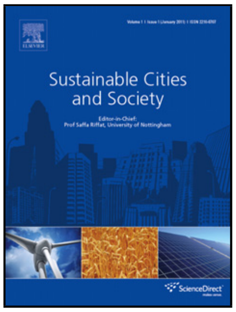

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Integrating Urban Metabolism, Material Flow Analysis and Life Cycle Assessment in the environmental evaluation of Santiago de Compostela

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Highlights:

- The MFA-LCA method assessed the environmental profile of Santiago de Compostela.
- Five environmental impact categories, uncommon in UM studies, have been accounted.
- A simplified MFA-LCA provides results similar to those of more complete studies.
- Fossil fuels are the main contributors in all impact categories, followed by food and beverage production.
- The MFA-LCA method allows the development of a broad environmental strategy plan.

Abstract

Achieving urban sustainability has become imperative. The combination of Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) could be considered an attractive method to assess the sustainability of a city’s metabolism. However, the need for exhaustive data makes this method time-consuming and uncertain. This study carries out a simplified UM-MFA-LCA analysis of the city of Santiago de Compostela (Spain) based on 7 primary flows. This approach allows: i) to determine the environmental profile of a city never before studied and ii) to determine whether a simplified analysis provides environmental impacts results similar to those of more complete studies – i.e. those in which other flows such as manufactures and building materials were also considered in the inventory data. The findings of this analysis report that the flows considered, combined with the MFA-LCA methodology, provide a 'sufficiently accurate' environmental impacts account when no further data is available. Furthermore, the results are highly disaggregated and a comprehensive environmental strategy plan for a city can be developed. The LCA results of Santiago de Compostela indicate that most of city's impact happens outside its limits. Direct emissions are also identified and a number of improvement measures are proposed for both cases.

Keywords:

Environmental impacts; Flows quantification; Spain; Sustainable city; Urban planning.

Abbreviations:

Urban Metabolism (UM)

Material Flow Analysis (MFA)

Life Cycle Assessment (LCA)

Wastewater Treatment (WWT)

Municipal Solid Waste (MSW)

Highlights:

1) The MFA-LCA method assessed the environmental profile of Santiago de Compostela.

2) Five environmental impact categories, uncommon in UM studies, have been accounted.

3) A simplified MFA-LCA provides results similar to those of more complete studies.

4) Fossil fuels are the main contributors in all impact categories, followed by food and beverage production.

5) The MFA-LCA method allows the development of a broad environmental strategy plan.

1. Introduction

Cities are voracious resource-consumers, whose contribution to environmental impact is recognized (Dias et al., 2014; Moore et al., 2013; Petit-Boix et al., 2017). Today, more than half of the population live in urban areas, and this number is expected to grow up to 66% in 2050 (United Nations, 2014). Therefore, the demand for energy and materials will increase together with the generation of wastes and pressure on the environment. In fact, this fast urban development motivated the consideration of cities as relevant organisms for achieving sustainable development, as it can be seen in the 7th Environment Action Plan of the European Commission (European Commission, 2012) and the Global Goals proposed by the UN (United Nations, 2015). These two examples constitute attempts to accomplish the targets of urban sustainability: to maintain the quality of life (in terms of employment availability, housing and culture among others) while enjoying a healthy environment (Conke and Ferreira, 2015). The first step for urban sustainability is to promote the proper management of an urban region, for what it is necessary to understand how the city works, i.e. to model the behaviour of the city (Rosado et al., 2014). An attempt was carried out by Wolman (1965), who regarded the city as analogous to a living organism, and described how materials and energy flowed into the system, introducing the urban metabolism metaphor (UM). Nutrients (resources) must be imported to the city to maintain its metabolism, and their consumption generate metabolites (wastes), which harm the ecological environment of the organism if not correctly managed (Kennedy et al., 2007). Since then, the UM approach has undergone transformations, such as the Cyclic Model of Girardet (1990), to describe the reused materials and other fluxes that return into the system; and the Extended Metabolism Model of Newman (1999), where the liveability of the city was first considered. These two researchers, as well as Sahely et al. (2003) and Balocco et al. (2004), based their UM studies on the “black box” approach, which relies on the description of flows coming in and going out of the system (Beloin-Saint-Pierre et al., 2017). Later, Zhang et al. (2009) developed a network process for UM to improve the black box approach, disaggregating inputs and outputs to be assessed from a life cycle perspective (Beloin-Saint-Pierre et al., 2017).

Kennedy and Hoornweg (2012) proposed a list of recommended urban metabolism flows to be included in any related study. However, UM remains as a conceptual approach with remarkable variations between studies regarding the materials, energy sources and pollutants included in the individual assessments (Goldstein et al., 2013; Petit-Boix et al., 2017). As a consequence of this lack of standardization, several methods have been developed to account for UM flows such as Material/Energy Flow Analysis, Energy Assessment, Ecological Footprint, Input-Output analysis, Life Cycle Assessment, Network Analysis and even a combination (Beloin-Saint-Pierre et al., 2017). Among all of them, Material Flow Analysis (MFA) receives special attention. The reason for its success is that MFA allows an easy-understanding of the material basis of the economy of the system, while it facilitates the identification of inefficiencies in the use of resources. In fact, MFA is recommended by the Organization for Economic Cooperation and Development for those involved in the interpretation of such measures (OECD, 2008). However, MFA lacks standardization, although some attempts have been carried out in this way (European Commission, 2001).

MFA alone cannot accurately calculate the environmental impacts of the system. Although it can measure the flows in and out of the system, MFA does not take into account the actual environmental consequences of the emission of such flows. To overcome this drawback, it has been combined with environmental analysis tools such as Life Cycle Assessment (LCA). The combined methodology allows providing an in-depth analysis of the system behaviour (Lopes Silva et al., 2015; Nakem et al., 2016; Rochat et al., 2013; Turner et al., 2016). LCA is a tool based on a standardized framework capable of quantifying all the environmental impacts from a life cycle perspective (ISO, 2006). When combined with MFA under an UM perspective, LCA allows determining the environmental pressure of cities by modelling impacts embedded in the foreground and background flows of the system (Goldstein et al., 2013). For instance, Turner et al. (2016) adapted MFA-LCA to develop a decision support system for solid waste management in Cardiff (Wales).

In this study, a combination of i) MFA for the definition and quantification of the energy and material metabolic flows and ii) LCA for estimation of the corresponding environmental analysis is applied to the metabolism of the city of Santiago de Compostela (NW Spain) over a period of one year. The main goals are i) to carry out a cradle-to-gate evaluation of the city’s environmental profile, considering all the foreground and background flows involved in the consumption of resources reported in the MFA; and ii) to identify the key responsible flows of these environmental burdens. The assessment has been carried out considering a simplified MFA and some material and energy data typically missing on official sources have not been considered (e.g., building materials and finished products such as textiles and electronics). Since full MFA are complex and time-consuming studies, it could be interesting to identify similar trends on the environmental profiles when a simplified study is performed. Consequently, this article could help to detect the environmental burdens of Santiago de Compostela and therefore, to optimize the development of its future environmental policies. Furthermore, it could support the identification of to what extent detailed inventory data are required. Some previous studies have accounted the flows (Álvarez et al., 2018; Navamuel et al., 2018) or the environmental profile of different Spanish cities (Andrade et al., 2018; Gonzalez-García et al., 2018; Vedrenne et al., 2014) or regions (Gonzalez-García et al., 2018; Roibás et al., 2017), but none with such a level of detail at municipality scale. Therefore, the combination of LCA and MFA is essential for the proposal of effective sustainability policies as well as it could allow bridging gaps related to UM. In fact, the findings from this analysis may let politicians and researchers carry out a comprehensive evaluation of the urban activities performed in the city considering items such as transportation, waste management and energy use, which will finally imply reductions on the environmental impact of the city.

2. Materials and methods

The environmental profile of the UM of Santiago de Compostela (NW Spain) has been determined by using a combined MFA-LCA method. To this purpose, both the method and the case study were initially defined; then data from different sources were collected and adapted if necessary. Finally, an LCA was carried out and its results discussed.

2.1 Description of the MFA-LCA method

Using the UM metaphor, the city is assimilated to an ecosystem with a conjunction of flows entering and leaving the system, which are identified according to the MFA methodology (Brunner and Rechberger, 2004). It establishes material flows and balances for the entire system. The LCA approach is performed to evaluate the environmental pressure of the city. The impact assessment method chosen is the hierarchist approach of ReCiPe v.1.12 Midpoint (Huijbregts et al., 2016). ReCiPe has been chosen as it is the most updated method, and, unlike other LCIA methods, allows an overview to assess impacts (Goedkoop et al., 2013). In addition, it is commonly used by other authors (e.g., Goldstein et al., 2013), making it easier to compare studies. The hierarchist perspective has been assumed as it is based on the most common policy principles regarding the timeframe and other issues (Goedkoop et al., 2013). Finally, the attributional modelling and the allocation for co-products have been selected. The environmental profile of the city has been characterized in terms of five impact categories: climate change, ozone layer depletion, terrestrial acidification, freshwater eutrophication and human toxicity.

2.2 Case study

Santiago de Compostela is the capital of Galicia, a region located in northwestern Spain. Its climate is rainy (148 days of rain in 2016) and its temperature varies seasonably from a minimum of -1ºC to a maximum of 40ºC, as recorded for the year 2016 (IGE, 2016). The average household income in Santiago de Compostela reached 35,040 € in 2009 (IGE, 2009), above the Spanish value of 30,045 € in the same year (INE, 2009).

Santiago de Compostela has a well-provided infrastructure to sustain the everyday life of its inhabitants. This fact makes the city doubly attractive for an environmental study. Firstly, to identify the hotspots this infrastructure might have and propose improvement measures. Secondly, as an example of a typical European city. Concerning the latter, Santiago de Compostela is also a good choice because of its medium population: the city has 95,966 permanent inhabitants (IGE, 2016a) and 18,900 university students (University of Santiago de Compostela, 2016) within an area of 220 km^2. Furthermore, in 2015 the city received 752,675 tourists (IGE, 2018). The permanent population has kept virtually constant over the period 2016-2011, as the population grew by less than 1% (IGE, 2016).

The European Commission establishes that around 13,500 European cities have less than 1 million inhabitants where half of the total population of the continent lives (European Commission, 2016). Furthermore, its strong dependence on the service sector also goes in line with other European cities. In 2014, 82.1% of its GDP in 2014 was provided by the service sector, followed by industry (6.4%), construction (3.8%) and the primary sector (0.4%), according to IGE (2014). Within the service sector, the major contributor was the tourism, motivated by the St. James Way (Doménech et al., 2016). Tourism, together with the fact that Santiago de Compostela holds the fourth oldest university in Spain, causes a high seasonal variation of the population. From an exclusively environmental point of view, this scenario may be representative from the migration movements that European cities are living nowadays. Finally, data are more accessible in Santiago de Compostela than other Spanish cities, which has been reflected in previous work performed by researchers from the University of Santiago de Compostela (Gonzalez-García et al., 2018; Iribarren et al., 2010; Lorenzo-Toja et al., 2015; Noya et al., 2017a; Vázquez-Rowe et al., 2014). On the one hand, the Galician Statistics Institute (IGE) provides public data on Galician municipalities. Moreover, Santiago de Compostela is the capital of the Autonomous Community of Galicia, which makes it more likely that it will be included in national reports and other official sources.

2.3 Functional unit

The functional unit is the quantified performance of a product system used as a reference unit (ISO 14040, 2006). For example, one bottle of extra virgin olive oil with a volume of 1 L when assessing olive oil production (Tsarouhas et al., 2015). Since cities are ecosystems whose characteristics depend on a considerable number of factors (culture, wealth, total population and geographical location to cite a few examples), defining a functional unit for these systems is extremely challenging. This study follows the same strategy applied by Goldstein et al (2013), Dias et al. (2014) and Roibás et al. (2017). Thus, the gross annual metabolic impacts of cities have been referenced at per capita level considering the officially registered population to do so. Therefore, the results correspond to an average conceptual citizen (inhabitant-equivalent). The students of the University of Santiago de Compostela (USC) are not obliged to register in the official census of the city as it happens in most European and North American universities, so this number was added to the permanent population. However, an average USC student stays in Santiago de Compostela 220 days a year (around 60% of the year). The total number of university students was multiplied by this percentage to determine the ‘effective student population’. In other words, the number of inhabitants-equivalent per year with the same effect in the UM as the actual number of students living only 220 days in the city was also estimated. Therefore, the final number of inhabitants-equivalent is 107,358 and the temporal frame is 2015.

2.4. System boundaries

The current study is focused on seven flows (Figure 1) that represent the main metabolic flows of the city and constitute the foreground level. They have been selected in line with other studies available in the literature (Russo et al., 2014; Shafie et al., 2016). Other researchers added construction materials in the MFA (Moore et al., 2013; Zhang et al., 2011). However, the building sector has undergone a sharp decline in Santiago de Compostela since 2012 - new construction passed from 46 to 20 buildings in three years (IGE, 2016b). As no accurate data are available for building materials, it has been assumed that a minor environmental impact from this flow should take place over the global profile. Goldstein et al. (2013) added manufactures like electronic components and paper, but again these flows were not accounted because of lack of proper information. Goldstein et al. (2013) revealed that they could have a negligible impact on climate change. However, discrepancies have been identified with studies available in the literature. Environmental results from EPA (Environmental Protection Agency, 2016) revealed that manufacturing accounts for 18.2% of total GHG emissions. Similar results were found for Galicia: 16.8% (Roibás et al., 2017). Kalbar et al. (2016) conducted a UM-LCA study that included impacts related to the construction, maintenance and renovation of buildings (grouped as accommodation) along with energy, food, water and transport. In that study, accommodation had a low relative impact on ozone layer depletion (5.8% of total emissions), terrestrial acidification (9.2%), climate change (11.6%) and freshwater eutrophication (11.4%), whereas it becomes outstanding in human toxicity (20.4%). The consequences of not considering manufacturing and building materials in the current system will be discussed in Section 4.

This study follows a cradle-to-gate approach based on the idea that background processes are a consequence of the demand of the city. Background processes related to the production of energy, water, food and beverages as well as the management of wastewater and solid wastes have also been computed as displayed in Figure 1.

Figure 1. Schematic representation of the background and foreground flows considered in the MFA.

Concerning the energy flow, raw material extraction, transportation, processing, distribution and final use of fossil fuels for electricity/heat production activities have been included within the system boundaries. In the case of renewable energy, operation and maintenance activities have been computed. Only wind and hydraulic power are considered. The electricity mix of Galicia (INEGA, 2017) is characterized by a high consumption of coal, natural gas, petroleum and its derivates which are all entirely imported from foreign countries. These fuels, together with biomass, are transformed into electricity in 20 power plants distributed all over the region or directly used as fuel for transportation (petrol and diesel) or heating (natural gas and LPG).

Regarding transport, it corresponds with urban transport related activities and includes the extraction of raw materials, processing and use of petrol and diesel in cars, buses, motorbikes and trucks, as well as kerosene for air traffic. Background operations regarding with urban transport maintenance have been excluded from analysis.

Regarding the water flow, it includes water for human consumption as well as for sanitary and parks maintenance purposes. Extraction, purification and pumping activities have been considered within the system boundaries. The Water Purification Facilities that assists Santiago de Compostela consists of seven stages: catchment, coagulation-flocculation, remineralisation, sedimentation, filtration, disinfection and pumping (Concello de Santiago de Compostela, 2017).

Raw materials production in orchard/farm, processing, refrigeration (when needed) and distribution to wholesalers have been computed with regard to the food and beverages flow. Table 1 shows the flows included in the model.

The treatment of wastewater produced from metabolic activities in the city together with the treatment and final disposal of derived sludge have been included in the analysis. The wastewater treatment plant of Santiago de Compostela consists of a pre-treatment, a conventional primary treatment and a bioreactor with suspended biomass to remove organic matter, but no nutrients are eliminated. In addition, organic sludge is composted, fats are derived for further post-treatment and inert waste is landfilled (Lorenzo-Toja et al., 2015).

Finally, regarding the Municipal Solid Waste (MSW) produced in the city, the collection, transportation, treatment following the model described in SOGAMA (2014) and final disposal of the different waste flows have been considered in the assessment.

2.5 Data collection and assumptions on consumption and production activities

Whenever possible, real data corresponding to the MFA of the system under study (the city of Santiago de Compostela) must be managed to obtain representative results. Otherwise, it is necessary to downscale data from regional or national sources to the local level, as described in the next section (2.4.4).

In this study, the foreground flows that constitute the UM of Santiago de Compostela have been mainly supplied by national and regional governmental corporations. Fossil fuels and energy consumption rates at the regional level have been consulted in the Energy Institute of Galicia (INEGA, 2017). National data on food and beverages consumption have been provided by the Ministry of Agriculture and Fishery, Food and Environment (MAPAMA, 2015). Information regarding the amount and the use of drinking water at regional level has been shared by the National Statistics Institute (INE, 2013); Communication on Municipal Solid Waste (MSW) collection and management at regional the scale has been carried out by the Galician Society for the Environment (SOGAMA, 2014). Surveys revealing kilometres travelled by vehicle type at the city level have been provided by the Spanish Traffic General Directory (DGT, 2016). Data regarding the WWTP of Santiago de Compostela were taken from Lorenzo-Toja et al. (2015). The Galician Statistic Institute has shared information about GDP (IGE, 2014), number of dwellings (IGE, 2011), km^2 of green area (IGE, 2005) and population in Santiago de Compostela (IGE, 2016a).

Finally, some background data regarding the production of all required inputs (i.e., energy, drinking water, food and beverages) were taken from scientific reports. Inventory data concerning the energy production were taken from Dones et al. (2007). Regarding food and beverages group, data corresponding to olive oil production were taken from Salomone and Ioppolo (2012). Data from pork meat production came from Noya et al. (2017). Data concerning fish production were taken from Ramos et al. (2011), Vázquez-Rowe et al. (2011) and Vázquez-Rowe et al. (2016). Data concerning water purification and distribution came from Lorenzo-Toja et al. (2015). Other information was gathered from Ecoinvent® 3.2 database (Steubing et al., 2016; Wernet et al., 2016).

Moreover, the following assumptions have been made to perform the MFA:

- *Energy flow*. No photovoltaic contribution was taken into account, as it represents less than 1% of the energy mix of Galicia (INEGA, 2017). Only the contribution of the fossil fuels to electricity production and to non-industrial heating is considered.
- *Urban transport flow.* Cars, motorbikes, buses and trucks follow the European average EURO 4 design and air traffic is responsible for all kerosene consumption.
- *Food and beverages flow*. Meat products were disaggregated in three groups: pig, chicken and red meat; and fish was categorized as white and bluefish. Furthermore, the ready meals considered were the two studied by Schmidt Rivera et al. (2014). Concerning

soft beverages, only cola drinks are considered to simplify the analysis. This group alone represents 50% of total soft drinks consumption (MAPAMA, 2017). Bottled water is taken as a combination of tap water and a 1.5 L PET bottle. Transport of goods is embedded in this category. The concept of “total responsibility” was applied i.e., all emissions due to traffic, no matter where they were released, were considered as part of the system under study. Although most emissions occur outside the city limits, they are a consequence of the demand of the city and therefore would not exist without it. Finally, when no data were available, it was supposed that materials were transported 600 km in 24-tons trucks. This value is an average of the distance existing between Santiago de Compostela and the capital cities from its three principal food importers: Portugal, France and Galicia itself (IGE, 2016c).

- *Wastewater flow*. Wastewater treatment plant of Santiago de Compostela was reported to treat 18,031,831 m^3 of wastewater in 2012 (Lorenzo-Toja et al., 2015), whereas water consumption in Santiago de Compostela was slightly minor to 5,000,000 m^3 (IGE, 2012). The reason for this difference is that the wastewater treatment plant of Santiago de Compostela does not only collect water from the system under study but also from nearby settlements and rainfall. It was assumed that the amount of wastewater treated is equal to the amount of water consumed in the case study to avoid overestimating the final environmental burden.

2.6.1 Data downscaling

Data available at national and regional level has been downscaled to obtain representative information about the system under study. In this case, ratio-based downscaling has been selected because of its simplicity. Furthermore, it has proved its usefulness in other UM studies (Dias et al., 2014). Usually, this method is based on the idea that the higher the consumption of resources, the higher must be the production to satisfy the demand and thus the higher the environmental impact. Thus, ratios based on production or consumption indicators (named downscaling factors) are common in the literature (Courtonne et al., 2015; Rosado et al., 2014). In this study, several downscaling factors have been proposed to represent the reality of Santiago de Compostela as accurately as possible. GDP has been chosen for those resources directly related with the economy of the city: fossil fuels and energy consumption. The number of dwellings has been used for those products whose consumption takes place mainly in the households: food and beverages, including drinking water. In Spain, around 70% of total expenditure in the food and beverages belongs to households (MAPAMA, 2015). Green surface has been applied to municipal water consumption (irrigation is considered as the only municipal water consumer). Road and air traffic have been selected for those fossil fuels used in vehicles, such as diesel and kerosene. Finally, population has been used to downscale MSW generation.

2.6.2 Inventory

Inventory data considered to perform the LCA are based on the MFA. Table 1 shows the import (inlet) flows of Santiago de Compostela. Table 2 presents the direct output flows of the system.

Table 1. Detailed description of the direct input flows from the city. Average population of the city: 107,358 inhabitants.

Table 2. Detailed description of the direct output flows from the city. Average population of the city: 107,358 inhabitants.

3. Results

3.1 Overall results

Table 3 presents the environmental impacts of Santiago de Compostela per inhabitant-equivalent. According to it, total GHG emissions reached 9.1 tCO_2-eq.inhab-eq^{-1} in 2015. It also presents the effects on ozone layer depletion, terrestrial acidification, freshwater eutrophication and human toxicity.

When it comes to assessing the contribution of the different flows assessed to each impact category (Figure 2), the largest impacts correspond to the use of fossil fuels and energy required in the extraction, processing, distribution and burning of fossil fuels for transport, heat and electricity production. Similar results have been reported by Rahman and Miah (2017). However, in Galicia, the region where Santiago de Compostela is located, this reality is further accentuated by the fact that up to 60% of the energy consumption of the city (including transport) has a fossil origin (IGE, 2016). The pressure of fossil fuels on the environment is followed by that of food and beverage production in all the environmental impact categories considered. Wastewater Treatment (WWT), drinking water production and MSW management have a negligible relative impact.

Figure 2. Distribution of environmental burdens from the main flows considered in the MFA per impact category. Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity.

Table 3. LCA results per capita in year 2015 for Santiago de Compostela. Average population: 107,358 inhabitants-equivalent.

3.2 Detailed assessment per flux

3.2.1 Production and use of energy requirements

According to the results depicted in Figure 3, coal and natural gas can be considered as hotspots due to their outstanding contributions in all the categories under study. In the case of climate change, both fuels are responsible for a total contributing ratio of 78%. Natural gas and fuel oil also have a considerable effect on ozone layer depletion due to the use of halons as fire retardants and coolants required for transportation (Stamford and Azapagic, 2014).

Terrestrial acidification is linked to the combustion of fossil fuels. It stands out coal and fuel oil because of its high sulphur composition. Considering freshwater eutrophication and human toxicity, coal is again the major responsible one, although phosphates and heavy metals emitted within the background level of the system –i.e. during extraction of raw materials and their processing- are the rationale behind its effect in both categories.

Figure 3. Distribution of environmental burdens derived from the production of energy requirements per impact category. Note: Renewable energy includes wind and hydroelectric power. Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity.

3.2.2 Production and use of fuels for urban transport

Direct emissions are the main cause of climate change. Among fuels, all three have similar GHG emissions per kg of fuel: 3.13 kg CO_2-eq/kg fuel for gasoline, 3.20 for diesel and 3.16 for kerosene (Wernet et al., 2016). Therefore, its effect on climate change is related to the amount consumed (see Table 1). Terrestrial acidification also occurs mainly due to direct emissions. On the other hand, direct emissions from transport have a negligible impact on ozone layer depletion compared to background process flows, probably due to the use of halons and chlorofluorocarbons for refinery refrigeration (Morales et al., 2015; Yang et al., 2016). The same goes for freshwater and human toxicity. Phosphates and heavy metals are emitted within the background level of the system. Figure 4 shows the LCA results for fossil fuels. Figure 5 disaggregates the relative contribution to climate change by vehicle type.

Figure 4. Distribution of environmental burdens arising from the production and use of transport fuels. Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity.

Figure 5. Distribution of GHG emissions derived from the use of transport fuels per type of vehicle.

3.2.2 Production of food and beverages flows

According to the results displayed in Figure 6, livestock-based products present the highest effect on climate change, predominantly due to the methane emissions from pig slurry. Enteric fermentation also contributes to climate change, whereas other types of meat such as chicken have negligible impact. The following most important foodstuffs in terms of GHG emissions are fish and milk production. The former owes its impact principally to fuel use in fishing activities and the latter to the enteric fermentation involved in farming activities. In general, it is observed that the agricultural sector involved in the production of fruit and vegetables presents lower impact on climate change. However, the production of some vegetables such as tomatoes (1,608 t) and potatoes (2,556 t) as well as cereals (wheat, 4,120 t) reports the most remarkable effect on climate change due to its high consumption. Within these foodstuffs, nitrous oxide from fertilizers application is the major contributor to climate change. Regarding beverages, cola drinks are those with a higher impact on climate change. The reason is that they are highly consumed by the population (2,393 m^3), reaching around 18% of all beverages in Santiago de Compostela.

The use and leakage of cooling agents such as halons and chlorofluorocarbons during fishing stages are responsible for the impact on ozone layer depletion. Similar results were obtained by Iribarren et al. (2012). Meat consumption (5,682 t) doubles fish (2,890 t) according to MAPAMA (2015). However, because of the nature of its procurement, fish remains chilled longer than meat (Cano-Muñóz, 1991; Johnston et al., 1994) and therefore its impact on ozone layer depletion is greater.

Terrestrial acidification occurs principally because of ammonia emissions, which are produced during manure management (Aguirre-Villegas and Larson, 2016). It is observed that meat and milk production, the two foodstuffs where livestock farming is implied, present a significant impact on terrestrial acidification (70% the former and around 10% the latter). However, contributions from fish production slightly overcome those from milk due to the use of fossil fuels for both fishing operations and refrigeration stages. Livestock farming is again the major contributor to freshwater eutrophication, with about 40% of total contributions to this impact category. The reason for this is the leaching of nitrates and phosphorus from manure to the groundwater during meat and milk production (Brandjes et al., 1996). The impact from oil on freshwater eutrophication is due to the high content of phosphorus present in the wastewater produced in the factories. Fertilizers for olives cultivation present negligible relative impact in comparison. It is observed that freshwater eutrophication is the impact category where drinks present a higher impact. The rationale behind this value is the application of fertilizers for the cultivation of the raw materials. The same fact is observed with fruits and vegetables. Human toxicity is linked to i) the release of heavy metals within the background flows of energy production for livestock products and ii) the use of phytosanitaries in agriculture within the first stages of crop production – i.e. cultivation of fruit and vegetables for direct consumption or for beverages production.

Figure 6. Distribution of environmental burdens per items that constitute the flow of food and beverages in the city. Note: Other foods includes lentils, rice, pasta, eggs, olives and ready meals. Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity.

3.2.3 Production of water requirements

The effect of drinking water consumption on climate change, ozone layer depletion and terrestrial acidification is almost exclusively due to energy demand. Raw water treatment and supply are energy intensive activities, reaching in Spain up to 1.5 kWh/m^3 (Wakeel et al., 2016). Though, the use of chemicals such as sulphuric acid (1.2 kg $H_2SO_4 \cdot m^{-3}$ water) for controlling pH and preventing corrosion during water purification also contribute to terrestrial acidification.

Impact on freshwater eutrophication and human toxicity also takes place mainly by the high energy requirements for both water purification and pumping. Phosphates (freshwater eutrophication) and heavy metals (human toxicity) are released to the environment in the early stages of energy production (Wernet et al., 2016).

Figure 7. Distribution of environmental burdens per processes involved in the production of drinking water. Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity.

3.2.4 Wastewater treatment

The impact on climate change is equally distributed among the production of electricity requirements, the treatment of solid waste and the production of chemicals used (Figure 8). Sludge is concentrated in a filter press and then derived to the landfill, where the decomposition of organic matter releases methane. The effect of the direct use of chemicals on climate change is negligible against the impact of its background flows e.g., the electricity required for synthesizing the chemicals.

The high impact of chemicals on ozone layer depletion (around 65% of total contributing emissions) is a direct consequence of iron chloride as a disinfectant for wastewater. Ozone layer depletion effect of electricity might be due to the use of halons and chlorofluorocarbons within the background processes (Morales et al., 2015; Yang et al., 2016). Impact from wastes treatment on ozone layer depletion is also related to energy requirements.

The contribution of composting to terrestrial acidification is due to the release of ammonia during degradation of organic matter. Emissions of sulphur oxides from fossil energy production also affect terrestrial acidification. In the case of freshwater eutrophication and human toxicity, impact from electricity and chemicals is related with the extraction of raw materials and its processing, both belonging to the background flows.

Figure 8. Distribution of burdens per contributing processes involved in Wastewater treatment. Note: wastes treatment includes MSW incineration and fats treatment. Final disposal includes sludge and inerts derived to landfill. Electricity and chemicals include the production steps. Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity.

3.2.5 Municipal Solid Waste management

MSW management is conceived as a process to limit the environmental pressure of the outlet solid fluxes of the city. Two perspectives have been taken into account: i) MSW management treats residues so its potential environmental impact is lowered and ii) limits the amount of materials and energy that must be imported to the city thanks to recycling and energy valorisation. According to the results presented in Figure 9, SOGAMA model fulfils both perspectives by reducing the environmental impact of MSW to a larger extent than the impact of MSW management itself. The exception is climate change, a category closely related with energy production. In fact, the most terrestrial acidification-reducer process is precisely the one that permits the higher energy saving: energy valorisation by transforming the MSW into a refuse-derived fuel for electricity production. Recycling leads to a significant environmental benefit in all the studied categories. These environmental benefits come predominantly from the avoided products. Plastic and glass are the fluxes whose recycling has a higher environmental potential. First because of its volume (49% of total recovered materials according to SOGAMA (2014)) and second because of the energy demand of plastic and glass industry.

Figure 9. Distribution of burdens per processes involved in Municipal Solid Wastes management. Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity.

4. Discussion

This study employs LCA to determine the environmental impacts related with the metabolic activities performed in the city of Santiago de Compostela. More specifically, the impact categories of climate change, ozone layer depletion, terrestrial acidification, freshwater eutrophication and human toxicity have been considered to report the environmental profile. For this purpose, a methodology adapted to the specificities of the data available is proposed - a combination of LCA with a simplified MFA under an UM approach. This section identifies and discusses the limitations of this combined methodology, provides a comparison with other studies and proposes measures to reduce the corresponding environmental impacts.

4.1. Limitations

Data availability is one of the main drawbacks while performing an UM-MFA analysis (Schwab et al., 2017). In this case study, all data except for the WWTP were only published at a national or regional (Autonomous Community of Galicia) scale. Therefore, a downscaling procedure based on a ratio was carried out.

Another limitation is the lack of spatiality. Referring the gross annual metabolic impacts at the per capital level (i.e, an average citizen), is useful for understanding the complex metabolism of a city, as well as for comparison with other studies. However, it misses the real demographics of the city. It does not allow disaggregating among social and economic groups and therefore limits the development of an optimal strategy plan. Social and economic aspects should be included in future studies.

Temporal discrepancy of datasets is also a limitation of this study, as not all information is available for the same year. For instance, energy, food and beverages data are referred to year 2015, while MSW management and wastewater management to 2013. In all cases, the most updated published datasets were selected –i.e. as representative as possible of the current situation. The temporal discrepancy has a considerable impact on GDP and traffic as downscaling factors and consequently, on the estimated flows. The other downscaling factors (population and surface of green area) have undergone few changes in the time range considered. However, no significant variations in LCA results are expected. Other sources of error typically associated with MFA and LCA, although not specific of this study, affect its results (Curran, 2014). On the other hand, the major MFA limitation is the necessity of good data quality (Allesch and Brunner, 2015), which was discussed above.

Some UM studies reveal that the construction sector presents a significant environmental impact on climate change (Dias et al., 2014; Moore et al., 2013; Zhang et al., 2011). Although the construction sector has undergone a sharp decline in Santiago de Compostela since 2012 (IGE, 2016b), the final LCA results obtained in this study can be underestimated. When analysing other cities, it may be necessary to include construction materials in the MFA.

4.2. Comparison with other studies

The GHG emissions registered in Galicia reached 12.1 tCO_2-eq·cap^{-1}·year^{-1} (Roibás et al., 2017). The current study establishes the carbon footprint of Santiago de Compostela at 9.1 tCO_2-eq·cap^{-1}·year^{-1} – that is, below the average for Galicia.

Dias et al. (2014) carried out an environmentally extended input-output analysis in the city of Aveiro (Portugal), with a total population of 73,559 inhabitants, in 2005 (National Statistics Institute, 2013). Both background and foreground flows were considered. The results of this study show that GHG emissions of Aveiro in 2005 reached 9.5 t CO_2-eq·cap^{-1}·year^{-1}. In addition, the high influence of energy production and food and beverages consumption on climate change is pointed out. This was also identified by Goldstein et al. (2013), who applied the UM-LCA model to 5 case studies: Beijing, Cape Town, Hong Kong, London and Toronto. In all the cases except Beijing, goods such as paper, glass, construction materials and electronics had little impact on climate change. Furthermore, the calculated values of tCO_2-eq·cap^{-1}·year^{-1} in Cape Town (11.2), Hong Kong (10.2) and London (12.2) were not far from Santiago de Compostela (9.1).

An independent research institute (Análisis e Investigación, 2012) evaluated the environmental sustainability of 25 Spanish cities, including three Galician municipalities: A Coruña, Vigo and Santiago de Compostela. Seven categories were considered: CO_2-eq emissions from metabolic activities, energy, building, transport, MSW and land use, water and air quality. Their results exceed the ones reported here: 11.5 t CO_2-eq·cap^{-1}·year^{-1} for Santiago de Compostela. However, this study did not take university students into account as they considered a population of 95,207 inhabitants. The methodology followed is based on a critical review of the data available in official inventories. These sources include energy, industrial processes, product use, agriculture and livestock farming and wastes. Furthermore, the Spanish carbon footprint is estimated at 10.3 t CO_2-eq·cap^{-1}·year^{-1} (Gonzalez-García et al., 2018).

For other environmental impact categories, housing (construction, maintenance and renovation of buildings) has a significant contribution to ozone layer depletion (5.8% of total emissions), terrestrial acidification (9.2%), freshwater eutrophication (11.4%) and human toxicity (20.4%) in a Danish case study (Kalbar et al., 2016). These authors also included energy, transport and food. Thus, an underestimation of the real environmental burdens of Santiago de Compostela is expected.

It is concluded that a simplified UM-MFA-LCA analysis to determine the environmental profile considering only the most relevant flows that a city provides, if no more data are available, lower but ‘good enough’ results than those of more complete studies – i.e. those in which some more flows such as manufactures and building materials were also inventoried.

4.3. Improvement measures

Healthy environments contribute to prevent disease as well as guaranteeing human development in the long-term (Corvalán, 2006). Thus, several policies and actions in this direction have been proposed. The European Commission, for instance, has promoted environmental strategies for cities and funding for research purposes (European Commission, 2010). In this article, hotspots of each of the fluxes involved in the UM are identified and evaluated to determine the improvement measures that could be applied.

Production and use of transport fuels are the main contributor to climate change and ozone layer depletion, whereas coal and diesel are relevant in terrestrial acidification, freshwater eutrophication and human toxicity. Therefore, the first step on the road to sustainability consists of reducing the energy demand of the city by gradually substituting fossil fuels with renewable sources. Concerning fuels for transport, the best option for reducing its consumption is to favour the use of public transport. Initial efforts should focus on raising awareness among citizens, whose first option of transport is private cars. It would also be useful to implement bicycle infrastructure or services such as car sharing, as well as limiting private vehicle access to the city centre. The latter measure would reduce traffic and facilitate the circulation of buses, making it more attractive to citizens. Electric cars, however, are difficult to implement in Santiago de Compostela on a large scale. It will require a strong investment in infrastructure (there is only one charging point in Santiago de Compostela, and none in the small towns nearby, which together with the low autonomy of electric vehicles makes them impractical). Hybrid buses may be easier to implement, despite the drawbacks discussed above. In addition, the city heritage severely limits the reforms that can be carried out in the city centre. Another option is to favour the use of NGV vehicles with economic aids or prohibiting diesel cars in the city center.

In addition, the production of non-renewable electricity and heat should be reduced. Santiago de Compostela, due to its climate and landscape, is particularly suitable for decentralised wind energy. This technology has proven to be functional in the German city of Saerbeck (Hoppe et al., 2015). Another option, supported by the regional government since 2015, is biomass boilers. The humid climate would also allow the installation of natural CO_2 capture systems such as the moss walls of Dresden (Germany). In addition, as urban population growth will require new buildings and infrastructure, plus-energy and zero-energy houses become an option with high potential (Peuportier and Herfray, 2010).

Food and beverage production is the second most polluting process in all categories studied. Since most of their environmental pressure is produced in upstream processes, improvements should focus on optimising industrial food and beverage processing, for example by limiting the consumption of raw materials or applying sustainable agricultural techniques. However, there are some actions that households can take: i) to put pressure on the industrial sector by demanding products with a "green label", ii) to reduce food loss and iii) to change dietary patterns to reduce meat consumption, especially ruminants (Hallström et al., 2015). Teaching citizens about vegetarian cooking may help, especially young people. In addition, urban gardens would also limit background food production and transport. However, the latter improvement measure might not be easily applicable in Santiago de Compostela, at least in the centre, due to the city’s heritage. Another option is to promote organic agriculture by supporting local and small or medium size farms, which nowadays have a clear financial disadvantage over large companies.

The environmental pressure of wastewater treatment prevails over water purification and its consumption, especially in the category of fresh water eutrophication. The reason is the inadequate design of the wastewater treatment plant of Santiago de Compostela. On one hand, it lacks a nutrient removal system; on the other hand, it has been historically undersized and forced to pour untreated water into the river Sar, and it was not until recently that it counted with a particulate and dissolved organic matter removal stage for treating the excess water (ACUAES, 2014). Efforts have therefore been made, although some gaps remain. In addition, other measures can be implemented to improve the level of water consumption. One would be to eliminate the "minimum consumption rate" on the water bill, as it hurts and does not benefit citizens who save water. Another option would be to install rainwater catchment systems. This measure would, firstly, reduce water stress and, secondly, reduce the amount of water entering the wastewater treatment plant as the present Santiago de Compostela sewerage network does not separate rainwater and wastewater.

Finally, the key contribution to climate change, ozone layer depletion, terrestrial acidification and freshwater eutrophication from MSW management corresponds to energy consumption. More specifically, the higher CO_2-eq amounts are emitted in the thermoelectric power plant, where refuse-derived fuels are burnt to obtain energy, followed by the cogeneration plant (CMATI, 2010). The thermoelectric plant already uses a high-tech combustion system, based on a fluidized bed furnace, under controlled oxygen level conditions to avoid the formation of dioxins and furans. In addition, residual gases pass through a purification stage before being released to the atmosphere (CMATI, 2010). Minor improvement measures can be applied here, apart from regular maintenance to guarantee that the technology applied works properly. Therefore, efforts should be focused on the cogeneration plant. This consists of 6 motors fed with natural gas with the capacity to produce 22 MW (CMATI, 2010). Natural gas is the principal contributor to climate change of the whole USW management process.

5. Conclusions

As cities continue to grow, modelling their behaviour as well as evaluating the environmental impact of their metabolism became imperative to achieve sustainable development. Combined MFA-LCA methodology has proved to be well suited to this end, as it allows considering all the background and foreground flows associated with the metabolism of a city, then grouping them into certain impact categories and finally identifying the sectors causing those impacts.

This study focuses on five impact categories: climate change, ozone layer depletion, terrestrial acidification, freshwater eutrophication and human toxicity. They were evaluated for the city of Santiago de Compostela, located in the Northwest of the Iberian Peninsula. When possible, data at the municipal scale has been used, although most of them had to be downscaled from regional (Autonomous Community of Galicia) or national level. This procedure is transposable to other municipalities.

The main responsible of environmental pressure in the five categories studied is energy production from fossil fuels, with a relative contribution of more than 50% in all the cases. Food and beverages consumption contributes to ozone layer depletion with around 30% of the total kg CFC-11-eq emissions, and with close to 40% of all the kg P-eq (freshwater eutrophication). Wastewater environmental relative impact insignificant in all the categories studied. Thus, improvement actions should be focused on energy production.

Furthermore, this study proved that a simplified MFA-LCA analysis for determining the environmental profile of UM is appropriate if some grade of uncertainty is allowed. However, it may be interesting to add building materials flows for reducing the uncertainty, especially in areas where the construction sector is important. Examples of these areas are cities from developing countries and dormitory towns from industrialized regions.

Further research work should face the drawback of data availability to improve the accuracy of the results obtained by using mostly local data. These results could also be compared with those determined via a different environmental analysis technique. In addition, integrating economic and social indicators with environmental ones might facilitate the identification of the causes that lead to a certain demand of products as well as helping decision makers in the road to achieving sustainability.

Declaration of interest

Declaration of interest: none

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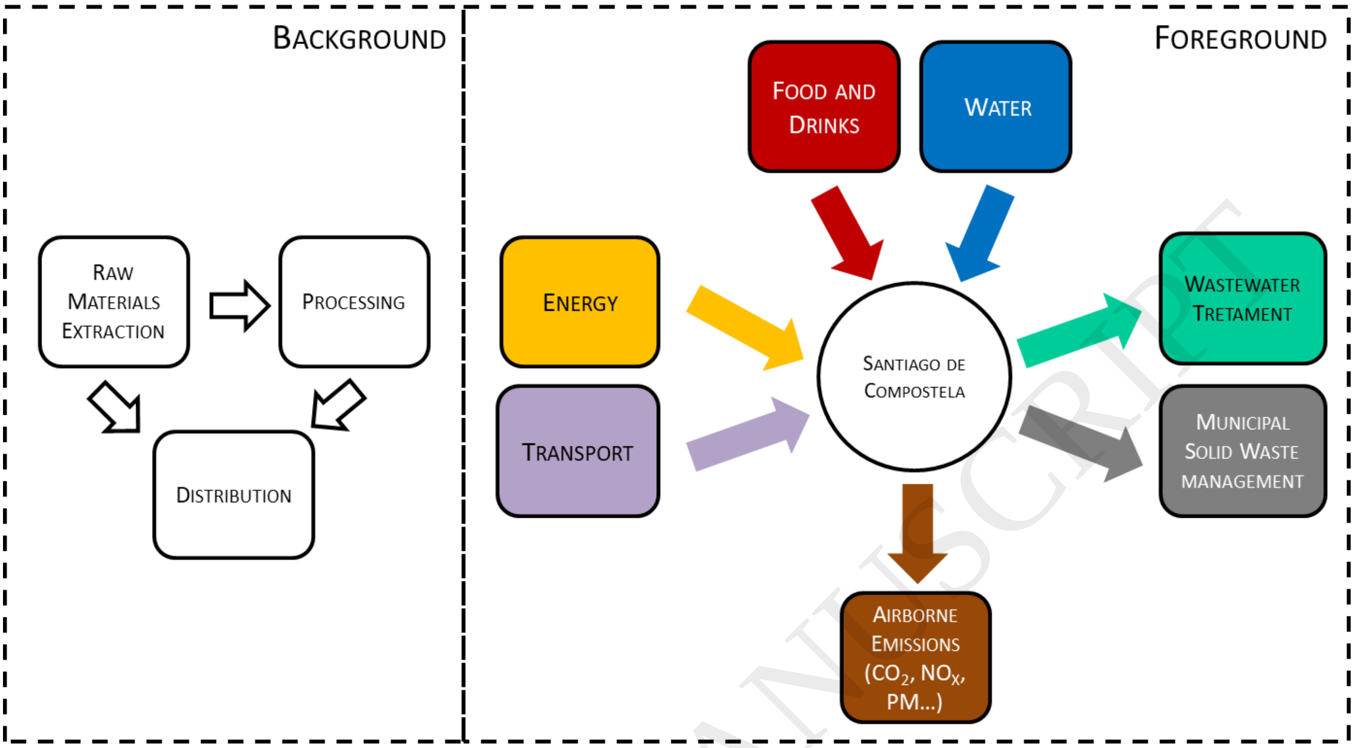

Figure 1. Schematic representation of the background and foreground flows considered in the MFA. 2-column fitting image.

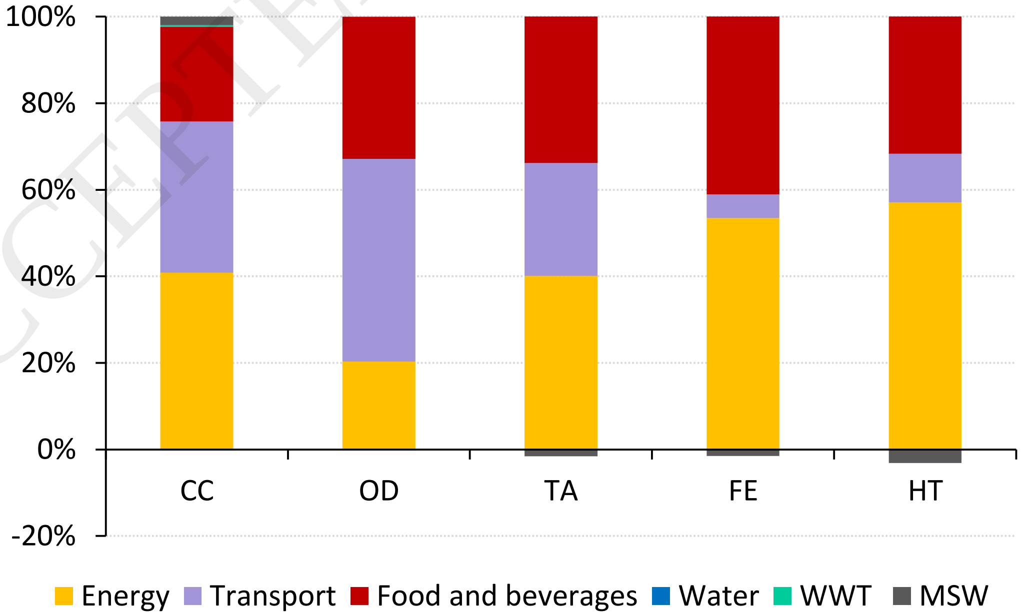

Figure 2. Distribution of environmental burdens from the main flows considered in the MFA per impact category. Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity. 1-column fitting image.

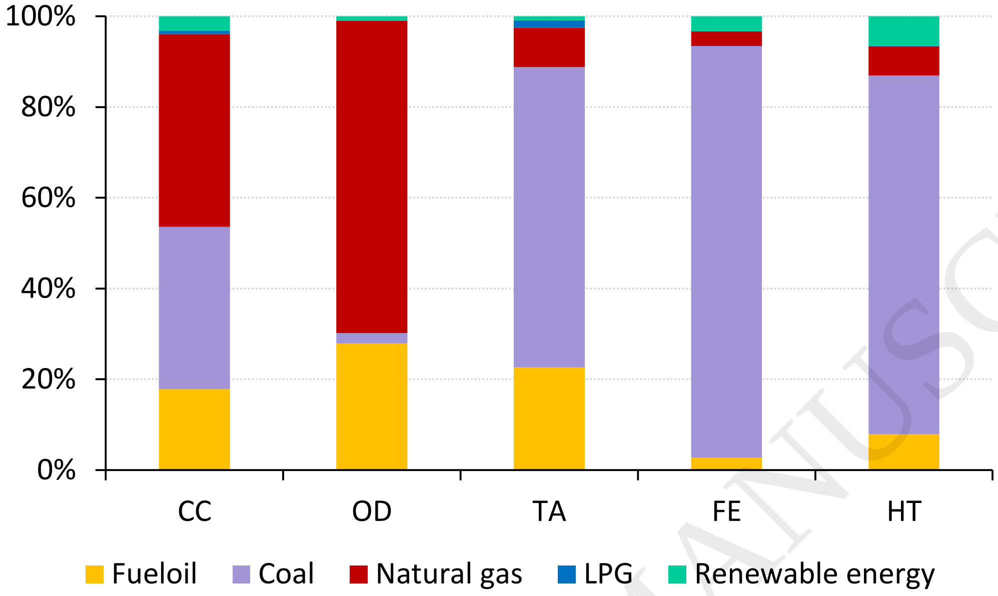

Figure 3. Distribution of environmental burdens derived from the production of energy requirements (without transport). Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity. 1-column fitting image.

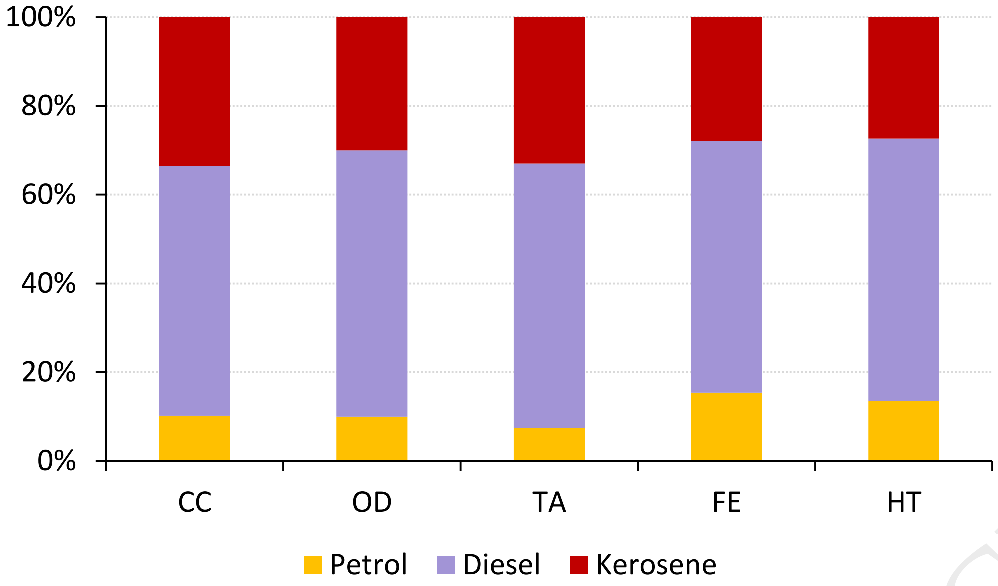

Figure 4. Distribution of environmental burdens derived from the production and use of transport fuels. Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity. 1-column fitting image.

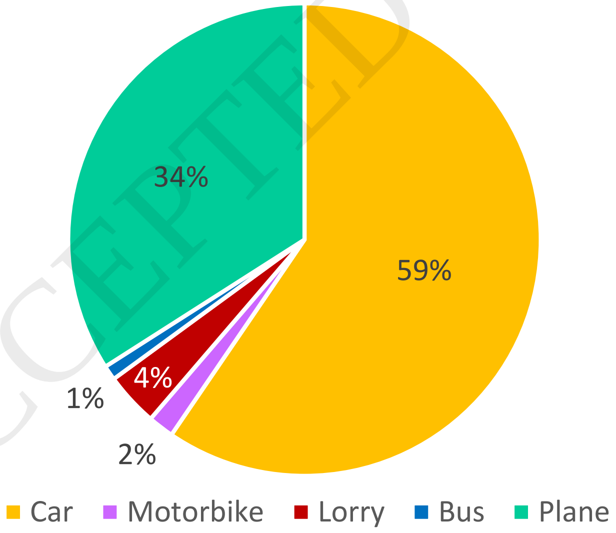

Figure 5. Distribution of GHG emissions derived from the use of transport fuels per type of vehicle. 1-column fitting image.

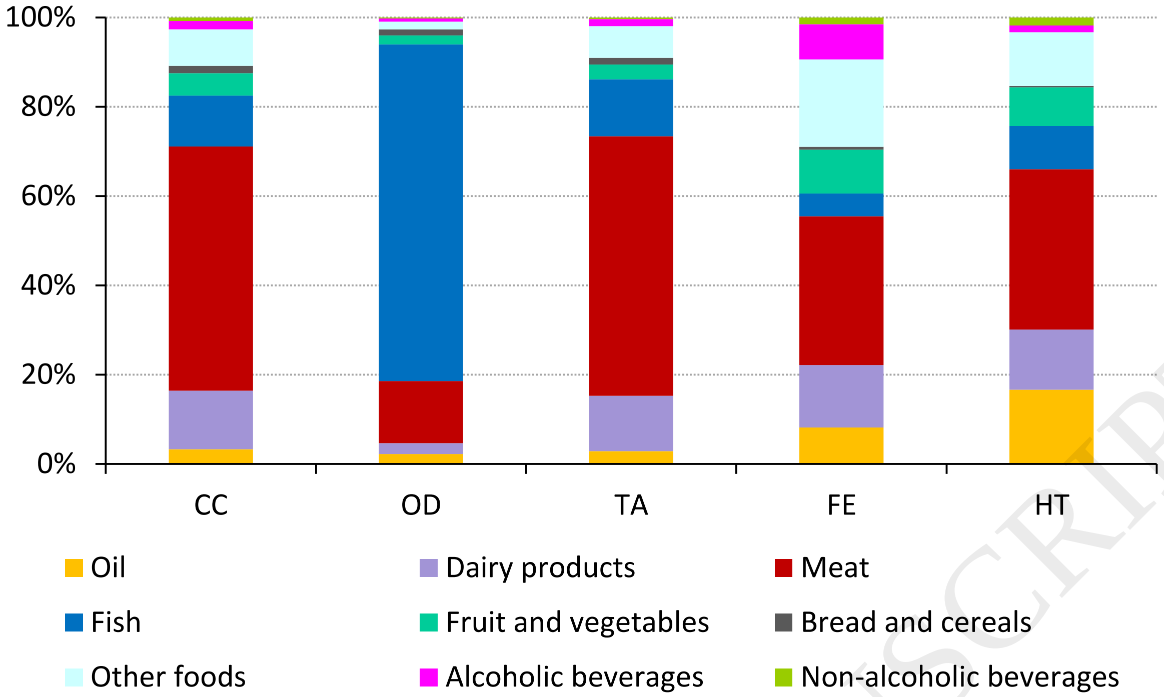

Figure 6. Distribution of environmental burdens derived from the production of food and beverages. Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity. Other foods include: lentils, rice, pasta, eggs, olives and ready meals. 1-column fitting image.

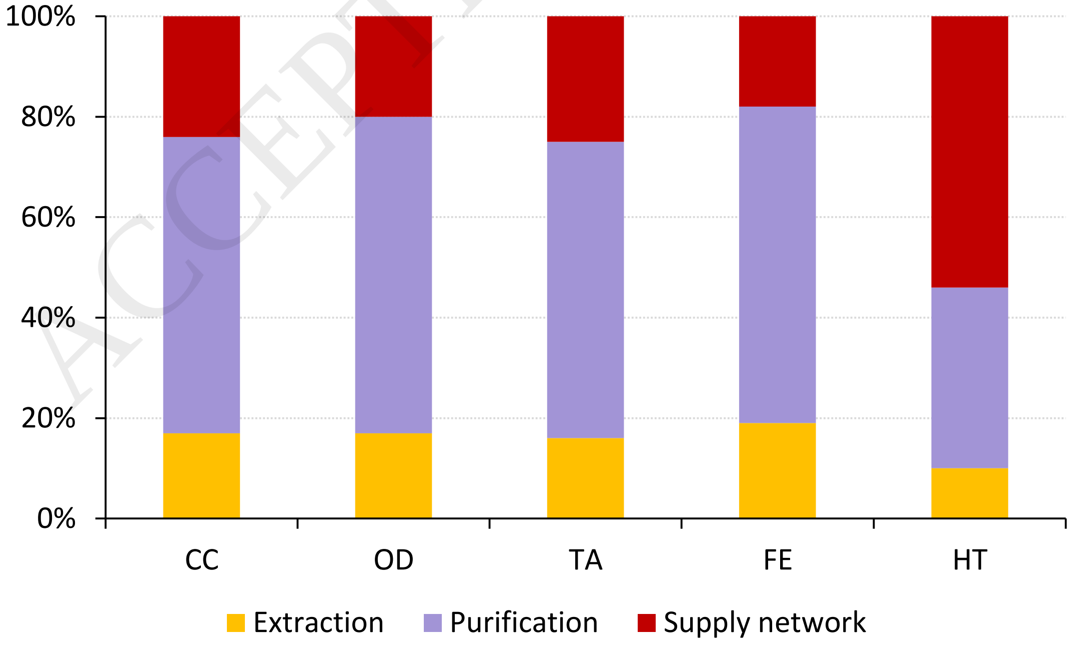

Figure 7. Distribution of environmental burdens derived from the production and distribution of water. Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity. 1-column fitting image.

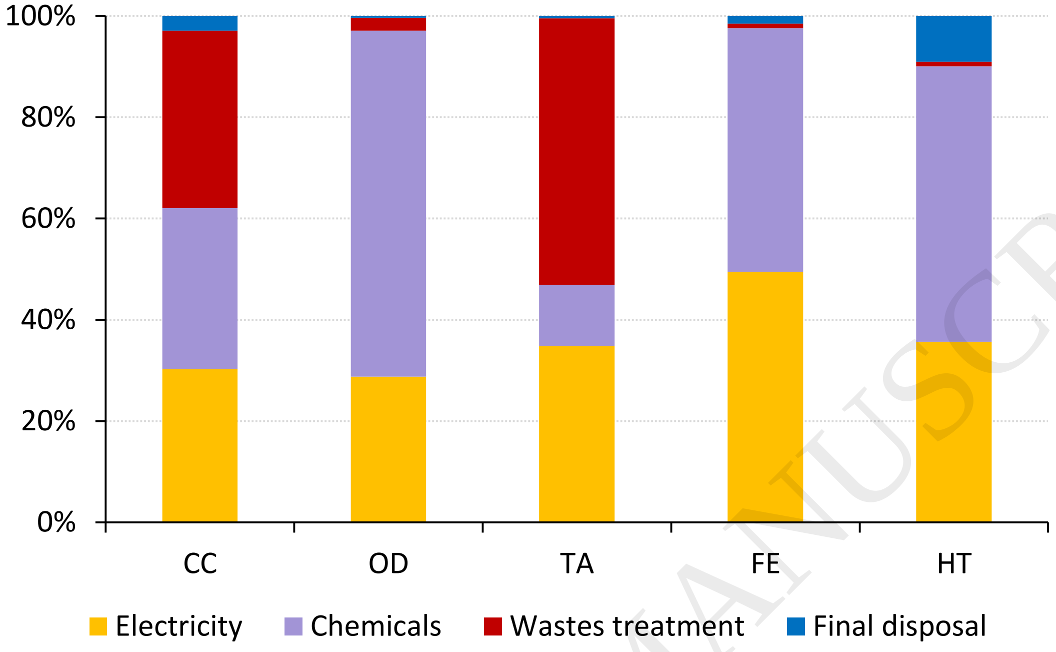

Figure 8. Distribution of environmental burdens derived from the wastewater treatment. Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity. 1-column fitting image.

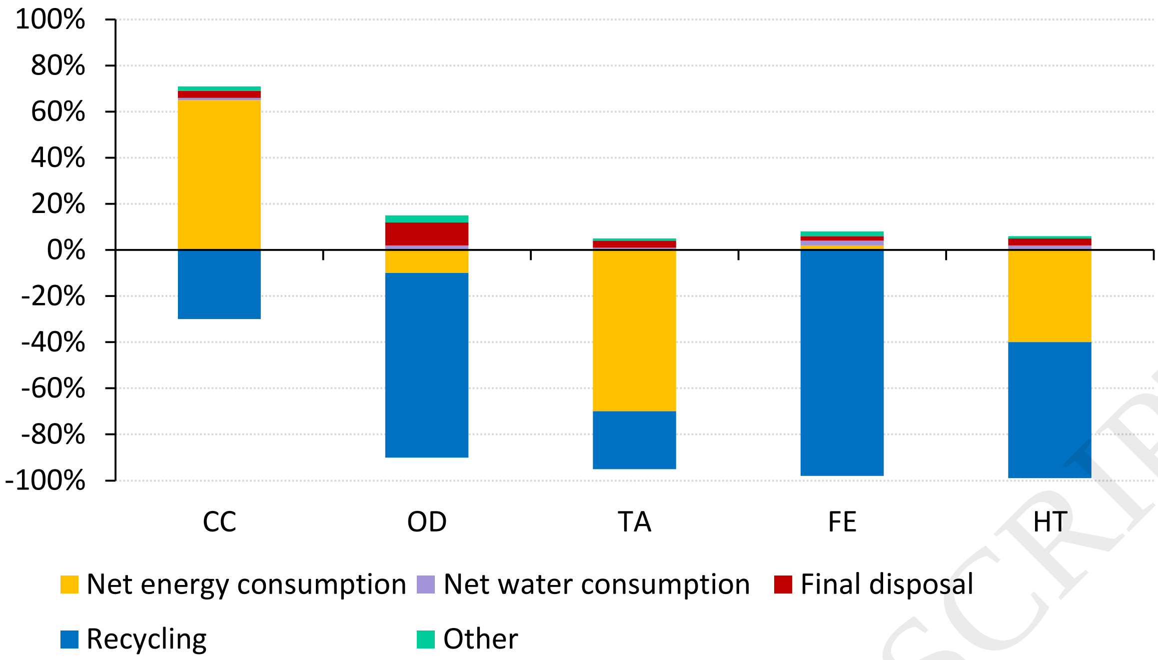

Figure 9. Distribution of environmental burdens derived from the municipal solid waste management. Acronyms: CC – Climate Change, OD – Ozone Layer Depletion, TA – Terrestrial Acidification, FE – Freshwater Eutrophication, HT – Human Toxicity. 1-column fitting image.

Table 1. Detailed description of the direct input flows from the city, data sources and downscaling factors applied. Average population of the city: 107,358 inhabitants-equivalent.

Flow	Total (local scale)	Per inhab-eq (local scale)	Units	Source	Original data scale	Downscaling factor	Source of background data
Water							
Total consumed	4,813,330	45	m^3	1	National	ND	
Fossil fuels							
Coal	95.670	891	kg	2	Regional	GDP	4
Natural gas	30.269.840	282	Nm^3	2	Regional	GDP	4
LPG	13.934	130	L	2	Regional	GDP	4
Fueloil	20.651	192	L	2	Regional	GDP	4
Kerosene	37.075	345	L	2	Regional	AT	4
Petrol	11.904	111	L	2	Regional	RT	4
Diesel	71.913	670	L	2	Regional	RT	4
Biomass							
Oil	1.435	13	kg	3	National	ND	
Milk	8.259	77	kg	3	National	ND	4
Yoghurt	1.737	16	kg	3	National	ND	4
Cheese	907	8	kg	3	National	ND	4
Fresh meat	5.682	53	kg	3	National	ND	4,5
Fresh fish	2.890	27	kg	3	National	ND	6,7
Frozen fish	309	3	kg	3	National	ND	8
Seafood	693	6	kg	3	National	ND	8
Fruit	11.283	105	kg	3	National	ND	4,9,10
Fresh vegetables	9.364	87	kg	3	National	ND	4
Bread and cereals	4.120	38	kg	3	National	ND	4
Other food	4.078	38	kg	3	National	ND	4,11
Soft drinks	3.526	33	kg	3	National	ND	9,12
Alcoholic drinks	3.102	29	kg	3	National	ND	13,14
Bottled water	6.838	64	kg	3	National	ND	15

1. INE (2013); 2. INEGA (2017); 3. MAPAMA (2017); 4. Wernet et al. (2016); 5. Noya et al. (2017); 6. Vázquez-Rowe et al. (2011); 7. Ramos et al. (2011); 8. Vázquez-Rowe et al. (2016); 9. Doublet et al. (2013); 10. Basset-Mens et al. (2014); 11. Schmidt Rivera et al. (2014); 12. Amienyo et al. (2013); 13. Villanueva-Rey et al. (2014); 14. Kløverpris and Spillane (2010); 15. Garfí et al. (2016).

Table 2. Detailed description of the direct output flows from the city, data sources and downscaling factors applied. Average population of the city: 107,358 inhabitants-equivalent.

	Total (local scale)	Per inhab-eq (local scale)	Units	Source	Original data scale	Downscaling factor	Source of background data
Emissions to air							
CO_2	850,260	7,920	t	4	Local	-	-
NO_X	3,020	28	t	4	Local	-	-
CH_4	3,663	34	t	4	Local	-	-
SO_2	2,040	19	t	4	Local	-	-
PM_{10}	266	2	t	4	Local	-	-
$PM_{2,5}$	68	0.6	t	4	Local	-	-
Emissions to water							
Nitrogen compounds	460	4	Mt	4	Local	-	-
Phosphorus compounds	87	800	t	4	Local	-	-
Organic matter	3,020	28	Mt	4	Local	-	-
Solid wastes							
Waste landfilled							
Organic matter	12,848	120	t	16	Regional	Population	4
Glass	335	3	t	16	Regional	Population	4
Plastics	10	100	kg	16	Regional	Population	4
Other	1,823	17	t	16	Regional	Population	4
Wastes from WWTP							
Sludge	1,190	11	kt	17	Local	-	4
Sand	156	1	kt	17	Local	-	4
Fats	45,727	426	t	17	Local	-	4

4. Wernet et al. (2016); 16. SOGAMA (2015); 17. Lorenzo-Toja et al. (2015).

Table 3. LCA results per capita in year 2015 for the overall case study. Average population of the city: 107,358 inhabitants-equivalent.

	Units·. inhab-eq^{-1}·year^{-1}	**Total**
Climate change	t CO_2 eq	9,1
Ozone depletion	g CFC-11 eq	1,4
Terrestrial acidification	kg SO_2 eq	45
Freshwater eutrophication	kg P eq	1,1
Human toxicity	kg 1,4-DB eq	912