.0	0.3	0.1	0.0	0.2	0.2
		<i>Population Connected to Sewerage Systems (D in % of Total Population)</i>								
1970		61	25	64	10	61	9	3	6	77
1990		65	40	73	12	53	14	9	10	82
2000		70	46	79	14	66	18	9	19	82
2030	GO	80	67	86	30	73	37	24	44	89
2050	GO	83	73	89	36	77	44	31	53	91
2030	OS	75	52	86	16	70	24	12	33	86
2050	OS	78	54	89	17	74	27	15	41	88

Table 4. (continued)

Year	Scenario	Region ^a								
		North America	Central and South America	Europe	Africa	North Asia	South Asia	Southern Asia	Eastern Asia	Oceania
2030	TG	80	67	86	30	73	37	24	44	89
2050	TG	83	73	89	36	77	43	31	53	91
2030	AM	75	52	86	16	69	24	12	32	86
2050	AM	77	54	88	16	71	26	15	38	88
<i>N Removal From Sewage Water (R^N in % of Influent to Wastewater Treatment Plants)</i>										
1970		28	0	10	0	0	3	0	0	4
1990		44	4	36	3	6	14	10	10	31
2000		46	7	50	5	21	16	10	10	31
2030	GO	56	17	59	10	37	24	22	22	46
2050	GO	63	32	66	20	51	38	40	40	58
2030	OS	50	12	54	9	29	19	16	16	39
2050	OS	54	18	58	14	37	25	24	23	45
2030	TG	56	17	59	10	37	24	22	22	46
2050	TG	62	32	66	20	51	38	40	40	58
2030	AM	50	12	54	9	29	19	16	16	39
2050	AM	54	18	58	14	37	25	24	23	45
<i>P Removal From Sewage Water (R^P in % of Influent to Wastewater Treatment Plants)</i>										
1970		34	0	11	0	0	3	0	0	4
1990		52	4	44	3	6	16	10	10	38
2000		54	7	59	5	26	18	10	10	38
2030	GO	64	20	69	12	44	29	27	27	54
2050	GO	72	38	76	24	60	45	47	47	67
2030	OS	58	13	64	10	35	23	19	18	46
2050	OS	62	21	68	16	43	30	28	28	53
2030	TG	64	20	69	12	44	29	27	27	54
2050	TG	71	38	76	24	60	45	47	47	67
2030	AM	58	13	64	10	35	23	19	18	46
2050	AM	62	21	68	17	44	30	28	28	53

^aSee Figure 6 for definition of the world regions. Two additional regions are eastern and southern Asia which are part of South Asia. Eastern Asia includes China and Mongolia; southern Asia includes Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka.

increases rapidly in GO (+100% in 2000–2030 and a further 43% between 2030 and 2050). Economy grows more slowly in TG than in GO, while in the other scenarios the per capita GDP increases by 98% (OS) and 114% (AM) over the period 2000–2050. This has consequences for human N and P emissions, which increase by 31% to 8 kg N and 1.3 kg P person⁻¹ a⁻¹ (GO), and by 26% (TG), 21% (AM) and 18% (OS) (Figure S2). Changes in detergent P emissions vary, with an increase of 62% (AM) to 69% (GO) over the period 2000–2050, mainly as a result of increasing use of automatic dishwashers. The population with a sewage connection increases further to 77–93%. N and P removal rates increase most rapidly in TG and GO to values of 62–63% in 2050 for N and 71–72% for P, and about 9% slower in OS and AM. Despite the technological progress, the combination of fast population and economic growth results in increasing N discharge to surface water (+39% to 1332 Gg a⁻¹ between 2000 and 2030 and +4% in the period 2030–2050) in GO; a similar development is seen in TG; in OS and AM the increase for 2000–2030 is even more (43–44%), with a further 4–14% increase to 1550–1575 Gg a⁻¹ for 2030–2050 (Figure 7). P discharge will increase more strongly in OS and AM (+67–70% between 2000 and 2050) than in GO and TG (+36–39%).

3.2.2. Oceania

[34] Estimated historic changes in sewage N and P loading to surface waters in Oceania between 1970 and 2000 are comparable to those in North America. In the period 1970–2000 the population increased by 52%,

GDP_{mer} increased by 61%, human N and P emissions increased by 11%, and detergent P emissions decreased by 32% (Table 4). The population with a sewage connection started from a high 77% and increased further to 82% between 1970 and 2000. The N and P removal in wastewater treatment installations increased from 4% for N and P in 1970 to 31% for N and 38% for P in 2000 (Figure S2). The resulting discharge of N to surface water increased from 67 to 87 Gg a⁻¹ (+30%), and that of P was almost stable at about 18 Gg a⁻¹ (Figure 7).

[35] Similar to North America, future population and economic growth is most rapid in GO and TG (about +30% to 32 to 33 million persons for 2000–2030 and a further 9–13% increase to 33–38 million persons for 2030–2050). OS and AM have slower population growth (19–21% for 2000–2030 and 2–7% for 2030–2050). Per capita GDP will increase by 92–106% for 2000–2030 in GO and TG and by 43–46% for 2030–2050. Incomes remain somewhat lower than in North America, and therefore we see values for human N and P and detergent P emissions comparable to Europe and lower than in North America. In all scenarios, close to 90% of the population will have a sewage connection, and N and P removal rates rise to values of close to 60% for N and 66–75% for P (Figure S2). The discharge of N will increase in all scenarios by 24–30% to 110–112 Gg N a⁻¹ in 2000–2030 (Figure 7). Between 2030 and 2050 we predict a 5% decrease in N discharge in TG and stabilization in the other

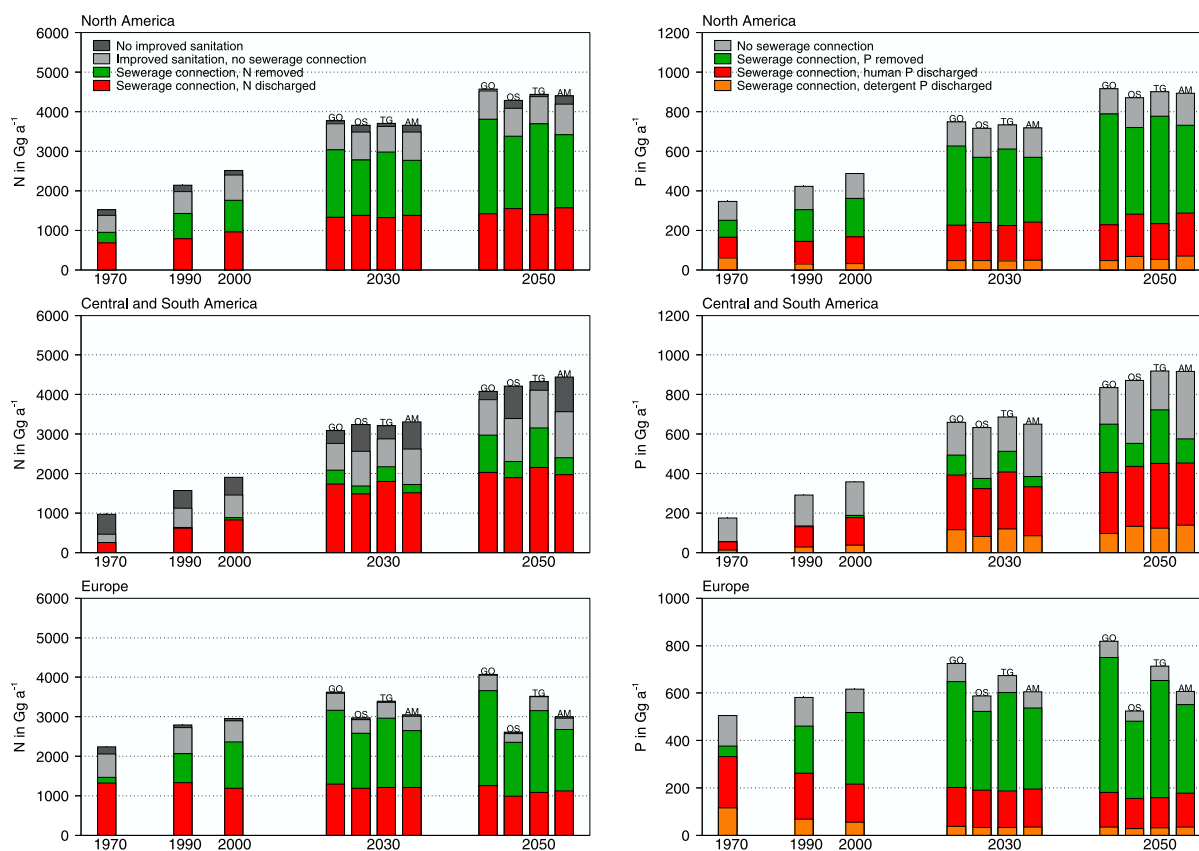


Figure 7. Trends in (left) human N and (right) P emission by type of sanitation, sewage, and N removal for 1970, 1990, and 2000 and for 2030 and 2050 for the four MEA scenarios (from left to right: GO, OS, TG, and AM) for world regions. Units, Gg a^{-1} . Please note that the scale of the y axes is different. See Figure 1 for a scheme indicating the calculation procedure and Figure 6 and Table 4 for the definition of regions.

scenarios. Annual P discharge to surface water is predicted to decrease in TG by 7% to 16 Gg a^{-1} for 2000–2050, while other scenarios show a slight increase for 2000–2030 and stabilization for 2030–2050.

3.2.3. Europe

[36] In Europe the per capita GDP increased from 10,000 to 20,810 U.S. dollars and population increased from 466 to 519 million inhabitants (+11%) between 1970 and 2000, which is a slower growth than in North America and Oceania (Table 4). Human N (increasing from 4.8 to $5.7 \text{ kg person}^{-1} \text{ a}^{-1}$ in the period 1970–2000), human P emissions (increasing from 0.8 to $1.0 \text{ kg person}^{-1} \text{ a}^{-1}$), and detergent P emissions (decreasing from 0.3 to $0.2 \text{ kg person}^{-1} \text{ a}^{-1}$, with a peak in the 1980s) are comparable to those in the North America (Figure S2). In 1970 about 64% of the population was connected to sewage systems, increasing to 79% in 2000. In the same period the N removal increased from 10 to 50%, and P removal increased from 11 to 59% (Figure S2). The sum of all these changes was a slight decrease of the N discharge to surface water (after treatment) from 1326 to 1192 Gg a^{-1} (Figure 7). P discharge to surface water decreased from 333 to 216 Gg a^{-1} . Hence, despite the enormous investments in the construction of sewage systems and wastewater treatment facilities,

the N flow from households to surface waters is reduced only slightly. With higher P removal rates the flows of P are reduced more effectively.

[37] The future population change in Europe also differs from that in North America and Oceania. GO shows a slow growth by 4% to 541 million inhabitants for 2000–2050, while in the other scenarios a decrease is foreseen, most strongly in OS (–17% for 2000–2050). In contrast to population, economic growth is comparable to that in North America and Oceania. However, income levels will be lower than in North America and comparable to those in Oceania. As a result, human N and P and detergent emissions are smaller than in North America and slightly smaller than in Oceania. Close to 90% of the population will be connected to public sewage systems in 2050, while nutrient removal fractions rise to almost 60% for N and 68–76% for P (Figure S2). In all scenarios we see constant N discharge to surface water between 2000 and 2030, and over the period 2000–2050 we see an increase of 5% in GO and a decrease by –17% to 988 Gg N a^{-1} in OS, –9% to 1088 Gg a^{-1} in TG, and –6% to 1121 Gg a^{-1} in AM (Figure 7). P discharge will decrease by 27–28% from 216 to 155 – 159 Gg P a^{-1} in OS and TG for 2000–2050, and the other scenarios show a 16–18% decline.

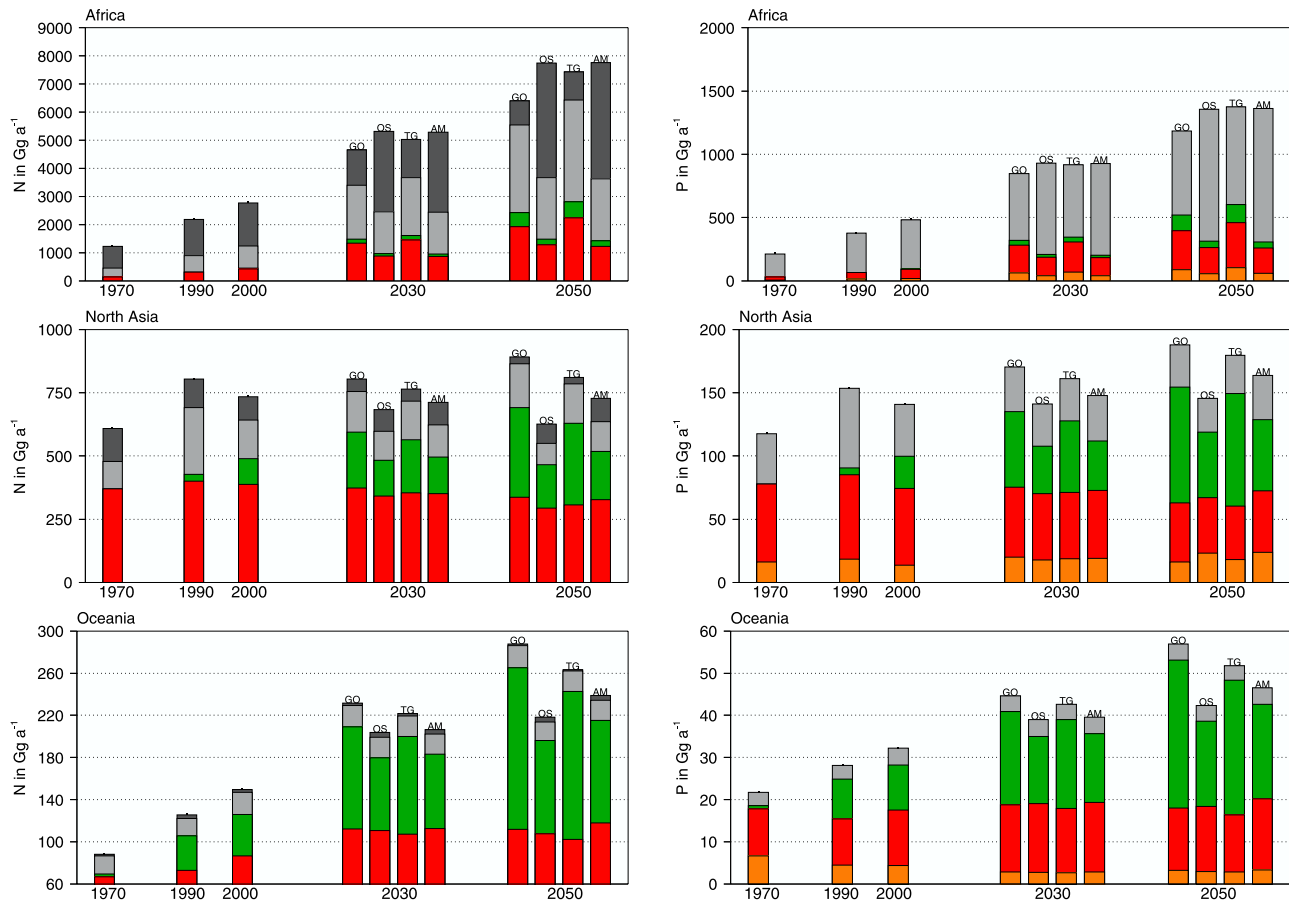


Figure 7. (continued)

3.2.4. North Asia

[38] Historic and projected patterns of sewage N and P emission in North Asia are similar to those estimated to occur in Europe, but the forcing mechanisms are somewhat different. The population in North Asia (Russian Federation, Armenia, Azerbaijan, and Georgia) increased by 13% from 143 to 162 million inhabitants, while GDP increased by 58%, with a peak around 1990 and a sharp decline in the early 1990s (Table 4). Human N and P emissions increased slightly (6%), and detergent P emissions were constant at a low value of $0.1 \text{ kg person}^{-1} \text{ a}^{-1}$ (Figure S2). The population with a sewage connection increased from 61 to 66%, while N and P removal increased from 0% in 1970 to 21% for N and 26% for P in 2000. These values are much lower than for other industrialized countries. The net result of all these changes was a slight increase of N discharge to surface water of 4% and a slight decrease in P (Figure 7).

[39] Population is projected to decline in all MEA scenarios, by up to 14% in OS over the period 2000–2050. From the per capita GDP of 2,700 U.S. dollars in 2000 (compared to 24,000 U.S. dollars in North America) there will be a rapid increase to 9,171 and 23,002 U.S. dollars in 2030 and 2050, respectively, in GO. Eastern Asia and North Asia are projected to reach about the same income level by 2050. TG has a slower growth (to 18,075 U.S. dollars in 2050), and much slower in OS and AM. As a result, the human N

emissions are estimated to increase from $4.5 \text{ kg person}^{-1} \text{ a}^{-1}$ in 2000 to 5.2 in 2030 and 6.1 in 2050 in GO and fall to lower values of 5.0 – $5.7 \text{ kg person}^{-1} \text{ a}^{-1}$ in the other scenarios. Human P emissions show a similar development, with values of $1 \text{ kg person}^{-1} \text{ a}^{-1}$ in GO in 2050 (24% less than in North America). Detergent P emissions will increase to levels of 0.27 – $0.33 \text{ kg person}^{-1} \text{ a}^{-1}$, which is comparable to or higher than those in North America. Sewage connection will increase from 66% of the population in 2000 to 77% in 2050 in GO and TG and in the other scenarios to 71–74%. Projected N and P removal rates are lower than in Europe or North America, with highest values for 2050 of 51% for N and 60% for P in GO and TG (Figure S2). Declining population and technological progress will cause a decline in N discharge from 387 Gg a^{-1} in 2000 of 21–24% in OS and TG for 2050, respectively, and a decrease by 13–15% in GO and AM (Figure 7). GO and TG show considerable reduction of P discharge (from current 74 Gg P a^{-1} by -16 to -19% in 2050).

3.2.5. South Asia

[40] In South Asia, changes have been exceedingly rapid in recent decades, and future changes are projected to be similarly striking. Population increased from about 2200 to 3750 million persons between 1970 and 2000, while GDP_{mer} increased by more than 100%, from about 1300 to 2700 U.S. dollars (Table 4). South Asia finds itself in the

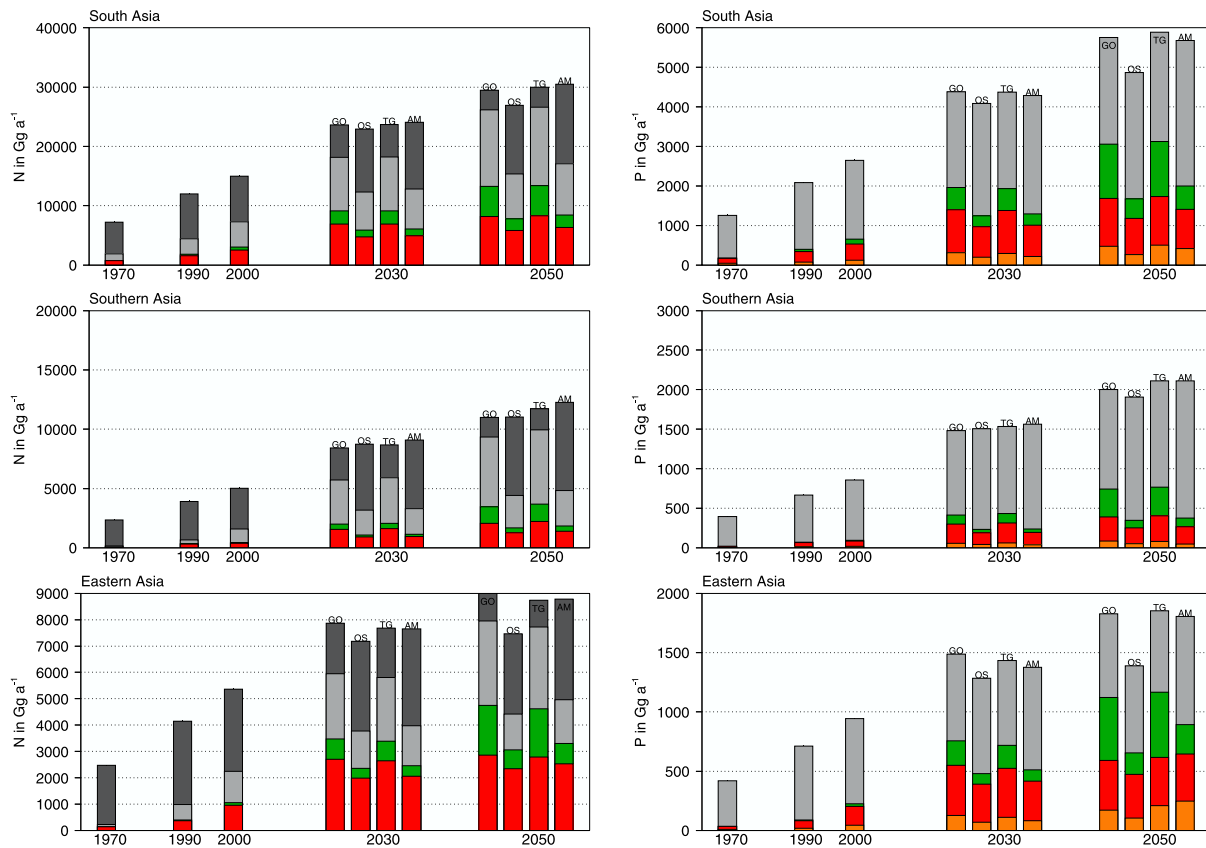


Figure 7. (continued)

low-income region of Figure 2, and in this part of the curve this income growth yields a fast increase in human N and P production by 22%. However, the values for South Asia are still lower than those found in industrialized countries. Detergent use is low throughout the period 1970–2000. The population with a sewage connection increased from 9 to 18%, and nutrient removal from sewage water increased from 3% for N and P in 1970 to 16% for N and 18% for P in 2000. The resulting changes in N and P discharge were fast (+247% from 731 to 2539 Gg a⁻¹ for N and +211% from 172 to 535 Gg a⁻¹ for P) (Figure 7).

[41] Future population growth in South Asia is strongest in OS and AM, with an increase from 3750 million persons in 2000 by 40% between 2000 and 2030 and another 10% for 2030–2050. In GO, population growth is 25% for 2000–2030 and a further 3% for 2030–2050, and in TG this is 32% and 6%, respectively, for 2000–2030 and 2030–2050. In GO the per capita GDP will grow rapidly by 239% for 2000–2030 and a further 151% for 2030–2050; the other scenarios have a slower growth. Human N emissions will increase from 4 kg person⁻¹ a⁻¹ in 2000 to 6.1 kg a⁻¹ in 2050 (equal to the North American level in 2000) in GO, 5.7 kg N person⁻¹ a⁻¹ in TG, and somewhat less in OS and AM. Human P emissions will grow to the North American level of 1 kg person⁻¹ a⁻¹ in GO in 2050 and lower values in the other scenarios. Detergent P emission grows from 0.04 kg person⁻¹ a⁻¹ in 2000 to a

level of 0.17 kg person⁻¹ a⁻¹ in GO for 2050 (comparable to the North American level in 2000). Sewage connection increases from 18% in 2000 to 43–44% in GO and TG in 2050, and 26–27% in OS and AM. N and P removal rates grow from current 16–18% to 38% for N and 45% for P in GO and TG for 2050 and to 25% for N and 30% for P in OS and AM. Despite the fast development of wastewater treatment installations, the dramatic population growth, economic progress, and increasing access to sewage systems cause rapid increases in N and P discharge. Between 2000 and 2050, GO and TG show an increase in discharge from 2,539 to ~8,200 Gg of N a⁻¹ (>200% increase), while in OS and AM the increase is 130–150%. Discharge of P shows similar increases for 2000–2050, from 535 Gg P a⁻¹ to about 1700 Gg P a⁻¹ in GO and TG and 1200–1400 Gg P a⁻¹ in OS and AM.

3.2.6. Africa

[42] Population growth in Africa was close to 120% between 1970 and 2000, while because of lack of strong income growth (from 695 to 746 U.S. dollars) the per capita human N and P emissions as well as the detergent P emission did not increase strongly (Table 4). At the same time there has been an increase in the number of Africans with a sewage connection (from 10 to 14% of total population), while the N and P removal in wastewater treatment increased from almost zero to only 5% (mixture of no treatment and mechanical treatment) (Figure S2). The

discharge of N and P therefore increased almost entirely as a result of population growth and sewage connection, N effluent increasing from 139 to 428 Gg a⁻¹, and P effluent increasing from 30 to 91 Gg a⁻¹ (Figure 7).

[43] Population is projected to grow from almost 800 to close to 2000 million inhabitants between 2000 and 2050 in OS and AM and to 1400 million in GO and 1700 million in TG). Economic growth is fast in the 2030–2050 period, with an increase of 131–139% for GO and TG, compared to growth by 54–68% in 2000–2030. OS and AM have slower growth. Human N and P emissions will be lower than the European level for 1970 in all scenarios, and detergent P emissions also remain at low levels. Sewage connection grows to 36% in GO and TG in 2050 and only 16–17% in OS and AM. Similarly, the removal rates will reach 20% for N and 24% for P in GO and TG and 14% for N and 16–17% for P in OS and AM (Figure S2). In all MEA scenarios for Africa, income levels and N and P emissions remain low, and the population with a sewage connection grows only slowly. However, because of the fast population growth between 2000 and 2050, the N discharge to surface water grows by up to 425% in TG in 2050 (from 428 to 2247 Gg N a⁻¹ between 2000 and 2050), and P discharge grows by 408% (from 91 to 460 Gg P a⁻¹) (Figure 7).

3.2.7. Central and South America

[44] The changes between 1970 and 2000 in Central and South America are different from those in Africa, with less population growth (+80%) and more GDP growth (+50%) (Table 4). Human N and P (+8%) and detergent P emissions (+30%) increased faster than in Africa. The population connected to sewage systems grew from 25% (compared to 10% in Africa) in 1970 to 46% in 2000 (compared to 14% in Africa). Wastewater treatment did not change rapidly (from zero in 1970 to 7% for both N and P in 2000) (Figure S2). As a result, the N and P discharge increased by close to 220% (from 254 to 827 Gg a⁻¹ for N and from 55 to 177 Gg a⁻¹ for P).

[45] Population growth is 52% and 18–19% for 2000–2030 and 2030–2050, respectively, in OS and AM (from 421 to 750–760 million persons in 2050), while in GO (+40%) and TG (+60%) the growth over the 2000–2050 period is less. Projected economic growth is 155% for 2000–2030 and 129% for 2030–2050 in GO, and for TG (117% and 118%), OS (67% and 52%), and AM (87% and 79%), growth for these periods is less rapid. Human emissions will grow from 4.5 kg N and 0.8 kg P person⁻¹ a⁻¹ to values comparable to those in Europe and North America for the 1970–2000 period in OS and AM, while in GO and TG growth is more rapid, reaching values of 6.4–6.8 kg N and 1.1 kg P person⁻¹ a⁻¹. Future detergent P emissions are comparable to those in North America for the same scenarios and years. Sewage connection will reach values of 73% in GO and TG for 2050 (close to the situation in North America in 2000) and in AM and OS somewhat less (54%). Nutrient removal in wastewater treatment will increase from 7% in 2000 to 32% for N and 38% for P in GO and TG in 2050 and 18% for N and 21% for P in OS and AM (Figure S2). N discharge will increase by 145–160% in GO (to 2029 Gg a⁻¹) and TG (to 2155 Gg a⁻¹) and 130–

140% in OS and AM during the period 2000–2050. P discharge will also grow dramatically (+130% in GO, +147% in OS, +155% in TG, and +157% in AM).

4. Conclusions

[46] To our knowledge, this analysis constitutes the first spatially explicit global assessment of sewage N and P emissions to surface water and the first projection of such N and P emissions for the future. We estimate that major increases in sewage N and P inputs to surface waters occurred between 1970 and 2000, globally and in all world regions discussed, except for North Asia, Europe, and Oceania. With the expected population growth in developing countries in the coming decades, sewage N and P discharge to surface water is expected to increase substantially between 2000 and 2050, especially in southern Asia, where increases of up to a factor of 4–5 are predicted for N and P, respectively. This is a combined effect of increasing numbers of people, urbanization, and enhanced sewerage connectivity. Even in optimistic scenarios for the development of wastewater treatment systems, the N and P effluents will not decline. In North America (with high levels of N and P removal), rapid population and economic growth may also lead to rapidly increasing sewage N and P discharge to surface water.

[47] Although this conclusion is robust across the scenarios, there are uncertainties in many of the model parts. The main uncertainties concern industrial emissions, which are not explicitly included in our approach for human emissions, and the fate of emissions from rural populations. Data suggest that in many countries with large numbers of people lacking a connection to sewerage systems, human excreta may be discharged directly to surface water. However, data are lacking to develop a consistent approach for all countries. However, ignoring sewage N and P emissions from rural and urban populations and from urban populations without sewerage connection may not be unrealistic in many countries where there is extensive recycling of human N and P. For example, using faecal sludge and urine collected in pit latrines and septic tanks as fertilizer is common in China [FAO, 1977] and in many countries in southeast Asia, Africa, and South America [Quynh et al., 2005; Strauss, 2000]. In the AM scenario this part of human N and P is assumed to be recycled in crop production systems (see A. F. Bouwman et al., Human alteration of the global nitrogen and phosphorous soil balances for the period 1970–1950, submitted to *Global Biogeochemical Cycles*, 2009). If the concept of ecological sanitation and recycling of human N and P [Langergraber and Muelleggera, 2005; Robinson, 2005] will also become important in urban areas, this may reduce our estimates of N and P in urban wastewater.

[48] A further major uncertainty concerns the data on the use of P-based and P-free detergents in laundry machines and dishwashers. The availability of such data would greatly enhance future efforts to estimate patterns, magnitudes, and trends in sewage N and P emission to surface waters. Nonetheless, our analysis clearly indicates that sewage N and P have increased significantly in recent years

and are likely to continue to do so over the next several decades.

[49] Our results will be used together with the developments for the diffuse (nonpoint) sources of nutrients (agricultural and natural ecosystems) (A. F. Bouwman et al., submitted manuscript, 2009) as input for the various Global NEWS model analyses presented in this issue. The full data set will be made available on the Web site of the Netherlands Environmental Assessment Agency (PBL) (<http://www.pbl.nl>).

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