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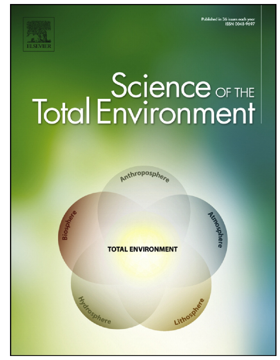

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Evaluating the Carbon Footprint of a Spanish City through Environmentally Extended Input Output Analysis and comparison with Life Cycle Assessment

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Abstract

Currently, most of the greenhouse gas (GHG) emissions are attributed to cities, as they are the global centers of business, residential and cultural activity, cities are expected to play a leading role in proposing climate change mitigation actions. To do so, it is important to have tools that allow the carbon footprint of cities to be assessed as accurately as possible. This study aims to quantify the carbon footprint (CF) associated with the activities developed in a Spanish city (Cadiz, Southwest Spain) by means of two available environmental methodologies, namely Environmentally Extended Input-Output Analysis (EEIOA) and Life Cycle assessment (LCA). When EEIOA is considered, two downscaling factors were proposed for the analysis due to the nature of the data handled (monetary data), based on the incomes (DF_1) and expenditures (DF_2) per inhabitant at city level. Regarding LCA, the rates of consumption of goods and production of waste per inhabitant have been processed to estimate the CF. The CF scores identified were 5.25 and 3.83 tCO_2-eq·inhabitant^{-1}·year^{-1} for DF_1 and DF_2 respectively, according to EEIOA, and 5.43 tCO_2-eq·inhabitant^{-1}·year^{-1}, considering LCA. Therefore, a similarity can be concluded between the results obtained with both methodologies despite the inherent differences. Considering the results, the downscaling procedure based on income per inhabitant should be preferred, pointing to EEIOA as a good alternative to LCA for evaluating the CF at city level, requiring less time and effort. In contrast, EEIOA reports more limitations when critical flows were identified, which LCA can solve. Finally, this study can be of great interest to policy makers and city governments to know the CF and the main flows that contribute and in this way, can develop new policies and city models for reducing GHG emission new policies and city models for reducing GHG emission and addressing climate change.

Key words

Greenhouse gas emissions; Spain; Sustainable City; Urban environmental management; Urban Metabolism.

1. Introduction

Greenhouse Gases (GHGs) emission has increased exponentially since 1950 and, as a result, this fact has led to an acceleration of climate change (Steffen et al., 2015). Different impacts on the natural environment derive from global warming, such as i) alteration of hydrological systems, ii) change in both the migration patterns and the behavior of some species, iii) increased flooding events, and iv) extreme weather conditions, among others (IPCC, 2014). In addition, human health is being either directly or indirectly affected (especially in the poorest population) by climate change, along with some economic sectors such as agriculture (e.g., due to problematic weather conditions such as droughts and frost) and tourism (tourism destinations change depending on the weather) (Hein et al., 2009, IPCC, 2014). In this framework, climate change becomes relevant within the strategic plan Agenda 2030, which considers it as one of the main challenges to be addressed and, consequently, it is explicitly considered in the Sustainable Development Goal (SDG) number 13 (*Climate Action*) which promotes urgent actions to combat climate change and its derived impacts. Therefore, the targets defined in this SDG aim to increase the adaptability of different countries as well as to reduce GHG emission. Furthermore, bearing in mind the objective of SDG 11 (Make cities inclusive, safe, resilient and sustainable), there is a need to promote and implement integrated policies and plans for climate change mitigation and adaptation in cities and urban systems (United Nations, 2020).

In this sense, cities play a fundamental role, not only in the fight against climate change, but also in the mitigation of various environmental impacts. Currently, more than 50% of the world population lives in cities, and this figure is expected to increase to 60% by 2050 (Ibrahim et al., 2018). Cities are socio-technical systems, which involve cultural, economic, institutional and technical subsystems (Chester et al., 2012). Therefore, cities have become spaces of high concentration of people that demand considerable flows of material and energy (John et al., 2019). As consequence, cities are responsible for most of the environmental impacts derived from human activities. Thus, 70% of global GHG emissions, 75% of the natural resources extracted and 50% of the waste generated worldwide are due to the different daily activities of citizens (Ellen MacArthur Foundation, 2017; World Bank, 2019).Life Cycle Assessment (LCA) is a well-known standardized methodology which allows different environmental impacts to be measured from a life cycle perspective (González-García and Dias, 2019). It is widely used to assess the direct and indirect impacts derived from products, processes and activities (Cordella et al., 2008; Schau and Fet, 2008). Recently, this methodology has been applied to analyze the direct and indirect impacts derived from the demands of energy and materials flows in cities and urban systems (Dias et al., 2018; Goldstein et al., 2013; González-García and Dias, 2019). In this sense, the Urban Metabolism (UM) approach has been combined with LCA to assess the environmental consequences of cities, considering the UM as the driving force to identify the different energy and material flows demanded by the inhabitants of a city (Goldstein et al., 2013; Ipsen et al., 2019; Maranghi et al., 2020) UM attempts to conceptualize a city as a living organism which requires goods and energy and generates wastes (Goldstein et al., 2013). Thus, UM allows the identification of different flows grouped into four main categories: materials, water, energy and waste (Ghaemi and Smith, 2020). Therefore, the indirect emissions and discharges derived from the flows considered by UM are quantified with the LCA methodology and transformed into environmental impacts (Huijbregts et al., 2016). In this way, the environmental profile associated with a city can be reported in terms of these impact categories, among which are indicators such as the Carbon Footprint (CF). CF is a renowned and recognized environmental indicator that quantifies the GHGs emitted into the atmosphere by an individual, organization, process, product or event within defined limits (Pandey and Agrawal, 2011). Thus, CF is expressed in an amount of carbon dioxide (CO_2eq) equivalent emissions that includes different GHGs such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) among others (Ghaemi and Smith, 2020).

However, the most widespread tool to be implemented with UM to assess the environmental impacts of cities is the Environmentally Extended Input-Output Analysis (EEIOA). This tool is based on the economic data provided by the Input-Output tables which reflect the monetary transactions between the different industrial sectors (Leontief, 1936), associating their corresponding environmental burdens (Dias et al., 2018, 2014). Thus, EEIOA transforms the money spent per inhabitant or household during a period (usually one year), into CO_2-eq units. Different environmental footprints as those related to water-scarcity (Ridoutt et al., 2018), land and material (Bertram et al., 2019) can be calculated considering EEIOA and depending on the environmental impact data provided and recorded by each country for all economic sectors (e.g., GHG emission and water consumption by sector) (Bertram et al., 2019; Dias et al., 2014). Similarly, CF can be evaluated at country level (Bertram et al., 2019), at regional level (Roibás et al., 2017) or at city level (Dias et al., 2014) taking into account the expenditures of the inhabitants or households of the country, region or city, respectively.

Although it has not been established which methodology is best (or not) to apply together with UM in the assessment of cities and urban systems, Dias et al. (2018b) reported some advantages of EEIOA regarding LCA, namely shorter data collection times and the use of public databases (LCA usually requires the use of payment software). In addition, EEIOA avoids double counting while in LCA it is sometimes quite difficult to avoid (Kitzes, 2013). Bearing in mind the methodologies mentioned above (LCA and EEIOA, combined with UM), the aim of this study is to compare both the assessment of a specific city to identify possible discrepancies in the results, as well as what the advantages and disadvantages of one over the other methodology may be. In this sense, the results of this study may be of interest to policy makers in order to determine which of these tools is the most advisable for the estimation of the CF indicator. As far as we know, this is the first study that evaluates the environmental profile of a Spanish city using the EEIOA methodology. Therefore, the starting point of this study is to provide an answer to the question: Do both methodologies lead to a similar result? Firstly, a positive answer is supported by the work of Dias et al. (2018) in which the CF associated to the city of Aveiro (Portugal) was evaluated through LCA and compared with the results of a previous study in which the EEIOA was applied (Dias et al., 2014). In this study, the CF scores resulting from both methodologies reach very similar values despite considering different flows from different databases between them. Secondly, Roibás et al (2018) evaluated CF in a Spanish region (Galicia) using the EEIOA and established that this methodology is a good choice to determine CF associated with production and consumption patterns at a regional level. Taking into account these conclusions, the present study aims to demonstrate if both methodologies are also alternative options in the estimation of CF in the case of a Spanish city taking into account the available information and the limitations of the databases at Spanish level.

The city of Cadiz, which is in the Autonomous Community of Andalusia (Southern Spain), has been selected as case study (**Figure 1**). This Spanish city has an economy highly dependent on tourism due to its location (southern coast of Spain) and very favorable weather conditions (Williams et al., 2016). Therefore, and given that tourism is one of the economic sectors most affected by climate change (Hein et al., 2009), the selection of this case study can be considered of potential interest not only for this Spanish city but also for similar cities with the aim of taking measures and developing policies to contrast or minimize its effects and addressing them towards more sustainable cities.

<Figure 1 around here>

2. Material and Methods

2.1. Case of Study

Cadiz is the capital of the homonymous province with a population of 116,027 inhabitants (IECA, 2018). Its population rate has decreased in recent years for many reasons, such as low birth rates and high rental and sale prices, mainly due to its high population density and the lack of residential area to continue growing as Cadiz is located on a peninsula. In economic terms, its inhabitants had an average gross income per capita of 26,891€ per capita in 2015, which corresponds to their average gross income (INE, 2015a). The tertiary sector (especially tourism) is its main economic driver. Nevertheless, tourism has a strong seasonality regime during the summer months and, as consequence, the city has a very high unemployment rate, above 33% (Instituto de estadísitica y cartografía de Andalucía (2015).

2.2. Carbon Footprint estimation

In this study, as detailed in the *Introduction section*, the CF per inhabitant was estimated taking into account the UM approach combined with two different environmental methodologies that are, EEIOA and LCA.

LCA is a widely implemented methodology for evaluating the CF of products, processes and services. In previous studies at the Spanish level, the application of the LCA methodology to determine the CF at the regional level (Galicia) was successfully performed (Roibás et al., 2017) as well as at the city level – for the cities of Bilbao, Seville (González-García and Dias, 2019) and Santiago de Compostela (García-Guaita et al., 2018). In this sense, the evaluation of the CF in the city of Cadiz is an additional case study and a further step in the application of this methodology on an urban scale.

In the case of EEIOA, Dias et al. (2014) adapted this methodology to evaluate the CF on an urban scale in the city of Aveiro (Portugal). However, to our knowledge, there are no studies evaluating CF on an urban scale in Spain using this methodology. Therefore, this study seeks to expand the use of this methodology to a city level in a different country, in this case, applied to a Spanish city.

2.2.1. Environmentally Extended Input-Output Analysis methodology

When the CF was estimated considering EEOIA, the procedure reported by Dias et al. (2014) has been followed in detail, although incorporating some modifications in order to adapt the methodology to this case study. A detailed description of the procedure and the information required is summarized below.

2.2.1.1. Data requirements

EEIOA mainly required three data sources as a starting point, which are IO tables, GHG emission per Branches of Activity and the expenditures of the households per group. Accordingly, some transformations were necessary. The IO tables provide information regarding the monetary interactions between economic sectors which are symmetrically distributed in the table in form of rows and columns. Therefore, each row indicates the revenues that each sector receives from each of the sectors located in each column.

In contrast, if the table is read vertically, each column indicates the expenditures that each sector has from the sectors of the corresponding rows (Leontief, 1936). To conduct an EEIOA it was necessary to transform the IO table into the inverse Leontief matrix $(I-A)^{-1}$; where I was the identity matrix and A was the matrix resulting from dividing the values of the IO table by the gross domestic product (GDP) of the corresponding sector (Dias et al., 2014a). In this study, it has been used the total IO table from Spain (INE, 2015b), which considered 64 economic sectors and was elaborated according to Regulation (EU) nº 549/2013 (European Union, 2013). This regulation indicates that the data from the IO table must be updated every 5 years since 2010. That is why the year selected to conduct this study was 2015, instead of another more updated period. In addition, this data source provided, in addition to the total IO table, the domestic IO table, the importations IO table and the corresponding inverse Leontief matrices (INE, 2015b).

GHG emission data by Branch of Activity are available at the national level from the National Statistics Institute (INE, 2015c). This source reports the GHG emissions for each of the 64 different Branches of activity according to the National Classification of Economic Activities established in the Regulation (EC) No 1893/2006 (European Commission, 2006). These GHG emission flows are provided in tons of CO_2-eq; however, in order to calculate the CF it was necessary to divide each value by the GDP of the corresponding Branch of activity, i.e. the emissions associated with the "*manufacture of food, beverages and tobacco products*" must be divided by the GDP of the same activity "*manufacture of food, beverages and tobacco products*". As a result, the GHG emission intensity in tons of CO_2-eq·€$^{-1}$ was obtained.

Finally, data on household expenditure per group are available at a regional level with a four-digit level of disaggregation corresponding to 116 expenditure groups (IECA, 2015). Moreover, data is available from different consumption sources such as average expenditure per person, per household or per consumption unit. Therefore, this work has taken into account the data on average expenditure per person in the region of Andalusia as a basis for subsequent extrapolation at city level with a specific downscaling factor, which will be developed below.

The lack of data at the city level made it necessary to transform some required data by means of downscaling factors (Shafie et al., 2013). Thus, these factors must be based on other variables with data available at different scales (Courtonne et al., 2015). In the present study, two downscaling factors (DF) have been proposed which were: i) DF_1 taking into account the average level of income per household in the city of Cadiz and the average level of income in the region of Andalusia; ii) DF_2 based on the average expenditures per person in the city of Cadiz and in the region of Andalusia. Concerning the first downscaling factor (DF_1) there were available data for both, Andalusia and Cadiz. On the contrary, since there was not available information regarding the average level of income per household at city level it has been considered data for the average expenditures per person in the municipalities with more than 100,000 inhabitants in the region of Andalusia (IECA, 2015), as assumption. In this sense, **Equation 1** and

Equation 2 show the how to estimate both downscaling factors.

$$DF_1 = \frac{Incomes\ per\ household\ in\ Cadiz}{Incomes\ per\ household\ in\ Andalusia} \qquad \textbf{(Equation 1)}$$

$$DF_2 = \frac{Expenditures\ per\ person\ in\ Cadiz}{Expenditures\ per\ person\ in\ Andalusia} \qquad \textbf{(Equation 2)}$$

2.2.1.2. Equivalences between expenditures groups and economic sectors of the IO table.

One of the most important points of the EEIOA was to establish the equivalences between the 116 expenditures groups, the 64 Branches of activity and the 64 economic sectors of the IO table. The relationship between Branches of activity and Economic sectors was evident, since each branch of activity corresponds to a specific economic sector. However, for the expenditures groups, relationships were established between each of the expenditure groups and the economic sectors, in such a way that several expenditure groups can belong to the same sector. To determine these relationships, this study used the Regulation (EC) No 1893/2006 (European Commission, 2006), which provides a breakdown of economic sectors, thus facilitating the establishment of equivalencies. **Figure 2** shows the case of the economic sector "*Products of agriculture, hunting and related services*", which is related to the branch of activity "*Crop and animal production, hunting and related service activities*" and to the expenditure groups "*Meat*" and "*Fruits*".

<Figure 2 around here>

Hence, expenditure on "*Products of agriculture, hunting and related services*" has been calculated as the sum of the expenditure per person on "*Meat*" and "*Fruits*". In this way, the expenditure groups were classified into 35 economic sectors as set out in the **Table SM1** in **Supplementary Material**. However, in the IO table, 29 economic sectors were considered that do not have a direct relation with the expenditure groups, such as "*Mining and quarrying*", "*Coke and refined petroleum products*" or "*Chemicals and chemical products*". Thus, these sectors did not affect directly the everyday life of citizens, but rather indirectly. For example, a family buys a car, this expense is associated with the economic sector "*Motor vehicles, trailers and semi-trailers*", but the manufacture of the car requires other sectors such as "*Mining and quarrying*", "*Fabricated metal products, except machinery and equipment* "or" *Rubber and plastics* *products* ".

2.2.1.3. Carbon Footprint calculation

EEIOA consists of transforming economic data into environmental impacts. Thus, in this study the CF was calculated by transforming the expenditures (in €) of the citizens of Cadiz in tons of CO_2-eq, following the methodology described by Dias et al. (2014). Consequently, this calculation was based on the three main databases that consist basically of a matrix ($(I-A)^{-1}$) and two vectors (Y and Z):

$$(I-A)^{-1} = \begin{pmatrix} c_{1,1} & \cdots & c_{1,35} \\ \vdots & \ddots & \vdots \\ c_{64,1} & \cdots & c_{64,35} \end{pmatrix} \quad \text{(Inverse Leontief matrix)}$$

$$Y = \begin{pmatrix} y_1 & \cdots & y_{35} \end{pmatrix} \quad \text{(Expenditures by economic sector vector)}$$

$$Z = \begin{pmatrix} z_1 \\ \vdots \\ z_{64} \end{pmatrix} \quad \text{(GHG emission vector)}$$

The inverse Leontief matrix ($(I-A)^{-1}$) was composed of the coefficients $c_{i,j}$ distributed in 64 rows according to the number of economic sectors, and 35 columns corresponding to the economic sectors related to the expenditure groups. The expenditures by economic sector vector (*Y*) was made up by the expenditure groups classified in the 35 economic sectors in accordance with *Section 2.2.1.1.* taking into account the downscaling factors.

Finally, in the GHG emission vector (*Z*), it was considered the emissions from the 64 economic sectors in tons of CO_2-eq·$€^{-1}$, resulting from dividing the emissions of each branch of activity by the GDP as specified in *Section 2.2.1.1*.

According to these parameters and the mentioned nomenclature, **Equation 3** shows the procedure for estimating the CF according to the EEIOA methodology.

$$CF = \sum_{j=1}^{35} \sum_{i=1}^{64} c_{ij} \cdot y_j \cdot z_i \quad \textbf{(Equation 3)}$$

Where *i* corresponded with each of the 64 economic sectors and *j* with the 35 economic sectors related with the expenditure groups.

2.2.2. Life Cycle Assessment

LCA is a methodology that, applied to cities, analyzes the different flows from a life cycle perspective (Goldstein et al., 2013; González-García and Dias, 2019). Hence, LCA quantifies the emissions and discharges throughout the life of a product, from its extraction, processing, transport and consumption up to its treatment as a waste. In this study, the CF score has been estimated taking into account a cradle-to-grave perspective and the characterization factors reported by the ReCiPe Midpoint (Hierarchist) (Huijbregts et al., 2016), which has been also used by other authors (García-Guaita et al., 2018; Goldstein et al., 2013; González-García and Dias, 2019) and allows for comparison of the results.

2.2.2.1. Functional Unit

The functional unit (FU) is the basis for comparing the CF scores using the two proposed methodologies. To establish the FU, it must be taken into account that the function of a city is to maintain the quality of life of its citizens, as well as other geographical areas that depend directly or indirectly on its socio-economic factors, and to support people with different cultures, habits, diets, etc. (Goldstein et al., 2013). In this sense, it was decided to consider one inhabitant and one year as a functional unit in line with other studies, which only take into account the residents registered in the cities under study (Goldstein et al., 2013; González-García and Dias, 2019; Roibás et al., 2017). Thus, the CF evaluated were calculated from the consumption of goods and services by an inhabitant in one year. However, other authors (García-Guaita et al., 2018), consider the equivalent inhabitant, i.e., considering also the non-resident population in the city (students who are not registered in the city, and workers who live in other municipalities and tourists. Nevertheless, the EEIOA databases are per resident (not equivalent). This discrepancy can lead to an overestimation of the carbon footprint calculated through LCA because a part of the residents' CF is associated with the consumption of goods and services by the non-resident population within the city. Thus, and with the aim of comparing both methodologies, a resident in the city should be taken as reference.

2.2.2.2. System boundaries and data collection

Under the UM perspective, this study has considered seven metabolic input and output flows (**Figure 3**) which are essential for the development of the cities. In the selection of these flows, those considered by González-García and Dias (2019) have been taken into account: fossil fuels, energy, foods and beverages, building materials, other flows (including paper and cardboard, glass bottles, cork, plastic containers and tap water) as inputs and wastewater and solid wastes as outputs. Bearing in mind that cities are considered as large consumers rather than producers of goods, some flows related to agriculture or industrial activities, such as fertilizers or chemicals, have not been taken into account (Dias et al., 2018; González-García and Dias, 2019). In addition, the production of goods in the city of Cadiz has been also excluded, i.e. it is assumed that all materials and energy flows are imported in order to avoid double counting in line with previous studies (Dias et al., 2018; González-García and Dias, 2019).

As for the input flows, the upstream activities involved in their production have been considered, taking into account the extraction of raw materials, processing, manufacturing and transport up to the city. Background data corresponding to these activities have been taken from Ecoinvent ® database version 3.5 (Moreno Ruiz et al., 2018). Specifically for some food products such as legumes (lentils, chickpeas), sugar, oil, pasta and some meat products (beef, pork and chicken), the background data have been taken from Agri-footprint database (Blonk Agri-footprint BV, 2015). Moreover, background data for wine and beer production have taken from Villanueva-Rey et al. (2014) and Koroneos et al. (2005) respectively.

<Figure 3 around here>

Concerning building materials, the consumption of concrete, natural stone, cement, aggregates, bricks, asphalt, varnish, tiles, ceramics, steel and wood has been considered. The corresponding consumption data have been collected from different sources, giving priority to local and provincial data over regional or national ones, whenever possible. In cases where the data correspond to a regional or national scale, it has been assumed that a resident of Andalusia or Spain would consume the same amount as a resident of Cadiz. In order to obtain a good-quality comparison between the CF scores estimated by EEIOA and LCA, the same reference year of 2015 (whenever possible) in both methodologies has been considered. **Table SM2** in the **Supplementary Material** details the inventory data and data sources corresponding to each flow considered in the LCA study.

3. Results and Discussion

3.1. Environmentally Extended Input-Output Analysis of Cadiz

As detailed above, two different downscaling factors have been estimated to be applied in the EEIOA (**Table SM3** in the **Supplementary Material**). DF_1 (1.41) was about 37% higher than DF_2 (1.03), indicating that the difference between the income per household between Cadiz and Andalusia was considerably higher than the difference in the expenses per person in both locations. While the income per household in Cadiz were around 40% higher than the income per household in Andalusia in 2015, the expenditures per person in Cadiz were only 3% higher than those in Andalusia. The rationale behind the low variation in the expenses was associated with the fact that the value estimated for expenses in Cadiz corresponds to the average expenditure per person for all Andalusian municipalities with more than 100,000 inhabitants, which accumulate a large part of the population of the entire region. Consequently, it was expected a minor variation with regard to the average expenditure per person in Andalusia.

The difference between the downscaling factors directly affects the expenditures by economic sector. **Table 1** shows the expenditures per person in Andalusia and Cadiz taking into account the estimated downscaling factors and disaggregated by each economic sector. The economic sector that contributed most to the annual citizens' expenses in Andalusia and Cadiz (around 23% of the total) was "*Real estate services*", which included the rental and the imputed income.

The second most important sector, with a 12% contribution to total expenditure, was "*Food products; beverages; tobacco products*". It was followed by "*Accommodation and food services*" (10% of the total). The rest of the sectors reported contributing ratios lower than 10%. The difference between the first two sectors is notable, since a person from Cadiz or Andalusia spends almost twice as much on rent as on food. Bearing in mind the averages income per person in Andalusia in 2015 was 7,942 € (INE, 2015d), Andalusians spent around 26% of their incomes on housing. This ratio was close to the alarming 30% from which a rent is considered high enough to harm a citizen's quality of life (Tanguay et al., 2010).

<Table 1 around here>

In terms of emissions by sector, **Table 2** details the top ten economic sectors with the highest GHG emissions for every euro produced by the same sector. In this sense, the economic sectors were classified according to their emissions and their size in economic terms. The sector with the highest GHG emission per € was "*Other non-metallic mineral products*", which includes activities such as the manufacture of construction materials such as glass, cement, concrete, ceramic materials, among others. Hence, if this sector generates 1 € in goods, it emits 1.85 kg CO_2-eq into the atmosphere. All of these economic sectors require large amounts of energy such as "*Other non-metallic mineral products*", "*Electricity, gas, steam and air conditioning*", "*Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery*" (partly due to the wastewater pumping involved in sewerage services), "*Coke and refined petroleum products*", "*Water transport services*" and "*Basic metals*"; or are related to the combustion of fossil fuels such as, "*Fish and other fishing products; aquaculture products; support services to fishing*", "*Air transport services*", "*Products of agriculture, hunting and related services*" and "*Land transport services and transport services via pipelines*").

<Table 2 around here>

Taking into account the downscaling factors, the expenditures by economic sector, the GHG emissions per € and the inverse Leontief matrix the CF scores have been calculated following the **Equation 3** described in *Section 2.2.1.3*. Thus, the estimated CF scores were 5.25 tCO_2-eq·inhabitant^{-1}·year^{-1} and 3.83 tCO_2-eq·inhabitant^{-1}·year^{-1} considering DF_1 and DF_2, respectively. However, the contribution of each sector to the CF score did not depend on the downscaling factor since it was applied to the expenses per person and applied equally to all sectors. **Figure 4** depicts the different contributions of each sector to the total CF, regardless the downscaling factor considered. Bearing in mind the information detailed in **Figure 4**, four sectors concentrated the 61% of the total contributions to the CF scores. These sectors were: "*Food products; beverages; tobacco products*", "*Electricity, gas, steam and air conditioning*", "*Products of agriculture, hunting and related services*" and "*Land transport services and transport services via pipelines*". All of them occupied leading positions in the ranking of expenditures per person detailed in **Table 1**. Furthermore, with the exception of "*Food products; beverages; tobacco products*", the remaining three sectors were also among the top ten of the sectors with the highest GHG emission rates per € (**Table 2**). Accordingly, these sectors that had an outstanding emission rate were those where the citizens of Cadiz mainly expended their incomes and therefore, were sectors with a significant contribution to the CF score estimated per inhabitant. In the case of "*Food products; beverages; tobacco products*", its important contribution to the CF score was associated with the fact that it was the second sector in which the citizens of Cadiz spent their incomes with a remarkable difference in comparison with the other three sectors. However, although "*Real estate services*" was the sector in which there was more spending per person, it had a contribution of only 3% to the total CF score due to its low GHG emission rate per euro in comparison with the other sectors.

<Figure 4 around here>

The findings of our EEIOA coincide with those reported by Dias et al., (2014) for the city of Aveiro (Portugal). In that study, about 72% of the CF score was associated to four economic sectors which were "*Land transport; transport via pipelines*", "*Food products, beverages and tobacco*", "*Construction*" and "*Production, collection and distribution of electricity*". The only sector that differed from our study was "*Construction*" due to the fact that Dias et al. (2014) considered rental and imputed rents for housing within this sector in contrast to this work. However, the global value of CF score was significantly different from those identified in our study. The CF score obtained for Aveiro was 9.41 tCO_2-eq·inhabitant^{-1}·year^{-1}, considerably higher than our results (5.25 tCO_2-eq·inhabitant^{-1}·year^{-1} and 3.83 tCO_2-eq·inhabitant^{-1}·year^{-1}). The reason behind these differences can be attributed to two issues:

i) the CF obtained for both cities depends directly on the GHG emissions by sector of the corresponding country in terms of kg CO_2-eq per €. Therefore, while for Portugal in 2005 they were 18.85 kg CO_2-eq·€$^{-1}$, for Spain in 2015 they were 11.17 kg CO_2-eq·€$^{-1}$, almost 40% less than in Portugal. One of the most important reasons behind this fact is related with the effect that electricity consumption had on these emission rates. Thus, a growth in the presence of renewable energy sources in the electrical country mix was considered in the case of Spain. Accordingly, the wind power ratio was increased from 14 % in 2006 to 30 % in 2015 in that country (Red Eléctrica de España, 2020), which directly affected the GHG emission, achieving a considerable reduction in the case of Spain in 2015.

ii) differences in methodological issues, especially related to the relationships established between economic sectors and expenditure groups (35 sectors in Cadiz and 21 in Aveiro) and data sources that are different, also cause an associated error when comparing both results. The critical aspect was the equivalences between the expenditures groups and the economic sectors. In the case of Aveiro, 47 expenditure groups were considered, and relations were established with 21 economic sectors. Nevertheless, in the case of Cadiz, 116 expenditure groups were considered, with which relations were established with up to 35 economic sectors. Therefore, the total expenditure per inhabitant of Cadiz was distributed in more economic sectors and, therefore, additional sectors were considered. For example, in the study of Cadiz the economic sector entitled "*Real estate services*" included rental and imputed income. In contrast, rental and imputed rents were considered within the sector "*Construction*" in the study of Aveiro, which had a much higher value in terms of kg CO_2-eq·€$^{-1}$ (0.104 kg CO_2-eq eq·€$^{-1}$ for the case of "Construction" in Aveiro, and 5.16 ·10^{-4} kg CO_2-eq eq·€$^{-1}$ for the case of " Real estate services" in Cadiz).

3.2. Life Cycle Assessment of Cadiz

The environmental study has been performed following a cradle-to-city approach and therefore, the inputs of different flows (building materials, fossil fuels, energy, food and beverages, water, packaging materials) to the city have been computed, as well as the generation of specific output flows due to the UM approach with the corresponding treatments (wastewater, landfill and recycling), which took place within the boundaries of the city (see **Table SM2**). The estimated CF score following an LCA perspective was 5.43 tCO_2-eq·inhabitant^{-1}·year^{-1}. **Table 3** summarizes the contributions to CF per input and output flow considered in the analysis. Bearing in mind these results, the main contributing flow responsible for the highest GHG emissions was that of "*Building Materials*". The rationale behind that outstanding effect (37% of the total CF score) was associated with large amounts of energy in the background processes of some construction materials (e.g. steel or cement). This flow, together with "*Energy*" and "*Food and Beverages*" (considering the production of foodstuffs and beverages), concentrated around 72% of the total CF estimated per inhabitant.

<Table 3 around here>

Attention has been given to the assessment per contributing flow in order to identify the hotspots. With respect to "*Building Materials*", the flows that contributed most to its CF were "*Steel*" (63%) and "*Cement*" (15%). Both construction materials have demanded large energy requirements in their production systems, as well as being the most energy-intensive. These results are in line with those identified for the cities of Bilbao and Seville by González-García and Dias (2019) where "*Steel*" and "*Cement*" were also the main responsible products for GHG emission from construction materials. As for "*Food and beverages*" the main contributors were meat products (44%) and "*dairy products*" (22%). Both flows involve livestock activities which produce significant GHG emissions, namely those directly linked to the metabolism of ruminants and those indirectly produced from the use of agricultural machinery in agricultural activities to produce animal feed. The consumption of fossil fuels which were used in transport activities and heat requirements, also made a significant contribution to the CF of Cadiz. Among the fossil fuels, the largest contributions are from the production of diesel required in transport activities, as well as the production of kerosene required for aviation and the production of natural gas required at homes in heating systems. **Figure 5** depicts the assessment in detail of contributions from "*Building materials*", "*Food and beverages*" and "*Fossil Fuels*".

<Figure 5 around here>

3.3. EEIOA vs LCA

Differences between the CF obtained by LCA and EEIOA, which have different methodological procedures, were found. In addition, both methodologies considered different approaches involving different sources and baseline data (LCA for consumption data and EEIOA for economic data). Moreover, the use of different ways to perform the downscaling to identify the expenditures in EEIOA derived also in remarkable differences on the CF score. The use of a downscaling factor based on the income per person (i.e., DF_1), resulted in a minor difference (around 3.4%) in the CF score estimated with both methodologies than that quantified with a downscaling based on expenditures per person (DF_2) (around 42%). This indicates that the DF that most closely matches the results obtained by both methodologies was DF_1. The reason behind this affirmation, bearing in mind that in the LCA the flows considered in the analysis were the most characteristic with the consumption of a city (such as building materials or fossil fuels), DF_1 of the EEIOA was also more specific to the city than the DF_2 which consider that the expenditures of the city of Cadiz were more similar to those of Andalusia.

Nevertheless, with respect to the contributions of the CFs of each methodology, more notable differences can be identified in some of the flows, as shown in **Table 4**. In order to compare the contributions to the CFs of the different methodologies, some relations were established between the main flows considered in LCA and the related economic sectors considered in EEIOA. In addition, for EEIOA the values of the contributions in tCO_2-eq·inhabitant^{-1}·year^{-1} obtained with DF_1 were taken into account. Thus, for "*Building Materials*" the contribution to CF was 2.03 tCO_2-eq·inhabitant^{-1}·year^{-1} and was related to the economic sectors "*Construction and construction works*" and "*Real estate services*" whose contribution was 0.27 tCO_2-eq·inhabitant^{-1}·year^{-1},which was seven and a half times less. This large difference was due to the fact that not all the flows considered within "*Building Materials*" were involved in the corresponding economic sectors (for example, consumption of steel which, in addition to construction, was used to manufacture cars). Regarding the "*Energy*" flow directly related to the economic sector "*Electricity, gas, steam and air conditioning*", there was not such a difference between each contribution value which was of the same order of magnitude. Nevertheless, the contribution to the CF of "*Food and Beverages*" was three times less than the economic sectors to which it was related "*Products of agriculture, hunting and related services*", "*Food products; beverages; tobacco products*" and "*Fish and other fishing products; aquaculture products; support services to fishing*". This difference was due to the fact that within these sectors, the emissions caused by some flows such as packaging was also implicit, which was not considered within "*Food and Beverages*". Finally, the sum of the contributions to the CF for the flows "*Solid Wastes*" and "*Wastewater*" was 0.44 tCO_2-eq·inhabitant^{-1}·year^{-1} and these flows were related to the economic sector "*Sewerage services; sewage sludge; waste collection, treatment and disposal services, materials recovery*", which resulted in a contribution to CF of 0.07 tCO_2-eq·inhabitant^{-1}·year^{-1}. In this case, the difference could be due to the fact that spending on waste management in Spain is a municipal competence and only part of its spending falls directly on citizens. Therefore, if the economic sector had a lower value in the expenditures in the EEIOA, it also had a lower impact in terms of CF.

<Table 4 around here>

However, each methodology considers different flows, and establishing relationships between them was not easy. For example, when considering the economic sector "*Land transport; transport via pipelines*", it was intuitive to relate it to transport or, in this case, to the consumption of fossil fuels, however, in "*Land transport;*

transport via pipelines", air transport was not considered, nor was natural gas, which was considered in the flow of "*Fossil Fuels*". This reason made it very difficult to compare the results on the basis of the contributions of both methodologies.

There are limitations in the availability of city-specific data in both methodologies. In the LCA inventory, most of the data compiled were at the regional or national level while the data availability at local level represented a minor contribution. In the same way, the databases considered to gather the data for the EEIOA corresponded to the national level (e.g., IO table or the inventory of emissions by sectors of activity) and the regional level (e.g., expenditures per inhabitant). In this sense, it is quite complicated to identify the amount of products consumed in the city that are produced in the same city, information that is required when applying LCA. Therefore, and in order to avoid double counting, it was assumed that all products consumed were imported. Furthermore, unlike other much larger cities such as Madrid or Barcelona, the production of goods in Cadiz is much lower, with the service sector being the main focus of its economy (trade, hotel and catering industry) (IECA, 2019).

Concerning EEIOA, the total IO table was taken into account in the analysis, which includes imports from other countries. However, GHG emissions by sector of activity considered in the EEIOA only corresponded to Spain. A third of the Spanish imports come from four countries: Germany, France, Italy and Portugal (OEC, 2018), which have CF scores in a similar order of magnitude (10.7, 6.9, 7.3 and 7.0 tCO_2-eq·inhabitant^{-1}·year^{-1} respectively) to that estimated in this study (7.5 tCO_2-eq·inhabitant^{-1}·year^{-1}) (Eurostat, 2018). It was therefore assumed that the Spanish CF was in line with those of other importing countries. This assumption implies that GHG emissions from imports were quantified on the basis of the emissions by sector of activity in Spain and not taking into account the emissions corresponding to each country from which these imports are produced.

The most important advantages of EEIOA over LCA are associated with the highest speed of data collection, since data is available in databases, monitored and regulated by governments. In contrast, collecting life cycle inventory data required to conduct an LCA is often tedious because information is scattered among different sources and is often only available at the national (or even regional) level. It is quite complicated to access data at the city level. Furthermore, the procedure for completing an LCA study requires the use of payment databases to identify inventory data of background processes, while the EEIO can be performed free of charge.

Nonetheless, LCA methodology also reports advantages since it is easier to calculate, identify and assess the contributions to the CF from each contributing flow, whereas in the EEIOA, because of the newly established relationships between the expenditure groups and the economic sectors, it is complicated to determine the contributions to the CF score of the expenditure groups. Moreover, the establishment of relationships between the economic sectors and spending groups is a key issue, not an objective one for the time being, which shows that there is still room for improvements in the development of the methodology.

4. Conclusions

Cities that are responsible for the majority of global GHG emissions have a key role to play in the mitigation of climate change. Thus, the quantification of the Carbon Footprint is crucial to define actions and plan strategies to minimize emissions and reduce the associated CF. There are different tools to quantify CF in cities, being LCA and EEIOA the most recognized ones. In this study the CF corresponding to an inhabitant of the city of Cadiz was compared considering the two mentioned methodologies with the purpose of identifying differences, advantages and disadvantages among them.

The results obtained show that EEIOA is a good alternative to LCA, which was more widely used, to analyze the CF of a city, involving some advantages over LCA, such as the speed of data availability and not depending on payment databases (e.g. Ecoinvent or Agri-footprint databases). However, the EEIOA methodology is not yet fully developed. In this regard, it is necessary to create more consensus mainly on two points: i) the use of downscaling factors due to the lack of availability of city-specific data and ii) the establishment of the relationships between expenditure groups and economic sectors in the IO table. In addition, the estimation of emissions derived from imports is another weakness to be considered in the aim of increasing the consistency of the methodology. In this regard, it could be interesting to create a factor that is as close as possible to the reality of the city's expenditure. In contrast, LCA has more advantages than EEIOA when information is required to obtain information on contributions from flows to the CF score. Thus, flows with higher contributions (i.e. that occupy a key role in the CF) are easier to calculate and identify when considering the LCA due to the level of disaggregation of the data.

Nevertheless, EEIOA could be considered as a great tool to quantify and compare the CF of different cities, as well as to identify the key economic sectors. In this regard, the EEIOA can be implemented as an efficient methodology for determining carbon footprint. It also leads to the definition of actions to offset GHG emissions and to foster the change towards a carbon neutral city. Furthermore, it could also be used to identify the main factors affecting the CF in a sample of cities (consumption habits, climate, traffic...). Moreover, it may be of great interest to policy makers, who can decide which methodology can be used depending on the available data or the objective of the study. In addition, both methodologies can be used consecutively: first, EEIOA as a quick first step to assess the profile of the city in terms of its emissions, and then, the LCA to acquire a more in-depth analysis to identify in more detail the flows that contribute most to these emissions.

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6. References

Bertram, F. de B., Rogrigues, J.F.D., Tukker, A., 2019. Modeling reductions in the environmental footprints embodied in European Union's imports through source shifting. Ecol. Econ. 164. https://doi.org/10.1016/j.ecolecon.2019.04.012

Blonk Agri-footprint BV, 2015. Agri-footprint - Part 2 - Description of Data. Gouda, the Nederlands BSI. (2012). PAS 2050-1: 2012 Assessment of life cycle greenhouse gas emissions from horticultural products. BSI.

Chester, M., Pincetl, S., Allenby, B., 2012. Avoiding unintended tradeoffs by integrating life-cycle impact assessment with urban metabolism. Curr. Opin. Environ. Sustain. 4, 451–457. https://doi.org/10.1016/j.cosust.2012.08.004

Cordella, M., Tugnoli, A., Spadoni, G., Santarelli, F., Zangrando, T., 2008. LCA of an Italian lager beer. Int. J. Life Cycle Assess. 13, 133–139. https://doi.org/10.1065/lca2007.02.306

Courtonne, J.Y., Alapetite, J., Longaretti, P.Y., Dupré, D., Prados, E., 2015. Downscaling material flow analysis: The case of the cereal supply chain in France. Ecol. Econ. 118, 67–80. https://doi.org/10.1016/j.ecolecon.2015.07.007

Dias, A.C., Lemos, D., Gabarrell, X., Arroja, L., 2014. Environmentally extended input-output analysis on a city scale - Application to Aveiro (Portugal). J. Clean. Prod. 75, 118–129. https://doi.org/10.1016/j.jclepro.2014.04.012

Dias, A., Lemos, D., Gabarrell, X., Arroja, L., 2018. Comparison of tools for quantifying the environmental performance of an urban territory. J. Ind. Ecol. 22, 868–880. https://doi.org/10.1111/jiec.12614

Ellen MacArthur Foundation, 2017. Cities in the circular economy: an initial exploration. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Cities-in-the-CE_An-Initial-Exploration.pdf (accessed April 2020)

European Commission, 2006. Regulation (EC) No 1893/2006 of the Eurpean Parliament and of the Council of 20 December 2006.

European Union, 2013. Regulation (EU) No 549/2013 of the European Parliament and of the Council of 21 May 2013 2013.

Eurostat, 2018. Greenhouse gas emissions per capita https://ec.europa.eu/eurostat/databrowser/view/t2020_rd300/default/table?lang=en (accessed September 2020)

García-Guaita, F., González-García, S., Villanueva-Rey, P., Moreira, M.T., Feijoo, G., 2018. Integrating Urban Metabolism, Material Flow Analysis and Life Cycle Assessment in the environmental evaluation of Santiago de Compostela. Sustain. Cities Soc. 40, 569–580. https://doi.org/https://doi.org/10.1016/j.scs.2018.04.027

Ghaemi, Z., Smith, A.D., 2020. A review on the quanti fi cation of life cycle greenhouse gas emissions at urban scale. J. Clean. Prod. 252, 119634. https://doi.org/10.1016/j.jclepro.2019.119634

Goldstein, B., Birkved, M., Quitzau, M.B., Hauschild, M., 2013. Quantification of urban metabolism through coupling with the life cycle assessment framework: Concept development and case study. Environ. Res. Lett. 8. https://doi.org/10.1088/1748-9326/8/3/035024

González-García, S., Dias, A.C., 2019. Integrating lifecycle assessment and urban metabolism at city level: Comparison between Spanish cities. J. Ind. Ecol. 23, 1062–1076. https://doi.org/10.1111/jiec.12844

Hein, L., Metzger, M.J., Moreno, A., 2009. Potential impacts of climate change on tourism; a case study for Spain. Curr. Opin. Environ. Sustain. 1, 170–178. https://doi.org/10.1016/j.cosust.2009.10.011

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., van Zelm, R., 2016. ReCiPe2016 : a harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterisation. Int. J. Life Cycle Assess. 1–152. https://doi.org/10.1007/s11367-016-1246-y

Ibrahim, M., El-Zaart, A., Adams, C., 2018. Smart sustainable cities roadmap: Readiness for transformation towards urban sustainability. Sustain. Cities Soc. 37, 530–540. https://doi.org/10.1016/j.scs.2017.10.008

IECA, 2019. Andalucia town by town - Municipal Files. Andalusian Institute of Statistics and Cartography (in Spanish) [WWW Document]. URL https://www.juntadeandalucia.es/institutodeestadisticaycartografia/sima/ficha.htm?mun=11012

INE, 2015a. Urban Audit indicators for cities. National Institute of Statistics (in Spanish). https://www.ine.es/jaxiT3/Tabla.htm?t=10849 (accessed April 2020)

INE, 2015b. National annual accounting of Spain: Input-Output tables. National Statistical Institute (in Spanish). https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736177058&menu=resultados&idp=1254735576581 (accessed April 2020)

INE, 2015c. Air emissions accounts by branches of activity (CNAE 2009). National Statistical Institute (in Spanish). https://www.ine.es/jaxi/Tabla.htm?path=/t26/p084/base_2010/serie/l0/&file=01001.px&L=0 (accessed April 2020)

INE, 2015d. Income per person and consumption unit by Autonomous Community. National Institute of Stadistics (in Spanish) https://www.ine.es/jaxiT3/Tabla.htm?t=9947 (accessed April 2020)

Instituto de estadísitica y cartografía de Andalucía, 2015. Institute of Statistics and Cartography (in Spanish). https://www.juntadeandalucia.es/institutodeestadisticaycartografia (accessed April 2020)

IPCC, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ipsen, K.L., Zimmermann, R.K., Nielsen, P.S., Birkved, M., 2019. Environmental assessment of Smart City Solutions using a coupled urban metabolism—life cycle impact assessment approach. Int. J. Life Cycle Assess. 24, 1239–1253. https://doi.org/10.1007/s11367-018-1453-9

John, B., Luederitz, C., Lang, D.J., von Wehrden, H., 2019. Toward Sustainable Urban Metabolisms. From System Understanding to System Transformation. Ecol. Econ. 157, 402–414. https://doi.org/10.1016/j.ecolecon.2018.12.007

Kitzes, J., 2013. An introduction to environmentally-extended input-output analysis. Resources 2, 489–503. https://doi.org/10.3390/resources2040489

Koroneos, C., Roumbas, G., Gabari, Z., Papagiannidou, E., Moussiopoulos, N., 2005. Life cycle assessment of beer production in Greece. J. Clean. Prod. 13, 433–439. https://doi.org/10.1016/j.jclepro.2003.09.010

Leontief, W.W., 1936. Quantitative Input and Output Relations in the Economic Systems of the United States. Rev. Econ. Stat. 18, 105–125.

Maranghi, S., Parisi, M.L., Facchini, A., Rubino, A., Kordas, O., Basosi, R., 2020. Integrating urban metabolism and life cycle assessment to analyse urban sustainability. Ecol. Indic. 112, 106074. https://doi.org/10.1016/j.ecolind.2020.106074

Moreno Ruiz, E., Valsasina, L., Brunner, F., Symeonidis, A., FitzGerald, D., Treyer, K., Bourgault, G., Wernet, G., 2018. Documentation of changes implemented in ecoinvent database v3.5. Ecoinvent, Zürich, Switzerland. 5, 1–97.

OEC, 2018. Imports of Spain. The Observatory of Economic Complexity.

Pandey, D., Agrawal, M., 2011. Carbon footprint : current methods of estimation 135–160. https://doi.org/10.1007/s10661-010-1678-y

Red Eléctrica de España, 2020. National statistical series (in Spanish) [WWW Document]. URL https://www.ree.es/es/datos/publicaciones/series-estadisticas-nacionales

Ridoutt, B.G., Hadjikakou, M., Nolan, M., Bryan, B.A., 2018. From Water-Use to Water-Scarcity Footprinting in Environmentally Extended Input-Output Analysis. Environ. Sci. Technol. 52, 6761–6770. https://doi.org/10.1021/acs.est.8b00416

Roibás, L., Loiseau, E., Hospido, A., 2017. Determination of the carbon footprint of all Galician production and consumption activities: Lessons learnt and guidelines for policymakers. J. Environ. Manage. 198, 289–299. https://doi.org/10.1016/j.jenvman.2017.04.071

Roibás, L., Loiseau, E., Hospido, A., 2018. A simplified approach to determine the carbon footprint of a region: Key learning points from a Galician study. J. Environ. Manage. 217, 832–844. https://doi.org/10.1016/j.jenvman.2018.04.039

Schau, E.M., Fet, A.M., 2008. LCA studies of food products as background for environmental product declarations. Int. J. Life Cycle Assess. 13, 255–264. https://doi.org/10.1065/lca2007.12.372

Shafie, F.A., Omar, D., Karupannan, S., Gabarrell, X., 2013. Urban metabolism using economic input-output analysis for the city of Barcelona. WIT Trans. Ecol. Environ. 179 VOLUME, 27–37. https://doi.org/10.2495/SC130031

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., Ludwig, C., 2015. The trajectory of the anthropocene: The great acceleration. Anthr. Rev. 2, 81–98. https://doi.org/10.1177/2053019614564785

Tanguay, G.A., Rajaonson, J., Lanoie, P., 2010. Measuring the sustainability of cities : An analysis of the use of local indicators. Ecol. Indic. 10, 407–418. https://doi.org/10.1016/j.ecolind.2009.07.013

United Nations, 2020. Sustainable Development Goal 13: Take urgent action to combat climate change and its impacts. https://www.un.org/sustainabledevelopment/climate-change/ (accessed September 2020)

Villanueva-Rey, P., Vázquez-Rowe, I., Moreira, M.T., Feijoo, G., 2014. Comparative life cycle assessment in the wine sector: Biodynamic vs. conventional viticulture activities in NW Spain. J. Clean. Prod. 65, 330–341. https://doi.org/10.1016/j.jclepro.2013.08.026

Williams, A.T., Randerson, P., Di Giacomo, C., Anfuso, G., Macias, A., Perales, J.A., 2016. Distribution of beach litter along the coastline of Cádiz, Spain. Mar. Pollut. Bull. 107, 77–87. https://doi.org/10.1016/j.marpolbul.2016.04.015

World Bank, 2019. Urban Development. https://www.worldbank.org/en/topic/urbandevelopment/overview (accessed April 2020)

Table 1. Expenditure in € by economic sector in Andalusia and Cadiz considering the downscaling factors in 2015.

Economic Sector	**Andalusia**	**Cadiz (DF_1)**	**Cadiz (DF_2)**
Real estate services	2,029	2,856	2,087
Food products; beverages; tobacco products	1,071	1,507	1,101
Accommodation and food services	824	1,159	847
Textiles; wearing apparel; leather and related products	545	767	560

Land transport services and transport services via pipelines	529	745	544
Motor vehicles, trailers and semi-trailers	515	725	530
Products of agriculture, hunting and related services	472	664	485
Electricity, gas, steam and air conditioning	341	480	351
Insurance, reinsurance and pension funding services, except compulsory social security	318	448	327
Human health services	306	431	315
Other personal services	262	369	270
Telecommunications services	256	361	264
Creative, arts and entertainment services; library, archive, museum and other cultural services; gambling and betting services	180	254	186
Fish and other fishing products; aquaculture products, support services to fishing	166	234	171
Retail trade services, except of motor vehicles and motorcycles	151	213	155
Rental and leasing services	141	198	145
Repair services of computers and personal and household goods	98	138	101
Furniture; other manufactured goods	97	136	100
Education services	95	134	98
Natural water; water treatment and supply services	84	119	87
Computer, electronic and optical products	77	108	79
Electrical equipment	59	84	61
Constructions and construction work	58	82	60
Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery	42	59	43
Sporting services and amusement and recreation services	39	54	40
Other professional, scientific and technical services; veterinary services	31	44	32
Publishing services	31	44	32
Computer programming, consultancy and related services; information services	25	36	26
Air transport services	23	33	24

Public administration and defense services; compulsory social security services	23	32	23
Paper and paper products	18	25	18
Machinery and equipment n.e.c.	17	24	18
Repair and installation services of machinery and equipment	15	21	15
Other transport equipment	6	9	7
Postal and courier services	2	3	2
TOTAL	**8,950**	**12,597**	**9,204**

Table 2. The top ten economic sectors in terms of greenhouse gases emission per €.

Economic Sector	**kg CO_2-eq/€**
Other non-metallic mineral products	1.85
Fish and other fishing products; aquaculture products; support services to fishing	1.36
Air transport services	1.33
Electricity, gas, steam and air conditioning	0.92
Products of agriculture, hunting and related services	0.90
Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery	0.76
Land transport services and transport services via pipelines	0.67
Coke and refined petroleum products	0.55
Water transport services	0.51
Basic metals	0.33

Table 3. Carbon Footprint (CF) score per inhabitant and year estimated from an LCA approach. Contributions per analyzed flow are also indicated.

Flows	**Contribution**	**CF**
	%	**tCO_2-eq·inhabitant^{-1}·year^{-1}**
Building Materials	37.4	2.03
Energy	20.9	1.14
Food and Beverages	13.3	0.72
Fossil fuels	11.6	0.63
Other flows	8.7	0.47
Solid Wastes	6.7	0.37
Wastewater	1.4	0.07
TOTAL	**100**	**5.43**

Table 4. Contributions from the key flows and the corresponding related economic sectors to the Carbon Footprint score in LCA and EEIOA considering the DF_1.

LCA flow	**tCO_2-eq·inhabitant^{-1}·year^{-1}**	**Economic Sector**	**tCO_2-eq·inhabitant^{-1}·year^{-1}**
Building Materials	2.03	Constructions and construction works Real estate services	0.27
Energy	1.14	Electricity, gas, steam and air conditioning	0.87
Food and Beverages	0.72	Products of agriculture, hunting and related services Food products; beverages; tobacco products Fish and other fishing products; aquaculture products; support services to fishing	2.1
Solid Wastes Wastewater	0.44	Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery	0.07

Figure 1. Location of the City of Cadiz in the map of Spain

Figure 2. Equivalences between Branches of activities, Economic sectors of the Input-Output (IO) table and Expenditure groups corresponding to the first economic sector considered "Products of agriculture, hunting and related services".

Figure 3. Schematic representation of the considered flows in the Life Cycle Analysis. Inputs and output flows involve the production processes and the management treatments, respectively.

Figure 4. Contributions from the different economic sectors to the Carbon Footprint regardless of the downscaling factor, corresponding to the city of Cadiz.

Figure 5. Main flows corresponding with (a) “Building Materials” (b) “Food and Beverages” and (c) “Fossil Fuels” and their contributions to CF.

Declaration of competing interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Credit author statement

Manuel Rama: Conceptualization, Data collection, methodology, results presentation, validation, writing- original draft preparation. **Eduardo Entrena-Barbero:** Data collection, data calculation. **Ana Claudia Dias:** Methodology, validation, data calculation **Maria Teresa Moreira**: Methodology development, funding acquisition, project administration, supervision, validation and writing-reviewing manuscript. **Gumersindo Feijoo**: Methodology, funding acquisition, project administration, supervision and validation. **Sara González-García**: Conceptualization, methodology, funding acquisition, project administration, software, supervision, validation and writing-reviewing manuscript.

Graphical abstract

Highlights

- ✓ EEIOA can be a good alternative to LCA to assess the carbon footprint of a city.
- ✓ The downscaling factor in EEIOA may significantly affect the results.
- ✓ An advantage of EEIOA over LCA is the speed and availability of data in public sources.
- ✓ LCA can identify the contributions of the different flows to the CF, this being more complex in EEIOA.

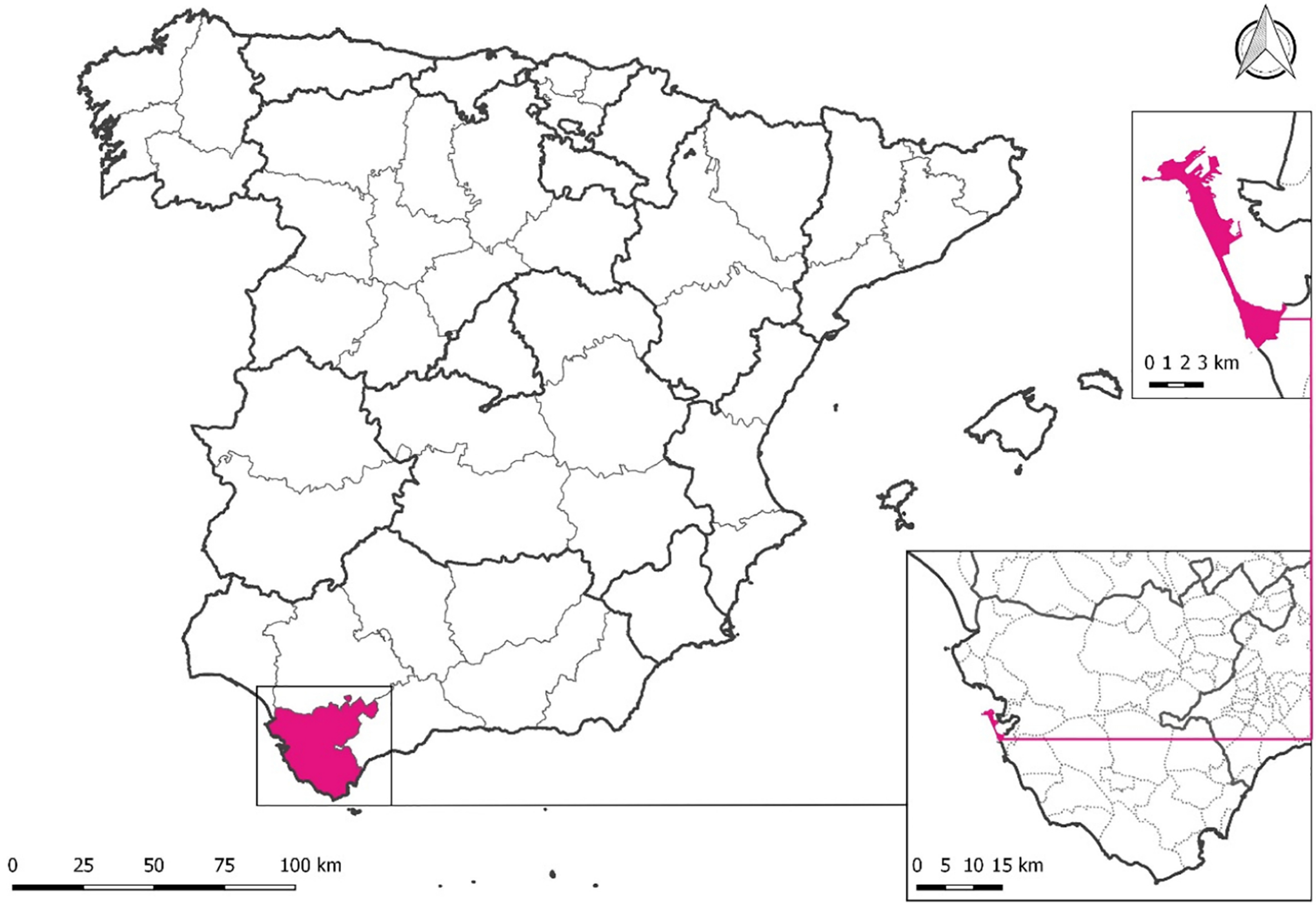

Figure 1


Products of agriculture, hunting and related services
Crop and animal production, hunting and related service activities
Meat
Fruits

Figure 2

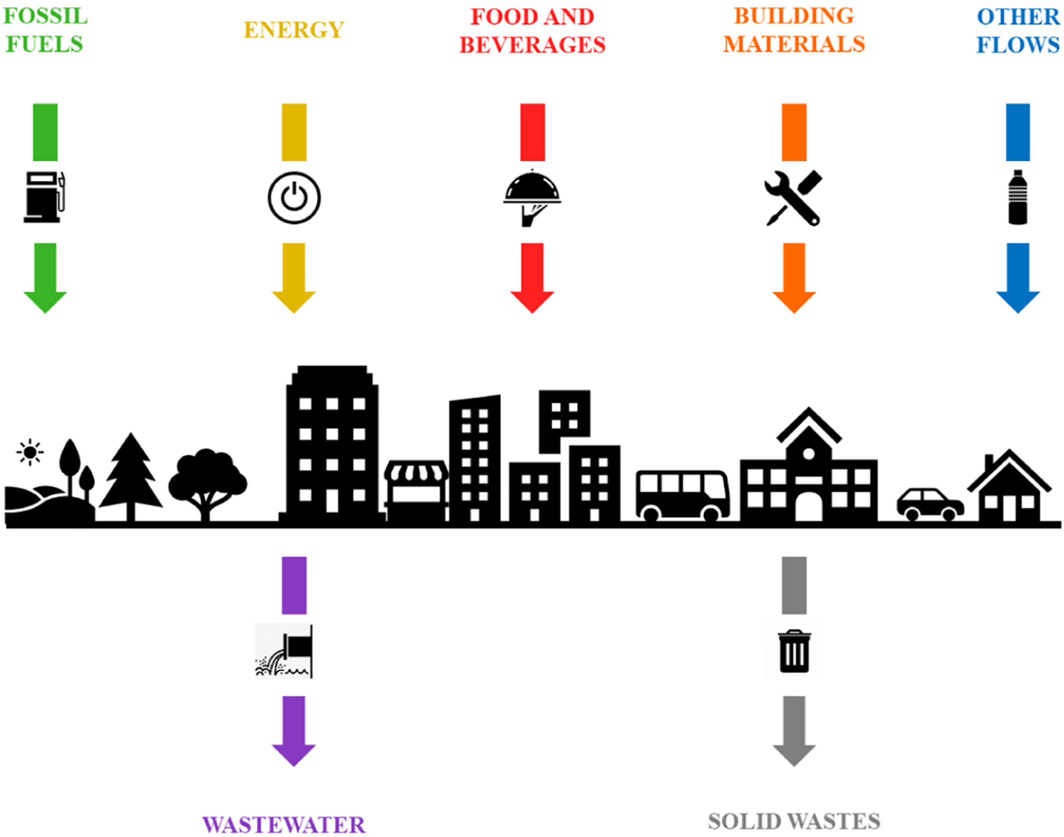
FOSSIL FUELS
ENERGY
FOOD AND BEVERAGES
BUILDING MATERIALS
OTHER FLOWS
WASTEWATER
SOLID WASTES

Figure 3

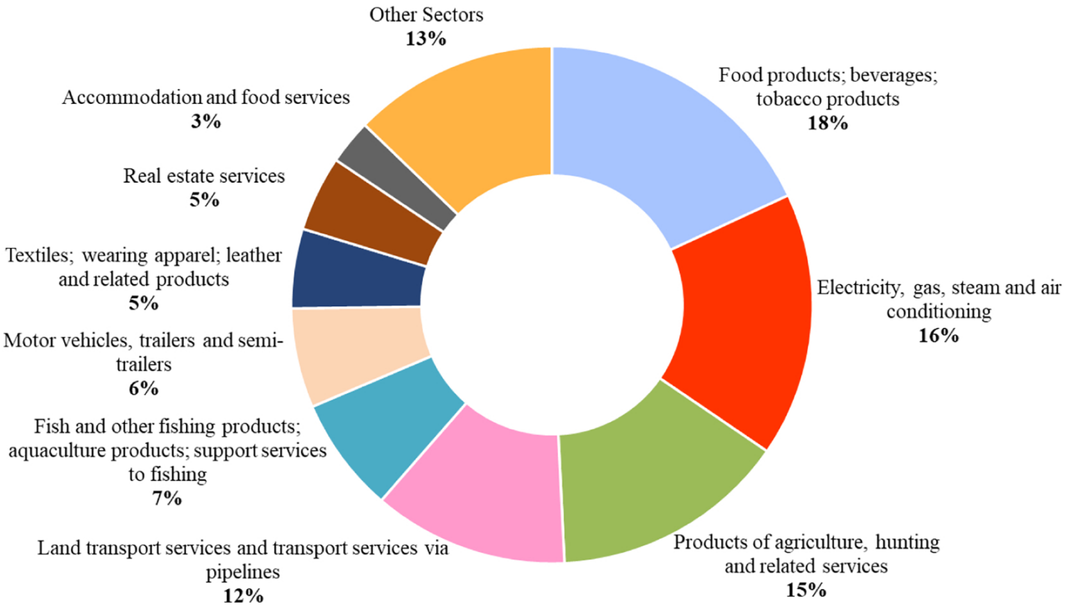
Other Sectors
13%
Food products; beverages; tobacco products
18%
Electricity, gas, steam and air conditioning
16%
Products of agriculture, hunting and related services
15%
Land transport services and transport services via pipelines
12%
Fish and other fishing products; aquaculture products; support services to fishing
7%
Motor vehicles, trailers and semi-trailers
6%
Textiles; wearing apparel; leather and related products
5%
Real estate services
5%
Accommodation and food services
3%

Figure 4

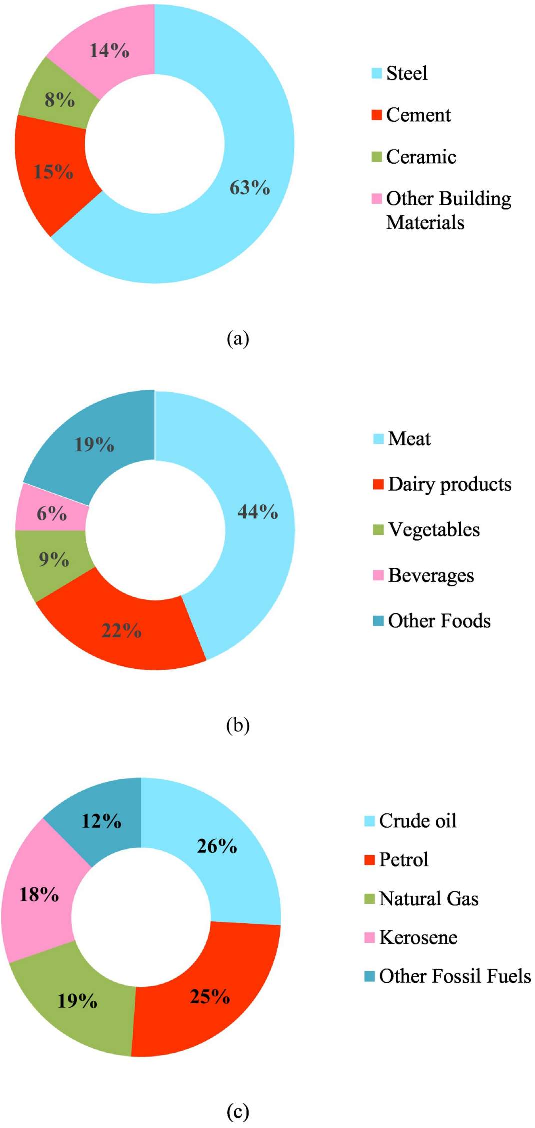
14%
8%
15%
63%
Steel
Cement
Ceramic
Other Building Materials
(a)
19%
6%
9%
22%
44%
Meat
Dairy products
Vegetables
Beverages
Other Foods
(b)
12%
26%
18%
19%
25%
Crude oil
Petrol
Natural Gas
Kerosene
Other Fossil Fuels
(c)

Figure 5