

The carbon-sequestration potential of municipal wastewater treatment

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Received 20 February 2007; received in revised form 17 August 2007; accepted 22 August 2007

Available online 17 October 2007

Abstract

The lack of proper wastewater treatment results in production of CO₂ and CH₄ without the opportunity for carbon sequestration and energy recovery, with deleterious effects for global warming. Without extending wastewater treatment to all urban areas worldwide, CO₂ and CH₄ emissions associated with wastewater discharges could reach the equivalent of 1.91×10^5 tCO₂ d⁻¹ in 2025, with even more dramatic impact in the short-term. The carbon sequestration benefits of wastewater treatment have enormous potential, which adds an energy conservation incentive to upgrading existing facilities to complete wastewater treatment. The potential greenhouse gases discharges which can be converted to a net equivalent CO₂ credit can be as large as 1.21×10^4 tCO₂ d⁻¹ by 2025. Biomass sequestration and biogas conversion energy recovery are the two main strategies for carbon sequestration and emission offset, respectively. The greatest potential for improvement is outside Europe and North America, which have largely completed treatment plant construction. Europe and North America can partially offset their CO₂ emissions and receive benefits through the carbon emission trading system, as established by the Kyoto protocol, by extending existing technologies or subsidizing wastewater treatment plant construction in urban areas lacking treatment.

This strategy can help mitigate global warming, in addition to providing a sustainable solution for extending the health, environmental, and humanitarian benefits of proper sanitation.

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Keywords: Biogas; Carbon sequestration; Energy recovery; Global warming; Greenhouse gases; Wastewater

1. Introduction

Global warming is an alarming phenomenon that was recognized as early as 1975 by measuring increasing temperature trends over the past two millennia (Broecker, 1975; Mann and Jones, 2003; Mann et al., 2003). Numerous sources are reporting impacts of global warming such as increasing instances of atmospheric instabilities (e.g.: Tett et al., 1999), which are creating major concerns on an international level. Nevertheless, sceptic comments regarding future projections of global warming effects exist outside the scientific community (Lomborg, 2001). The reason for the accelerated increase of global temperature in the past 60 years has been attributed largely to anthropogenic greenhouse gas (GHG) emissions (Tett et al., 1999).

The Kyoto protocol sets an emission limit for the six GHG with highest global warming potential. Their emission rates are to be reduced by at least 6% by 2008 as compared to 1990. Thus, the protocol establishes a trading system for carbon emission credits, with a current market value for CO₂ emissions in the range of USD 15–25 t⁻¹ (Greenfield and Batstone, 2005). One of the carbon emission sources derives from the lack of wastewater treatment, which is equivalent to the discharge of the carbon contaminating the wastewater in the environment.

In the year 2000, 2.8 billion people lived in urban areas worldwide, and 400 million (14%) did not have access to “improved” sanitation (WHO/UNICEF, 2000), which is defined as a system where “excreta are disposed of in such a way that they reduce the risk of fecal-oral transmission to its users and the environment” (UNDP, 2005). Improved sanitation may imply only conveyance systems (e.g., sewers) and not wastewater treatment. In order to distinguish

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between those served locations that have or do not have wastewater treatment, we introduce the term “sewered” to mean those areas which have collections to segregate wastewaters to reduce human exposure and “fully treated” for those areas with collection systems and secondary treatment plants. Using these two definitions an approximation can be made to estimate sewered and fully treated areas, which is needed because the available census documents only the presence of sewers. During our careers we have visited numerous urban areas worldwide where “improved” sanitation corresponded to full wastewater treatment and, with some exceptions, they were all located in Europe, North America, and Japan. In our calculation Japan is grouped within Asia, i.e. without proper treatment, in spite of their well developed treatment plants. This does not bias the final result since there exist urban areas in the world outside Europe and North America where full biological wastewater treatment is practiced (e.g., Singapore), but are not as large as Japan’s population. One of the United Nations Millennium Development Goals is to increase the level of sanitation by 2015 so that only 8% of the worldwide population is without access to improved sanitation. This task is challenging if we consider that world urban population in 2015 is projected to be 3.8 billion, 1 billion more than in 2000 (WHO/UNICEF, 2000).

Proper treatment sequesters carbon as inert biomass, recovers biogas energy which can defray treatment costs, and avoids uncontrolled carbon discharge, thus reducing carbon released to the atmosphere (Cakir and Stenstrom, 2005; Monteith et al., 2005). Biomass disposal in confined landfills creates a net carbon sink, with little opportunity to return to the atmosphere in any foreseeable time-span because the biomass is largely devoid of methane forming potential due to prior digestion in the treatment plant (Pohland and Al-Yousfi, 1994). Biogas energy recovery is a renewable and economically viable substitute for energy production which could otherwise be met through fossil fuels. Due to the presence of inert CO₂, biogas has lower combustion temperatures which reduce the generation of NO_x, which is also an advantage. Furthermore, inert gases retain the heat of combustion in the form of sensible heat, which can be recovered in heat exchangers.

The contaminants present in domestic wastewater in urban areas arise not only from human faecal material, but also from synthetic sources (30–50%) such as chemicals from petrochemical industries and therefore they cannot be considered a renewable source of carbon (Gray, 2004). These contaminants are in the form of detergents and surfactants and oil and grease, which are introduced not only as personal care products and household detergents, but also from industries that discharge pre-treated wastewaters to municipal treatment systems. For example, in the City of Los Angeles, only one industry (a petroleum oil refinery) discharges through its own treatment plant and permit. All other industries, which include several other refineries and chemical industries, pretreat and discharge to publicly owned treatment plants. This is common practice in other

US cities and large metropolitan areas, worldwide. In countries where food waste is disposed through sewers (as in the United States, for example) the percentage of non-renewable carbon in the wastewater maybe lower, but outside those regions there may be variation. Furthermore, cultural and economic needs in underdeveloped areas may encourage reuse of food considered waste in developed countries. In this paper, we do not quantify the origin of wastewater contaminants, but show the potential benefits of sequestration of the carbon present in wastewater independently from its origin.

In this paper, we show the benefits for global warming mitigation associated with proper wastewater treatment. The driving force that traditionally has promoted wastewater treatment is the removal of: carbon-, nitrogen-, and phosphorous-contaminants; bacteria and viruses; anthropogenic and endocrine disruptive compounds. Additional advantages are biomass stabilization/segregation, and biogas energy recovery. These last two play a crucial role as global warming mitigation factors. We show how these advantages can be quantified and we propose a strategy for developed countries to partially offset their carbon emissions. For the purpose of this paper, we quantified only energy and mass fluxes concerning treatment operations, as the treatment plant construction is too site specific to be generally quantified. Finally, we ignore the notion that carbon from biogenic sources is sustainable and does not contribute to the greenhouse effect. The sequestration of carbon from sustainable sources may reduce the rate of warming and partially avoid the positive feedback mechanisms that may trigger large temperature increases. Even if carbon sequestration only lasts for 50 years, the reduction is still valuable because of its retardation on the emission cycle.

2. Methods

To quantify the equivalent CO₂ emissions of wastewater treatment in large urban areas, we gathered data on urban population with access to improved sanitation for each continent (WHO/UNICEF, 2000). Table 1 shows data from 1990 and 2000, and projected data for 2015 and 2025. The projected data show a targeted increase of urban population with access to improved sanitation from 86% to 92% and 100%, respectively. The difference in percentages may appear small, but we must observe that between 2000 and 2025 the world urban population may increase by 60% (from 2442 million in 2000 to 4536 million in 2025; WHO/UNICEF, 2000).

Using the WHO/UNICEF datasets, we calculated energy and mass fluxes for wastewater treatment with biological nutrient removal (BNR). Fig. 1 shows a layout of the process, which is the activated sludge layout with lowest specific energy consumption (Rosso and Stenstrom, 2005). We assumed in order: headworks, primary clarifiers, modified Ludzack-Ettinger biological treatment, secondary clarifiers; anaerobic treatment of the sludge. Small fluxes of

Table 1
Summary of Actual and potential energy and mass emissions and offsets (1990–2025)

	Year	Urban wastewater		CO ₂ production		CH ₄ production		Biomass production		CH ₄ energy recovery		Gross CO ₂ emissions (10 ³ t d ⁻¹)	Total CO ₂ offsets (10 ³ t d ⁻¹)	Net CO ₂ emissions (10 ³ t d ⁻¹)
		Sewered (10 ⁶ m ³ d ⁻¹)	Unsewered (10 ⁶ m ³ d ⁻¹)	Sewered (10 ³ t d ⁻¹)	Unsewered (10 ³ t d ⁻¹)	Sewered (10 ³ t d ⁻¹)	Unsewered (10 ³ t d ⁻¹)	Sewered (10 ³ tvss d ⁻¹)	Unsewered (10 ³ tvss d ⁻¹)	Sewered (TJ d ⁻¹)	Unsewered (TJ d ⁻¹)			
Africa	1990	16.7	2.95	1.65	0.29	0.20	0.04	1.16	0.20	5.29	0.93	3.03	−2.63	0.40
	2000	25.1	4.43	2.48	0.44	0.30	0.05	1.74	0.31	7.95	1.40	4.55	−3.96	0.59
	2015 [‡]	46.2	4.02	4.57	0.40	0.56	0.05	3.20	0.28	14.6	1.27	7.22	−7.28	−0.06
	2025 [‡]	67.3	0	6.65	0	0.81	0	4.66	0	21.3	0	8.89	−10.6	−1.71
Asia	1990	138	68.0	9.52	4.69	1.11	0.55	6.35	3.13	29.0	14.3	25.1	−14.4	10.7
	2000	211	59.5	14.6	4.10	1.70	0.48	9.71	2.74	44.4	12.5	30.2	−22.1	8.14
	2015 [‡]	346	42.8	23.9	2.95	2.78	0.34	15.9	1.97	72.7	8.99	39.4	−36.2	3.21
	2025 [‡]	477	0	32.9	0	3.84	0	22.0	0	100	0	43.5	−50.0	−6.48
Latin America and Caribbean	1990	40.1	7.07	2.76	0.49	0.32	0.06	1.84	0.33	8.42	1.49	4.95	−4.19	0.76
	2000	51.0	7.62	3.52	0.53	0.41	0.06	2.35	0.35	10.7	1.60	6.05	−5.34	0.72
	2015 [‡]	70.7	5.32	4.87	0.37	0.57	0.04	3.25	0.24	14.9	1.12	7.42	−7.39	0.02
	2025 [‡]	85.8	0	5.92	0	0.69	0	3.95	0	18.0	0	7.81	−8.98	−1.16
Oceania	1990	2.70	0.03	0.146	0.001	0.02	0	0.09	0.00	0.42	0.004	0.19	−0.21	−0.02
	2000	3.15	0.03	0.170	0.002	0.02	0	0.11	0.00	0.49	0.005	0.23	−0.25	−0.02
	2015 [‡]	3.83	0.04	0.207	0.002	0.02	0	0.13	0.00	0.60	0.006	0.28	−0.30	−0.02
	2025 [‡]	4.50	0	0.243	0	0.03	0	0.15	0	0.71	0	0.32	−0.35	−0.03
Europe	1990	131	0	7.05	0	0.78	0	4.48	0.00	20.5	0	9.20	−10.2	−1.00
	2000	134	2.74	7.25	0.15	0.81	0	4.61	0.09	21.1	0.43	9.85	−10.5	−0.65
	2015 [‡]	140	1.42	7.58	0.08	0.84	0	4.82	0.05	22.0	0.22	10.1	−11.0	−0.87
	2025 [‡]	143	0	7.71	0	0.86	0	4.90	0	22.4	0	10.1	−11.2	−1.09
North America	1990	85.2	0	5.88	0	0.68	0	3.92	0	17.9	0	7.76	−8.92	−1.16
	2000	95.6	0	6.59	0	0.77	0	4.40	0	20.1	0	8.71	−10.0	−1.30
	2015 [‡]	111	0	7.67	0	0.89	0	5.11	0	23.4	0	10.1	−11.6	−1.51
	2025 [‡]	121	0	8.36	0	0.97	0	5.57	0	25.5	0	11.0	−12.7	−1.65
Global	1990	413	78.0	27.0	5.47	3.12	0.64	17.8	3.66	81.5	16.7	50.3	−40.6	9.68
	2000	520	74.3	34.6	5.22	4.00	0.61	22.9	3.49	105	16.0	59.6	−52.1	7.49
	2015 [‡]	718	53.6	48.8	3.79	5.67	0.44	32.4	2.54	148	11.6	74.5	−73.8	0.77
	2025 [‡]	899	0	61.8	0	7.20	0	41.2	0	188	0	81.6	−93.7	−12.1

Assumptions: MCRT = 15 d; nitrification/denitrification; influent N-NH₄ = 20 mg l⁻¹; SRT_{dig} = 30 d; biogas = 65% CH₄ + 35% CO₂; biogas energy content = 38.5 kJ m⁻³; digestion yield = 0.75 m³_{biogas} kg⁻¹_{vss}; biomass destruction rate = 50%. Key: MCRT, mean cell retention time; SRT_{dig}, sludge retention time in digester; VSS, volatile suspended solids; ‡ = estimate. Regional assumptions: Africa (100 l p⁻¹ d⁻¹, 300 mg_{BOD} l⁻¹); Asia (200 l p⁻¹ d⁻¹, 200 mg_{BOD} l⁻¹); Latin America and Caribbean (150 l p⁻¹ d⁻¹, 200 mg_{BOD} l⁻¹); Oceania (150 l p⁻¹ d⁻¹, 150 mg_{BOD} l⁻¹); Europe (250 l p⁻¹ d⁻¹, 150 mg_{BOD} l⁻¹); North America (400 l p⁻¹ d⁻¹, 200 mg_{BOD} l⁻¹).

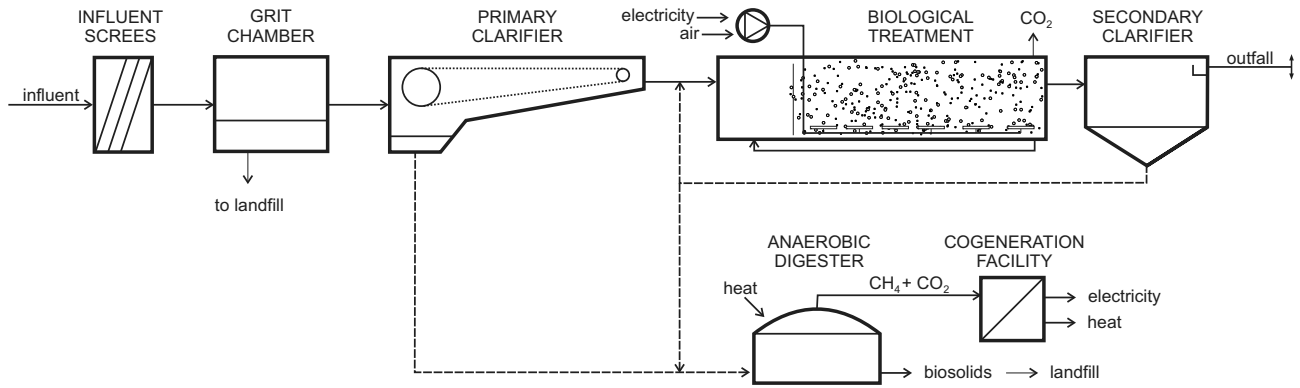
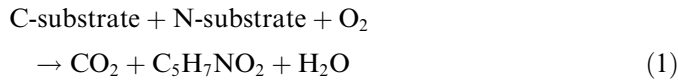


Fig. 1. Layout of a typical municipal wastewater treatment plant. This was used as basis for our calculations for mass and energy fluxes.

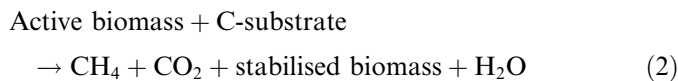
energy and GHG exist for head works and clarifiers, but are negligible (Reardon, 1995; Monteith et al., 2005). Our calculations are divided into equivalent CO₂ emissions and offsets. The net effect is the sum of the two. Also, we assume no N₂O production.

2.1. Calculation of equivalent carbon dioxide emissions

Carbon- and nitrogen-substrate oxidation is described by:



Eq. (1) shows that the elimination of C-substrate yields to production of CO₂ and partial segregation of carbon as biomass (C₅H₇NO₂; Metcalf and Eddy, 2003). This is the first global warming mitigation benefit offered by wastewater treatment. Biomass digestion produces CH₄ and stabilised biomass following the reaction:



Typically, the biogas (CH₄ + CO₂) is either flared or refined for further utilization in power generation units. The stabilised biomass can be sent to landfills, if available, land application, or incinerated. Eq. (2) shows the other global warming mitigation benefit associated with wastewater treatment: the energy recovered by burning the biogas. The mitigation benefit goes beyond CH₄ energy recovery, as the energy production eliminates discharge of CH₄, which has a severely worse effect on global warming than CO₂ (IPCC, 2001). Methane production, in theory, is just an intermediate step before final discharge of CO₂ to the atmosphere. If the combustion



is performed in a power generation unit, the equivalent CO₂ emissions w_{biogas} are:

$$w_{\text{biogas}}^{\text{comb}} = \frac{2.75 \text{ kg}_{\text{CO}_2}}{\text{kg}_{\text{CH}_4}} \quad (4)$$

We calculated the energy recovery associated with the increase in urban population served by improved sanitation in 2015 and 2025. This spreadsheet contains detailed forms of Eqs. (1) and (2), and a detailed wastewater treatment plant design algorithm.

The equivalent CO₂ emission associated with biological aerobic treatment ($\dot{m}_{\text{CO}_2}^{\text{resp}}$) is the CO₂ production due to Eq. (1). The emissions of uncombusted CH₄ ($\dot{m}_{\text{CH}_4}^{\text{emitted}}$) and the CO₂ emitted ($\dot{m}_{\text{CO}_2}^{\text{comb}}$) after biogas energy recovery (Eq. (3)) have to be added to calculate the total equivalent CO₂ emissions ($\dot{m}_{\text{CO}_2}^{\text{emissions}}$). The sum of CO₂ emissions from the aerobic biological treatment ($\dot{m}_{\text{CO}_2}^{\text{resp}}$) and CO₂ emitted in the biogas combustion ($\dot{m}_{\text{CO}_2}^{\text{comb}}$) is defined as the gross CO₂ emissions ($\dot{m}_{\text{CO}_2}^{\text{gross}}$). Since the emitted CH₄ decays over time, a time-horizon must be assumed. Typically, the assumed time-horizon is 100 year, and in order to be consistent with the current literature, for the CH₄ fugitive emissions, we used a mass conversion factor (IPCC, 2001):

$$w_{\text{CH}_4}^{\text{emitted}} = \frac{23 \text{ kg}_{\text{CO}_2}}{1 \text{ kg}_{\text{CH}_4}} \quad (5)$$

Since the impact of methane on the total emissions is heavily dependent on this parameter, an analysis of different time-horizons is reported in the discussion.

The CO₂ total equivalent emissions are therefore:

$$\dot{m}_{\text{CO}_2}^{\text{emissions}} = \dot{m}_{\text{CO}_2}^{\text{gross}} + w_{\text{CH}_4}^{\text{emitted}} \dot{m}_{\text{CH}_4}^{\text{emitted}} + w_{\text{biogas}}^{\text{comb}} \dot{m}_{\text{CH}_4}^{\text{comb}} \quad (6)$$

2.2. Calculation of equivalent carbon dioxide offsets

The carbon segregation associated with biomass production can be quantified with the endogenous respiration equation (Metcalf and Eddy, 2003):



Eq. (7) concludes that for each mol of biomass (C₅H₇NO₂) reacting, 5 mol of CO₂ are segregated. In mass terms, the carbon sequestration potential associated with biomass production w_{biomass} is:

$$w_{\text{biomass}} = \frac{1.95 \text{ kg}_{\text{CO}_2}}{\text{kg}_{\text{biomass}}} \quad (8)$$

The total CO₂ offsets are the sum of the segregated biomass and of the equivalent CO₂ that would have been emitted if the biogas energy recovered were produced with fossil fuels ($\dot{m}_{\text{CO}_2}^{\text{energy offset}}$):

$$\begin{aligned}\dot{m}_{\text{CO}_2}^{\text{offsets}} &= w_{\text{biomass}} \dot{m}_{\text{biomass}} + \dot{m}_{\text{CO}_2}^{\text{energy offset}} \\ &= w_{\text{biomass}} \dot{m}_{\text{biomass}} + e_{\text{bg}} \frac{\eta_{\text{ff}}}{h_{\text{ff}}}\end{aligned}\quad (9)$$

where e_{bg} is the recovered biogas energy, η_{ff} is the efficiency of another power generation unit that produces the same energy as e_{bg} is the with fossil fuels and h_{ff} is the calorific value of the fossil fuel.

We assumed η_{ff} as 75% but its value is site specific and may vary (Sahely et al., 2006). We also assumed 50% losses in the value of the combusted gases in order to account for the upstream cleanup. This value is also site specific and is conservative, in our experience.

2.3. Calculation of net equivalent carbon dioxide emissions

The net, effective CO₂ production $\dot{m}_{\text{CO}_2}^{\text{net}}$ is then:

$$\dot{m}_{\text{CO}_2}^{\text{net}} = \dot{m}_{\text{CO}_2}^{\text{emissions}} - \dot{m}_{\text{CO}_2}^{\text{offsets}} \quad (10)$$

which, in this case, is

$$\begin{aligned}\dot{m}_{\text{CO}_2}^{\text{net}} &= \dot{m}_{\text{CO}_2}^{\text{gross}} + w_{\text{equiv}} \dot{m}_{\text{CH}_4}^{\text{emitted}} + w_{\text{biogas}}^{\text{comb}} \dot{m}_{\text{CH}_4}^{\text{comb}} \\ &\quad - w_{\text{biomass}} \dot{m}_{\text{biomass}} - \dot{m}_{\text{CO}_2}^{\text{energy offset}}\end{aligned}\quad (11)$$

Results calculated with Eq. (11) are reported in Table 1 and as scenarios in Fig. 2. All negative values are credits which are biomass segregation and methane energy recovery

(Eqs. (2) and (5)), and offset the CO₂ production by bacterial respiration and methane combustion (Eqs. (1) and (3)).

3. Results and discussion

Our results assume that all sewered areas perform secondary treatment with BNR, full energy recovery in a cogeneration facility and biomass sequestration. BNR will be valuable in urban areas where water quality may be impacted, but if the treated wastewaters can be reclaimed for agriculture, the analysis could be modified excluding nutrient removal. Table 1 shows the results of our calculations for sewered and unsewered areas.

Fig. 2 shows the worldwide emission/credit scenarios for levels of treatment outside Europe and North America ranging from 0% to 100%. If we consider the UN projected population growth and without any improvement of the current situation, the equivalent CO₂ daily discharge may reach 191 kt_{CO₂} d^{−1} in 2025. Note the extremely large difference between the 0% and 100% boundaries (worst and best scenarios, respectively). By 2025, the worldwide equivalent CO₂ flux could be −12.1 kt_{CO₂} d^{−1} (negative, hence a credit), mainly because Asia has the potential of doubling its own credit. The most likely current scenario is shown by the shaded area which, without improvement of the current situation, is very close to the worst scenario.

A detailed plot of the emissions outside Europe and North America, with the current situation, is plotted in Fig. 3. The boxes in this plot have 25% of wastewater treatment as upper boundary, and 0% as lower boundary. The disproportion between Asia and all other continents added together is large, and requires a non-linear scale for clarity

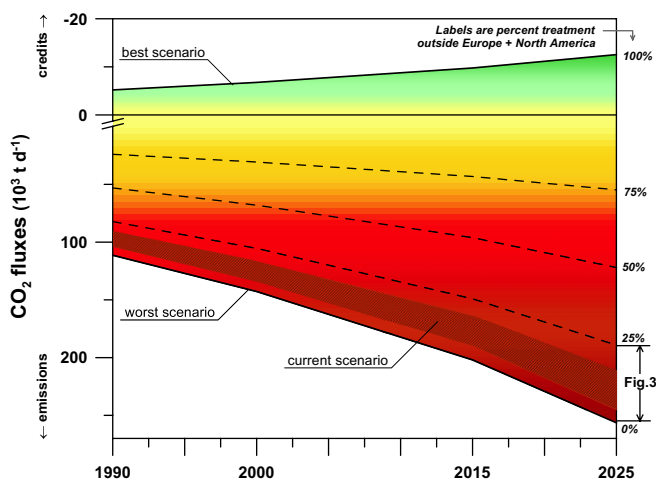


Fig. 2. Current and possible scenarios for CO₂ fluxes from urban wastewater treatment. On the vertical axis are CO₂ credits (−) and emissions (+). Labels (on the far right) show the percent treatment outside Europe + North America (where treatment is already 100%). The most likely current scenario is between 0% and 25% of treatment outside developed countries. The most optimistic projection is to approach the top of the graph (100%). Without any improvement of the current situation, the worldwide net CO₂ emissions due to lack of wastewater treatment may be between 150 and 191 kt_{CO₂} d^{−1} by 2025 (in detail in Fig. 3).

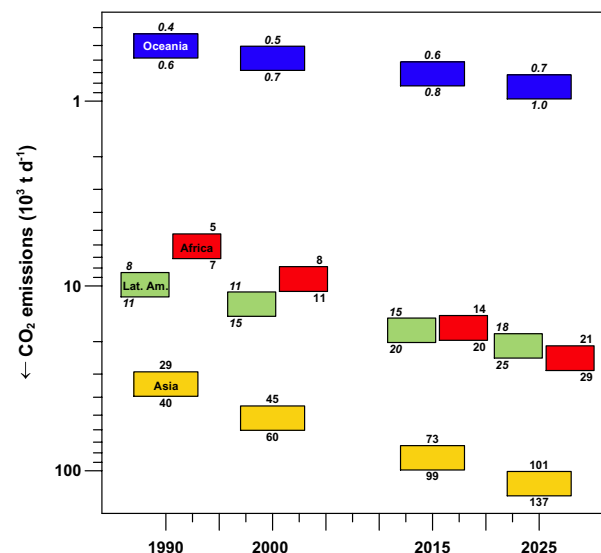


Fig. 3. CO₂ emissions from urban wastewaters outside Europe + North America: current scenario. The upper and lower boundaries of each box in the plot correspond to 25% and 0% treatment, respectively. This is the range containing the most likely current scenario which, with no improvement, is the most likely future scenario. Labels are emissions in equivalent kt_{CO₂} d^{−1}.

of graphing. If wastewater treatment is implemented in all urban areas of Asia alone, the worldwide balance would be in significant credit. If in the year 2000 all urban areas of Asia alone performed full biological wastewater treatment, the total CO₂ credits from wastewater treatment worldwide will approximately double.

Fig. 4 shows the biomass production and biogas recovery in equivalent ktCO₂ d⁻¹. In the period 1990–2025, Asia's production outnumbers the other continents combined, while tripling its absolute value. In each bar plot, the coloured area represents the biomass production, and the outlined area the biogas recovery. The shaded black areas represent the most likely current scenario for recovery in each continent, which for Europe and North America approaches completion. It is important to sequester the carbon in the biomass for this strategy to be successful. Approximately 3/4 of the carbon sequestration potential occurs because of biosolids sequestration and only 1/4 comes from energy production from biogas. Therefore, treatment strategies that do not sequester the carbon in the biosolids (i.e., land farming of the biosolids where they are degraded in 2–3 years, or biosolids incineration that requires additional fuel) will not result in a net GHG reduction. Biosolids disposal strategies that sequester the carbon for limited periods (20 years or more) may still be beneficial since they may delay return of carbon to the atmosphere, providing time for other GHG reduction strategies to become effective.

Fig. 5 shows the potential biogas energy recovery in 10¹² J d⁻¹. Due to the magnitude of its urban population growth, Asia has the highest energy recovery potentials, followed by Africa and Latin America. For each graph, the solid lines show the urban population with access to

improved sanitation (labels in million people). In each bar plot, the non-coloured area (top of the bar) corresponds to the energy that could be recovered if those urban areas were served by improved sanitation, but at the moment cannot benefit of any recovery. As the Millennium Development Goals indicate, the bar disappears in 2025, for all urban areas worldwide will be served by improved sanitation. The solid coloured areas in each bar plot represent the potential recovery that can already be achieved, if the full wastewater treatment and methane energy recovery were added to improved sanitation. The dark area in each bar plot is the most likely scenario without any improvement over the current situation, i.e. with full treatment and biogas energy fully recovered in Europe and North America, and almost no treatment and recovery elsewhere.

Wastewater treatment is and should be considered a global warming mitigation factor. Without proper treatment, the carbon in discharged wastewater will eventually enter the ecosystem as CH₄ (or CO₂), without the potentials for offset associated with biomass segregation and biogas energy recovery. We assume that all untreated wastewater is degraded anaerobically, yielding 50% CO₂ and 50% CH₄. Even in the event of no biomass segregation (e.g., where biomass is incinerated), the energy recovery associated with methane recovery is an advantageous benefit, which should always be considered when the methane production is significant. In our experience, in North America and Europe, methane is combusted in a power/steam generation facility when the plant is large (depending on site-specific conditions, with threshold sizes from 7500 to 110000 m³ d⁻¹) and is flared or used only for heat generation (i.e., anaerobic digester heating, building heating, etc.) when the plant is smaller. In both cases no methane is discharged to the

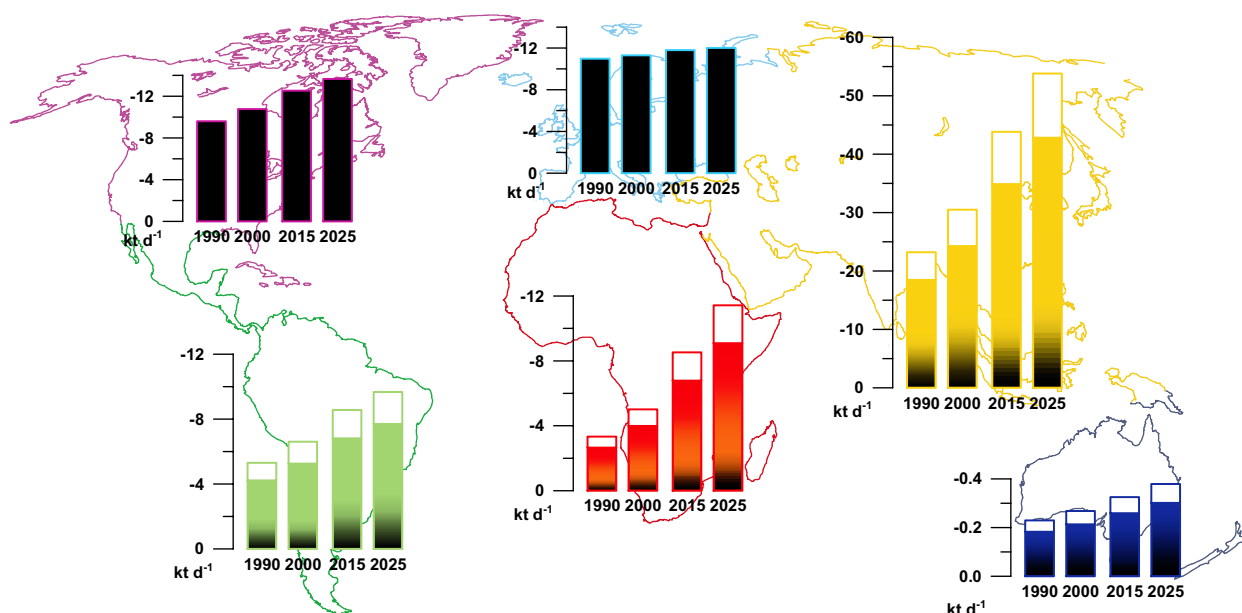


Fig. 4. Biomass production and biogas recovery in equivalent ktCO₂ d⁻¹. For each bar, the top outlined area is the carbon offset by biogas recovery; the solid coloured area is the carbon sequestered by biomass conversion; the black area is the amount of carbon most likely to be offset today.

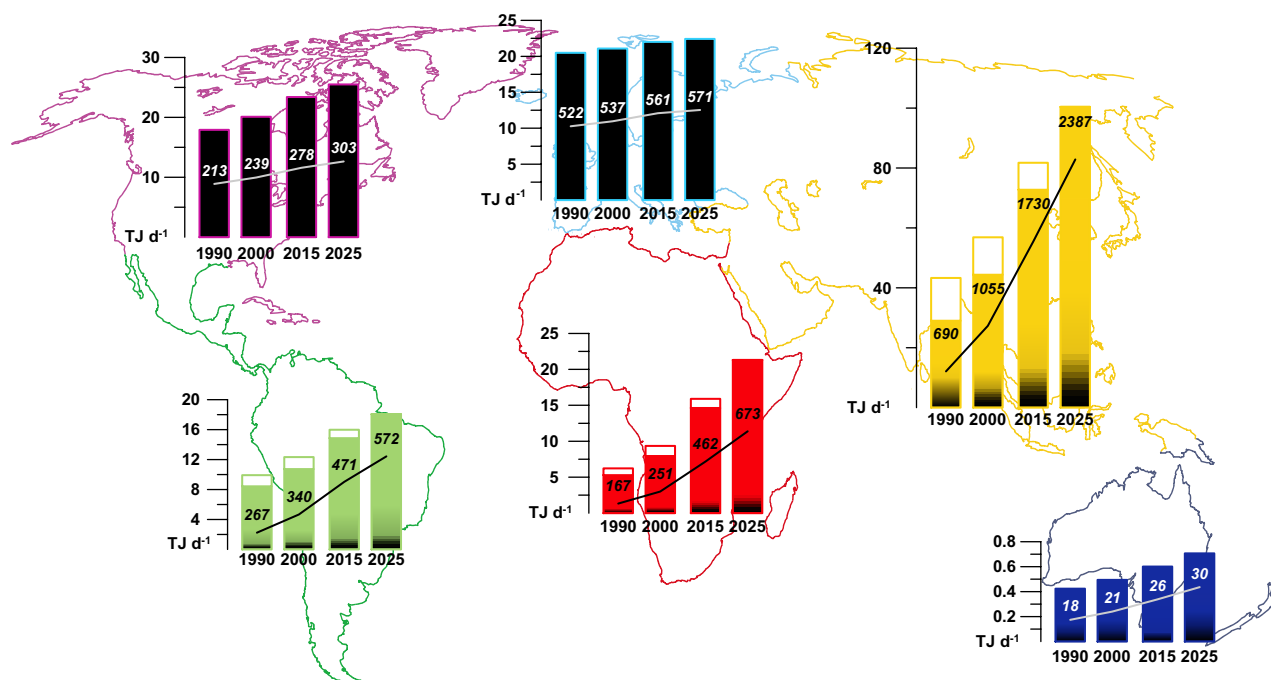


Fig. 5. Currently and potentially achievable biogas energy recovery in 10^{12} J d^{-1} . In each bar plot, the solid coloured areas represent the recovery that can already be achieved, if full wastewater treatment and methane energy recovery were added to improved sanitation. The dark area in each bar plot is the most likely scenario without any improvement over the current situation, i.e. full treatment and biogas energy fully recovered in Europe + North America, and almost no treatment/recovery elsewhere. Line plots are urban population served by improved sanitation (labels in million people).

atmosphere other than fugitive emissions or methane dissolved in liquid waste streams (thus reducing the greenhouse impact), with the additional advantage that larger wastewater treatment plants recover energy (with further reduction of greenhouse impacts). In any case, to reduce greenhouse impacts no methane should be discharged to the atmosphere.

The CH_4 weighing parameter ($w_{\text{CH}_4}^{\text{emitted}}$) has an important effect on the forecast of emission scenarios. In the current literature, the time-horizon of 100 years is typically adopted, corresponding to a value of 23 for $w_{\text{CH}_4}^{\text{emitted}}$ (IPCC, 2001). We calculated the net equivalent CO_2 emissions without improvement of the current situation with different values for $w_{\text{CH}_4}^{\text{emitted}}$ (Fig. 6). The results are dramatically different when choosing different time-horizons. The horizons chosen for this sensitivity analysis were 20 years, 100 years, and 500 years (with values for $w_{\text{CH}_4}^{\text{emitted}}$ of 62, 23, and $7 \text{ kg}_{\text{CO}_2} \text{ kg}_{\text{CH}_4}^{-1}$, respectively). Forecasting models for economic impact of mitigation measures used 20 or 30 years time-horizons (IPCC, 1999). In the short-term, i.e. when the mitigation is immediately needed, the effect of methane discharge is several times worse. It is important to distinguish between the time-span of methane release/recovery and biomass sequestration. Methane decays in the atmosphere in a scale of centuries, whilst biomass can be segregated immediately and perpetually or at least for lengthy periods of time. Therefore, the effective benefits of segregating biomass in the short-term are higher, and are more useful to curb the short-term effective CO_2 emissions

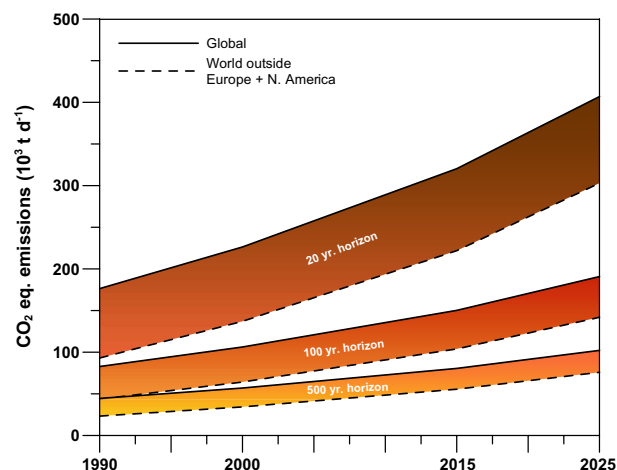


Fig. 6. Effect of the CH_4 global warming potential on the equivalent CO_2 emissions. When converting CH_4 to equivalent CO_2 emissions in a 20 years time span (most immediate effect) we observe the dramatic need for immediate measures. In the long term (500 years – horizon), CH_4 will decay and not have as a significant impact.

($407 \text{ kt}_{\text{CO}_2} \text{ d}^{-1}$ with 20 years horizon, vs. $191 \text{ kt}_{\text{CO}_2} \text{ d}^{-1}$ with 100 years horizon).

Presently the emphasis on green house gas emissions is concentrated on non-biogenic sources, and in this paper we show that there are significant opportunities to curb emissions from both non-biogenic and biogenic sources. This may become more important in the short term as

more is learned about positive feed-back mechanisms and the need to quickly reduce GHG emissions. The notion that only non-biogenic sources are important has been discussed in greater depth by Monteith et al. (2005), and they note that the IPCC's (2000) calculation methods are most appropriate on a large scale, such as national inventories, and in need of improvement for end-users wishing to make abatement decisions.

4. Strategy for carbon trading

We propose a strategy that developed countries could adopt to exchange carbon credits with countries without full wastewater treatment and/or energy recovery. The traditional driving force for the treatment in developed areas is public health and environmental preservation. All these benefits could be exported to developing countries, and can be advantageous for both parties, since the developed countries can obtain carbon emission credits (the emission that the developing country would cause by not performing wastewater treatment) in exchange for exporting wastewater treatment technologies. The receiving urban area would receive public health, environmental, as well as economic benefits (the recovered energy remains in the area, reducing the local need of fossil fuel, and with additional improvements for the fishing and tourism industries).

Equivalent CO₂ emissions from urban wastewater treatment in underdeveloped countries amount to 1.4% of the non-fossil fuel related emissions. Since no country experiences a shortage of wastewater, this strategy for trading (or, better, exchanging) is applicable to all countries. Countries that have ratified the Kyoto protocol have an additional compelling motive. Performing full wastewater treatment in all urban areas worldwide has substantial economic incentives, but is also a necessity and an obligation towards the sustainable management of the global environment.

5. Conclusions

Proper wastewater treatment reduces greenhouse gases emissions and should be considered a global warming mitigation factor. Full wastewater treatment with biomass sequestration and biogas energy recovery can be a net carbon sequestration process. Currently, the worldwide scenario is close to the worst possible, but has large margin of improvement, if wastewater treatment is performed in urban areas with sewers.

Our data analysis projects global warming benefits in urban areas not served by improved sanitation, and quantifies the actual benefits enjoyed by urban areas already served. The potential of extending full wastewater treatment to urban areas lacking treatment is enormous, as

shown by our results, and is equivalent to trading emission credits. By exporting treatment technologies and subsidizing construction to underdeveloped countries, for example, developed countries could partially offset their CO₂ emissions, in addition to extending ecological, humanitarian, and economical benefits.

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