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Urban form and spatial structure as determinants of per capita greenhouse gas emissions considering possible endogeneity and compensation behaviors

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Abstract

Modifying the form and spatial structure of cities through urban planning can be an effective means to reduce greenhouse gas (GHG) emissions in cities. The supporters of the Compact City Approach to urban sustainability propose dense and centralized urban systems. In the case of population density, they argue that it promotes displacements of foot and public transport, and that typical apartments of compact fabrics require less energy than single-family dwellings. Therefore, high density should lead to low greenhouse gas (GHG) emissions. During the last decade this association has been questioned because: a) there may be compensatory behaviors (more energy consumption and more GHG in mobility and housing during weekends and holidays, and b) the fact of not considering the effects of the endogeneity associated with self-selection. In this paper, we analyze population density as a determinant of mobility and residential GHG emissions in Gran Concepción (Chile) using multivariate regression models. The results obtained indicate that density does not exert a significant impact on GHG emissions in mobility and housing. It is income differences that mostly explain individual GHG emissions variability. This calls into question the possible effectiveness of compactness policies in regional, cultural and climatic contexts different from those of the US and Europe and are excessively oriented towards the maintenance and increase of density in urban centers and slowing down the expansion of suburban neighborhoods.

KEYWORDS

GHG emissions, Latin-American cities, population density, compact city approach

HIGHLIGHTS

Population density does not significantly affect per capita greenhouse-gas emissions in mobility and housing.

Distance from the economic center of the city influences greenhouse-gas emissions in mobility and housing.

Similar parameters are obtained both with and without endogeneity controls.

No significant compensation has been detected linked to mobility and housing greenhouse-gas emissions.

Abbreviations

GHG (greenhouse gas emissions); CBD (Central Business District); CO_{2eq} (GHG emissions measure); OLS (Ordinary Least Squares); GIS (Geographic Information System).

1. Introduction

Cities are responsible for between 30% and 40% of global greenhouse gas (GHG) emissions (Satterthwaite, 2008; Walraven, 2009; Dodman, 2009). The volume of emissions depends on a multitude of factors, such as climate, demographics, the economic model, technology, income, or lifestyle. The form and spatial structure of cities could also play a key role. (Dhakal, 2008; Markham, 2009; Croci et al. 2013). There is no general agreement on what is considered urban form and what is considered spatial structure. As Dempsey et al., (2010), for example, consider that the spatial structure is one of the dimensions of the urban form, and Krehl et al. (2016) consider density as one of the dimensions of the spatial structure, it is important to clarify some concepts used in this study. Following Lynch (1984) and Frey (2003) *urban form* refers to density conditions, land uses, and morphology of urbanized spaces. *spatial structure* is the skeleton that supports the urban mass. This skeleton is made up of employment centers (Central Business Dictrict (CBD), sub-centers, satellite cities), transport infrastructures (highways, trails), and natural borders (coasts, rivers, lakes, mountains, valleys, etc.). The most studied spatial structures, according to the spatial distribution of employment, are the monocentric, the polycentric, and the scattered.

The form and spatial structure of cities occupies a central place in the debate on urban sustainability. There are numerous studies that see in urban planning a great potential to increase city sustainability. In this context, the commonly termed Compact City Approach, also called “Re-designing City Model”(Haughton, 1999; Lynch, 1984; C.E.C. (1990); Ewing, 1997; Frey, 2003; Holden, 2004; Holden y Norland, 2005; Jabareen, 2006; Muñiz et al. 2013) holds that cities will be more sustainable the greater their compactness, considering compactness as a combination of high density, urbanized land continuity and mix of land uses. This model would have low GHG emissions associated with mobility because it would involve shorter distances and less car dependency (Newman and Kenworthy, 1989, 1999; Satterthwaite, 1997, 2009, Holtzclaw, 1994, Holtzclaw et al., 2002, Ewing and Cervero, 2001; Bürer et al., 2004; Litman, 2015).

On the other hand, compactness policies would also have effects on the emissions associated with domestic energy consumption. An apartment in a multi-story building, the typical housing in dense and compact neighbourhoods, requires less energy than single-family housing, typical of suburban, low-density, neighbourhoods (Dong, 2006; Ewing and Rong, 2008; Mollay, 2010).

The advantages of high density would not be restricted to energy savings in housing and mobility, but this energy would be used more efficiently in terms of GHG, since high density reduces the infrastructure needed per person, facilitates cogeneration, reduces the consumption of developed land -thus allowing unoccupied space to be used for GHG sequestration- and restricts losses from electricity lines in energy transmission and distribution (Jabareen, 2006; Frey, 2003)

Most of the studies that have addressed this issue obtain empirical evidence in favor of the Compact City Approach. However, literature that addresses the question by taking GHG emissions as dependent variable is scarcer, and the results offered are less convincing. For example, in the case of large cities in the United States, three studies have focused on capturing the effect of urban form and spatial structure on GHG emissions associated with housing and mobility for the same year (2000) (Brown) et al., 2008; Glaeser and Kahn, 2010, Lee and Lee, 2014). While Brown et al. (2008) and Lee and Lee (2014) find environmental benefits associated with density, Glaeser and Khan (2010) do not find a significant effect.

The principal objectives of this study are: a) to calculate GHG emissions from individual mobility and residential energy uses, and b) to address how urban form and spatial structure can determine mobility and housing GHG emissions in the Metropolitan Area of Concepción (Gran Concepción), Chile.

The work is novel in two aspects. First, we include information on mobility and energy consumption during the weekends and holiday periods in the regression models. In this way, we can check if there are compensatory behaviors associated with mobility and housing transferred to GHG emissions (Høyer and Holden, 2003, Muñiz et al., 2013). If such behavior occurs, the impact of the density variables on GHG emissions during weekends and holidays should be the opposite to that obtained with information regarding working days. In addition, we propose to control endogeneity associated with self-selection, including preferences of individuals in terms of life-style and environmental awareness as explanatory variables. We have not found any research that simultaneously addresses both statistical issues.

2. Literature review on the impact of urban form and spatial structure on GHG emissions

There is a large body of literature on the impact of the built environment on mobility and energy consumption. Most of these studies point to the existence of environmental benefits -lower energy consumption- in mobility and housing in dense urban centers (Cervero, 2002; Giuliano and Mayaran, 2003; Ewing and Rong, 2008; Rickwood et al., 2008; Marshall, 2008; Weisz and Steinberg, 2010). Some studies detect a low impact (Handy; 1996; Levinson and Kumar, 1997; Boarnet and Sarmiento, 1998, Crane, 2000; Lenzen et al., 2008; Mindali et al., 2004; Handy et al., 2005; Echenique et al., 2012; Heinonen, 2012).

Since a significant proportion of the energy used by individuals as consumers comes from the burning of fossil fuels, the main question addressed here is, does urban form and spatial structure affect GHG emissions in the same way that it affects mobility and residential energy consumption? A significant number of investigations have addressed this issue in the last decade. Although most of them detect benefits associated with high density in terms of low emissions (van de Weghe and Kennedy, 2007; Andrews, 2008; Kennedy et al. , 2009; Weisz et al., 2010; Hankey and Marshall, 2010; Hoorneg et al., 2011; Liu et al., 2012; Creintzig et al., 2012; Makido et al., 2012; Croci et al, 2013; Ma et al., 2014; Lee and Lee, 2014), some find a very low or / and statistically insignificant correlation (Norman et al., 2006; Glaeser and Kahn, 2010; Ishii et al., 2010; Liu and Shen, 2011; Heinonen and Junila, 2011; Heinonen et al., 2013).

A first group of studies present correlations between density and GHG emissions, or compare the estimated emissions in dense spaces with those of the low-density peripheral spaces of a certain urban region (Norman et al., 2006; van de Weghe and Kennnedy, 2007; Andrews, 2008; Weisz et al., 2010; Ishii et al., 2010; Hoornweg et al., 2011; Heinonen and Junila, 2011; Liu et al., 2012; Creintzig et al., 2012; Ma et al., 2014; Jones and Kammen, 2014). In most cases they detect advantages associated with high density in terms of low GHG emissions. A second group uses regression models, taking GHG emissions as dependent variable and density and other socio-economic controls as explanatory variables (Grazi et al., 2008; Kennedy et al., 2009; Zahabi et al., 2012; Liu and Shen, 2011; Makido et al., 2012; Croci et al., 2013). Density is the variable referring to the built environment that has received more attention, several works have incorporated an indicator that measures the effect of urban spatial structure such as monocentrism

(Glaeser and Kahn, 2010; Norman et al., 2006; Van de Weghe and Kennedy, 2007; Andrews, 2008) and polycentrism as an essential variable (Veneri, 2010; Lee and Lee, 2014).

There are also studies that, without focusing on the case of density, have also contributed to the knowledge on the potential benefits of high density. Eaton et al. (2007) and Parshall et al. (2010) compare emissions in urban, rural, and suburban environments, with results showing that suburban environments generate the highest level of emissions. Makido et al. (2012) used other urban form indicators, such as its complexity and fragmentation[1], finding that greater morphological complexity leads to greater emissions.

Most of these works have focused on the impact of density on mobility and housing GHG emissions (Norman et al., 2006; Van de Weghe and Kennedy, 2007; Andrews, 2008; Kennedy et al., 2009; Glaeser and Kahn, 2010; Heinonen et al., 2013). Some analyze only in the case of mobility (Grazi et al., 2008; Hankey and Marshall, 2010, Zahabi et al., 2012; Liu and Shen, 2011; Creintzig et al., 2012) and some only housing (Ishii et al. al., 2012). According to Wackernagel and Rees (1998) density would only affect these two sectors. In other words, the urban form would not explain the GHG differences associated with dietary or consumer goods[2].

One of the statistical aspects that may be behind a minimal impact or a non-significant impact of the density variable is endogeneity associated with self-selection. In such a case, the direction of causality would be the reverse. The built environment would

[1] There is an extensive literature on how to measure urban spatial shape and structure using a combination of spatial elements (Galster et al., 2001; Torrens and Alberti, 2000; Malpezzi and Guo, 2001; Wolman et al., 2005; López and Hynes, 2003).

[2] Several studies do not share this vision, stating that the effects can occur in all sectors. For example, if more local foods are consumed in the periphery than in the center, indirect GHG emissions associated with their transport would be reduced to the final consumer. (Weisz et al., 2010; Liu et al., 2012; Heinonen and Junila, 2011; Jones and Kammen, 2014).

not affect mobility and housing energy consumption, but the preferences of individuals with regard to mobility (travel on foot, by bicycle, public transport, or private car) makes population self-select in dense and mixed urban centers, or in peripheral, sparse and dispersed suburban neighborhoods. In theory, the failure to contemplate these preferences would be biasing the value of the density variable parameter upwards. However, applied research shows that the value and significance of the built environment indicators can both increase and decrease (Næss; 2014; Chatman, 2009). As Næss and Jensen (2000), Næss (2014) and Chatman, (2009; 2014) assert, strategies for endogeneity correction may actually underestimate the real impact of the built environment. A small group of studies that have addressed the relationship between the built environment and GHG emissions have followed some type of strategy to control endogeneity, obtaining disparate results. While Liu and Shen (2011) do not find a significant correlation between density and GHG emissions per capita, Grazi et al. (2008), Zahabi et al. (2012) and Jones and Kammen (2014) detect a significant negative correlation.

The potential environmental benefits of a high density can disappear in the presence of "compensatory behaviors". The idea of "compensation" is that, although living close to the main urban center is very useful in terms of accessibility to employment and all kinds of services, which leads to low emissions during the working days, a high density also implies congestion and low access to nature, creating the conditions for high mobility during holidays, thus generating greater emissions in mobility and housing (Holden and Norland, 2005; Holden, 2007; Holden and Linnerud, 2011; Strandell and Hall, 2015; Ambrosius and Gilderbloom, 2015). If total energy consumption is not considered, including emissions associated with energy consumption in principal and second homes, and energy in transport, on working days and holidays, a negative correlation between density and GHG emissions in mobility and housing would only partially explain the complex relationship between the built environment and GHG emissions.

"Compensation" is the most common explanation for the low impact of urban from and spatial structure variables. However, an alternative explanation is possible. If individuals or households with a greater preference for a suburban type of life (single-family housing, car preference, direct access to nature, no second residence, or vacations in remote destinations) self-select in the suburban periphery, the correlation between both variables continue to be low, but the cause is very different. Instead of compensation, there is self-selection (Holden, 2007).

3. Material and methods

3.1. Case study

We choose the Metropolitan Area of Concepcion as case study, because it gives us the opportunity to validate to what extent certain predictions and proposals from the Compact City Approach -designed for Western countries with a high average income- may not make sense in the Latin American urban context, especially in the case of medium-sized metropolises. In other words, context matters, and therefore, extrapolating methodologies and policies must be done with caution.

The Metropolitan Area of Concepción, also known as Gran Concepción, is in the central-southern part of Chile, on the Pacific coast. Concepción is the capital of the Bio-Bio Region. Its physical expansion has been conditioned by its geography, in particular the River Bio-Bio and the coastal ridge. Gran Concepción is made up of eleven communes that together occupy 2,831 km^2. Gran Concepción is the second largest metropolitan area in Chile, after Santiago. It currently has a population of around 892,000 according to the latest census data (Salinas and Pérez, 2011). Although low density is the norm in the Metropolitan Area of Concepción (Rojas et al, 2013), in the most central areas there are buildings of between eight and twenty-five stories, and relatively dense residential fabrics, but the form and spatial structure of Gran Concepción is far from being compact. The most used public transport is the bus (in the most central areas) and the shared taxi. Also, there are a series of inter-urban bus lines that structure the metropolitan space. Rail transport is limited to two lines, an urban one (Biotrén), and another one that connects the old towns of the northern bank of the Biobío River (Division of Regional Public Transport, 2014).

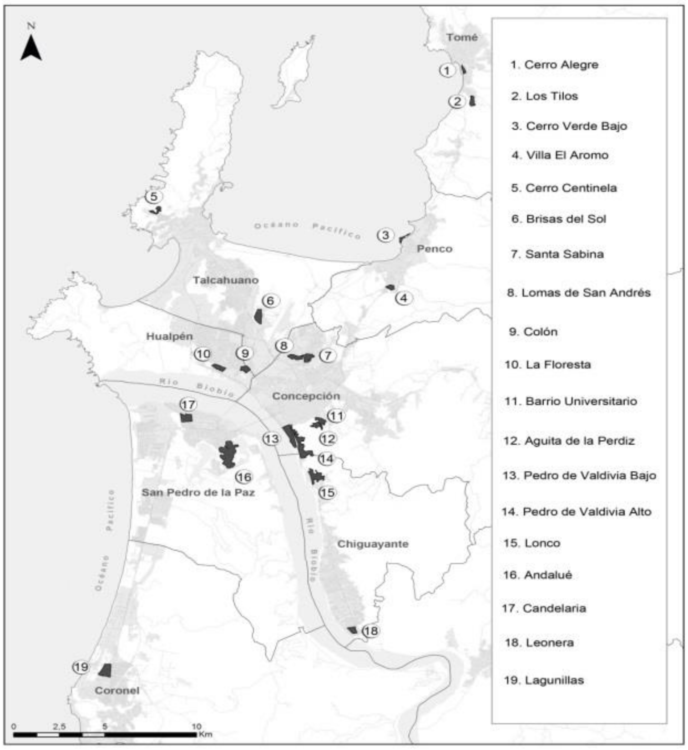
3.2. Data, variables and methods

The scope of the study is households and individuals living inside the administrative borders of Gran Concepción, which implies considering high, medium, and low-density areas. Also, all kind of trips are considered, including those beyond the Biobío region (especially at weekends and holidays). The selection of neighborhoods is aimed at capturing the variety of situations regarding density, centrality, and income levels. On this basis, residents of 19 neighborhoods (Rojas et al. 2013) belonging to 8 communes[3] have been asked about individual mobility patterns, housing energy consumption, as well as socio economic characteristics and attitudes towards mobility and housing (475 questionnaires, 25 surveys per neighborhood). (Table Annex 2)

[3] (Concepción, Hualpén, Talcahuano, San Pedro de la Paz, Chiguayante, Coronel, Penco and Tomé) .The more rural communes of Hualqui and Santa Juana were ruled out as they are poorly integrated in functional terms. Lota was also left out due to its similarity with Coronel.

Figure 1

Selected and analyzed neighborhoods of the study area Gran Concepción



The information is grouped into four categories: a) *household profile*; b) *dwelling characteristics;* c) *mobility*; and d) *controls for residential self-selection*. Distances covered were estimated on the basis of straight-line distances between starting points and destinations.

The information on energy consumption on housing and mobility can be transformed into individual GHG emissions. This value is obtained by adding together three sources of emissions: 1) housing CO_{2eq} emissions; 2) CO_{2eq} emissions from commuting mobility; and 3) CO_{2eq} emissions from weekend and holiday mobility.

CO_{2eq} emissions associated with mobility are mainly composed of direct emissions from motor vehicles. Mobility by other means such as rail is scarce but considered. Muñiz and Galindo (2005) provide CO_{2eq} emissions conversion factors for the case of mobility. Total emissions include the energy need for traction, vehicle manufacturing, construction and maintenance of the infrastructure. Other conversion factors similar to Muñiz and Galindo (2005) can be found in Stokenberga (2012) and Bertaud et al. (2009) although these two additional sources do not include the emissions embodied in vehicles and infrastructures. The calculation of emissions for each means of transport is obtained from the following equation taken directly from Muñiz and Galindo (2005).

$$CO_{2,ir} = \sum_z [EC_z \; EG_z D_{ij} \, Trip_{rjz}]$$

where CO_{2ir} is the annual CO_{2eq} emissions of individual i that resides in area r, EC_z is the energy consumption of mode of transport z per km and passenger (Gj/km), EG_z is CO_{2eq} emission per Gj in mode of transport z, D_{rj} is the straight line between origin r and destination j. $Trip_{ijz}$ is the number of trips of individual i with origin r and destination j by mode of transport z.

As for residential energy consumption, the conversion factors that appear in Chambers et al. (2000) are used. There are other sources with conversion factors for different energy sources, for example, Gov UK (2018). But, in general, these sources do not include indirect energy in infrastructures and facilities in their calculations, so they tend to provide lower values.

Housing CO_{2eq} emissions are measured at the place of consumption (energy consumption in individual mobility and in housing) when it comes to the use of coal, fuel, firewood, or electricity. In the case of electricity, the CO_{2eq} emissions are estimated according to the primary sources industry-mix in Chile. Por lo tanto, en esta investigación no se computan las emisiones directas de las plantas de energía (termal power stations) localizadas dentro del Gran Concepción, sino que se imputan las emisiones producidas para conseguir la energía eléctrica utilizada en los hogares independiente de dónde se produzcan dichas emisiones. Esta metodología utilizada para computar las emisiones asociadas a la vivienda en otros estudios como Glaeser y Kahn (2010) y Brown et al. (2008).

This research therefore does not compute the direct emissions of power plants located within Gran Concepción, but, instead, the emissions produced to obtain the domestic electric energy used, regardless of where these are produced. This methodology is used in other studies such as Glaeser and Kahn (2010) and Brown et al. (2008) in order to compute the emissions associated with housing.

Housing emissions are calculated directly by multiplying the value of the estimated MWh during a year from the information on the expenditure of households in different energy sources. Taking energy bills as a reference, energy consumption is deducted and converted into CO_2 emissions by applying the factors shown in tables 1 and 2. These data include the indirect emissions associated with the construction of facilities and power plants. As can be seen when comparing the values shown in tables 2 and 3, burning gas to obtain electricity is twice as inefficient in terms of CO_2 emissions as burning it directly using stoves.

Table 1
Delivered CO_{2eq} emissions for non-renewable sources.

Energy primary and secondary fuels	tn CO_{2eq} /MWh
Natural gas	0.24
Fuel oil	0.31
Bottled gas (LPG)	0.27

Source: Chambers et al., (2000)

Table 2
Delivered electricity CO_{2eq} for non-renewable Sources

Energy: electricity generation	tn CO_{2eq} per MWh
Hard coal power stations	0.86
coal	1.06
oil	0.81
Natural gas	0.50

Sources: Chambers et al. (2000), and European Union and Government of Chile (Conacyt) (2007) "The energy sector in Chile. Research capabilities and Science and Technology development areas"

The CO_2 emission indicator used in this research is the carbon footprint, which implies: a) attributing consumptions to the final consumer; b) accounting for direct emissions, as well as the facilities and buildings required to supply the energy; and c) accounting for the carbon intensity of vehicles and homes (Pon and Pon, 2009; Wiedman and Sanchez, 2018; Lombardi et al., 2017). However, in this study we have not accounted for the grey energy embodied in the homes themselves. The calculation of grey energy in buildings requires very specific knowledge of the carbon content in construction materials, their durability over time and their ability to be recycled, as well as the energy used during the building process. In the study by Muñiz et al. (2013), grey energy in the building was 35 percent of direct-emission values, and 14 percent of the total footprint. We therefore underestimate the value of the total footprint by a similar percentage.

The following is the estimation of a multiple regression model by Ordinary Least Squares (OLS), taking the logarithm of the CO_{2eq} emissions per capita associated with housing energy consumption and mobility as the dependent variable. The explanatory variables are grouped into three categories: a) *socioeconomic variables*; b) *controls for endogeneity variables,* and c) *urban form and spatial structure variables*.

The main endogeneity problem is the possible presence of a double causality. Mobility can be affected by urban form and spatial structure, but the reverse could also be the case: the urban form and spatial structure can be a result of the mobility patterns (Baum-Snow et al. 2012; Duranton and Turner, 2012; García-López et al., 2015). In the regression models, with individual data, the most common endogeneity problem is "self-selection". If individuals consider their mobility preferences when choosing their place of residence, failure to consider this information could skew the parameter values. The most common solutions are the following: a) work with a population sample that has little chance of choosing a place of residence, such as young people who work and live with their parents (O'Reagan and Quigley, 1998; Dujardin et al, 2008;); b) use the Heckman estimator and treat the endogeneity associated with the omission of variables that capture mobility preferences as a case of unobserved heterogeneity (Greene, 2003); and c) include a question in the individual questionnaire that explicitly elicits individuals' preferences regarding mobility, and include this information in the regression model (Høyer and Holden, 2003; Holden and Linnerud, 2011; Muñiz et al. 2013).

We choose the third option because the first requires a very large universe of observations that we do not have, and because the second works well when it comes to evaluating the effect of the built environment, for example, on car use, discriminating between those who have and those who do not. This is not the case of our models.

After considering socioeconomic characteristics and possible residential self-selection, urban form and spatial structure variables should capture their net impact on individual GHG emissions. In the estimated models, population density and distance to the main center (CBD) are included simultaneously. Distance to the CBD squared and density squared were also included as regressors with the aim of capturing the possible existence of local maximums or minimums (U-shape or inverted U-shape).

4. Results

Table 3 presents the mean values of the information obtained from the questionnaires that will be used to calculate GHG emissions, or as explanatory variables in the regression model. These values indicate that average income is low by European and American standards, but high in the Latin-American context. The most common housing is the single-family home. These homes are relatively new and only fifteen percent of families have second homes. Each family unit has an average of 0.87 cars, but only 21 percent use this on a daily basis. In our assessment of these families, mobility is of intermediate importance when choosing where to live. The table in Annex 1 reports average individual emissions per commune and population density.

Table 3
Basic information obtained from questionnaires

	Average values
Socio-economics	
Individuals per household (No)	3.84
Monthly Average household income (Chilean peso)	561,614*
Dwelling characteristics	
Surface (m^2)	106
Year of construction	1987
Most common materials (%)	Concrete (28), Mixed (33), Wood (24)
Second residence (%)	15
Type of dwelling (%)	Detached house
Mobility	
Distance to work place (km)	3.65
Percentage of workers that use car with regularity (%)	21
Mobility during weekends and holidays (%)	41
Number of cars/household	0.78
Mobility and sustainability preferences	
Mobility type considered in choosing where to live (subjective scale 1 to 10)	4.27
Interest in sustainability (subjective scale 1 to 10)	4.72

*842 American $ considering a rate of change (peso dollar) one peso 0.0015 American $

The mean annual emissions associated with individual mobility and residential energy consumption is 0.532 tons of CO_{2eq}/capita (Table 4). A low value compared with other researches[4]. It should be noted, however, that the values provided by the studies consulted are not strictly comparable, as, for the same city, the value estimated depends on the urban spatial scale chosen, the method for calculating residential energy consumption, and the corresponding method for mobility.

[4] Between 3.6 and 5.2 GHG emissions per capita in three Norwegian cities (Høyer and Holden, 2003; 24 in Dallas county, US (Ryu (2005); 6.9 in Toronto, Canada (Van de Weghe and Kennedy; 2007); between 4 and 7 in New Jersey, US (Andrews, 2008); between 5 and 7 in the largest US metropolitan regions (Glaeser and Kahn, 2010); 4.4 in the Barcelona Metropolitan Region, Spain (Muñiz et al., 2013).

Table 4
Estimated Annual CO_{2eq} emissions per capita from mobility and housing.

Housing	
Gas	0.036
Electricity	0.218
Other sources	0.020
Total Housing Emissions per capita	**0.274**
Mobility	
Commuting mobility	0.218
Holidays mobility	0.020
Weekend mobility	0.020
Total Mobility	**0.258**
Total	**0.532**

The low carbon footprint estimated may be due to different factors: 1) the fact that the grey energy in buildings is not accounted for; 2) the city's temperate climate; 3) level of income; and 4) the wide use of renewable energy sources such as firewood. This last aspect is important, since the low footprint assigned to firewood is contrasted with local pollution (carbon monoxide, hydrocarbons and particles in suspension) that are consequences of its use (Smith et al., 2005).

Table 5 summarizes the indicators obtained from the five regression models estimated by OLS. The dependent variable appears in the first row and the explanatory variables in the first column. The global adjustment capacity of the model (R^2_{adj}) is presented at the end of each column. The first column reports the results corresponding to the estimated models using the CO_{2eq} emissions from commuting mobility as a dependent variable; in the second, the CO_{2eq} emissions from leisure mobility (weekends and holidays); in the third, total emissions from mobility (sum of the two above); in the fourth, emissions from household energy consumption; and in the fifth, total emissions in mobility and housing. The estimation is made by taking the logarithm of the individual emissions as a dependent variable, which allows us to directly interpret as elasticities the parameters of the explanatory variables, also expressed in logarithms[5]. The value of the estimated parameter appears in each cell and below, in parentheses, the Student "t" indicator that measures the statistical significance of the parameter. The significant parameters are marked with asterisks. The more asterisks, the more the statistical significance.

The common explanatory variables for the five estimated models are: the number of members in each household, household income per capita, Population Density and Population Density Squared, distance to the CBD, and distance to the CBD squared. In the first tests, the number of cars and the surface area of the dwelling were added as explanatory variables, but these were eventually discarded as they were too highly correlated to income. No household type was statistically significant.

Population density is not significant in the most aggregated model (Table 6, column 5). This could point to the existence of compensatory behaviors. However, the parameter corresponding to the above variable does not show a positive sign in the model where the dependent variable is emissions associated with leisure and holiday mobility (Table 6**,** column 2), and for this reason, such a hypothesis should be rejected. Distance to the CBD exerts a positive-sign effect on the mobility footprint – both the commuting and the leisure and holidays types– so compensatory behaviors associated with an "excess of centrality" are not detected either. In addition, a significant quadratic effect is identified, which meant that, although CO_{2eq} emissions grow in line with distance to the CBD, the association is inverted at a certain distance to the CBD. Once that distance is reached, larger distances to the CBD imply lower GHG emissions.

[5] Estimations were made without applying logarithms, and the results were very similar in terms of the sign and the significance of the parameters.

The estimated parameters of the socioeconomic variables present the expected sign. The number of inhabitants per dwelling exerts a negative impact, confirming the existence of economies of scale in energy consumption and in mobility, especially leisure and holiday mobility. On being the principal factor in explaining the variability observed, household income level exerts a significant positive impact (as income increases, so do emissions) on the five models. The self-selection endogeneity controls are all included at the same time, but none of them were statistically significant.

The controls for self-selection generally present the expected sign, although they do not prove to be statistically significant. Comparing the impact of population density and distance to the center with the other socioeconomic variables, it seems obvious that, in the case of Concepción, the factor that best explains the individual volume of emissions variability is income.

Table 5
OLS Regression Models

	1. Commuting Mobility (Ln Tonnes of CO_{2eq} per capita)	2. Weekends and Holidays Mobility (Ln Tonnes of CO_{2eq} per capita)	3. Total Mobility (Ln Tonnes of CO_{2eq} per capita)	4. Residential Energy use (Ln Tonnes of CO_{2eq} per capita)	5. Total Mobility and Residence (Ln Tonnes of CO_{2eq} per capita)
Persons per household	-0.075** (1.8)	-0.32**** (8.5)	-0.07** (1.9)	-0.46**** (23.6)	-0.13**** (6.9)
Ln household per capita income	0.33**** (4.5)	0.47**** (7.2)	0.46**** (7.2)	0.17**** (6.4)	0.28**** (8.5)
Ln Population Density	-0.10 (1.3)	-0.08 (0.1)	0.04 (0.5)	-0.02 (0.5)	-0.04 (0.5)
Ln Population Density Squared	0.04 (0.4)	-0.02 (0.6)	0.007 (0.09)	0.04 (0.06)	0.001 (0.05)
Ln dist. to the CBD	1.24**** (4.2)	0.68*** (2.3)	0.9**** (3.5)	0.001 (0.01)	0.20*** (2.3)
Ln dist. to the CBD Squared	-0.21*** (2.7)	-0.17*** (2.3)	-0.17*** (2.3)	-0.03 (0.7)	-0.04* (1.9)
Preference auto	0.13 (1.8)	-0.04 (1.1)	0.9 (1.2)	0.21 (0.82)	0.12 (0.94)
Mobility preferences when choosing residence	0.04 (1.7)	0.08 (1.5)	0.12 (1.2)	0.002 (0.4)	0.09 (0.8)
Awareness of local environmental problems	-0.01 (0.09)	-0.04 (0.07)	-0.06 (0.06)	0.02 (0.08)	0.03 (0.12)
Awareness of global environmental problems	-0.02 (0.04)	-0.03 (0.009)	0.04 (0.002)	-0.01 (0.08)	-0.04 (0.07)
Importance of awareness on local and global environmental problems when choosing the place of residence	0.04 (0.04)	-0.002 (0.09)	-0.001 (0.02)	0.041 (0.009)	0.037 (0.04)
Constant	-2.5**** (2.8)	-4.06**** (4.2)	-4.3**** (5.0)	4.5**** (11.8)	0.63* (1.5)
R^2adjusted	0.19	0.32	0.28	0.66	0.37
Nº Observations	475	475	475	475	475

(Statistic "t" in brackets)
**p<0.15; **p<0.1; ***p<0.05; ****p<0.01*
Ln: Napierian Logarithms

5. Conclusions

One of the most important results of the study is that density does not appear to exert any impact on the volume of emissions, which clearly comes into conflict with the results obtained in most of the studies reviewed for this paper, in which population density variability is sufficient in itself to explain much of the variability observed in the volume of emissions. Another significant result is that the non-significant impact of density is not due to the existence of compensatory behaviors.

With regard to the variables, distance to CBD (distance to the main center) and distance to CBD squared, GHG emissions increase as the distance to the CBD increases, but if the parameter [dist. CBD^2] is negative and significant, this association is reversed for the more peripheral localities. These results could justify a regional planning program to check the process of decentralization that the city is undergoing, and at the same time preserve the low-footprint lifestyle present in the communes further away from the main center.

An aspect that should be improved in future studies, is the density indicator. In our study, it is population divided by the urbanized land of each commune. However, as argued by Lee and Lee (2014) and Krehl et al. (2016), there is no commonly accepted indicator in the international specialized literature, and no one scale is considered relevant. It is possible that the lack of significance of the density variable is due in part to the failure to capture it correctly, that is, with an appropriate scale and appropriate land uses (Krehl et al., 2016). Therefore, the results obtained should be interpreted with due caution.

Another result to highlight is that the per-capita income affects the value of emissions relating to any of the indicators of urban form and spatial structure. In a context of prolonged economic growth—independently of urban policies—it is expected that emissions will grow significantly. (43) In future studies, research should be expanded to include various Latin-American cities in order to validate the results obtained in this research.

Our future research aims to address the following aspects: a) the calculation of grey energy in buildings; b) the importance of climatology; and c) the possible trade-off between low residential footprint due to the low consumption of non-renewable energy and the high local pollutants caused by the use of firewood, a particularly worrying aspect for cities in southern Chile.

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Annex Table 1

Housing and Mobility CO_2 emissions. Mean values per commune

Commune	**Population density (persons/ha)**	**Tn $CO_{2\,eq}$ housing per capita**	**Tn $CO_{2\,eq}$ mobility per capita**	**Tn $CO_{2\,eq}$ per TOTAL per capita**
Agüita de la Perdiz	1241.41	0.22	0.08	0.30
Barrio Colón	56.59	0.31	0.30	0.61
Barrio Universitario	234.64	0.54	0.37	0.91
Brisas del Sol	107.56	0.30	0.41	0.71
Cerro Alegre	286.72	0.21	0.21	0.42
Cerro Verde Bajo	195.82	0.19	0.10	0.29
Cerros Centinela	22.53	0.19	0.12	0.30
Jorge Alessandri	216.73	0.25	0.16	0.41
La Condola	143.25	0.19	0.11	0.30
Lagunillas	100.04	0.26	0.28	0.54
Leonera	460.6	0.18	0.12	0.30
Lomas de San Andrés	82.35	0.31	0.48	0.79
Lonco	139.24	0.45	0.50	0.95
Los Tilos	190.35	0.20	0.15	0.35
Pedro Valdivia Alto	353.35	0.48	0.40	0.87
Pedro Valdivia Bajo	72.98	0.30	0.09	0.39
Peñuelas	138.15	0.20	0.10	0.30
Santa Sabina	220.12	0.28	0.06	0.34
Villa el Aromo	35.71	0.30	0.45	0.75

Annex Table 2

Questionnaire

	Individual 1	Individual 2	Individual 3	Individual 4	Individual 5	Individual 6	**total**
Socio-economic							
Number of individuals							
Per capita income							
Mobility emissions							
Number of weekly journeys between home and place of work/study							
Distance between home and place of work							
Mode of transport mobility home place of work/study							
Number of journeys during the last weekend							
Distance between home and weekend destination							
Mode of transport journeys between home and weekend destination							
Number of journeys during vacations							
Distance between home and vacation destination							
Mode of transport during vacations							
Housing emissions							
Electricity bill							
Other energy sources							
Firewood							
Fuel							
Gas							
Preferences (1 to 10)							
auto							
Awareness of local environmental problems							
Awareness of global environmental problems							
Importance of awareness of local and global environmental problems when choosing place of residence							