Characterization of Greenhouse Gases Emissions from Urban Solid Waste in Baja California: A Proposal to Incorporate Technical Input into Decision-Making

Caracterización de emisiones de gases de efecto invernadero generados por residuos sólidos urbanos en Baja California: Una propuesta para usar información técnica en la toma de desiciones

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ABSTRACT

This study details estimates of greenhouse gas (GHG) emissions from urban solid waste in Baja California using the IPCC 1996 method. Calculations showed an increase of 0.604 Gg/year for the period 1990-2010. The forecast for emissions predicts a continuous increase for the next 35 years. Seven mitigation scenarios were developed: *1)* 30 percent emission reduction, *2)* biodigester, *3)* a comprehensive option, *4)* biowindows, *5)* composting, *6)* vermicomposting, and *7)* biocover. Results from scenario building showed that it is possible to design actions or even combine strategies, with the most effective being those including social components and technological options.

Keywords: 1. urban solid waste, 2. GHG, 3. decision-making, 4. mitigation strategies, 5. Baja California.

RESUMEN

Este estudio detalla la estimación de emisiones de gases de efecto invernadero (GEI) generados por desechos sólidos urbanos en Baja California usando el método PICC 1996. Los resultados muestran un aumento de 0.604 Gg/año en el período 1990-2010. La proyección de emisiones exhibe un aumento continuo para los siguientes 35 años. Fueron construidos siete escenarios de reducción: *1)* 30 por ciento de disminución, *2)* biodigestor, *3)* una opción integral, *4)* bioventanas, *5)* compostaje, *6)* vermicompostaje, y *7)* biocubierta. Los resultados revelaron que es posible planear medidas o combinar estrategias inclusive, identificando como mejores los escenarios que incluyen aspectos sociales y opciones tecnológicas.

Palabras clave: 1. residuos sólidos urbanos, 2. GEI, 3. toma de decisiones, 4. estrategias de mitigación, 5. Baja California.

INTRODUCTION

The excessive generation of waste constitutes one of the most serious problems of our time, conundrum that is becoming larger with our active participation. However as multifarious as activities are in society, many could be the types of waste generated and their impacts.

Landfilling is a widespread waste management option practiced around the world. Notwithstanding waste does not stop being a source of concern after being deposited in a landfill site. Quite the contrary, waste will be modified by physical, chemical and biological processes once inside the landfill, and generate two main end products: leachate and gas (for the most part methane) and both of them impact on the environment (Muñoz-Meléndez, 1999). The chemicals contained in the leachate may eventually escape from the landfill base and become potential groundwater contaminants, whereas methane is a greenhouse gas with a global warming potential of 21 units of carbon dioxide (CO_2) equivalent per each methane unit[1]; and hence a contributory factor in climate change.

The international literature on the association between waste and climate change is largely focused on urban solid waste (USW) in developed countries, and there is limited information about the impact of other waste streams or waste management in developing countries. Current studies in developed nations rely on the availability of extensive waste data sources, information that does not exist or is incomplete in developing countries (UNEP, 2010).

Greenhouse Gases (GHG) emissions—including those coming from waste— are commonly estimated using both the Guidelines for National Greenhouse Gas Inventories developed by the Intergovernmental Panel on Climate Change (IPCC) and national statistics.

Mexico has prepared five GHG national inventories—one per national communication—for the United Nations Framework Convention on Climate Change. According to the latest communication (in 2010), total emissions of GHG in carbon dioxide equivalent ($CO_{2\ eq.}$) were 748 252.2 Gigagrams (Gg)[2]; this amount showed a rise in 33.4 percent compared to 1990 levels. The category "waste"

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[1] Methane global warming potential (GWP) is 21 times that of CO_2 when a time horizon of 100 years is considered (IPCC, 1996); the GWP is much higher when a 20-year time horizon is applied. Evidently, the choice of time horizon can have a dramatic effect on the estimated climate impact of methane emissions. On the other hand, GWP of methane is 25 $CO_{2\ eq.}$ under 2006 IPCC methodology.

[2] 1 Gg = 10^9 = 1 000 tonnes.

contributed 5.9 percent (44 130.8 Gg) to that total; the "waste" GHG emissions increased in 167 percent compared to 1990 levels. The "waste" sub-categories behaved as follows: "disposal of solid waste" (USW) provided 50.1 percent (22 117.7 Gg), "treatment and disposal of wastewater" 46.2 percent (20 396.4 Gg), "incineration and uncontrolled burning of waste" 2.8 percent (1 239.9 Gg) and "biological treatment of solid waste" 0.9 percent (376.8 Gg).

National GHG inventories as useful as they can be are also limited tools to characterise emission sources, for the reason that regions inside a country display a wide variety of emission's origins. This heterogeneity gives rise to both different degrees of vulnerability from location to location; and the need to develop measures at local-level for response and adaptation (Muñoz-Melendez, 2009).

Conveniently, Mexico has engaged in elaborating local GHG inventories as part of State-level Climate Change Acts (or "Programas Estatales de Acción ante el Cambio Climático": PEACC), these instruments take advantage of the feasibility provided by a subnational entity with legal jurisdiction (State or *estado*) and a specific social organisation to implement—through its own institutions—mitigation measures as well as policies on adaptation to Climate Change within its territory (Tejeda and Conde, 2008).

In Mexico, there are 31 States and one Federal District; by 2010 all had their PEACCs at several degrees of accomplishment (Semarnat and INECC, 2012). Baja California completed its PEACC and GHG inventory in 2012.

The hypothesis for this study was that the regional characterisation of GHG emissions from USW would provide a valuable input into decision-making on local mitigation actions. To demonstrate this, the northern State of Baja California was selected and its regional GHG emissions from USW were characterised. Thus, this paper has three objectives. The first is to present the GHG emissions from USW in Baja California for the period 1990-2010 and their projections to 2050. The second objective is to build as well as to compare feasible strategies to reduce GHG emissions from USW to the medium and long term. Finally, the third objective is to present how the analysis of reduction scenarios could be used into decision-making.

In order to achive these objectives this document is comprised of six sections. The first describes the "official" status of USW in Mexico. The second section presents the "accepted" USW context in Baja California. The third part details calculation methods and reduction scenario building. The fourth segment shows results, while the fifth discusses them. Finally, conclusions are given in section six.

USW IN MEXICO

The current definition of waste—in force—in Mexico is established in article 5 (XXIX) of the General Act on Prevention and Integral Management of Waste—*Ley General de Prevención y Gestión Integral de los Residuos* (LGPGIR)—that states (Semarnat, 2013): "Residuo: Material o producto cuyo propietario o poseedor desecha y que se encuentra en estado sólido o semisólido, o es un líquido o gas contenido en recipientes o depósitos, y que puede ser susceptible de ser valorizado o requiere sujetarse a tratamiento o disposición final conforme a lo dispuesto en esta Ley y demás ordenamientos que de ella deriven;". There are currently three waste categories in the LGPGIR: Urban Solid Waste (USW), Special Handling Waste (SHW) and Hazardous Waste (HW).

Although each waste category is important on its own right, the USW management is imperious because of its ever-increasing production. By 2011 USW generation was 21 and 586 times higher than HW and SHW, respectively (calculated by authors based on Semarnat, 2012). Additional factors to focus on the USW management are: *1)* the demand of large land areas for disposal, *2)* potential damages on human and environmental systems during the collection, transport and disposal of expanding amounts of USW; and *3)* the effectiveness of collection services—in charge of municipality governments—not only to smoothly carry out the management process but to stop HW and SHW being dumped in USW landfills; and discouraged illicit dumping, burning and other improper disposal of USW.

Before going further, it is suitable at this moment to visit once more the LGPGIR and check the USW definition (Semarnat, 2013):

> Residuos Sólidos Urbanos: Los generados en las casas habitación, que resultan de la eliminación de los materiales que utilizan en sus actividades domésticas, de los productos que consumen y de sus envases, embalajes o empaques; los residuos que provienen de cualquier otra actividad dentro de establecimientos o en la vía pública que genere residuos con características domiciliarias, y los resultantes de la limpieza de las vías y lugares públicos, siempre que no sean considerados por esta Ley como residuos de otra índole.

National statistics on the USW generation are based on calculations developed by the Social Development Secretary (Secretaría de Desarrollo Social: Sedesol) following the norm NMX-AA-61-1985 on Estimation of Solid Waste Generation.

The Secretary of Environment and Natural Resources (Semarnat, 2012) reported on the most recent status of USW in Mexico that:

- The generation of USW in tonnage per day (tpd) rose in 30 percent during ten years from 86 268 tpd in 2001 to 112 500 tpd in 2011. This increase was due to factors such as: urban growth, industrial development, technological advances, the purchasing power of average citizens and changes in consumption patterns.

- The USW generation showed marked differences at geographic level (Sedesol division in Figure 1). In 2011, the Center generated 51 percent of the national grand total, followed by the Northern region with a 16 percent contribution and Mexico City with 12 percent. The augmentation in USW generation during the period 1997-2011 showed noticeable differences; regions that increased the most their USW generation were in decreasing order: the northern border (207 %), Center (49 %), South (44 %) and Mexico City (19 %).

- The composition of USW in percentages by 2011 was as follows: 52.4 percent were organic substances, followed by 35 percent of recyclable material—such paper and cardboard (14 %), glass (6 %), plastics (11 %), metals (3 %) and textiles (1 %)—; and 12 percent of other type of materials.

- The collection of USW reached 93 percent in 2011. However it varied per locality size; for example 90 percent of USW collection happened in metropolitan areas, 80 percent in medium cities, 26 percent in small cities and 13 percent in rural and semi-urban regions.

- The most used and cost-effective waste management option is containment landfill. By 2011, 72 percent of USW was landfilled, 23 percent was disposed illegally in garbage dumps; and only five percent was recycled.

USW IN BAJA CALIFORNIA

The legal framework that regulates USW management in Baja California includes the LGPGIR (Semarnat, 2013), the Act on Prevention and Integral Management of Waste for Baja California[*Ley de Prevención y Gestión Integral de los Residuos para el Estado de Baja California*: LPGIRBC (Congreso del Estado de Baja California, 2007)] and (five) Municipal Plans for the Prevention and Integral Management of Waste. In addition USW management must observe both the General Act of Ecological Balance and Environmental Protection (LGEEPA) and the Environmental Protection Law for Baja California.

Existing regulation states that USW management is responsibility of municipalities. It is common that authorities operate under different schemes, mostly under

a contract regime for private companies to manage the whole (household-landfill) or part of (either collection or final disposal) the process.

According to official statistics (Inegi, 2013) 2 725 tpd of USW were collected in Baja California by 2013; this figure is closed to the volume generated as 97.5 percent of USW produced is collected (Semarnat, 2012).

FIGURE 1. MSW Generation per Region by 2011

Region
1. Northern border
2. South
3. North
4. Mexico City
5. Center
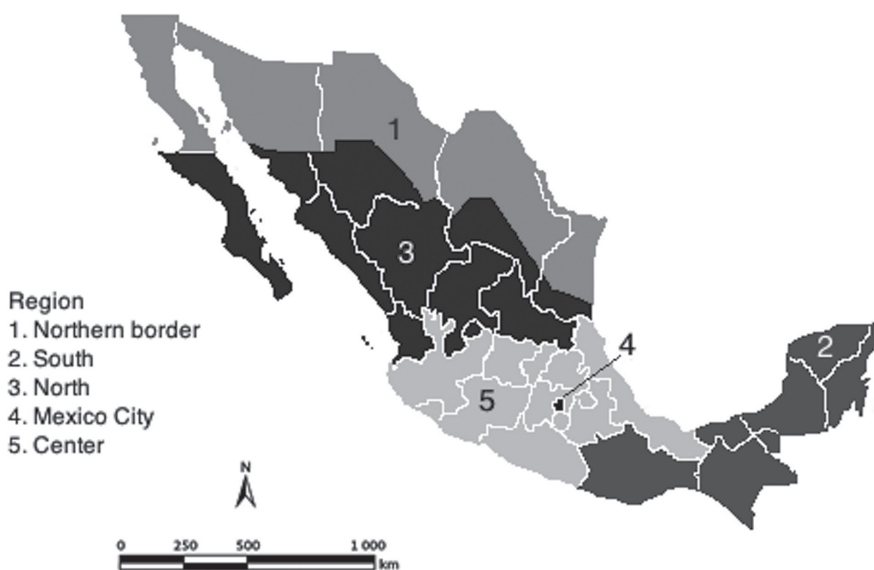
Source: Semarnat (2012).

Municipality contribution to daily tonnage of USW varied as follows: 43 percent (1 163 tpd) were collected at Tijuana, 27 percent (725 tpd) in Mexicali, 22 percent (620 tpd) in Ensenada, and the remaining eight percent (217 tpd) between Tecate and Rosarito.

Taking into account the population of Baja California, the average amount collected per person was less than one kilogram per day: 0.864 kg. However there are marked differences in that figure per municipality; for tourists destinations such as Ensenada and Rosarito, this amount was: 1.328 and 1.577 kg per inhabitant per day; respectively. Whereas for the three remaining municipalities, the

amount collected per person was smaller than the regional rate; for Mexicali was 0.774, for Tijuana was 0.746 and for Tecate was 0.732.

In general, waste collection is simple in the main cities of Baja California. Garbage trucks collect household waste—usually inside bags in garbage bins—at residential areas. Then it is transferred to landfills located outside city limits. There is not a formal process of waste separation, although there is informal recycling of aluminum cans, metals and other type of items. It has been reported that although the collection system does not served industries, is likely that special handling waste end at municipal landfills (Martínez, 2008).

In particular, there are differences associated to each municipality in Baja California; for example by 2008 Martínez reported for Mexicali—where waste management is entirely run by the local government—the existence of one landfill site with three transfer centers, three dumpsites formally managed by the local government as final disposal and 23 illegal dumping sites. For Tijuana—where the waste management is privately run—, there were one landfill under construction with two transfer centers, five dumpsites and 98 illegal dumping sites. By 2008, Cuoto mentioned the existence of a dumpsite in Rosarito where USW from Tijuana— specifically Playas de Tijuana and San Antonio de los Buenos—disposed part of its waste flows.

Currently there are five landfills in the State, one per municipality. These disposal sites partially fulfil the appropriate regulation (NOM-083-Semarnat-2003); the presence of scavengers at rubbish tips usually difficult landfill operations.

As previously mentioned, waste does not stop being a source of concern after being deposited in a landfill site, even "properly" disposed waste is subjected to processes that will end generating two main end products: leachate and gas. As the interest of this document is on the relationship between USW and climate change, the following paragraphs aim to elucidate the generation and nature of landfill gas.
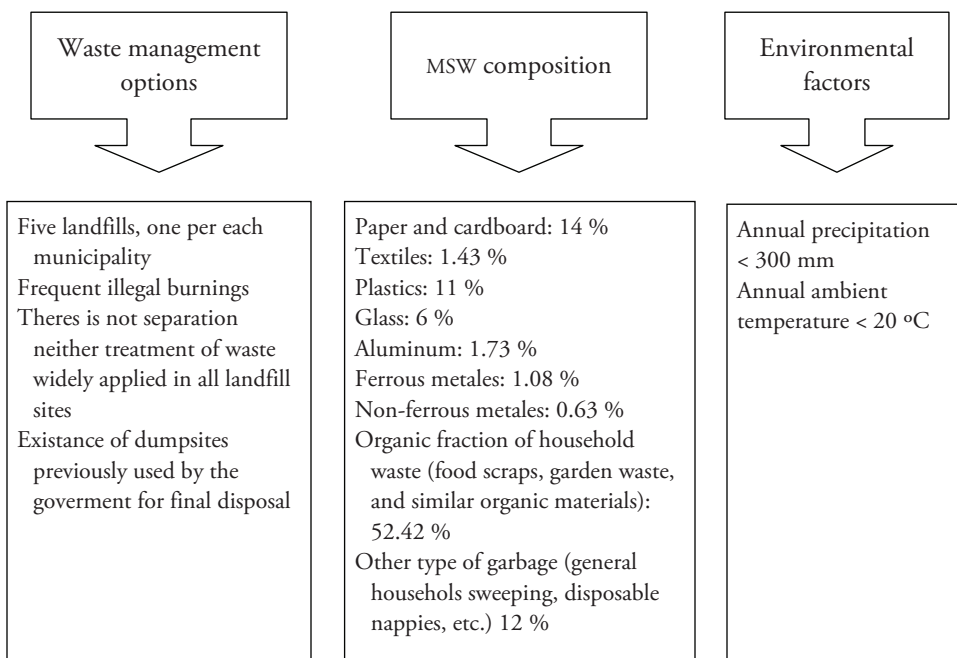
Biogas within a landfill is produced by the anaerobic decomposition of domestic refuse (USW). It is a mixture of gases and is colourless with an offensive odour due to the traces of organosulphur compounds. Its production varies with time, stars within three months to one year after waste deposition; reaches its peak at 5-10 years and tapers off over 20-40 years (Porteus, 2008).

The composition of landfill gas is 55-70 percent methane, 30-45 percent carbon dioxide, some inert gases and sulfur compounds and energy content—of CH_4 per ton USW—of 167-373 MJ/Ton USW; usually 100-200 m^3 of gas are produced per ton of organic USW digested (Hesnawi and Mohamed, 2013).

The production of landfill gas, however, is determined by a number of factors; these include but are not limited to the type and age of the waste buried in the landfill, the quantity and type of organic compounds in the disposed waste; and landfill conditions, in particular moisture content and temperature whose levels are influenced by the surrounding weather conditions.

Figure 2 depicts three main factors that influence landfill gas generation: waste management options, "typical" composition and environmental factors; for each set of parameters values are provided for the Baja California conditions.

FIGURE 2. MSW Composition, Environmental Factors
and Waste Management in Baja California by 2013

Waste management options	MSW composition	Environmental factors
Five landfills, one per each municipality Frequent illegal burnings Theres is not separation neither treatment of waste widely applied in all landfill sites Existance of dumpsites previously used by the goverment for final disposal	Paper and cardboard: 14 % Textiles: 1.43 % Plastics: 11 % Glass: 6 % Aluminum: 1.73 % Ferrous metales: 1.08 % Non-ferrous metales: 0.63 % Organic fraction of household waste (food scraps, garden waste, and similar organic materials): 52.42 % Other type of garbage (general househols sweeping, disposable nappies, etc.) 12 %	Annual precipitation < 300 mm Annual ambient temperature < 20 ºC

Source: Compilation based on SPA-BC and INE (2012), and Inegi (2013).

As seen in Figure 2, the "typical" composition of USW in Baja California is rich in carbon and hence likely to generate landfill gas by anaerobic decomposition of domestic refuse (USW) (Semarnat, 2012). Given variations between municipalities over time, one may wonder if USW composition changes to the point of not being

carbon rich. But after careful revision observation holds. For example, by 2011 the composition of USW in Ensenada was: 39.15 percent food scraps, 21.59 percent paper and cardboard, 12.12 percent plastics, and the rest were textiles, glass and metals (Taboada-González, Aguilar-Virgen y Ojeda-Benítez, 2011). For Mexicali, 65.5 percent was organic materials, 21 percent paper and cardboard, 10.8 percent garden waste; and the remaining were wood residues, leather and others. Whereas for Tijuana, it was reported that the main component of USW was: 30 percent of food scraps, 15 percent of sanitary solid waste, 5.8 percent of garden waste, 4.7 textiles; and 4.1 percent plastics (Parra, Aguilar-Virgen y Ojeda-Benítez, 2010). As seen, there is plentiful substrate to generate landfill gas in the end disposal sites of Baja California.

Excess of substrate is not enough, as gas generation will occur if the following landfill conditions are met (Haug, 1993):

- Temperature: 25-40 °C.
- Moisture content: 40-60 percent.
- Oxygen concentration.
- pH: 5.5 to 8.

From the annual environmental factors shown in Figure 2 is not easy to discern if anaerobic conditions will be achieved at regional landfills. But checking seasonal changes (SPA-BC and INE, 2012) is observed that precipitation is scarce in Baja California. In the northwestern side of the State, maximum rates happen during winter (November to March). In the oriental side of the region, rain also occurs during summer. This precipitation patters could result in percolation and storage of rainwater in landfill sites, this could enhance moisture contents levels in time.

On the other hand, annual average temperature in Figure 2 is indeed representative of the region but for the area of the Gulf of California and Mexicali, where average temperature is usually higher than 25 °C. The maximum temperature occurs between July and August (> 27 °C), while the minimum temperatures take place during December and January (< 12 °C). As observed, environmental conditions are likely to propitiate anaerobic conditions inside local landfills in Baja California.

Finally, the waste management options shown in Figure 2 are a brief summary of the conditions officially reported (Inegi, 2013). During the period studied, many changes happened in the ways waste was handled in the Baja California

municipalities. For example, Tijuana disposed its waste in a dumpsite from 1970 until 1997 when it was transformed to a controlled dumpsite under private management. This controlled dumpsite reached the end of its useful life in 2004. By 2003, the local government bought a piece of land and put it under private management to built and run a landfill site for a lease of 20 years. The beginning of the new landfill operations brought many changes in particular limited operation due to access to the site (because of an unpaved and rough road), partial abandonment of transfers stations and shortages of garbage trucks; these and further changes caused a crisis in 2007 same that was resolved in 2008; in that year it was reported that 70 illegal dumping sites were closed and 3 000 tonnes of waste were collected; at the same time it was announced the opening of a recycling center (Cuoto, 2008). As noticed, the generation of gas is likely to occur in the ways waste has been and is managed in Baja California.

CALCULATION METHODS

Estimation of Methane from usw

GHG emissions, methane is particular, from USW in Baja California were estimated using the IPCC methodology (1996)[3, 4] and data of both population and USW annually generated in Baja California.

Population data were taken from the National Censuses (Inegi, 1990, 1995, 2000, 2005, 2010). Population for the in-between years was calculated by interpolation. Data on the amount and composition of waste were obtained from Semarnat (2012).

In order to compute the carbon content in USW, first its average composition was estimated using official data reported from 1992 to 2005 (results are shown

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[3] Although there is an IPCC methodology dated 2006. The 1996 methodology was applied because has international recognition and acceptance. The 2006 is still under international scrutiny.

[4] The IPCC methodology for estimating CH_4 emissions from disposal sites is based on the First Order Decay (FOD) method. This method assumes that the degradable organic component (degradable organic carbon, DOC) in waste decays slowly throughout a few decades, during which CH_4 and CO_2 are formed. If conditions are constant, the rate of CH_4 production depends solely on the amount of carbon remaining in the waste. As a result emissions of CH_4 from waste deposited in a disposal site are highest in the first few years after deposition, then gradually decline as the degradable carbon in the waste is consumed by the bacteria responsible for the decay (IPCC, 2006).

in Figure 2). Then the different percentages of organic substances in USW were multiplied by their appropriate default factor and summed up, such multiplication was equal to 0.15; this fraction was "the degradable organic carbon."

To estimate the methane emissions from the degradable organic carbon fraction in USW, Equation 1 was used (IPCC, 1996):

Methane emissions = (USW$_T$ x USW$_F$ x MCF x DOC x F x 16/12)   (1)

where:
USW$_T$ = total USW generated (G/yr).
USW$_F$ = fraction of USW disposed to solid waste disposal sites.
MCF = methane correction factor (fraction).
DOC = degradable organic carbon (fraction).
F = fraction of CH_4 in landfill gas (default is 0.5).

Methane emissions were transformed to equivalent units of CO_2, by multiplying them times 21.

In Equation 1, the fraction of USW disposed to solid waste disposal sites (USW$_F$) and MCF reflect the way waste is managed and the effect of site structure and management practices on CH_4 generation (IPCC, 2006). The waste management options identified for Baja California are three: 1) anaerobic managed solid waste disposal sites (MCF = 1), 2) unmanaged shallow solid waste disposal sites (MCF = 0.8); and 3) uncategorised solid waste disposal sites (MCF = 0.6). For the period studied 1990 to 2010, the MCF was taken as 1; this was decided in a way to balance the variability of waste management options used in the municipalities of Baja California. This assumption is likely to overestimate in nearly 20 percent methane emissions in the first third of the period; however, this amount aims to compensate for known but not quantified open pit burning activities. Despite this assumption, it is likely that the methane emissions in Baja California for the period 1990-2010 are conservative estimations.

Forecasting of usw Generation and Methane Emissions

In order to forecast GHG emissions until 2050 (in periods of five years); first the expected volume of USW was computed; to do so population projections to 2030 were used (Conapo, 2010). For the period 2035 to 2050 population data was extrapolated using the linear model shown in Equation 2:

$\hat{Y}_t$ = 1 617 601 + 77 109.2 x t (2)

The number "1 617 601" in Equation 2 indicates the average number of inhabitants at the beginning of the period t (in years).

Once population projections were ready, the USW expected volume was computed using the multiplicative Winters model; this was chosen because fairly describes seasonal changes that are not constant; in addition it is appropriate to apply when dealing with growing seasonal trends. To apply the Winters model the Equation 3 was used:

$$\widehat{Y_t} = (0.2_{t-1} + 0.4_{t-1}) \times 0.2_{t-p} \tag{3}$$

where:

$\hat{Y}_t = \left(L_{t-1} + T_{t-1} \right) \text{x } S_{t-k}$

Lt_{-1}: Series random factor, volume of USW at t-1.

Tt_{-1}: Series trend (slope of the trend component), increment of the USW volume at t-1.

St-p: Seasonal component (seasonal factor at the period t), volume of USW at the current year t, k represents the forecasting periods ($k \leq p$).

Once USW volumes were forecasted from 2015 to 2050 in five-year periods. The expected GHG emissions were calculated applying Equation 1. It was assumed that USW composition remain constant for the forecasted period. However, changes in the constitution of USW compounds could be used to update the degradable organic carbon fraction in USW.

Reduction Scenarios of ghg from usw

To build reduction scenarios, selected technologies and strategies were chosen after careful review to identified the best and more suitable alternatives for the region in terms of low technical needs, accessible costs and feasibility of implementation. A potential GHG mitigation potential—in percentage—was associated to each selection and eight scenarios were built as described in Table 1. The potential percentages for each scenario were deducted from the baseline—given by the Business-as-usual scenario—along the period 2015-2050.

RESULTS

Estimations of methane emissions from USW showed a steady increase of 0.604 Gg/year for the period 1990-2010. In 1990 USW generated 5.4 Gg of methane,

equivalent to 114.4 Gg of CO_2. In 2010 methane emissions reached 17.5 Gg, this is 368 Gg of $CO_{2\,eq}$.

TABLE 1. Reduction Scenarios of GHG from USW

| Scenario	Potential of GHG emissions reduction	Context
A: Business-as-usual	None	No mitigation actions are carried out
B: Reduction of USW generation	30 %	This goal could be reached through reduction of USW generation from 0.98 to 0.69 kg/person/day (the lowest existing rate—that happens in the South of Mexico—). The net downgrade of 0.29 kg/person/day could be achieved through recycling and separation of organic-rich waste
C: Power generation biodigestor	60 %	It is assumed that during the biodigestor useful life (20 to 25 years) this reduction will remain constant; and there won't be further biodigestor installations
D: Change in consumption patterns + anaerobic digestion	90 %	This scenario considers a mix of social components and technological strategies, summing up scenarios B + C
E: Biowindow	28.83 % (Scheutz *et al.*, 2011)	Biowindows are relatively small units of biofilter material—often compost—placed on top of the landfill cover; where material is integrated enhancing biological oxidation of methane
F: Composting	46 % (Jäckel, Thummes and Kämpfer, 2005)	Biodegradable matter such as grasses, leaves, paper and kitchen waste may be broken down by aerobic micro-organisms to form a stable compost material which can be used for a variety of horticultural and agricultural applications (Porteous, 2008)
G: Vermicomposting	65 % (Singh *et al.*, 2011)	It involves the stabilization of organic solid waste through the use of earthworm (*Eisenia foetida*)
H: Biocover	71.8 (Pedersen, Scheutz and Kjeldsen, 2011)	This is a composting cover on top of the landfill that will promote biological oxidation of landfill methane

Source: Compilation based on the references above mentioned.

Forecasted methane emissions tended to growth at a rate of 0.205 Gg/year for the period 2015-2050. Projection results indicated that 18.5 Gg of methane from USW—equivalent to 389.5 Gg of CO_2—would be generated by 2015. By 2050 methane emissions will reach 25.7 Gg that accounts for 539.9 Gg of $CO_{2eq.}$; this

latter value is 1.5 times higher than corresponding estimations for 2010. Forecasted results defined the BAU or inertia scenario; these computations were used as the baseline to compare reductions brought by mitigation actions considered in the other seven scenarios.

Results for estimated and forecasted methane emissions are depicted in Figure 3. The former are shown in silver and the latter in graphite. The gap between the years 2010 and 2015 is purposely left blank; in order to remain readers that such increase is but a possible scenario.

FIGURE 3. Methane emissions from UWS in Baja California
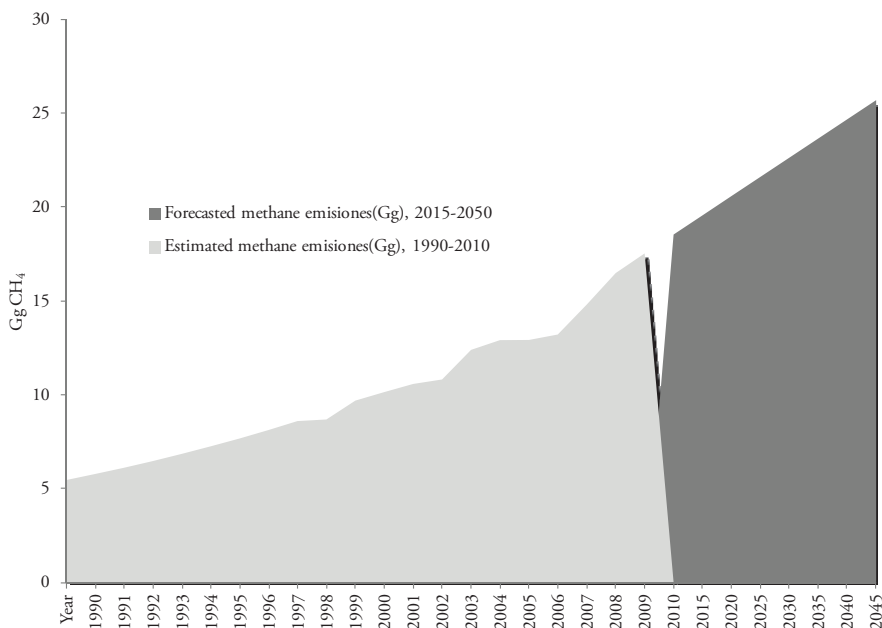
Source: Prepared by the authors on the basis of results obtained.

Reductions scenarios are sumarised in Table 2, where GHG emissions in Gg of $CO_{2eq.}$ are shown for the first and last forecasted years; together with the average generation for the whole period. In addition, reduction scenarios are depicted and compared in Figure 4.

FIGURE 4. Scenarios for Forecasted Methane Emissions from USW, 2015 to 2050
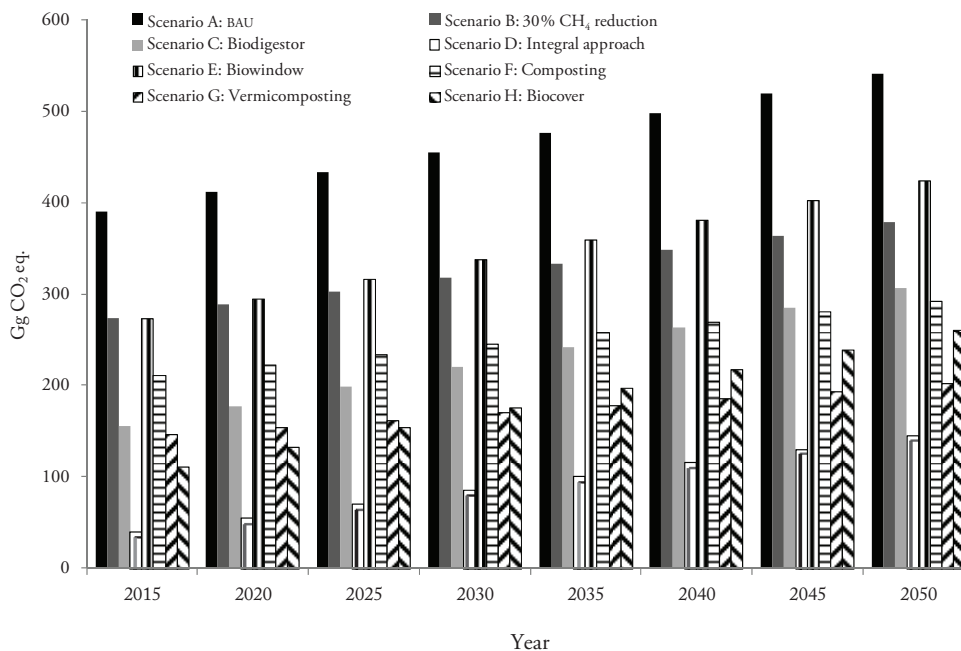
Source: Prepared by authors on the basis of results obtained.

TABLE 2. GHG Emissions from USW under Eight Reduction Scenarios;
Units Are Given in Gg of CO_2 eq.

Scenario	2015	2050	Average generation
A: Business-as-usual	398.5	539.9	464.7 ± 52.6
B: Reduction of USW generation	272.6	378	325.3 ± 34.5
C: Power generation biodigestor	155.8	306.2	231 ± 49.2
D: Change in consumption patterns + anaerobic digestion	38.9	144.3	92.1 ± 34.6
E: Biowindow	116.8	423.1	347.9 ± 49.2
F: Composting	179.2	248.4	250.9 ± 26.6
G: Vermicomposting	145.1	201.2	173.2 ± 18.3
H: Biocover	109.8	260.3	185.1 ± 49.2

Source: Prepared by authors on the basis of results obtained.

DISCUSSION

It is widely recognised that the accelerated industrialization and urbanization in the region, the ever growing population and the adoption of consumption patterns from the neighbouring country have contributed to increase the USW generation in Baja California.

In addition; despite the existence of legal instruments regarding USW management at regional level, tools' application has not been fully functional neither effective because the lack of knowledge and limited technical capacity of personnel involved in the process (Martínez, 2008). Although, another reason was that USW management has been almost limited to technical aspects leaving behind the social component (Cuoto, 2008).

As a consequence of the failure at reducing USW generation, methane emissions have been steadily growing for the period 1990-2010. Furthermore, methane emission from USW will tend to increase until 2050—and forward—if measures are not taken. Facing this situation, it is urgent to implement effective actions to reduce emissions. However, to put measures into effect implementers will have to deal with a mix of intricate factors in reality, where reduction of USW generation could not be expected to be visible any time soon. But, previous experiences have shown that even under an scenario of 60 percent rise in USW volume, it was possible to reduce methane emissions using a mix of recycling, composting and generation of electricity through biogas (Weitz *et al.*, 2002).

It is at this point that scenario building comes in handy into decision-making; previous experiences have shown the usefulness of scenarios building to identify more sustainable use of resources and waste management (Thorneloe, Weitz and Jambeck, 2007).

Clearly, inaction is not an option; however, instrumentation of actions to mitigate methane emissions from USW reserves a meticulous consideration of the appropriate reduction strategy or mix of strategies, as they entail falling into expenses, investing at long term, impacting environment and society; and generating employment and revenues. Scenarios considered in this study have advantages as well as disadvantages as described next:

Scenario B has the advantage of a constant reduction rate but the disadvantage of requiring it to be from the organic rich fraction. As reported elsewhere it is possible to recover and recycle only 45.71 percent of the organic rich USW, this percentage corresponds to paper and cardboard (Ojeda-Benitez, Armijo and Ramírez-Barreto, 2000). The rest of organic rich waste such as food scraps and gar-

den waste are difficult to reduce without a profound change on the consumption pattern of the general public. Lessons from this scenario are *1)* that it is possible to reduce almost in half the USW volume through recover and recycling, particularly of paper and cardboard; and *2)* that this measure should be complementary of any other appropriate strategy.

Scenario C shows that methane emissions could be drastically reduce through the use of biodigestors, especially during the first ten years after installation. Furthermore, this option has the advantage to potentially generate energy prior an investment of around 112 000 U.S. dollar for a large, field-erected, water wall cogeneration or electric generation facility with a dry scrubber with between 2 000 and 3 000 tpd processing capacity (Velzy and Grillo, 2007). Energy can be used in applications for the industry or households alike (IPCC, 2011). However, despite of the economic benefits this option does not reduce USW generation neither methane emissions. It does buy time to implement alternative strategies during the lifespan (~25 years) of this type of infrastructure. This could be an attractive option for cities such as Ensenada, Tijuana and Mexicali.

Scenario D made clear that the most effective strategy requires both social components—such as willingness and knowledge from the general public to separate and recycle materials—and technical strategies. This option is more attractive for bigger USW generators such as Ensenada, Tijuana and Mexicali.

Scenario E underperformed compared with the rest of scenarios, particularly five years after installation. This is not a feasible alternative for Tijuana, Mexicali or Ensenada. However, it could be an option for small cities such as San Quintín.

Scenarios F and *G* reduced moderate to considerable volumes of methane emissions. Major drawbacks for these two options are the large land areas needed for USW treatment; and the transportation required—and its emissions and costs—(Andersen, Christensen and Scheutz, 2010). Although transportation can be avoided if waste is treated *in situ*; then general public training on composting and vermicomposting is a must. A possible outcome of these options is public awareness regarding USW generation.

Though involving population could become a barrier for these options. Taboada, Aguilar and Ojeda-Benítez (2010) determined that social perception in Ensenada is not positive, although general population considered that waste generation was a problem, they also acknowledge that the solution to such problem was a sole responsibility of the municipal government in turn. Thus after waste collection occurred, people stopped worrying about waste. These findings should

warn anyone interested in implementing composting and vermicomposting strategies—or any other alternative considering social involvement. For a successful completion, first a command-and-control strategy should be applied; such as commanding population to treat organic rich waste from home and to apply fines to offenders or to reward people that go beyond the stipulated measure.

Scenario H is similar to Scenario E but to a bigger scale in terms of methane emissions reductions. And could be an option for medium size cities.

After this revision, it is clear that there is not a single answer to reduce once and for all methane emissions from USW. To deal efficaciously with this problem a mix of strategies should be adopted taking into account local conditions. It should be also consider that implementation may happen in consecutive periods of time.

To ensure a successful outcome, implementers have to make the most of advantages and even disadvantages of strategies appropriate for the region, and in addition to encompass existing initiatives related to USW.

For example, Tijuana's municipality could decide to install a biodigestor through a public-private partnership to generate electricity from biogas generated in the existing landfill, and for 10 years reduce methane emissions while earning revenues. This action will require to offer alternative employment to current scavengers and to create points-based incentive programs—or similar—where participants collect and redeem points for rewards. At the same time, planners should make the most of the recently open composting center under management of NGO's with US Environmental Protection Agency (USEPA, 2013) funding. While this is happening, administrators should advance Environmental Education strategies for long-term solutions.

Saying that is convenient to reflect upon the current status of Environmental Education in Baja California. The Environmental Protection Law for Baja California in its article 51 establishes that educational institutions at all levels must incorporate courses on environmental subjects in their curricula. Additionally, the Education Act in Baja California in its article 14 stipulates that regional education goals must include instilling foundations and principles of environmental science, sustainable development and protection and conservation of the environment; and encouraging the understanding of environmental problems and how to prevent and solve them. However, none of these two Acts lie down a sound strategy to reduce waste; education is limited to both correct final disposal and separation. This gap opens up an opportunity to introduce strategies on changing consumption patterns in tools currently under development such as the Environmental

Education, Training and Communication Plan (Plan de Educación, Capacitación y Comunicación Ambiental: PECCA) (PFEA, n. d.).

In summary, the solution to reduce emissions in Baja California needs a mix of strategies that include the use of technology—as commonly done—in the short term, while buying time—around 20 years—to implement changes at social level using environmental education that goes beyond teaching how to separate waste and centers in reducing waste generation.

CONCLUSIONS

Results showed that estimations of methane emissions from USW for the period 1990-2010 displayed a steady increment, with an annual rate of 0.604 Gg. In 1990 USW generated a total of 5.4 Gg of methane, or the equivalent to 114.4 Gg of CO_2. By 2010, methane emissions reached 17.5 Gg; this is 368 Gg of $CO_{2\ eq}$.

Forecasted methane emissions also exhibited a continuous increase for the following 35 years. These were 1.5 times higher than for 2010 by the end of the period. Results indicated that 18.5 Gg of methane from USW—equivalent to 389.5 Gg of CO_2—would be generated by 2015. By 2050 methane emissions will reach 25.7 Gg that accounts for 539.9 Gg of CO_2. Forecasted methane emission were developed under the assumption that patterns observed for the 1990-2010 will continue undisturbed for the next 35 years, or in other words under a BAU or inertia scenario. These results set the baseline and were used to project scenarios of reductions of methane emissions from USW.

This work contemplated seven scenarios to reduce GHG emission from USW generation in Baja California: *1)* 30 percent reduction of methane emissions, *2)* the installation of power generation biodigestor, *3)* an join strategy of social components leading to modify consumption patterns + the use of biodigestor, *4)* biowindow, *5)* composting, *6)* vermicomposting, and *7)* biocover. Results from scenario building showed that is possible to plan measures or even combine strategies.

It should be noticed that scenarios including the use of end-of-pipe technologies—such as the installation of biodigestors—have the potential to achieve moderate to high reductions and could be considered as short/medium-term solutions.

Scenario building results also showed that is feasible to plan under constraints; for example if funds are limited to opt for a biodigestor installation, scenario building analysis could help to prioritise cheaper mitigation options such as composting, vermicomposting and biocover; or others not considered here.

Additionally, scenario building revealed the importance of involving the general public in mitigation actions; if not USW generation and their emissions will continue to increase in time.

Results proved the hypothesis of this study that regional characterisation of GHG emissions from USW generation provides an input into local decision making. Furthermore, this information could help to delineate public policies on mitigation actions in the local waste sector at short and long term; however, to ensure success a wide participation of key actors is needed to mobilise locally existing resources, including political will and social pressure to respect medium and long term objectives. This last finding coincides with a crucial result from a 2013 workshop on finding solutions to the USW generation in Tijuana, then participants identified as priorities both engagement and collaborations among key players involved in USW management to solve the waste problem in the city (Puma, 2013).

Finally, it should be recognised that information provided by PEACCs, specifically in their GHG emissions inventories; is but an approximation to reality; based very much on official statistics and assumptions that are not likely to exactly represent the changing nature of USW generation within a municipality. Limitations imposed by aggregate information could be overcome if detailed and local information is used. It must be added that by 2011 there were nearly 50 municipalities in sundry regions engaged in developing Climate Change Acts at their own level and jurisdiction (Semarnat and INECC, 2012) together with their GHG inventories.

Saying this, the findings of the present study still remain; as demonstrated here even though using aggregate and limited information as those depicted in official statistics, it is possible to delineate measures to reduce GHG emission from USW via regional reduction scenarios building. Moreover, the process detailed here could well become a blueprint for other regions in Mexico.

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