

1 **Addressing the Carbon Footprint of a Spanish city through Environmentally**
2 **Extended Input-Output Analysis and Life Cycle Assessment**

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10 **Abstract**

11 Climate change is one of the most important challenges facing society today.
12 Considering that most greenhouse gas (GHG) emissions are attributed to cities, as they
13 are the global centers of business, residential and cultural activity, cities are expected to
14 play a leading role in proposing climate change mitigation actions. To do so, it is
15 important to have tools that allow the carbon footprint of cities to be assessed as
16 accurately as possible. This study aims to quantify the carbon footprint (CF) associated
17 with the activities developed in a Spanish city (Cadiz, Southwest Spain) by means of
18 two available environmental methodologies, namely Environmentally Extended Input-
19 Output Analysis (EEIOA) and Life Cycle assessment (LCA). When EEIOA is
20 considered, two downscaling factors were proposed for the analysis due to the nature of
21 the data handled (monetary data), based on the incomes (DF₁) and expenditures (DF₂)
22 per inhabitant at city level. Regarding LCA, the rates of consumption of goods and
23 production of waste per inhabitant have been processed to estimate the CF. The CF
24 scores identified were 5.25 and 3.83 tCO₂-eq·inhabitant⁻¹·year⁻¹ for DF₁ and DF₂
25 respectively, according to EEIOA, and 5.43 tCO₂-eq·inhabitant⁻¹·year⁻¹, considering
26 LCA. Therefore, a similarity can be concluded between the results obtained with both
27 methodologies despite the inherent differences. Considering the results, the downscaling
28 procedure based on income per inhabitant should be preferred, pointing to EEIOA as a
29 good alternative to LCA for evaluating the CF at city level, requiring less time and
30 effort. In contrast, EEIOA reports more limitations when critical flows were identified,
31 which LCA can solve. Finally, this study can be of great interest to policy makers and

32 city governments in developing new policies and city models for reducing GHG
33 emission and addressing climate change.

34

35 **This paper compares EEIOA and LCA as methodologies to evaluate the**
36 **carbon footprint at city level applying both on a case study of a Spanish city.**

37 **Key words**

38 Greenhouse gas emissions; Spain; Sustainable City; Urban environmental management;

39 Urban Metabolism.

40 1. Introduction

41 Greenhouse Gases (GHGs) emission has increased exponentially since 1950 and,
42 as a result, this fact has led to an acceleration of climate change (Steffen et al., 2015).
43 Different impacts on the natural environment derive from global warming, such as i)
44 alteration of hydrological systems, ii) change in both the migration patterns and the
45 behavior of some species, iii) increased flooding events, and iv) extreme weather
46 conditions, among others (IPCC, 2014). In addition, human health is being either
47 directly or indirectly affected (especially in the poorest population) by climate change,
48 along with some economic sectors such as agriculture (e.g., due to problematic weather
49 conditions such as droughts and frost) and tourism (tourism destinations change
50 depending on the weather) (Hein et al., 2009; IPCC, 2014). In this framework, climate
51 change becomes relevant within the strategic plan Agenda 2030, which considers it as
52 one of the main challenges to be addressed and, consequently, it is explicitly considered
53 in the Sustainable Development Goal (SDG) number 13 (*Climate Action*) which
54 promotes urgent actions to combat climate change and its derived impacts. Therefore,
55 the targets defined in this SDG aim to increase the adaptability of different countries as
56 well as to reduce GHG emission (United Nations, 2020).

57 In this sense, cities play a fundamental role, not only in the fight against climate
58 change, but also in the mitigation of various environmental impacts. Currently, more
59 than 50% of the world population lives in cities, and this figure is expected to increase
60 to 60% by 2050 (Ibrahim et al., 2018). Cities are socio-technical systems, which involve
61 cultural, economic, institutional and technical subsystems (Chester et al., 2012).
62 Therefore, cities have become spaces of high concentration of people that demand
63 considerable flows of material and energy (John et al., 2019). As consequence, cities are
64 responsible for most of the environmental impacts derived from human activities. Thus,
65 70% of global GHG emissions, 75% of the natural resources extracted and 50% of the
66 waste generated worldwide are due to the different daily activities of citizens (Ellen
67 MacArthur Foundation, 2017; World Bank, 2019). Life Cycle Assessment (LCA) is a
68 well-known standardized methodology which allows different environmental impacts to
69 be measured from a life cycle perspective (González-García and Dias, 2019). It is
70 widely used to assess the direct and indirect impacts derived from products, processes
71 and activities (Cordella et al., 2008; Schau and Fet, 2008). Recently, this methodology
72 has been applied to analyze the direct and indirect impacts derived from the demands of

73 energy and materials flows in cities and urban systems (Dias et al., 2018a; Goldstein et
74 al., 2013; González-García and Dias, 2019). In this sense, the Urban Metabolism (UM)
75 approach has been combined with LCA to assess the environmental consequences of
76 cities, considering the UM as the driving force to identify the different energy and
77 material flows demanded by the inhabitants of a city (Goldstein et al., 2013; Ipsen et al.,
78 2019; Maranghi et al., 2020) UM attempts to conceptualize a city as a living organism
79 which requires goods and energy and generates wastes (Goldstein et al., 2013). Thus,
80 UM allows the identification of different flows grouped into four main categories:
81 materials, water, energy and waste (Ghaemi and Smith, 2020). Therefore, the indirect
82 emissions and discharges derived from the flows considered by UM are quantified with
83 the LCA methodology and transformed into environmental impacts (Huijbregts et al.,
84 2016). In this way, the environmental profile associated with a city can be reported in
85 terms of these impact categories, among which are indicators such as the Carbon
86 Footprint (CF). CF is a renowned and recognized environmental indicator that
87 quantifies the GHGs emitted into the atmosphere by an individual, organization,
88 process, product or event within defined limits (Pandey and Agrawal, 2011). Thus, CF
89 is expressed in an amount of carbon dioxide (CO₂eq) equivalent emissions that includes
90 different GHGs such as carbon dioxide (CO₂), nitrous oxide (N₂O) and methane (CH₄)
91 among others (Ghaemi and Smith, 2020).

92 However, the most widespread tool to be implemented with UM to assess the
93 environmental impacts of cities is the Environmentally Extended Input-Output Analysis
94 (EEIOA). This tool is based on the economic data provided by the Input-Output tables
95 which reflect the monetary transactions between the different industrial sectors
96 (Leontief, 1936), associating their corresponding environmental burdens (Dias et al.,
97 2018, 2014b). Thus, EEIOA transforms the money spent per inhabitant or household
98 during a period (usually one year), into CO₂-eq units. Different environmental footprints
99 as those related to water-scarcity (Ridoutt et al., 2018), land and material (Bertram et
100 al., 2019) can be calculated considering EEIOA and depending on the environmental
101 impact data provided and recorded by each country for all economic sectors (e.g., GHG
102 emission and water consumption by sector) (Bertram et al., 2019; Dias et al., 2014b).
103 Similarly, CF can be evaluated at country level (Bertram et al., 2019), at regional level
104 (Roibás et al., 2017) or at city level (Dias et al., 2014b) taking into account the

105 expenditures of the inhabitants or households of the country, region or city,
106 respectively.

107 Although it has not been established which methodology is best (or not) to apply
108 together with UM in the assessment of cities and urban systems, Dias et al. (2018b)
109 reported some advantages of EEIOA regarding LCA, namely shorter data collection
110 times and the use of public databases (LCA usually requires the use of payment
111 software). In addition, EEIOA avoids double counting while in LCA it is sometimes
112 quite difficult to avoid (Kitzes, 2013). Bearing in mind the methodologies mentioned
113 above (LCA and EEIOA, combined with UM), the main goal of this study is to
114 determine the CF of a Spanish city in order to compare the results and identify the main
115 differences, limitations, advantages and drawbacks that one methodology has over the
116 other. Moreover, attention will be paid to the material and energy flows that are
117 responsible for the highest contributions to the CF scores in both methodologies. The
118 city of Cadiz, which is in the Autonomous Community of Andalusia (Southern Spain),
119 has been selected as case study (**Figure 1**). This Spanish city has an economy highly
120 dependent on tourism due to its location (southern coast of Spain) and very favorable
121 weather conditions (Williams et al., 2016). Therefore, and given that tourism is one of
122 the economic sectors most affected by climate change (Hein et al., 2009), the selection
123 of this case study can be considered of potential interest not only for this Spanish city
124 but also for similar cities with the aim of taking measures and developing policies to
125 contrast or minimize its effects and addressing them towards more sustainable cities.

126

127 <Figure 1 around here>

128 **2. Material and Methods**

129 *2.1. Case of Study*

130 Cadiz is the capital of the homonymous province with a population of 116,027
131 inhabitants (IECA, 2018). Its population rate has decreased in recent years for many
132 reasons, such as low birth rates and high rental and sale prices, mainly due to its high
133 population density and the lack of residential area to continue growing as Cadiz is
134 located on a peninsula. In economic terms, its inhabitants had a an average gross income
135 per capita of 26,891€ per capita in 2015, which corresponds to their average gross

136 income (INE, 2015a). The tertiary sector (especially tourism) is its main economic
137 driver. Nevertheless, tourism has a strong seasonality regime during the summer months
138 and, as consequence, the city has a very high unemployment rate, above 33% (Instituto
139 de estadística y cartografía de Andalucía (2015).

140 *2.2. Carbon Footprint estimation*

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

144 *2.2.1. Environmentally Extended Input-Output Analysis methodology*

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

149 *2.2.1.1. Data requirements*

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

157 In contrast, if the table is read vertically, each column indicates the expenditures
158 that each sector has from the sectors of the corresponding rows (Leontief, 1936). To
159 conduct an EEIOA it was necessary to transform the IO table into the inverse Leontief
160 matrix $(I-A)^{-1}$; where I was the identity matrix and A was the matrix resulting from
161 dividing the values of the IO table by the gross domestic product (GDP) of the
162 corresponding sector (Dias et al., 2014b). In this study, it has been used the total IO
163 table from Spain (INE, 2015b), which considered 64 economic sectors and was
164 elaborated according to Regulation (EU) n° 549/2013 (European Union, 2013). This
165 regulation indicates that the data from the IO table must be updated every 5 years since
166 2010. That is why the year selected to conduct this study was 2015, instead of another
167 more updated period. In addition, this data source provided, in addition to the total IO

168 table, the domestic IO table, the importations IO table and the corresponding inverse
169 Leontief matrices (INE, 2015b).

170 GHG emission data by Branch of Activity are available at the national level from
171 the National Statistics Institute (INE, 2015c). This source reports the GHG emissions
172 for each of the 64 different Branches of activity according to the National Classification
173 of Economic Activities established in the Regulation (EC) No 1893/2006 (European
174 Commission, 2006). These GHG emission flows are provided in tons of CO₂-eq;
175 however, in order to calculate the CF it was necessary to divide each value by the GDP
176 of the corresponding Branch of activity, i.e. the emissions associated with the
177 “*manufacture of food, beverages and tobacco products*” must be divided by the GDP of
178 the same activity “*manufacture of food, beverages and tobacco products*”. As a result,
179 the GHG emission intensity in tons of CO₂-eq·€⁻¹ was obtained.

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

187 The lack of data at the city level made it necessary to transform some required
188 data by means of downscaling factors (Shafie et al., 2013). Thus, these factors must be
189 based on other variables with data available at different scales (Courtonne et al., 2015).
190 In the present study, two downscaling factors (DF) have been proposed which were: i)
191 DF₁ taking into account the average level of income per household in the city of Cadiz
192 and the average level of income in the region of Andalusia; ii) DF₂ based on the average
193 expenditures per person in the city of Cadiz and in the region of Andalusia. Concerning
194 the first downscaling factor (DF₁) there were available data for both, Andalusia and
195 Cadiz. On the contrary, since there was not available information regarding the average
196 level of income per household at city level it has been considered data for the average
197 expenditures per person in the municipalities with more than 100,000 inhabitants in the
198 region of Andalusia (IECA, 2015), as assumption. In this sense, **Equation 1** and
199 **Equation 2** show the how to estimate both downscaling factors.

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

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

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201 2.2.1.2. *Equivalences between expenditures groups and economic sectors of the*
202 *IO table.*

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

216

217 <**Figure 2 around here**>

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

228 "Fabricated metal products, except machinery and equipment "or" Rubber and plastics
 229 products ".

230 2.2.1.3. Carbon Footprint calculation

231 EEIOA consists of transforming economic data into environmental impacts. Thus,
 232 in this study the CF was calculated by transforming the expenditures (in €) of the
 233 citizens of Cadiz in tons of CO₂-eq, following the methodology described by Dias et al.
 234 (2014). Consequently, this calculation was based on the three main databases that
 235 consist basically of a matrix $((I-A)^{-1})$ and two vectors (Y and Z):

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

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

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

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

242 Finally, in the GHG emission vector (Z), it was considered the emissions from the
 243 64 economic sectors in tons of CO₂-eq·€⁻¹, resulting from dividing the emissions of
 244 each branch of activity by the GDP as specified in *Section 2.2.1.1.*

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

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

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

249 2.2.2. Life Cycle Assessment

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

259 2.2.2.1. Functional Unit

260 In the present paper, the consumption of goods by a resident in one year has
261 been considered as functional unit in line with other studies, which only take into
262 account the residents registered in the cities under study (Goldstein et al., 2013;
263 González-García and Dias, 2019; Roibás et al., 2017). However, other authors (García-
264 Guaita et al., 2018), consider the equivalent inhabitant (i.e., considering also the non-
265 resident population in the city) but the EEIOA databases are per inhabitant (not
266 equivalent). Thus, and with the aim of comparing both methodologies, a registered
267 inhabitant must be taken as reference.

268 2.2.2.2. System boundaries and data collection

269 Under the UM perspective, this study has considered seven metabolic input and
270 output flows (**Figure 3**) which are essential for the development of the cities. In the
271 selection of these flows, those considered by González-García and Dias (2019) have
272 been taken into account: fossil fuels, energy, foods and beverages, building materials,
273 other flows (including paper and cardboard, glass bottles, cork, plastic containers and
274 tap water) as inputs and wastewater and solid wastes as outputs. Bearing in mind that
275 cities are considered as large consumers rather than producers of goods, some flows
276 related to agriculture or industrial activities, such as fertilizers or chemicals, have not
277 been taken into account (Dias et al., 2018; González-García and Dias, 2019). In
278 addition, the production of goods in the city of Cadiz has been also excluded, i.e. it is
279 assumed that all materials and energy flows are imported in order to avoid double
280 counting in line with previous studies (Dias et al., 2018; González-García and Dias,
281 2019).

282 As for the input flows, the upstream activities involved in their production have
283 been considered, taking into account the extraction of raw materials, processing,
284 manufacturing and transport up to the city. Background data corresponding to these
285 activities have been taken from Ecoinvent ® database version 3.5 (Moreno Ruiz et al.,
286 2018). Specifically for some food products such as legumes (lentils, chickpeas), sugar,
287 oil, pasta and some meat products (beef, pork and chicken), the background data have
288 been taken from Agri-footprint database (Blonk Agri-footprint BV, 2015). Moreover,
289 background data for wine and beer production have taken from Villanueva-Rey et al.
290 (2014) and Koroneos et al. (2005) respectively.

291 <Figure 3 around here>

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

303 **3. Results and Discussion**

304 *3.1. Environmentally Extended Input-Output Analysis of Cadiz*

305 As detailed above, two different downscaling factors have been estimated to be
306 applied in the EEIOA (**Table SM3** in the **Supplementary Material**). DF_1 (1.41) was
307 about 37% higher than DF_2 (1.03), indicating that the difference between the income per
308 household between Cadiz and Andalusia was considerably higher than the difference in
309 the expenses per person in both locations. While the income per household in Cadiz
310 were around 40% higher than the income per household in Andalusia in 2015, the
311 expenditures per person in Cadiz were only 3% higher than those in Andalusia. The
312 rationale behind the low variation in the expenses was associated with the fact that the

313 value estimated for expenses in Cadiz corresponds to the average expenditure per
314 person for all Andalusian municipalities with more than 100,000 inhabitants, which
315 accumulate a large part of the population of the entire region. Consequently, it was
316 expected a minor variation with regard to the average expenditure per person in
317 Andalusia.

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

324 The second most important sector, with a 12% contribution to total expenditure,
325 was "*Food products; beverages; tobacco products*". It was followed by
326 "*Accommodation and food services*" (10% of the total). The rest of the sectors reported
327 contributing ratios lower than 10%. The difference between the first two sectors is
328 notable, since a person from Cadiz or Andalusia spends almost twice as much on rent as
329 on food. Bearing in mind the averages income per person in Andalusia in 2015 was
330 7,942 € (INE, 2015d), Andalusians spent around 26% of their incomes on housing. This
331 ratio was close to the alarming 30% from which a rent is considered high enough to
332 harm a citizen's quality of life. (Tanguay et al., 2010).

333 <**Table 1 around here**>

334 In terms of emissions by sector, **Table 2** details the top ten economic sectors with
335 the highest GHG emissions for every euro produced by the same sector. In this sense,
336 the economic sectors were classified according to their emissions and their size in
337 economic terms. The sector with the highest GHG emission per € was "*Other non-*
338 *metallic mineral products*", which includes activities such as the manufacture of
339 construction materials such as glass, cement, concrete, ceramic materials, among others.
340 Hence, if this sector generates 1 € in goods, it emits 1.85 kg CO₂-eq into the
341 atmosphere. All of these economic sectors require large amounts of energy such as
342 "*Other non-metallic mineral products*", "*Electricity, gas, steam and air conditioning*",
343 "*Sewerage services; sewage sludge; waste collection, treatment and disposal services;*
344 *materials recovery*" (partly due to the wastewater pumping involved in sewerage

345 services), "*Coke and refined petroleum products*", "*Water transport services*" and
346 "*Basic metals*"; or are related to the combustion of fossil fuels such as, "*Fish and other*
347 *fishing products; aquaculture products; support services to fishing*", "*Air transport*
348 *services*", "*Products of agriculture, hunting and related services*" and "*Land transport*
349 *services and transport services via pipelines*").

350 <Table 2 around here>

351 Taking into account the downscaling factors, the expenditures by economic
352 sector, the GHG emissions per € and the inverse Leontief matrix the CF scores have
353 been calculated following the **Equation 3** described in *Section 2.2.1.3*. Thus, the
354 estimated CF scores were 5.25 tCO₂-eq·inhabitant⁻¹·year⁻¹ and 3.83 tCO₂-eq·inhabitant⁻¹·year⁻¹
355 considering DF₁ and DF₂, respectively. However, the contribution of each sector
356 to the CF score did not depend on the downscaling factor since it was applied to the
357 expenses per person and applied equally to all sectors. **Figure 4** depicts the different
358 contributions of each sector to the total CF, regardless the downscaling factor
359 considered. Bearing in mind the information detailed in **Figure 4**, four sectors
360 concentrated the 61% of the total contributions to the CF scores. These sectors were:
361 "*Food products; beverages; tobacco products*", "*Electricity, gas, steam and air*
362 *conditioning*", "*Products of agriculture, hunting and related services*" and "*Land*
363 *transport services and transport services via pipelines*". All of them occupied leading
364 positions in the ranking of expenditures per person detailed in **Table 1**. Furthermore,
365 with the exception of "*Food products; beverages; tobacco products*", the remaining
366 three sectors were also among the top ten of the sectors with the highest GHG emission
367 rates per € (**Table 2**). Accordingly, these sectors that had an outstanding emission rate
368 were those where the citizens of Cadiz mainly expended their incomes and therefore,
369 were sectors with a significant contribution to the CF score estimated per inhabitant. In
370 the case of "*Food products; beverages; tobacco products*", its important contribution to
371 the CF score was associated with the fact that it was the second sector in which the
372 citizens of Cadiz spent their incomes with a remarkable difference in comparison with
373 the other three sectors. However, although "*Real estate services*" was the sector in
374 which there was more spending per person, it had a contribution of only 3% to the total
375 CF score due to its low GHG emission rate per euro in comparison with the other
376 sectors.

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<Figure 4 around here>

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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 $9.41 \text{ tCO}_2\text{-eq}\cdot\text{inhabitant}^{-1}\cdot\text{year}^{-1}$, considerably higher than our results ($5.25 \text{ tCO}_2\text{-eq}\cdot\text{inhabitant}^{-1}\cdot\text{year}^{-1}$ and $3.83 \text{ tCO}_2\text{-eq}\cdot\text{inhabitant}^{-1}\cdot\text{year}^{-1}$). The reason behind these differences can be attributed to two issues:

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i) the CF obtained for both cities depends directly on the GHG emissions by sector of the corresponding country in terms of kg CO₂-eq per €. Therefore, while for Portugal in 2005 they were $18.85 \text{ kg CO}_2\text{-eq}\cdot\text{€}^{-1}$, for Spain in 2015 they were $11.17 \text{ kg CO}_2\text{-eq}\cdot\text{€}^{-1}$, 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.

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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

409 economic sector entitled “*Real estate services*” included rental and imputed income. In
410 contrast, rental and imputed rents were considered within the sector “*Construction*” in
411 the study of Aveiro, which had a much higher value in terms of kg CO₂-eq·€⁻¹ (0.104 kg
412 CO₂-eq eq·€⁻¹ for the case of “*Construction*” in Aveiro, and $5.16 \cdot 10^{-4}$ kg CO₂-eq eq·€⁻¹
413 for the case of “*Real estate services*” in Cadiz).

414 3.2. *Life Cycle Assessment of Cadiz*

415 The environmental study has been performed following a cradle-to-city approach
416 and therefore, the inputs of different flows (building materials, fossil fuels, energy, food
417 and beverages, water, packaging materials) to the city have been computed, as well as
418 the generation of specific output flows due to the UM approach with the corresponding
419 treatments (wastewater, landfill and recycling), which took place within the boundaries
420 of the city (see **Table SM2**). The estimated CF score following an LCA perspective was
421 5.43 tCO₂-eq·inhabitant⁻¹·year⁻¹. **Table 3** summarizes the contributions to CF per input
422 and output flow considered in the analysis. Bearing in mind these results, the main
423 contributing flow responsible for the highest GHG emissions was that of “*Building*
424 *Materials*”. The rationale behind that outstanding effect (37% of the total CF score) was
425 associated with large amounts of energy in the background processes of some
426 construction materials (e.g. steel or cement). This flow, together with “*Energy*” and
427 “*Food and Beverages*” (considering the production of foodstuffs and beverages),
428 concentrated around 72% of the total CF estimated per inhabitant.

429 <**Table 3 around here**>

430 Attention has been given to the assessment per contributing flow in order to
431 identify the hotspots. With respect to “*Building Materials*”, the flows that contributed
432 most to its CF were “*Steel*” (63%) and “*Cement*” (15%). Both construction materials
433 have demanded large energy requirements in their production systems, as well as being
434 the most energy-intensive. These results are in line with those identified for the cities of
435 Bilbao and Seville by González-García and Dias (2019) where “*Steel*” and “*Cement*”
436 were also the main responsible products for GHG emission from construction materials.
437 As for “*Food and beverages*” the main contributors were meat products (44%) and
438 “*dairy products*” (22%). Both flows involve livestock activities which produce
439 significant GHG emissions, namely those directly linked to the metabolism of
440 ruminants and those indirectly produced from the use of agricultural machinery in

441 agricultural activities to produce animal feed. The consumption of fossil fuels which
442 were used in transport activities and heat requirements, also made a significant
443 contribution to the CF of Cadiz. Among the fossil fuels, the largest contributions are
444 from the production of diesel required in transport activities, as well as the production
445 of kerosene required for aviation and the production of natural gas required at homes in
446 heating systems. **Figure 5** depicts the assessment in detail of contributions from
447 “*Building materials*”, “*Food and beverages*” and “*Fossil Fuels*”.

448 <**Figure 5 around here**>

449 3.3. EEIOA vs LCA

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

465 Nevertheless, with respect to the contributions of the CFs of each methodology,
466 more notable differences can be identified in some of the flows, as shown in **Table 4**. In
467 order to compare the contributions to the CFs of the different methodologies, some
468 relations were established between the main flows considered in LCA and the related
469 economic sectors considered in EEIOA. In addition, for EEIOA the values of the
470 contributions in $tCO_2\text{-eq}\cdot\text{inhabitant}^{-1}\cdot\text{year}^{-1}$ obtained with DF_1 were taken into account.
471 Thus, for “*Building Materials*” the contribution to CF was $2.03 tCO_2\text{-eq}\cdot\text{inhabitant}^{-1}\cdot\text{year}^{-1}$
472 and was related to the economic sectors “*Construction and construction works*”

473 and “*Real estate services*” whose contribution was $0.27 \text{ tCO}_2\text{-eq}\cdot\text{inhabitant}^{-1}\cdot\text{year}^{-1}$
474 ¹, which was seven and a half times less. This large difference was due to the fact that
475 not all the flows considered within “*Building Materials*” were involved in the
476 corresponding economic sectors (for example, consumption of steel which, in addition
477 to construction, was used to manufacture cars). Regarding the “*Energy*” flow directly
478 related to the economic sector “*Electricity, gas, steam and air conditioning*”, there was
479 not such a difference between each contribution value which was of the same order of
480 magnitude. Nevertheless, the contribution to the CF of “*Food and Beverages*” was three
481 times less than the economic sectors to which it was related “*Products of agriculture,*
482 *hunting and related services*”, “*Food products; beverages; tobacco products*” and “*Fish*
483 *and other fishing products; aquaculture products; support services to fishing*”. This
484 difference was due to the fact that within these sectors, the emissions caused by some
485 flows such as packaging was also implicit, which was not considered within “*Food and*
486 *Beverages*”. Finally, the sum of the contributions to the CF for the flows “*Solid Wastes*”
487 and “*Wastewater*” was $0.44 \text{ tCO}_2\text{-eq}\cdot\text{inhabitant}^{-1}\cdot\text{year}^{-1}$ and these flows were related to
488 the economic sector “*Sewerage services; sewage sludge; waste collection, treatment*
489 *and disposal services; materials recovery*”, which resulted in a contribution to CF of
490 $0.07 \text{ tCO}_2\text{-eq}\cdot\text{inhabitant}^{-1}\cdot\text{year}^{-1}$. In this case, the difference could be due to the fact that
491 spending on waste management in Spain is a municipal competence and only part of its
492 spending falls directly on citizens. Therefore, if the economic sector had a lower value
493 in the expenditures in the EEIOA, it also had a lower impact in terms of CF.

494 **<Table 4 around here>**

495 However, each methodology considers different flows, and establishing
496 relationships between them was not easy. For example, when considering the economic
497 sector “*Land transport; transport via pipelines*”, it was intuitive to relate it to transport
498 or, in this case, to the consumption of fossil fuels, however, in “*Land transport;*
499 *transport via pipelines*”, air transport was not considered, nor was natural gas, which
500 was considered in the flow of “*Fossil Fuels*”. This reason made it very difficult to
501 compare the results on the basis of the contributions of both methodologies.

502 The most important advantages of EEIOA over LCA are associated with the
503 highest speed of data collection, since data is available in databases, monitored and
504 regulated by governments. In contrast, collecting life cycle inventory data required to

505 conduct an LCA is often tedious because information is scattered among different
506 sources and is often only available at the national (or even regional) level. It is quite
507 complicated to access data at the city level. Furthermore, the procedure for completing
508 an LCA study requires the use of payment databases to identify inventory data of
509 background processes, while the EEIO can be performed free of charge.

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

518 **4. Conclusions**

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

527 The results obtained show that EEIOA is a good alternative to LCA, which was
528 more widely used, to analyze the CF of a city, involving some advantages over LCA,
529 such as the speed of data availability and not depending on payment databases (e.g.
530 Ecoinvent or Agri-footprint databases). However, the EEIOA methodology is not yet
531 fully developed. In this sense, it is necessary to create more consensus mainly on two
532 points: i) the use of downscaling factors and ii) the establishment of the relationships
533 between expenditure groups and economic sectors in the IO table. In this regard, it
534 could be interesting to create a factor that is as close as possible to the reality of the
535 city's expenditure. In contrast, LCA has more advantages than EEIOA when

536 information is required to obtain information on contributions from flows to the CF
537 score. Thus, flows with higher contributions (i.e. that occupy a key role in the CF) are
538 easier to calculate and identify when considering the LCA due to the level of
539 disaggregation of the data.

540 Nevertheless, EEIOA could be considered as a great tool to quantify and compare
541 the CF of different cities, as well as to identify the key economic sectors. Moreover, it
542 can be of great interest to policy makers, as a quick first step to assess the reality in
543 terms of emissions of a city, which can then be combined with an LCA to acquire a
544 more in-depth analysis to identify in more detail the flows that contribute most to these
545 emissions.

546 **5. Acknowledgements**

547 This research was supported by a project granted by the Spanish Government and
548 FEDER/ Ministry of Science and Innovation – Spanish National Research Agency
549 (CTQ2016-75136-P) and by a project granted by Xunta de Galicia (project ref. ED431F
550 2016/001). Dr. S.G.-G. would like to express her gratitude to the Spanish Ministry of
551 Economy and Competitiveness for financial support (Grant reference RYC-2014-
552 14984). The authors belong to the Galician Competitive Research Group GRC ED431C
553 2017/29 and to the CRETUS Strategic Partnership (ED431E2018/01). All these
554 programs are co-funded by FEDER (UE).

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