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Adaptation and mitigation synergies to improve sanitation: a case study in Morelos, Mexico

Ines Navarro González, Blanca Jiménez Cisneros, Nidya Aponte Hernández and Raquel Montes Rojas

ABSTRACT

The management of wastewater is the fifth largest single source of CH_4 emissions and the sixth of N_2O. Options to improve sanitation within the Morelos State in Mexico were compared applying a modification of the IPCC guidelines to estimate greenhouse gas (GHG) emissions. A 2030 business-as-usual scenario which considers current sanitation practices and 2010 baseline-scenario, showed that septic tanks, the main state option for sanitation, were the principal source of emissions, even higher than from non-controlled wastewater discharges. These scenarios also revealed that the two metropolitan areas were key in terms of mitigation as they contributed 88% of the total GHG emissions. For the 2030A scenario (sanitation + adaptation), it was seen that if the policy of septic tank usage continues, and the existing wastewater treatment plants (WWTPs) are rehabilitated, the GHG emissions would be reduced by 2% compared to the business-as-usual (BAU) scenario. In contrast, if a policy were adopted considering in addition mitigation measures, 26% GHG emissions reduction might be achieved. Additional co-benefits will be obtained in several sectors, including health (diarrheal and dengue diseases control), agriculture, and the environment, performing a more efficient and integrated management of water and achieving savings on the operating costs of WWTPs through co-generation.

Key words | adaptation, developing countries, GHG emissions, mitigation, sanitation, septic tanks

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INTRODUCTION

Mitigation and adaptation are the two strategies available to address climate change. The main difference between them is in terms of their final goal: mitigation provides benefits to manage the risks of global climate over the long term while adaptation responds to local impacts and risks, providing benefits over the short and long term (Swart & Raes 2007). Mitigation and adaptation have evolved along different pathways, are discrete in terms of international and national policies, and are funded through different financial mechanisms (Tol 2005). However, both are necessary as they are complementary. Furthermore, given that mitigation may benefit or hinder adaptation, and vice versa, implementing activities that contribute to each other can minimize trade-offs and increase the efficiency of the associated economic investments.

Mitigation and adaptation are more likely to be undertaken if compelling co-benefits can be demonstrated. The importance of co-benefits lies in the fact that while they decrease vulnerability to climate change they may also allow the enhancement of ecological integrity and biodiversity, the sequestration of carbon and contribute to the creation of a healthier and more liveable environment (Naumann *et al.* 2011). The process of identifying adaptation and mitigation synergies may start from either the adaptation or the mitigation side. Directly exploring the use of integrated strategies may overcome the barriers faced by

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local communities due to the combinations of technology lock-in, policy and institutional rigidities, and even lack of support among the broader community (Smit & Wandel 2006; Lorenzoni *et al.* 2007; Burch 2010); these challenges have been identified in numerous communities around the world, and are not necessarily different to the situation observed in Mexico.

Universal sanitation coverage is considered a tool to increase resilience to climate change (Howard *et al.* 2016). Sanitation contributes to the protection of water sources, public health and the environment. For these reasons, universal sanitation coverage is also part of the 2030 Agenda for Sustainable Development. Specifically, it corresponds to target 6.2. Providing sanitation will contribute not only to adapting to climate change but also to improving quality of life and protecting human health and the environment. Given the goals of the different international agendas, governments are looking for solutions to both adapt and mitigate climate change while achieving sanitation and other co-benefits in different sectors. Within the above-mentioned context, and considering the lack of practical information for policy-makers, this paper presents a comparison of different options available to provide sanitation in the State of Morelos, Mexico, considering their respective greenhouse gas (GHG) emissions. In particular, the case study shows how under climate change conditions strategies for sanitation only, sanitation + adaptation, and sanitation + adaptation + mitigation impact on the production of GHG while producing co-benefits in several sectors.

Background

Even though, on a global scale, GHG emissions from the water sector only represent 3% to 10% (IPCC 2007), the management of wastewater itself is the fifth largest single source of anthropogenic emissions of methane (CH_4) and the sixth in terms of nitrous oxide (N_2O) (IPCC 2007; Zouboulis & Tolkou 2015). Methane is emitted during the transportation, treatment, and disposal of wastewater but also results from the management of wastewater sludge and water reuse. If aerobically treated, the processes used to decontaminate wastewater consume energy and, as a result, GHGs are released. If anaerobic processes are used to treat wastewater, as is the case for septic tanks or in anaerobic reactors, methane emissions are produced from the organic matter contained in the wastewater. Usually, the methane gas is dispersed into the atmosphere as its reclamation is only economically viable for wastewater treatment plants (WWTPs) with flowrates above 450 L/s. However, co-generation (generation of energy from wastewater) is viable for average daily wastewater flow above 30 L/s, provided several operating requirements are achieved (EPA 2008). N_2O, a potent GHG, is also emitted during the management of wastewater (Kampschreur *et al.* 2009). Methane and N_2O emissions from wastewater are expected to increase by 50% and 25%, respectively, over the next few decades (IPCC 2007). The rate of production depends on the type of process selected to treat the wastewater and the methods used to manage it. Thus, one way to contribute to the mitigation of GHG emissions is through the selection wastewater management options which minimize their production while achieving sanitation goals which are considered as part of adaptation practices.

Mexico has set a GHG emissions' reduction goal of 30% by 2020 and of 50% by 2050 with respect to the year 2000 considered as the baseline (Mexican General Climate Change Law, INECC 2012). Moreover, because of the Paris Action Plan (2015), the country committed itself to reduce its GHG emissions by 22% for 2030 which is equivalent to cutting down the emissions by 210 mega ton (SEMARNAT 2015). This commitment was made as an unconditional statement obliging the country to implement the target using only national financial resources. In this context, the government is looking for options that can simultaneously allow for GHG mitigation and adaptation while fulfilling wider goals such as those for the 2030 Agenda, for instance the one on sanitation.

To demonstrate the reduction in GHG emissions from wastewater, IPCC (2006), under the United Nations Framework Convention on Climate Change, proposed a methodology covering the different steps to treat and manage wastewater. The guidelines consider the carbon contained in wastewater to be biogenic, and thus on-site emissions of CO_2 are excluded from reporting, while CH_4 and N_2O emissions from WWTPs are part of national and local inventories (Bogner *et al.* 2008). Moreover, the guidelines for managing wastewater propose the evaluation of a broad set of sources from which the gases are released

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covering from the wastewater generation site to its final disposition/discharge, and including the processing of by-products. Unfortunately, case studies and data showcasing the application of the IPCC guidelines are still very limited in the literature (WRF 2013) and hence little is known with regard to its suitability to practical cases, notably in developing countries where, frequently, little information is available.

There have been a number of attempts (Cakir & Stenstrom 2005; Monteith *et al.* 2005; Bani Shahabadi *et al.* 2010) to estimate total CO_2 equivalent (CO_2e) emissions from WWTPs using different methodologies (e.g., mathematical modeling, case studies, and scenario analyses). However, these studies remain limited to the assessments of specific types of technologies that are used in WWTPs and do not cover the analysis of the entire sanitation chain nor the sanitation policies for a region. When studies are available on mitigation measures for the wastewater sector as a whole (wastewater transport, treatment, and disposal), these tend to make non-specific recommendations (Gupta & Singh 2012). As a result, information for decision-makers on the approaches to provide sanitation under different climate change scenarios and using adaptation and mitigation strategies is very limited.

Study area

Morelos State is located in the central area of Mexico, between 18°30′55″–19°07′20″ latitude north and 98°45′51″–99°26′13″ longitude west. The state is divided into 33 municipalities and has an altitude ranging from 720 to 5,432 masl. The climate is warm sub-humid with a minimum temperature of 10 °C and a maximum of 30 °C. The mean annual precipitation is 976 mm. In 2010, the population of the state was of 1,777,227, of which, 84% lived in urban areas. The economy is based on agriculture and tourism. The main crops are sugarcane, rice, corn, tomatoes, melon, mango, and sour lemon.

The provision of water comes from groundwater (30%) and surface water (70%). The water extraction rate is 1,249 million cubic meters per year and, based on the renewable available water index, the state is under high hydric stress (40%). Water is used for agricultural irrigation (71%) and municipal supply (23%). Of the total population, 92% has access to water supply and 95% to sanitation; however, this latter refers mostly to household connections to sewers discharging directly into rivers with no wastewater treatment at all, or to the discharge of partially treated wastewater from septic tanks. The coverage of water services is not homogenous throughout the state as there are four municipalities where only 34–49% of the population has water supply connection, seven have less than 32% of the people connected to sewerage, and five have a population between 62% and 79% using septic tanks. There are 46 WWTPs in the state with a design capacity of 2.8 m^3/s, of which only 46% is used. In total, 1.56 m^3/s of wastewater are collected from households to be discharged without any treatment into rivers flowing within the cities and irrigation channels. Wastewater is mostly treated through aerobic activated sludge processes (79%) but anaerobic digestion (15%) and wetland treatment systems (6%) are also used (Table 1). As a consequence, surface water bodies' pollution and the associated environmental impacts are evident. The main sources of pollution are not only the untreated municipal discharges, but as well, the effluents from WWTPs that are not operating efficiently and the effluents from septic tanks that infiltrate the aquifer.

There are two main metropolitan areas in Morelos State: Cuernavaca, with seven municipalities and Cuautla, with six. Cuernavaca hosts 49% of the total state population while Cuautla has 24% (Table 2). In both metropolitan areas, 87% of the population has access to drinking water. In contrast, only 56% is connected to sewers, 30% uses septic tanks, and 7% has no access to sanitation at all. Cuernavaca, which is the most urbanized city of the state, has two municipalities (Tepoztlán and Huitzilac), with a high percentage of the population living in rural areas, and a low water supply coverage. Where sanitation is available, it consists only of septic tanks. In contrast, in Cuautla, inequalities with regard to water services are lower. Within the two metropolitan areas, there are a total of 28 WWTPs (61% of the total number of facilities for the state) and although their design capacity is higher (1.91 m^3/s), they only treat 1.11 m^3/s. In Cuernavaca, there are three WWTPs which do not function at all, while in Cuautla there are four. Table 1 shows that the

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Table 1 | Wastewater treatment facilities in the Cuernavaca and Cuautla metropolitan areas

Municipality	WWTP number	Treatment process	WWTP flow design capacity (L/s)	WWTP mean operating flow 2010 (L/s)	Mean DBO_5 in influent (mg/L)	Effective treatment capacity in 2010 %	Wastewater collected (L/s)	Sanitation deficit 2010 %
Cuernavaca								
Cuernavaca	1	ASP	750	276.5	82	0.37	1,164.64	76%
	2	ASP	24	5.9	239	0.25		
	3	ASP	4	0	65			
	4	UASB	1	0.6	65	0.55		
Jiutepec	5	ASP	195	75.0	350	0.38	329.21	74%
	6	ASP	12	10.5	115	0.87		
Temixco	7	ASP	100	70.2	124	0.70	140.79	50%
	8	ASP	5	0	124			
Emiliano Zapata	9	ASP	30	4.0	409	0.13	122.61	74%
	10	ASP	30	14.6	177	0.49		
	11	ASP	30	9.3	76	0.31		
	12	ARBC	15	4.5	151	0.30		
Xochitepec	13	ASP	9	5.8	329	0.64	8.27	23%
	14	UASB	5	0.6	239	0.12		
Tepoztlán	15	ASP	15	0.05	24	0.00	5.63	99%
	16	ASP	2	0	24			
Huitzilac					125		0.74	100%
Cuautla								
Cuautla	17	ASP	439	328.0	253	0.75	320.88	−11%
	18	UASB	30	20.6	379	0.69		
	19	ASP	30	0.3	93	0.01		
	20	UASB	3.5	2.5	142	0.71		
	21	ASP	12.5	5.2	10	0.42		
	22	ASP	5	0	10			
	23	ASP	5	0	10			
Yautepec	24	ASP +	85	62.3	196	0.73	52.13	−20%
Ayala	25	ASP	25	0	196		47.97	100%
Yecapixtla	26	ASP	25	11.8	663	0.47	16.37	28%
Atlatlahucan	27	ASP	15	1.7	614	0.11	23.50	93%
Tlayacapan	28	ASP	10	0	614		5.94	100%

ASP, ativated sludge process; UASB, upflow anaerobic sludge blanket; ARBC, anaerobic rotating biological contactor; BOD, biochemical oxygen demand.

amount of wastewater collected in sewers is greater than the total amount of treated wastewater; for this reason, it is considered that the sanitation deficit refers not only to uncollected wastewater but also to the wastewater collected in sewers which remains untreated. This deficit is of 73% for Cuernavaca and 7% for Cuautla. Of the WWTPs located in the metropolitan areas, only three in Cuernavaca and four in Cuautla have facilities to treat sludge and, furthermore, the production of sludge is so low that it is neither technically nor economically viable to reclaim it or to produce biogas.

METHODOLOGY

To define the best sanitation actions contributing to adapt to climate change and mitigate GHG emissions, the study was

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Table 2 | Water supply and sanitation services for Cuernavaca and Cuautla metropolitan areas (INEGI 2010)

Municipality	Population (2010) Total (inhab.)	Urban %	Rural %	W/water service %	W/sanitation service %	W/septic use %	Without sanitation service %	Per capita mean water supply[a] (L/d)
Cuernavaca metropolitan area								
Cuernavaca	365,168	96	4	90	62	30	8	663
Jiutepec	196,953	96	4	93	74	23	3	282
Temixco	108,126	94	6	92	73	19	9	224
Emiliano Zapata	83,485	95	5	93	70	26	4	261
Xochitepec	63,382	78	22	81	32	62	6	57
Tepoztlán	41,629	53	47	55	13	73	14	221
Huitzilac	17,340	62	38	59	5	79	16	156
Cuautla metropolitan area								
Cuautla	175,207	90	10	90	79	17	4	297
Yautepec	97,827	83	17	84	57	39	4	129
Ayala	78,866	68	32	85	55	35	10	149
Yecapixtla	46,809	69	31	70	70	17	12	82
Atlatlahucan	18,895	56	44	68	63	30	8	335
Tlayacapan	16,543	48	52	69	53	39	8	113

[a]Per capital mean water supply in L/person/d: data provided by the water sector of the State of Morelos.

divided into three phases and four scenarios were considered. The scenarios considered were as follows:

- *Baseline scenario:* base on the provision of sanitation in 2010
- *Business-as-usual scenario (BAU):* does not consider any mitigation or adaptation for climate change, just the provision of sanitation
- *2030 A scenario*: which besides considering sanitation considers the need to further adapt to climate change impacts
- *2030 B scenario*: incorporates the two perspectives from the previous scenarios plus the need to reduce GHG emissions.

First phase: identification of emission pathways and estimation of the 2010 scenario or baseline

The first step consisted of identifying the GHG emissions pathways relevant to Morelos State from those suggested by IPCC (2006) for the management of wastewater. This was performed through a bibliographic research and on-site inspection. To set the baseline, the emissions originating from the management of wastewater for the 33 municipalities of the State of Morelos were estimated for 2010. This year was chosen as a wealth of relevant information was available from the 2010 Population and Household Census of Mexico. For the estimations, Equation (1) for CH_4 and Equation (2) for N_2O suggested by IPCC (2006) were used. The emissions results are expressed as equivalent carbon dioxide (CO_2e), considering an equivalent warming factor of 25 for methane and of 298 for the nitrous oxide.

$$CH_4 = \left[\sum_{ij}(U_i \cdot T_{i,j} \cdot EF_j)\right](TOW - S) - R \quad (1)$$

where CH_4 is amount of CH_4 emissions for the inventory year (kg CH_4/y); U_i is fraction of population in income group I; T_{ij} is extent of treatment/discharge pathway, j, for each income population group expressed as fraction i; i is social income group: rural, urban high income and urban low income; j is treatment/discharge pathway; EF_j is B_0MCF_j: 0.6 MCF_j = emission factor (kg CH_4/kg BOD);

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MCF: is methane correction factor (fraction): $TOW = P$ BOD (0.001) I (365) = total organic matter contained in wastewater (kg BOD/y); *P* is population (person); *BOD* is per capital BOD (g BOD/person-d); *S* is organic matter component removed as sludge (kg BOD/y); *R* is amount of CH_4 recovered (kg CH_4/y); and *I* is correction factor for industrial wastewater discharged into municipal sewer.

$$N_2O = N_{effluent} \cdot EF_{effluent} \cdot 44/28 \quad (2)$$

where N_2O is annual nitrous oxide emission (kg N_2O/y); $N_{effluent}$ is nitrogen in the effluent discharged to aquatic environments (kg N/y); and $E_{effluent}$ is emission factor for N_2O emissions from discharged wastewater (kg N_2O-N/kg N).

Emissions were estimated for the three pathways ($j =$ 1,2,3 variables) that resulted relevant for this research, i.e., for non-controlled wastewater discharges, septic tank, and WWTP effluents. To adapt both equations above to local conditions and the type of information available, three procedures were developed (Table 3). The first used a water balance, the second the population data classified by income level, and the third methane correction factors different to the default values provided by IPCC. For the water balance procedure, the variables U_i and T_{ij} from Equation (1) were set for the urban and rural population, based on actual water use data coming from the 1990, 2000, and 2010 population censuses. As a result, the U_i fractions do not correspond to the income ranking as established in the original methodology, but to the fractions of the wastewater produced by rural and urban populations; they were estimated following a water balance considering the per capita water supply and the percentage of it that becomes wastewater (75% for Mexico). This procedure was used to assess the 2010 and the 2030 BAU scenarios. The second procedure, applied only to assess the 2010 scenario, used the fraction of population per income level, the degree of urbanization, the type of treatment provided to wastewater or the amount of wastewater just discharged into the environment, which is information available at the database of the Population and Housing Census 2010 (INEGI 2016). From the analysis of these data, it was concluded that the IPCC guidelines default values for U_i and T_{ij} for Mexico (IPCC 2006, Table 6.5) regarding the urban and rural income levels were not appropriate for the local conditions, especially for the septic tank pathway, as the use of septic tanks does not depend on the population income level or on the level of urbanization but on the site characteristics (irregular mountainous areas).

For the procedures described above, the correction factors used were the IPCC default values (Table 4). Additionally, the actual BOD_5 and nitrogen values recorded over a 2-year period for the influent and effluent at each of the WWTP were used. To estimate the emissions resulting from the treated wastewater, an overall mean BOD_5 estimated value of 251 mg/L was applied to the influent to septic tanks and to the non-controlled wastewater discharges; while for each WWTP the actual mean BOD_5 value was used for each (see Table 1). A similar procedure was used to estimate nitrous oxide emissions; in this case, the overall calculated mean concentration of total nitrogen was 37 mg/L. For the second procedure, based on level of income, the N_2O emissions were evaluated using the annual per capita protein consumption factor which is 77 kg/person/per year for Mexico (FAO 2014). Finally, the third procedure consisted simply of using a 0.22 MCF (Leverenz *et al.* 2010) factor for the CH_4 releases from septic tanks instead of the 0.5 default value; it was based on the use of a static flux chamber method to measure the emission rates of methane from eight septic tanks used for the management of domestic wastewater. This third approach consisted of using an updated value for the factor, since it is relevant to the results of this study. Its use implies a nominal reduction of 56% of CH_4 emissions compared to those obtained with the IPCC guidelines factor, which comes from outdated research (Doorn & Liles 1999).

The *S*, *R*, and *I* variables for Equation (1), were not considered in any of the three procedures because of the lack of data to estimate the amount of organic matter removed from the sludge, the amount of methane recovered, and the fraction of industrial *BOD* discharged into the municipal sewer.

Second phase: assessment of the BAU 2030 scenario

GHG emissions for 2030 were estimated considering a business-as-usual scenario, which basically reflects the only aim to provide sanitation with no focus on better adapting to climate change or on contributing to mitigation. For this, a mean population growth of 26% was considered, and it

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Table 3 | Modifications (procedures) made to the IPCC guidelines summary and their application to 2010 scenario

Scenario	Methane correction factor, MCFj	Pathways description	Population data
Procedure 1: Baseline 2010 scenario			
2010	**All those from Table 4**	T_{11} = Rural population with non-controlled wastewater discharge; T_{12} = Rural population with septic tanks; T_{13} = Rural population with wastewater treated at WWTPs; T_{21} = Urban population with non-controlled wastewater discharges; T_{22} = Urban population with septic tanks; T_{23} = Urban population with treated wastewater at WWTP	U_1 = Rural population; U_2 = Urban population as considered in the 2010 Census
Procedure 2: Income level approach			
2010	**All those from Table 4** but for septic tanks, for which a MCF of 0.1 was used for small families (3–5 persons) and 0.5 (as proposed in the table) for bigger families as recommended by the IPCC guidelines	T_{11} = Low income rural population with non-controlled wastewater discharges; T_{12} = Low income rural population with septic tanks; T_{13} = Low income rural population with wastewater treated at WWTPs; T_{21} = High income rural population with non-controlled wastewater discharges; T_{22} = High income rural population with septic tanks; T_{23} = High income rural population with wastewater treated at WWTPs; T_{31} = Low income urban population with non-controlled wastewater discharges; T_{32} = Low income urban population with septic tanks; T_{33} = Low income urban population with wastewater treated at WWTPs; T_{41} = High income urban population with non-controlled wastewater discharges; T_{42} = High income urban population with septic tanks; T_{43} = High income urban population with wastewater treated at WWTPs	U_1 = Low income rural population; U_2 = High income rural population; U_3 = Low income urban population; U_4 = High income urban population. Data from the metadata base Population and Housing Census 2010 (INEGI 2016)
Procedure 3: Methane correction			
2010	**All those from Table 4**, but 0.22 MCF factor for releases from septic tanks (Leverenz *et al.* 2010)	T_{11} = Rural population with non-controlled wastewater discharge; T_{12} = Rural population with septic tanks; T_{13} = Rural population with wastewater treated at WWTPs; T_{21} = Urban population with non-controlled wastewater discharges; T_{22} = Urban population with septic tanks; T_{23} = Urban population with treated wastewater at WWTP	U_1 = Rural population; U_2 = urban population as considered in the 2010 Census

was assumed that the number and operating conditions for the 2010 WWTP infrastructure remained the same, while the number of septic tanks was increased following the historical trend. The same Equations (1) and (2) outlined above were used together with the *BOD* and nitrogen concentrations for the 2010 scenario. From the comparison of

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Table 4 | Methane correction factors used, MCF_j (IPCC 2006)

MCF	Treatment/discharge pathway or system	Pathway
0.1	Discharge to water body	$j = 1$
0.5	Septic tank	$j = 2$
0.3	Aerobic WWTP	$j = 3$
0.8	Anaerobic WWTP	$j = 3$

the 2030 BAU and 2010 scenarios, sanitation options were selected considering their impacts on GHG emissions.

Third phase: assessment of the 2030 A (sanitation + adaptation strategy) and 2030 B (sanitation + adaptation + mitigation strategy) scenarios

Based on the comparison of the 2010 baseline situation and the 2030 BAU (sanitation only) scenario, it was evident that to fulfill both a sanitation and a climate change agenda, it was necessary to: (1) avoid using a policy based on septic tanks; (2) expand the sewerage coverage; (3) increase the treated flow and the efficiencies at the existing WWTPs; and (4) build and efficiently operate new WWTPs. Moreover, considering that, by 2030, 75% of the Morelos population will live either in the Cuernavaca or Cuautla metropolitan areas and since these areas release 88% of the GHG emissions, they were set up as the main regions within which to act. Thus, policies and scenarios were only to be considered for these areas. Based on these considerations, two scenarios, A and B, were compiled, as follows.

Scenario 2030 A – sanitation and adaptation strategy:

(a) Retaining septic tanks and even increasing their use following historical trends
(b) Operating the existing WWTPs at their capacity and efficiency of design
(c) Continuing non-controlled discharges except for those managed either through (a) or (b)
(d) Not implementing planned reuse practices.

Scenario 2030 B – sanitation, adaptation, and mitigation strategy:

(a) Not installing new septic tanks but keeping those already built and functioning by 2016 in operation
(b) Fully controlling wastewater discharges, i.e., a zero non-controlled discharges policy
(c) Operating WWTPs already existing in 2010 at full efficiency and increasing their capacity considering conditions derived from (a) and (b)
(d) Promoting water reuse and sludge reclamation.

Scenario 2030 A involves sanitation activities plus activities to better adapt to climate change impacts which also have co-benefits on improving environmental conditions as they contribute to partially controlling surface water pollution, partially enhancing the safe use of water and reducing environmental habitats suitable for mosquito-borne viral disease spreading (dengue, chikungunya, and zika).

In contrast, scenario 2030 B, besides contributing to sanitation has important effects in both adaptation and mitigation goals. The activities proposed involve the benefits expected for scenario 2030 A, but additionally it contributes to the long-term viral vector control at household level. This is a very necessary local adaptation goal, but most importantly it contributes to mitigation by avoiding having new sources of GHG emission (septic tanks). Furthermore, it builds capacities for water reuse as a low emission practice and develops a strategy to reclaim water and sludge to enhance agricultural production.

Considering the socio-economic local conditions, for the implementation of both scenarios, 2030 A and 2030 B, a stepwise approach was considered in such a way that the additional wastewater generated by population growth is treated either at WWTPs or in septic tanks. For the estimation of the GHG emissions the same procedure used for the 2030 scenario was used.

RESULTS

Identification of emissions pathways and 2010 baseline

From the different IPCC (2006) wastewater pathways for GHG emissions, three resulted relevant to Morelos State (Figure 1): (1) non-controlled wastewater discharges; (2) septic tanks (>30% of total state population); and (3) wastewater that is collected in sewers and that is either treated at WWTPs or remains untreated. During the site inspection, it was found that of the 46 WWTPs only 32

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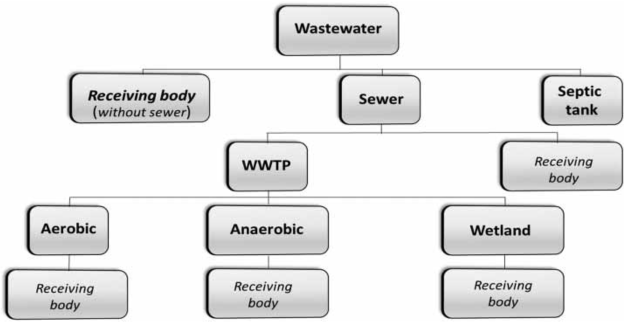

Figure 1 | GHG emission pathway sources identified for Morelos State (adapted from IPCC 2006).

were operating and, that where sludge facilities were supposed to exist, they were not in operation because sludge production was nil or very low. This was explained because the wastewater treatment facilities were performing well below their design capacity (i.e., with a high hydraulic retention time which degraded sludge in the water treatment line) or were operating with very low efficiencies. In both cases, the amount of sludge produced was insufficient to be treated and reclaimed for agricultural use or to produce biogas in an economically or technically efficient manner. From the site inspections, it was also found that water reuse is a current practice but in an unplanned and non-controlled way. As the operating conditions for wastewater infrastructure were assumed to be notably improved for the 2030 B scenario, water reuse and sludge reclamation were only considered for this case and their emissions and associated costs estimated (i.e., two additional pathways added to those presented in Figure 1).

After assessing the 2010 scenario, it was found that Morelos State had a total emission of 175,555 ton CO_2e from its wastewater management. This represented 2.9% of the total emissions for the state, which amounted to 6,117.8 GgCO_2e (Sheinbaum *et al.* 2014). Sixty-nine percent of the emissions were released only from wastes (i.e., solid wastes and wastewater). The GHG emissions estimated are consistent with the figures commonly provided for the water sector on the global scale varying from 3% to 10% of the total (IPCC 2007). However, in contrast to the global figures in which CH_4 emissions from wastewater generally represent 9% of the total (Zouboulis &Tolkou 2015), in Morelos State these accounted for 2.6% since methane is the main gas emitted.

Figure 2 shows the distribution of CH_4 emissions per source for the main municipalities, showing that, almost always, septic tanks are the predominant source, amounting to around 61–63% of the total for all 33 municipalities of the State of Morelos.

The results also showed that WWTPs are indeed a tool to reduce GHG releases to the environment. For example, of the total emissions for the metropolitan area of Cuernavaca, 117,120 ton CO_2e in 2010, 69% of the CH_4 emissions come from septic tanks, 6% from 13 WWTPs (477 L/s), and 25% from non-controlled discharges. The results therefore indicate that a policy is needed to mitigate emissions from septic tanks, and that the treatment of non-controlled wastewater discharges is a mitigation activity as stated by Listowski *et al.* (2011).

BAU 2030 scenario (sanitation only strategy)

For 2030 and under the BAU scenario which consider the provision of sanitation in a continuous business-as-usual scenario, the emissions from wastewater will increase by 23% compared to 2010 and amount to 216,080 ton CO_2e. However, the contribution to the total emissions for the state from the management of wastewater will decrease from 2.9% to 2.0%. In any case, the percentage of the emissions as CH_4 from the water sector remains the same and equal to 90%, with septic tanks being the predominant source of emissions (Figure 3) representing 61% of the total.

These results illustrate that in order to significantly reduce the emissions from wastewater management, as a policy, the number of septic tanks in use should be decreased. A more in-depth analysis of all the emissions sources for the 33 municipalities of Morelos reveals that 84% of these arise only from the Cuernavaca and Cuautla metropolitan areas, contributing 66% and 17% to the total, respectively, and that the per capita production of gases is higher for these areas (Figure 4) than for the rest of the municipalities. This is simply because most of the population using septic tanks in the state (73%) live in these urban regions, which surprisingly also have the highest number of the state's WWTPs (61% of the total). However, these plants not only have insufficient capacity to treat all the wastewater flow produced in cities but operate well below their design capacity.

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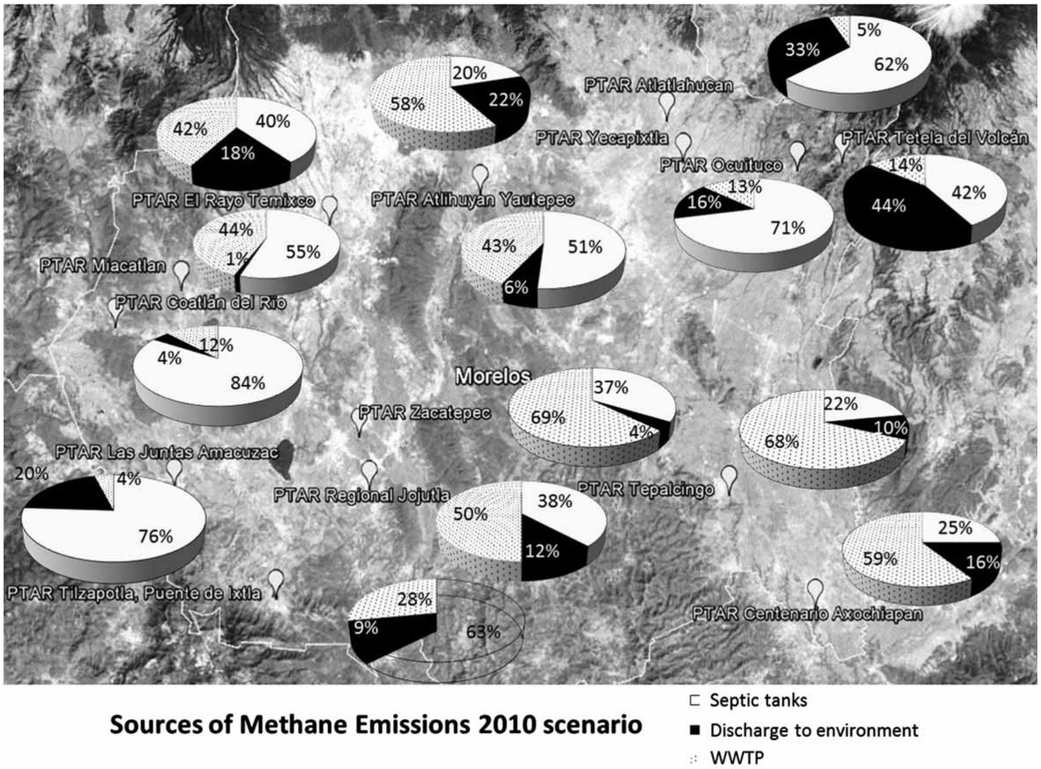

Figure 2 | Distribution of the methane emissions sources for the 2010 scenario at the main municipalities of Morelos State.

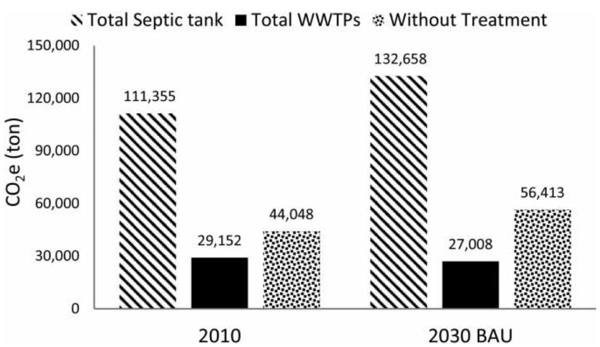

Figure 3 | GHG emissions for different sources' contributions to the total of emissions for the 2010 and 2030 BAU (sanitation only strategy) scenarios.

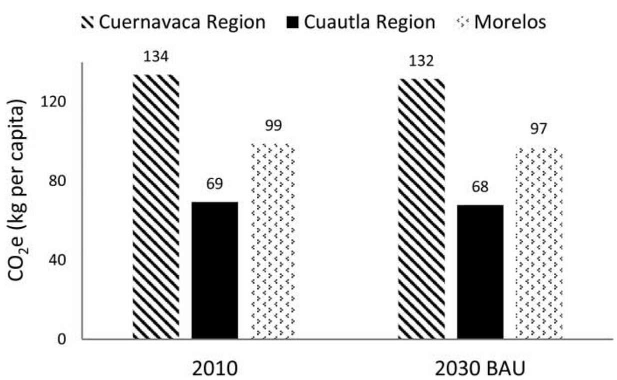

Figure 4 | Per capita GHG emission contribution for the metropolitan areas region of Morelos State for 2010 and 2030 BAU (sanitation only strategy) scenarios.

Scenario 2030 A (sanitation + adaptation strategy)

The 2030 A scenario (continuing the use of septic tanks already in use and additions of more following the 20-year historical trend, using the existent WWTPs at their full design capacity and keeping the non-controlled discharges to the environment that are not collected through any of these different disposal pathways) would require a moderate investment by the government. Scenario 2030 A results in a total production of GHG of 213,780 ton of CO_2e for all municipalities in the state, and total emissions of 176,680 ton of CO_2e for both metropolitan areas, Cuernavaca and Cuautla. It represents a small reduction of 2% (4,152 ton of CO_2e) of the emissions compared to the BAU scenario.

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Scenario 2030 B (sanitation + adaptation + mitigation strategy)

For scenario 2030 B, the goal is much more ambitious in order to achieve sanitation, adaptation, and mitigation goals, as it envisages no new septic tanks being installed after the year 2016, WWTPs (old and new) to be used at their full capacity and at optimal efficiency and no non-controlled discharges to water bodies. The new WWTPs proposed for this scenario address both the wastewater treatment deficit (wastewater collected in sewers that is not treated) of 81% and the total deficit of sanitation of 45% (wastewater that is neither collected nor treated). This scenario requires the construction of six new WWTPs in Cuernavaca to increase treatment capacity to 2,534 L/s and four in Cuautla to treat 798 L/s (Table 5). The new infrastructure represents a five-fold increase of the current sanitation coverage in Cuernavaca and an almost doubling of that of Cuautla.

The 2030 B scenario, for both the Cuernavaca and Cuautla metropolitan areas (Figure 5), resulted in total GHG emissions of 133,068 ton of CO_2e, which represents a reduction of 47,764 ton of CO_2e, 26% when compared to the 2030 BAU scenario (180,832 ton of CO_2e), i.e., a 24% additional reduction than for the 2030 A scenario. Figure 5 compares the emission for the 2030 B scenarios with the BAU scenario. Scenario 2030 A emissions are not shown since they are only 2% different to the BAU scenario ones.

The per capita emissions data for each municipality (Figure 6(a) and 6(b)) show that the selected sanitation/adaptation/mitigation activities for scenario 2030 B have a greater impact in the Cuautla metropolitan area than in the Cuernavaca one. This also illustrates that for the municipalities of Huitziliac and Tepoztlán in Cuernavaca and Atlatlahuacan in Cuautla the intensive use of septic tanks prior to 2016 remains the driving force for GHG emissions for 2030, even when the sanitation/adaptation/mitigation measures are implemented.

To illustrate the role of the use of septic tanks, Figure 7 compares methane emissions for the 2030 BAU and the 2030 B scenarios for each of the emission sources within the two metropolitan areas. In all cases septic tanks remain the main source of emissions.

Water reuse and sludge reclamation for the 2030 B scenario

Due to the widespread cultivation of sugar cane fields (59% of the irrigated land in the state) together with their high demand for fertilizers, the reuse of treated water was considered for the 2030 B scenario. For this scenario, a potential release of 0.065 kg CO_2e/m^3 was determined when reusing a secondary effluent to irrigate instead of the 0.342 kg CO_2e/m^3 that is released when raw wastewater is applied, as is the current practice (Fine & Hadas 2012).

For the sludge, land application in sugar cane fields was proposed in plots that were not irrigated with reclaimed water. As the reclamation of sludge is only economically viable for WWTPs with capacities higher than 450 L/s, its reclamation was considered only for the two WWTPs envisaged for Cuernavaca, with capacities of 750 L/s and 920 L/s, producing 12,700 ton (dry base). The amount of sludge produced from these two plants is sufficient to fertilize 500 ha.

Based on the current nitrogen application rate (344 ton N/ha), a sludge application rate of 19.93 ton/ha (dry base) would release 1.71 ton CO_2e/ha (using data from Pradel & Reverdy (2012)), which is lower than the current emissions obtained when conventional fertilizers are applied (2.13 ton CO_2e/ha). In addition, assuming the sludge is lime stabilized (25% w/w dose), most of the original nutrients and organic matter would be available for crops, avoiding the use of digested sludge and fertilizer. Under these conditions the GHG abatement potential would be 68.5 kg CO_2e/dry ton.

2030 A and B scenarios treatment costs

An estimation of the costs to implement scenario 2030 B indicates a significant difference from the 2030 A scenario costs (all values in current prices). The 2030 B costs involves an investment for infrastructure of 35.63 million USD to cover the increase in drainage coverage to achieve zero wastewater discharge (32%), the construction of new WWTPs (64%), sludge treatment (2%), and co-generation (2%). Both scenarios have in common the cost to rehabilitate the existing WWTPs to reach 100% of their physical efficiency, and which could be more than 13.35 million

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Table 5 | Scenario 2030 B (sanitation + adaptation + mitigation strategy) for Cuernavaca and Cuautla WWTPs

Municipality	WWTP name	Treatment process	WWTP mean operating flow 2010 (L/s)	Old WWTP mean operating flow 2030 B (L/s)	New WWTP 2030 B #	New WWTP mean operating flow 2030 B (L/s)	Total flow treatment 2030 B (L/s)
Cuernavaca							
Cuernavaca	Acapantzingo	ASP	276.5	750	1	920	1,670
	Chipitlan (L. Cardenas)	ASP	5.9	24			
	Sacatierra	ASP	0	4			
	Buenavista del Monte	UASB	0.6	1			
Jiutepec	La Gachupina	ASP	75.0	195	1	290	485
	El Texcal	ASP	10.5	12			
Temixco	El Rayo	ASP	70.2	100	1	112	212
	Acatlipa	ASP	0	5			
E. Zapata	El Encanto	ASP	4.0	30	1	100	130
	La Alameda	ASP	14.6	30			
	Tezoyuca	ASP	9.3	30			
	Nustar	ARBC	4.5	15			
Xochitepec	Regional de Xochitepec Alpuyeca	ASP	5.8	9	0	0	9
	Alpuyeca	UASB	0.6	5			
Tepoztlán	Tepoztlan	ASP	0.05	15	1	7	22
	La Obrera	ASP	0	2			
Huitzilac					1	5.5	5.5
Cuautla							
Cuautla	Cuautla	ASP	328.0	439	0	0	525
	Casasano	UASB	20.6	30			
	Calderón	ASP	0.3	30			
	El Hospital	UASB	2.5	3.5			
	Santa Ines	ASP	5.2	12.5			
	19 de Febrero	ASP	0	5			
	Cielito Lindo	ASP	0	5			
Yautepec	Atlihuyan Yautepec	ASP	62.3	85	0	0	85
Ayala	San Pedro Apatlaco	ASP	0	25	1	57	82
Yecapixtla	Yecapixtla	ASP	11.8	25	1	13	38
Atlatlahucan	Atlatlahucan	ASP	1.7	15	1	40	55
Tlayacapan	Nacatongo Tlayacapan	ASP	0	10	1	2.6	12.6

ASP, activated sludge process; UASB, up flow anaerobic sludge blanket; ARBC, anaerobic rotating biological contactors.

USD (CONAGUA 2016) depending on the specific improvements each plant would need. The WWTPs operating and maintenance costs for the 2030 B scenario are 89% (17.5 million USD) higher than those of the 2030 A scenario (9.25 million USD), since the treatment capacity is 3.5 m^3/s instead of 1.9 m^3/s. An important share of these costs (71%) are due to the energy consumption to operate the plants in Morelos State (INEGI 2014).

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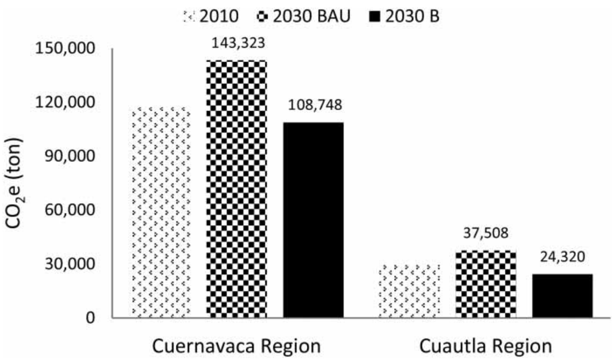

Figure 5 | GHG emissions estimated for the metropolitan regions under the BAU (sanitation only strategy) and the 2030 B (sanitation + adaptation + mitigation strategy) scenarios.

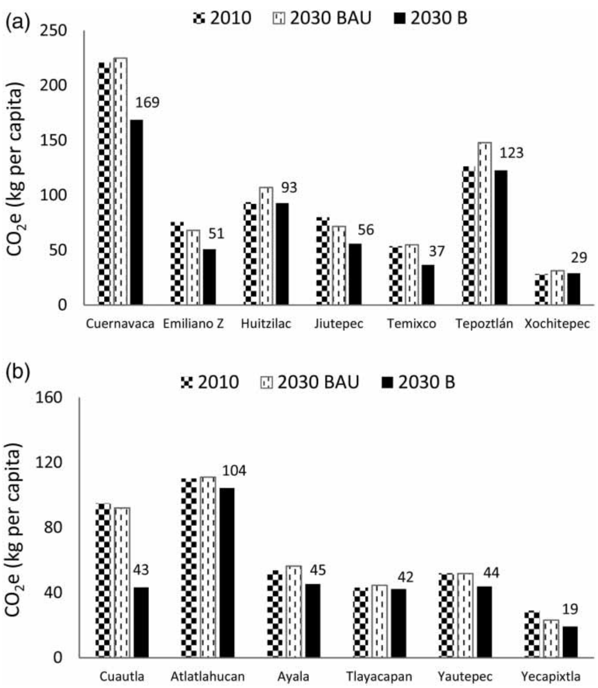

Figure 6 | Per capita GHG emissions estimated for Cuernavaca and Cuautla municipalities, scenario 2030 B (sanitation + adaptation + mitigation).

In summary, and as expected, the cost of the 2030 B scenario is substantial, and represents the second largest cost of the mitigation measures for all the sectors considered in the Action Plan for Morelos State ($2,398 USD/ton CO_2e). Sludge reclamation has a negative cost (−$8.58 USD/ton CO_2e). However, it remains possible to reduce the cost through sludge treatment for co-generation. For example, it was estimated that for a 450 L/s WWTP, the power production would be around 750 kW.

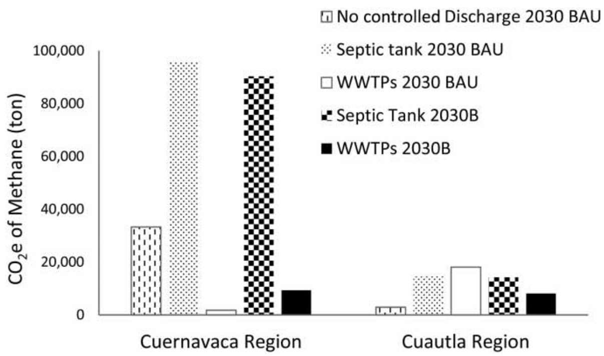

Figure 7 | Comparison by source CH_4 emissions – 2030 BAU (sanitation only), and 2030 B (sanitation + adaptation + mitigation) scenarios.

DISCUSSION

It is important to highlight that for all the assessed scenarios one implicit assumption is that the sewerage coverage increase would be performed simultaneously with the augmentation of the water supply. Should this be the case, the results showed that with integrated adaptation and mitigation activities, GHG emissions would decrease by increasing sewerage coverage; but additional co-benefits might be achieved as having access to clean water prevents waterborne diseases too. The introduction of both, a piped drinking water supply and improved sanitation coverage, reduce diarrheal diseases by 28% according to WHO (2014). This is highly relevant in Morelos State, as although the incidence of diarrheal diseases has decreased to 30% of the population, the still reported 100,000 cases per year is a high figure that has remained constant over the last decade. Furthermore, providing sanitation will assist in controlling other diseases such as dengue and chikungunya; both diseases are projected to increase under climate change scenarios (IPCC 2014). Mexico occupies fourth place in the list of the 30 countries most affected by dengue (WHO 2012). Six municipalities, all of them in the two metropolitan areas of Cuernavaca and Cuautla for which the sanitation activities are being proposed, have the highest dengue incidence rate of the state. Dengue disease has been associated with the storage of water within households as a result of the intermittent drinking water supply, the lack of proper sanitation, and the use of septic tanks (Cifuentes & Sánchez 2007). Moreover, the incidence of dengue and chikungunya has forced governments to

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invest in public health campaigns since 2005. Reducing the population's vulnerability to dengue and diarrheal diseases assists in achieving the economic benefits of having a healthier population by saving at least 5,750 USD per medical attention per one case of dengue (COFEPRIS 2015), and attain the 2020 goals set by the Health Minister to reduce the diarrheal incidence rate by at least 25%.

Additional benefits may be achieved for the agricultural (boost of production because of the fertilizers provided through wastewater and treated sludge) and energy (co-generation in WWTP from sludge) sectors. The activities proposed, such as expanding the sewerage coverage and increasing the efficiency and coverage of the WWTPs, although in a progressive manner, for the 2030 B scenario, allow a significant decrease of GHG emissions (of 26%) and will produce water to be reused in local sugar cane fields while reclaiming nutrients as fertilizers. Besides, the sludge generated in WWTPs efficiently operating, can be used to generate energy and amend agricultural land with a lower GHG release. The use of sludge for energy generation under the 2030 B scenario will reduce the WWTPs operation costs as energy use represents 71% of the annual expenses for it.

As expected, the predicted cost for scenario 2030 B would be the highest. For further research, it would be interesting to perform an optimization of specific measures to minimize costs while increasing benefits, as suggested by Nematian (2016).

This way, the results of this research show that the traditional sanitation measures may be set as part of an integrated strategy that includes as well adaptation and adaptation + mitigation. This way it is possible to contribute to several goals of the 2030 Agenda, and in particular to those related to water and climate change, while efficiently increasing population resiliency to several risks in the short-term, decreasing GHG emissions, and having additional co-benefits for the environment, health, and agricultural sectors.

Uncertainties

Uncertainties in the GHG emission estimations result mainly from the methane correction factor (MCF) used for all pathways, but in particular for septic tanks, as they are the largest source of emissions within Morelos State, as mentioned previously. There is a need to collect local information on the actual MCF to be applied. For instance, for the MCF proposed by Leverenz *et al.* (2010) of 0.22, the emissions estimated for scenario 2010 (Figure 8) are lower than those calculated with the IPCC value of 0.5 (denoted as Balance in Figure 8). This shows that the use of different MCF values has a significant impact on the emission estimates for septic tanks. However, since the operating conditions of septic tanks in Morelos have not been well-characterized, it is impossible to define whether using a lower factor is applicable to local conditions. In fact, what it is needed is a government program that, besides enforcing the adequate design and operation of septic tanks including the periodic extraction of sludge, evaluates the actual methane emissions from these facilities.

Another source of uncertainty is the lack of availability of local information to apply to the IPCC equations as proposed. Additionally, there is little standardized information (same year and same conditions) available at the municipal level. In fact, this seems to be a major challenge not only for Morelos State but for most developing countries. Challenges also arise from the different ways in which data are gathered and reported at national, regional, and local levels. This is extremely relevant since adaptation is a localized activity and has to be explored at the municipal level, for which information gathering is still a process to be developed in many cases.

Finally, from the lessons learned from this research, it can be seen there is a motivation to critically develop and implement mitigation and adaptation combined measures that can lead to synergies with other sectors. The results

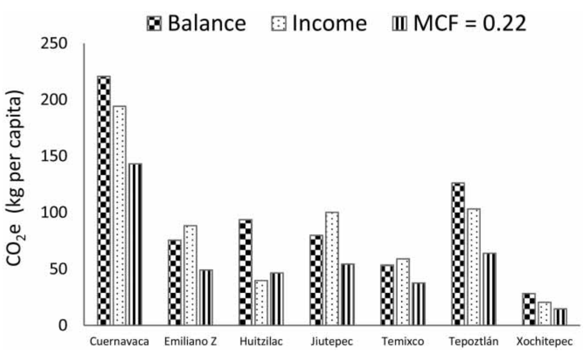

Figure 8 | GHG emissions estimated for the 2010 scenario using the different procedures considered and the IPCC guidelines for the Cuernavaca region.

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obtained show the importance of building the knowledge base necessary to address climate change, develop the institutional capacity to do so, and to increase sectoral collaboration in order to better guide local policies towards reducing GHG emissions, accelerating adaptation, and achieving sustainability. The results from this research show that in order to accomplish the ambitious GHG emissions reduction target set by Mexico at the national level, to which all sectors will need to contribute, there is a need to follow a new approach.

CONCLUSIONS

Fostering the 2030 agenda and the climate change international related agendas is motivating to critically develop and implement mitigation and adaptation combined measures that can lead to synergies with other sectors. As shown in this case study, the scenario 2030 B (sanitation + adaptation + mitigation) allows reduction of GHG emissions by 26%; while for the 2030 A (sanitation + adaptation) the reduction is only 2%, when compared both to the BAU (sanitation only) scenario and the 2030 B scenario. For the two scenarios, 2030 A and 2030 B, additional co-benefits could be identified. However, the 2030 B scenario is the one providing more benefits in the health sector, on the efficient use of water, the use of wastewater treatment by-products for agriculture and energy production, and in the environmental sector (cleansing of rivers and provision of a health environment to aquatic life). These results make evident the importance of building the knowledge base necessary to address climate change and develop institutional capacity to set sectoral collaboration to better guide local policies towards reducing GHG emissions, accelerating adaptation, and achieving sustainability. Subsequent to this work, and based on use of the IPCC guidelines, there is a clear need to adapt international criteria to estimate GHG emissions to local conditions and available data, notably in developing countries.

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