



Urban form and spatial structure as determinants of the ecological footprint of commuting



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ABSTRACT

In this research we examine the relationship between the ecological footprint of commuting and several variables of urban form and spatial structure for the case of the Barcelona Metropolitan Region, paying special attention to the role of population density and polycentrism. Stopping the low density urban dispersion and encourage polycentrism are two of the main policies advocated by the supporters of the Compact City Approach to achieve more sustainable cities. The literature on the impact of population density offers inconclusive results and studies that address the role of spatial structure are very scarce. The results obtained in this research indicate that polycentrism has advantages in terms of low footprint. The effect of population density is more controversial. These results indicate that polycentric spatial planning can be a good strategy to reduce the ecological footprint of cities.

1. Introduction

The problem of global warming due to excess greenhouse gas emissions (GHG) has worried academics in a variety of fields, such as ecology, geography, economics and urban planning. Over the last 20 years, several studies have measured such emissions in cities and explored its causes (Høyer and Holden, 2003; Muñiz and Galindo, 2005; Ryu, 2005; Norman et al., 2006; Van de Weghe and Kennedy, 2007; Andrews, 2008; Brown et al., 2008; Kennedy et al., 2009; Glaeser and Khan, 2010; Veneri, 2010; Croci et al., 2013). A significant part of emissions originates from cities,¹ suggesting that the application of strategies on an urban or metropolitan scale to reduce GHG emissions would be a reasonable idea.

According to the Compact City Approach (Newman & Kenworthy, 1989, 1999, 2015; CEE, 1990; Holtzclaw, 1994; Rogers, 1998; Ewing and Cervero, 2001; Holtzclaw et al., 2002; Bührer et al., 2004; Leck, 2006; Ewing et al., 2007), cities might achieve lower levels of GHG emissions if certain land use principles are observed, such as: (a) maintaining or increasing density levels; (b) concentrating peripheral employment and population in subcenters; and (c) enhancing the public transport network. If urban planning follows these principles it can contribute significantly to reducing the level of emissions, thereby achieving a more sustainable city.

The objective of this research is to estimate the impact of urban form and spatial structure on the ecological footprint of

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¹ Between 40 and 70% of the total, depending on the measurement method used (Satterthwaite, 2008; Walraven, 2009; Dodman, 2009; UN-Habitat, 2011).

commuting mobility in the Barcelona Metropolitan Region between 1991 and 2001.² The ecological footprint is an indicator of strong sustainability composed mainly of the space needed to sequester direct and indirect GHG emissions, as well as urbanized space and land occupied by transport infrastructure (Rees, 1992; 2000; Wackernagel et al., 2006). We try to capture the spatial complexity by means of a battery of urban form and spatial structure indicators. We believe the ecological footprint to be a particularly useful indicator since it incorporates in its calculation the existence of environmental boundaries, both global (the planet has a limited capacity to sequester all GHG emissions) and local (the surface occupied by transport infrastructures could have other uses, such as recreational activities or food crops).

The Barcelona Metropolitan Region has a large, dense and mixed historical center, a range of peripheral employment subcenters, as well as various corridors of economic activity along the main roadways. It is an interesting case study since it was planned, from the 1980s onwards, in accordance with the principles of the Compact City Approach (Bohigas, 1986; Busquets, 1992) obtaining questionable results (Muñiz and García-López, 2013). The issues we raise in this paper can be reformulated as follows: (a) to what extent do existing mobility patterns behave according to what is planned or theorized? and (b) are land use policies that follow the Compact City Approach emissions effective?

Our results indicate that urban spatial structure explain intra-metropolitan ecological footprint variation. Polycentricity reduces emissions and the ecological footprint, but the effect of the variable density is not so clear.

The remainder of the paper is structured as follows. Section 2 reviews empirical evidences on the influence of urban form and spatial structure on GHG emissions, the carbon footprint and the ecological footprint. Section 3 presents the city case study, data, variables and empirical strategy. Section 4 presents the main results. Section 5 discusses results, and Section 6 summarizes the conclusions of the research.

2. Empirical evidence regarding the impact of the built environment on direct GHG emissions, carbon footprint and ecological footprint

Table 1 compile and organizes urban form and spatial structure indicators. Table 2 summarizes the research that has analyzed the relationship between urban form and spatial structure and some indicator of environmental impact on a global scale. In most studies, the global environmental impact indicator is direct GHG emissions; although we report six papers that use the carbon footprint or the ecological footprint.³ Most studies analyze the behavior of housing and mobility since they are the two sources of GHG emissions that are potentially more influenced by the urban form and spatial structure of cities.⁴ The most common urban form and spatial structure indicators are density (urban form) and centrality (spatial structure). Few studies have included elements referring to either the concentrated (polycentric) or deconcentrated and discontinuous (scattered) decentralization model.

This situation contrasts with the large number of studies that relate the shape and spatial structure of cities with commuting activity and mobility in general. Most of these studies indicate that a high density reduces commuting distance (ECOTEC, 1993; Levinson and Kumar, 1995; Ewing and Cervero, 2001; Stead and Marshall, 2001; Holden and Norland, 2005; Banister, 2005). On the other hand, low density leads to poor access to the public transport network (Banister, 1996; Holden and Norland, 2005). Regarding the role of urban spatial structure variables, the empirical evidence indicates that the commuting distance of workers who live near the center is shorter than that of those who live far away (Tkocz and Kristensen, 1994; Wang, 2000; Schwanen et al., 2001; Stead, and Marshall, 2001; Buchanan, et al., 2006; Næss, 2007; Sultana and Weber, 2007; Muñiz et al., 2013; Sun et al., 2017; Song et al., 2017; Xiao et al., 2018).

A group of researchers maintain that polycentrism reduces commuting distances due to the existence of alternative centers to the CBD in the periphery of the urban region (Giuliano and Small, 1993; Wang, 2000; Næss, 2007; Zhao et al., 2011; Asikhia and Nkeki, 2013; Muñiz et al., 2013). On the contrary, some studies have found that workers who live near a sub-center perform more commuting activity (Cervero and Wu, 1998; Schwanen et al., 2001; Parolin, 2004; Alpkokin et al., 2008). Finally, some studies have found no significant correlation (Titheridge and Hall, 2006). Regarding the mode of transport, compared to monocentric cities, polycentric cities tend to use more private vehicles (Næss and Sandberg, 1996; Næss, 2007; Bartaud et al., 2009). There is little literature on the distinct nature of the subcenters (Meijers, 2008a, 2008b; Roca-Cladera et al., 2009; Vasanen, 2012; Burger and Meijers, 2012) and how these subcenters can affect mobility patterns (Bartaud, 2003; Bartaud et al., 2009). This is still a question that the literature on polycentrism has, in a certain sense, disregarded. Do subcentres generate a different commuting mobility pattern depending on their nature? If the answer is yes, then differentiated territorial instruments and policies should be used to reduce mobility impact in terms of GHG emissions. Finally, the impact of distance to the main road infrastructure can be both positive and negative. According to Stead and Marshall (2001), it implies a greater distance traveled, while Næss (2007) found the opposite.

² We decided not to incorporate data referring to the decade from 2001 to 2011 because this period was highly atypical due to the formation and subsequent bursting of the huge real estate bubble that affected Spain between 1998 and 2008. The major increase in the price of housing and the number of new houses gave way to the destruction of industrial employment and the creation of a tourism bubble. These shocks reconfigured the metropolitan space, making it more dispersed and unstructured, and affected commuting mobility in a context in which the labor market was seriously affected by the intensity of the crisis (unemployment rates exceeded 20%).

³ See Pon and Pon (2009), Wiedmann and Minx (2008) and Rees (1992; 2000) in regard differences between direct GHG emissions, carbon footprint and ecological footprint.

⁴ Although the results of some studies seem to indicate that the impact of the built environment could affect other consumptions, such as food or manufactured goods (Ryu, 2005; Kennedy et al., 2009; Yi et al., 2017)

Table 1
Urban form and spatial structure indicators.

Urban form	Population density Discontinuity index
Spatial structure	Distance to the main CBD 1/Distance to the closest subcentre Distance to the closest main transport infrastructure
Other built environment variables	Job-ratio

3. Case study, data and methods

3.1. Case study: The Barcelona Metropolitan Region

The Barcelona Metropolitan Region contains 164 municipalities. The main center is the municipality of Barcelona. Between 1991 and 2001 the urbanized area increased significantly from 49,917 ha to 67,998 ha (Table 1). The General Territorial Plan of Catalonia explicitly highlights its polycentric character. Legislators assert that traditional medium-sized cities structure a large peripheral area in a manner akin to English new towns and French *villes nouvelles*. These medium-sized cities concentrate a significant amount of employment and are the destination of a relevant part of home-to-work journeys (Àrea Metropolitana de Barcelona, 1995; Muñiz et al., 2003; Muñiz and Galindo, 2005; Boix and Trullén, 2007; Muñiz et al., 2008; Roca-Cladera et al., 2009; Garcia-López and Muñiz, 2010).

Fig. 1 shows the division of the (Barcelona Metropolitan Region into subareas: the *CBD* (municipality of Barcelona), the *first crown* (contiguous municipalities localized in the north and the south of Barcelona), old and new *subcenters*, and the *other municipalities*.

Fig. 2 shows the polycentric spatial structure of the Barcelona Metropolitan Region in a stylized form. The large black dot corresponds to the municipality of Barcelona and the smaller black dots to employment subcenters. The top of the graph is a mesh showing the spatial pattern of population density.⁵

The polycentrism of Barcelona has been shaped by two processes of a distinct nature. On the one hand, new subcenters emerge from the decentralization of activities that have moved to the periphery.⁶ These subcenters have come into place relatively close to the municipality of Barcelona. They are characterized by open labor markets, by being moderately self-contained and self-sufficient, located close to the main transport infrastructures and are specialized in certain manufacturing and services sectors. On the other hand, there are the old subcenters or *Christalerian* subcenters. These are municipalities, which already had a significant volume of population in 1900, and which have historically acted as centers (county capitals) of self-contained and segmented labor markets. In this case, the procedure for the appearance of the subcenter is the integration of previous settlements that in the past worked in a relatively disconnected manner from Barcelona, but which (by the 1980s) had already begun to integrate intensively with the city and its first metropolitan crown. These municipalities are more oriented towards population services, and their labor markets were more closed and self-contained in the past. Currently, however, they are converging towards a model similar to that of the new subcenters (Muñiz et al. 2003, 2008, Garcia-López and Muñiz, 2010). Appendix Tables A1–A5 provide basic statistics on population, employment, land consumption and mobility.

3.2. Data and variables

Population and employment data come from the 1991 and 2001 population censuses. The scale of information is smaller than the municipality and similar to American census tracts. Soil surfaces, from the *Mapes d'ús del sòl de Catalunya* for 1992 and 2002. These maps, developed by the *Institut Cartogràfic de Catalunya*, use multispectral data from the Thematic Mapper sensor of the LANDSAT-TM satellite. Performed at a scale of 1: 25,000, the minimum map unit is 0.36 ha. It presents a classification of 21 land uses, of which 4 are considered urban. We assume that land data for 1992 and 2002 can be considered good proxies of 1991 and 2001 data. Finally, data on road infrastructure and accesses come from the maps in GIS format provided by the *Departament de Territori i Obres Públiques* (Generalitat de Catalunya). The Data Source of mobility data is the matrix of intra-metropolitan commuting mobility associated with the censuses of 1991 and 2001. This treatment of census data provides information on the municipality of residence and the municipality where each worker works for each mode of transport. The information is presented in the form of a 164x164 matrix (origin municipalities and destination municipalities). No information is provided on commuters, only the places of origin and destination of their movements.⁷

The *ecological footprint of commuting mobility* includes the following surfaces: (a) the *energy land* associated with GHG emissions of each mode of transport (traction), (b) the *energy land* associated with the indirect energy used in the manufacture of the means of transport and the construction of transport infrastructures; and (c) the space occupied by such infrastructures. *Energy land associated*

⁵ This 3D surface is the result of a non-parametric estimation by Locally Weighted Regression (LWR). The vertical lines associate each employment center with the non-parametric estimate of their population density.

⁶ Generating economies of scale (lower than in the main center) and supporting congestion costs (again, lower than in the main center).

⁷ The reason why this data is presented in aggregate form is to preserve the anonymity of the workers.

Table 2
Studies on the impact of built environment on GHG emissions/carbon footprint/ ecological footprint.

Researches	Sectors	Global impact estimator	Built environment variables	City/Country	Methodology	Endogeneity controls	Socio-economic or geographic controls	Results
Høyer and Holden (2003)	Housing Mobility	Ecological Footprint	Density	3 Finnish cities	OLS regression	yes	yes	More density = > lower ecological footprint per capita
Muñiz and Galindo (2005)	Mobility (commuting)	Ecological Footprint	Density Distance to the CBD Job ratio	Barcelona Metropolitan Region (Spain)	OLS regression	no	yes	More density, more centrality and a larger job-ratio = > lower ecological footprint
Norman et al. (2006)	Housing mobility	GHG emissions	Central areas, peripheral areas	Toronto (Canada)	Comparison	–	–	More density = > lower GHG per capita
Van de Weghe and Kennedy (2007)	Housing Mobility	GHG emissions	Central areas, peripheral areas	Toronto (Canada)	Comparison	–	–	More centrality = > lower GHG emissions
Eaton et al. (2007)	All sectors	Ecological Footprint	Urban areas versus rural areas	Borough of Swindon County of Wiltshire (UK)	Comparison	–	–	Urban areas have a higher Ecological Footprint than rural areas
Brown and Logan. (2008)	Housing Mobility	Carbon Footprint	Density	100 largest US metropolitan areas	OLS regression	no	yes	More density = > lower GHG emissions
Andrews (2008)	Housing Mobility	GHG emissions	Urban-rural gradient	New Jersey (US)	Comparison	–	–	More density = > lower GHG emissions
Kennedy et al. (2009)	Buildings Mobility wastes	GHG emissions	Density	10 world cities	OLS regression	no	yes	More density = > lower GHG emissions
Glaeser and Khan (2010)	Housing Mobility	GHG emissions	Density	66 largest US metropolitan areas	OLS regression	yes	yes	Density has no impact
Parshall et al. (2010)	Housing Mobility	GHG emissions	Metropolitan US areas versus Rural US areas	All US cities and rural areas	Correlations	–	–	Rural areas have a higher Ecological Footprint than urban areas
Veneri (2010)	Mobility (commuting)	GHG emissions	Monocentric Polycentric Dispersed Density Concentration Compactness Intra-metropolitan density variation	82 Italian metropolitan areas	Spatial lag model Robust OLS	no	yes	Polycentric urban regions = > lower GHG emissions
Lindsey et al. (2011)	Mobility	GHG emissions		Chicago (US)	Visual inspection	–	–	High density areas and areas close to the main center present lower GHG emissions
Croci et al. (2013)	Mobility	GHG emissions	Density	32 European cities	OLS regression	no	yes	More density = > lower GHG emissions
Muñiz et al. (2013)	Housing Mobility	Ecological Footprint	Density Distance to the CBD	Barcelona Metropolitan Region (Spain)	OLS regression	yes	yes	More centrality and more density = > lower ecological footprint per capita

(continued on next page)

Table 2 (continued)

Researches	Sectors	Global impact estimator	Built environment variables	City/Country	Methodology	Endogeneity controls	Socio-economic or geographic controls	Results
Lee and Lee (2014)	Housing Mobility	GHG emissions	Density Polycentricism Centrality	125 largest US metro areas	Multilevel Structural Equation Model (SEM)	no	yes	Polycentricity reduces distances but discourages public transport
Ma et al. (2014)	Mobility	GHG emissions	Central areas Peripheral areas	Beijing (China)	Comparison	–	–	More centrality = > lower GHG emissions
Baur et al. (2015)	All sectors	GHG emissions	Density Urban form variables regarding land use shape	52 European cities	Correlations	–	–	More density = > lower GHG emissions More discontinuity = > higher GHG emissions
Muñiz et al. (2016)	Housing Mobility	Ecological Footprint	Density Distance to the CBD	Great Concepcion (Chile)	OLS regression	yes	yes	Density has no significant effect More centrality = > lower ecological footprint
Yi et al. (2017)	All sectors	GHG emissions	Density	108 Chinese cities	OLS regression	no	no	More density = > lower GHG emissions
Muñiz and Sánchez (2018)	Mobility	GHG emissions	Density Monocentricity Polycentricity	Metropolitan Zone of the Mexican Valley	OLS regression	yes	yes	More density = > lower emissions Proximity to subcenters = > lower emissions

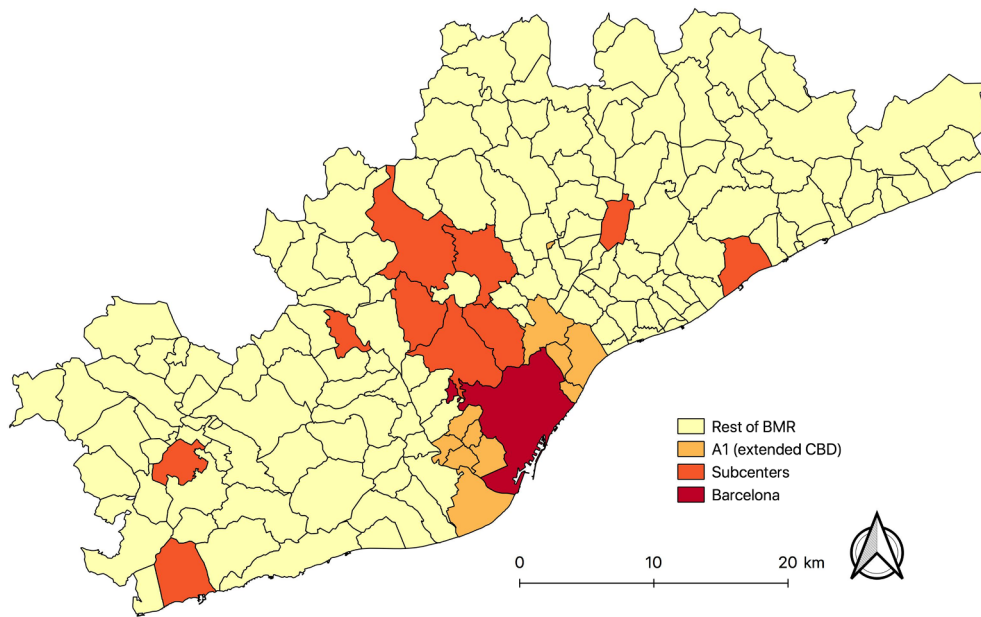


Fig. 1. Barcelona Metropolitan Region subareas.

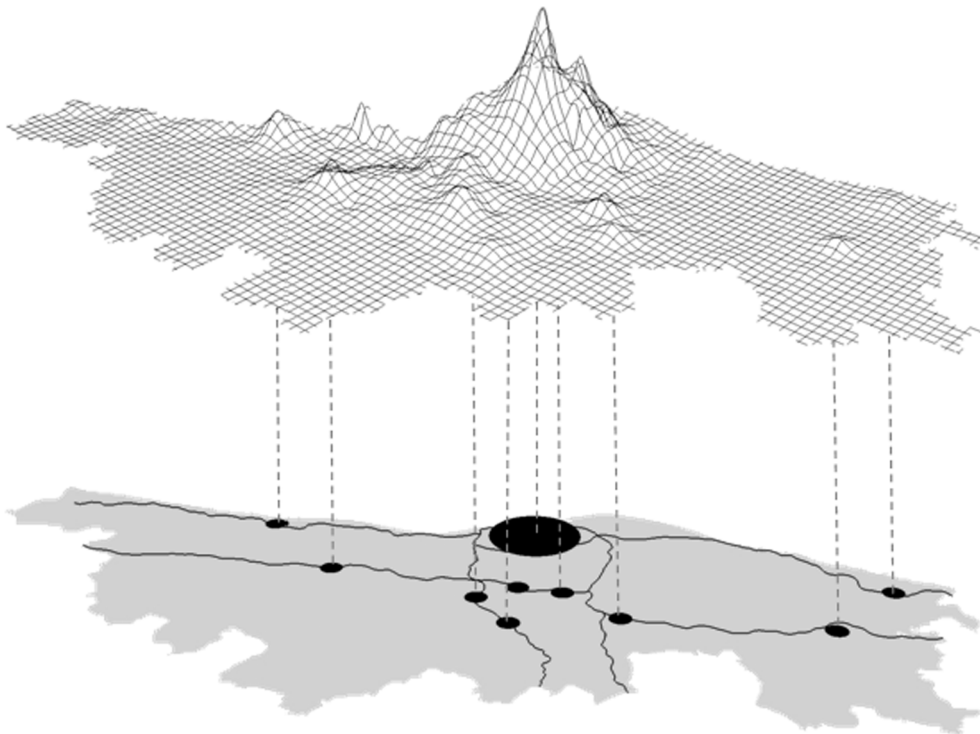


Fig. 2. Polycentricism and spatial pattern of 3-D population density.

with the direct energy of each mode of transport (traction) is the surface of forest needed to sequester the GHG emitted into the atmosphere during trips are counted. Two different information sources are required for its calculation. First, a measure of energy consumption per passenger and km.⁸ Second, a conversion factor that transforms energy consumption into energy land. The means of transport that use a combustion engine (car, bus and motorcycle) are assigned a correspondence of 100 Gigajoules per hectare,

⁸ In this research, the data provided in [Estevan and Sanz \(1996\)](#) is used.

Table 3
Ecological footprint per passenger-km and mode of transport.^a

Mode transport	Gj/Passenger-km (a)	Energy-ecological footprint ratio Has/Gigajoule (b)	Ecological footprint (ha/passenger-km) (axb)
Car	0.00259	0.01	2.59x10 ⁻⁵
Bus	0.00061	0.01	6.1x10 ⁻⁵
Motorcycle	0.00129	0.01	1.29x10 ⁻⁵
Train	0.0013	0.00085	1.1x10 ⁻⁵
Metro	0.00135	0.00085	1.1x10 ⁻⁵
Bike			2.6x10 ⁻⁶⁹

Sources: [Estevan and Sanz \(1996\)](#) and [Rees and Wackernagel \(1996\)](#).

^a The footprint of the bicycle has been taken directly from [Rees and Wackernagel \(1996\)](#) for the assumption of a commuter that moves 10 km (a round trip of 5 km) a day. This is a footprint assigned to the food sector, since it is calculated on the extra caloric intake necessary to make the trip. In the case of walking, a footprint of 0 has been assumed.

following the proposal by [Rees and Wackernagel \(1996\)](#). Table 3 summarizes shows the conversion factors for each mode of transport. For electrified modes (metro and train), we suppose a higher productivity, 117.6 Gigajoules per hectare, given that a significant part of the electricity in Barcelona is not obtained from burning fuel, but through more ecological methods like hydro-electricity.⁹

Trip length is measured by the *average trip distance per municipality*, and the modal split by the *proportion of trips made by car*. Both variables are calculated from the origin–destination matrix. Each trip is associated to the distance needed to cover the route between the origin and destination municipalities. By crossing the origin–destination matrix with the network distances (km) between the region's municipalities, we find the total distance traveled in each municipality. Dividing it by the number of commuters in each municipality, we obtain the average trip distance per worker in each municipality. Taking the information on the modal split of trips made by each municipality's residents, the proportion of trips made by car over the total of trips per municipality has also been calculated.

Energy land associated with the indirect energy used in the manufacture of the means of transport is the ratio between the energy land needed to sequester GHG emissions during the manufacture and maintenance of the means of transport used in the journeys, and the years of life of such infrastructures and means of transport (Table 4). Again, this research uses the estimations by [Estevan and Sanz \(1996\)](#) and [Rees and Wackernagel \(1996\)](#).¹⁰

The space occupied by transport infrastructures is measured departing from the total road surface of the Barcelona Metropolitan Region comes from the Land Use Maps. We compute only one third to eliminate the part assignable to other types of mobility, such as freight transport and mobility for recreation purposes.¹¹ Finally, this surface was evenly distributed for each trip according to the percentage of journeys made by car, bus and motorcycle. As for the railway network in the Barcelona Metropolitan Region, it is 569 km long. Assuming a width of 7 m, the area obtained is 398.3 has. Only 65% of this area has been taken, in order to eliminate the share of long-distance travel and non-commuting mobility. The subway surface is not considered in the calculation of the footprint when it is buried.

Trip distances were calculated considering the information on workers' places of residence and work. It has been assumed that commuters make 460 trips per year (230 workdays per year and 2 trips per working day). We use this constant frequency because only the number of commuters per municipality is shown in the database.

The formula for the calculation of the ecological footprint is

$$EF_i = \sum_z [EC_z EL_z D_{ij} Trip_{ijz}] + L_z$$

EF_i is the annual ecological footprint of trips made by municipality i workers, EC_z is the energy consumption of mode of transport z per km and passenger (Gj/km); EL_z is the ecological land per Gj in mode of transport z (ha/Gj), D_{ij} is the network distance between municipalities i and j ; $Trip_{ijz}$ are the annual trips made by residents from the municipality i towards municipality j made by mode of transport z ; L_z is the land area corresponding to the infrastructure space used by mode of transport z . The average value for the whole Barcelona Metropolitan Region in 2001 is 0.056 ha.

⁹ In Barcelona and Catalonia in general, hydroelectricity makes up a significant part of electricity consumption. Using the data from [Wackernagel and Rees \(1996\)](#) as a reference, electricity of fossil origin presents a productivity of one hectare per 100 Gigajoules per year. According to these authors, productivity of hydroelectricity is at least one hectare per 160 Gigajoules per year. The electricity footprint was calculated based on its primary sources. In terms of energy of nuclear origin (one hectare per 100 ha per 100 Gigajoule year), we also use data from [Wackernagel and Rees \(1996\)](#).

¹⁰ It should be noted that the direct and indirect energy allocated to cars by [Estevan and Sanz \(1996\)](#) is significantly below that assigned in other works. It only represents 45% of the energy per passenger and km used in [Rees and Wackernagel \(1996\)](#) and 62% of the value used in calculating London's ecological footprint ([Best Foot Forward, 2002](#)).

¹¹ The idea is that the surface area of transport infrastructures is not only used for commuting mobility, but for other uses, so the assignment of the whole transport infrastructure space to commuting mobility would imply overestimating the ecological footprint ([Wackernagel and Rees, 1996](#)). According to data from [Estevan and Sanz \(1996\)](#), for the Spanish case, the observed mobility can be divided into three parts, each of similar weight: commuting mobility, mobility for leisure reasons, purchases etc. and freight.

Population density (municipal) is calculated by dividing the municipal population by the area dedicated to residential uses. *Distance to CBD* is the direct distance from the centroid of the municipality in question to Plaça Catalunya (historical center of the municipality of Barcelona). *Distance to the nearest subcenter* is calculated by measuring the direct distance between the centroid of the municipality in question and the centroid of the nearest subcenter. It is calculated in its inverse form. Multicollinearity between variables expressed in distances is significantly lower than in the direct form.¹² Employment subcenters have been identified using statistical thresholds. We consider municipalities to be subcenters if they: (a) concentrate more than 1 per cent of total employment, and (b) have an employment density above the average. This method allows us to maintain the same criterion for both years, regardless of the variations in total employment due to the economic cycle. Numerical thresholds do not allow such a possibility and are therefore more subjective. The result of applying this methodology is the identification of six subcenters in 1991 and nine in 2001.¹³ *Distance to road infrastructure* is the direct distance between the centroid of the municipality and the closest access to the main road infrastructure. *Job-ratio* is the ratio between the number of jobs and the number of workers who live in the municipality. *Discontinuity* is the ratio between isolated built-up areas (continuous fabrics) and total urbanized land. This indicator is designed to capture the temporal variation of the discontinuity. If the number of isolated urbanized spaces with a constant soil surface increases, the discontinuity index increases. If urbanized land increases and the number of islands of urbanized land remains constant, the discontinuity index decreases. If urbanized land increases, but the number of isolated urbanized spaces decreases, the discontinuity index also decreases, since two or more previously isolated urbanized spaces may have joined together to form one.

Several potential control variables have been tested (temperature, terrain slope, family modality, etc.), but we have only been able to find one variable, in addition to the built environment variables, that significantly affects the ecological footprint of commuting: household income per capita.

To estimate the static impact of the built environment on the ecological footprint of commuting in municipality j , we estimate gradual specifications of Eq. (1) by Ordinary Least Squares (OLS).

$$EF_j = \beta_0 + \sum_i (\beta_{1,i} \times Distances_{i,j}) + \beta_2 \times Den_j + \beta_3 \times Disc_j + \beta_4 \times JobRatio_j + \beta_5 \times Income_j \quad (1)$$

EF_j is the average ecological footprint of commuting mobility in municipality j . $Income_j$ is the average income per capita of municipality j . $Job-ratio_j$ is the quotient between the number of jobs located in municipality j and workers living in municipality j . Den_j is population density in municipality j ; and $Disc_j$ is the discontinuity index of municipality j . Finally, $Distances_{i,j}$ includes three explanatory variables: the distance between the centroid of municipality j and the CBD ($dCBD$), the inverse of the distance from municipality j to the nearest subcenter ($1/dSUB$), and the distance of municipality j with respect to the nearest main road access ($dINFR$).

Although cross-section models provide valuable information on the relationship between urban spatial form and structure and mobility, causality analysis requires control for other variables and a dynamic perspective that indicates the sequence of the impact (Pearl, 2009). As a result, we also estimate gradual specifications of Eq. (2) by OLS. In this equation, the dependent variable is the variation between 1991 and 2001 of the average ecological footprint of commuting per worker, and the above mentioned explanatory variables are included with their 1991 values and their 1991–2001 variation.

$$\begin{aligned} \Delta EF_{j,91-01} = & \gamma_0 + \gamma_1 \times \Delta Den_{j,91-01} + \gamma_2 \times \Delta Disc_{j,91-01} + \gamma_3 \times \Delta JobRatio_{j,91-01} + \gamma_4 \times \Delta Income_{j,91-01} + \sum_i (\gamma_{5,i} \times Distances_{i,j}) \\ & + \gamma_6 \times Den_{j,91} + \gamma_7 \times Disc_{j,91} + \gamma_8 \times JobRatio_{j,91} + \gamma_9 \times Income_{j,91} \end{aligned} \quad (2)$$

4. Results

4.1. Total ecological footprint. Mode of transport and intra-metropolitan patterns

The total ecological footprint of commuting mobility increased from 65,362 ha in 1991 to 102,157 ha in 2001 (Table 4) which represents a growth rate of 56.3%. This is obviously a very notable increase. The spatial areas that experienced the highest increase in their ecological footprint are the “other municipalities” (small peripheral municipalities) (90%), followed by the recent subcenters (75.2%) (Table 5). Fig. 4 shows how GHG emissions per worker increases with distance to the CBD. The areas with the lowest increase are Barcelona (17.4%) and the first crown (35.3%) (Table 5).¹⁴ The average ecological footprint per worker in new and old subcenters also increased more than the other subareas (Table 6). The “other municipalities” is the subarea with the highest increase in ecological footprint per worker (90%) (Table 6). The average ecological footprint per worker was 0.041 has in 1991, reaching 0.056 has in 2001. The corresponding growth rate is 36.5% (Table 6).

The mode of transport responsible for most of the ecological footprint is the car (79.4% of the total ecological footprint in 1991, reaching 84.5% in 2001). The highest ecological footprint per worker and mode of transport corresponds to car trips (0.098 has in 2001). The lowest values correspond to bus trips (0.018 has) and bicycle/motorcycle trips (0.003 has).

¹² This implies the assumption that the impact only significantly affects localities close to each subcenter.

¹³ For a comprehensive review of the different methods proposed to identify subcenters, see García-López (1996), Muñiz et al. (2008) and García-López and Muñiz (2010).

¹⁴ The municipality with the highest average ecological footprint per worker (Sant Vicenç de Montalt) has a 5.7 times larger ecological footprint than the one with the smallest ecological footprint per worker (Barcelona municipality).

Table 4

Total ecological footprint by mode of transport 1991 and 2001.

	1991 (has)	% 1991	2001 (has)	% 2001	Δ91-01
Car	51,926	79.4	86,042	84.5	65.7
Bus	3463	5.2	4014	3.9	15.9
Train	3890	5.9	5581	5.4	43.4
Motorcycle	1597	2.4	2282	2.2	42.9
Metro	4451	6.8	4210	4.1	5.4
Bike	33	0.06	27	0.02	-0.2
Total	65,362	100	102,157	100	56.3

Table 5

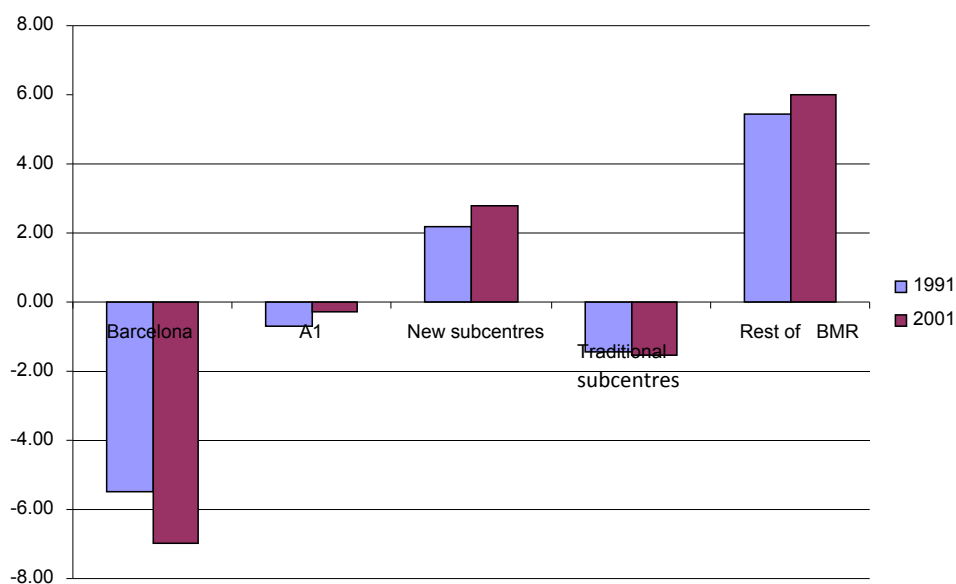
Total ecological footprint by spatial areas 1991 and 2001.

	1991 (has)	%1991	2001 (has)	%2001	Δ91-01%
BCN ^a	16,557	25.3	19,437	19	17.4
A1 ^b	14,261	21.8	19,299	18.8	35.3
New Subcentres	4,287	6.5	7,511	7.3	75.2
Old subcentres	7,433	11.3	12,572	12.3	69.1
Rest of municipalities	22,821	34.9	43,366	42.4	90
Total BMR	65,362	100	102,157	100	56.3

^a Barcelona municipality.^b A1: first metropolitan ring municipalities contiguous to Barcelona Municipality.**Table 6**

Ecological footprint per worker and spatial area.

	1991 (has)	2001 (has)	Δ91-01%
BCN ^a	0.026	0.031	19.2
A1 ^b	0.043	0.057	32.5
Old subcentres	0.052	0.065	25
New subcentres	0.040	0.056	40
Rest of municipalities	0.064	0.084	31.2
Total BMR	0.041	0.056	36.5

^a Barcelona municipality.^b A1: first metropolitan ring municipalities contiguous to Barcelona Municipality.**Fig. 3.** Difference between the percentage of trips and the percentage of ecological footprint per spatial area.

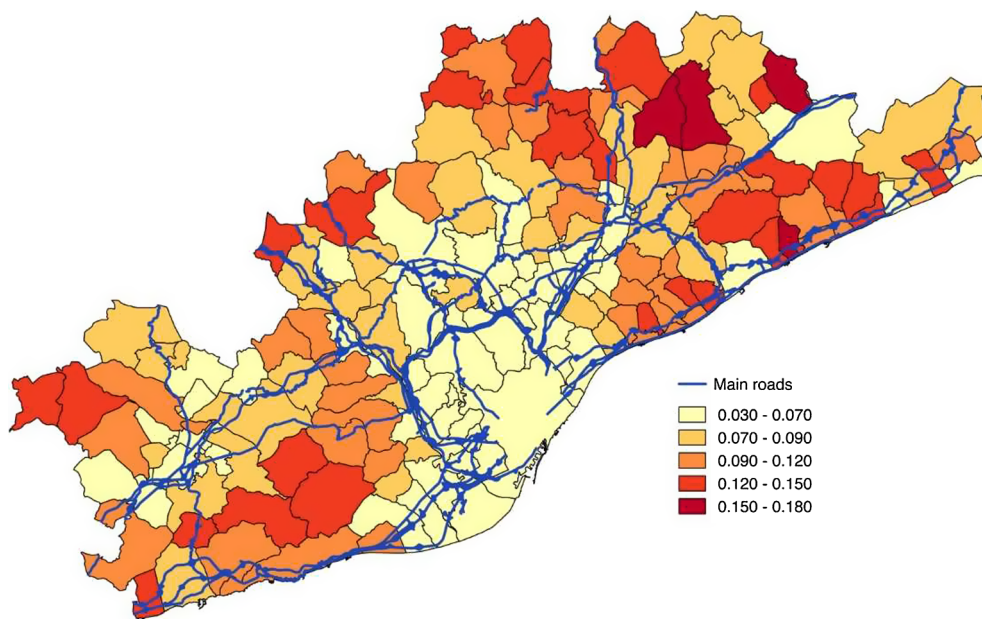


Fig. 4. Ecological footprint per worker 2001.

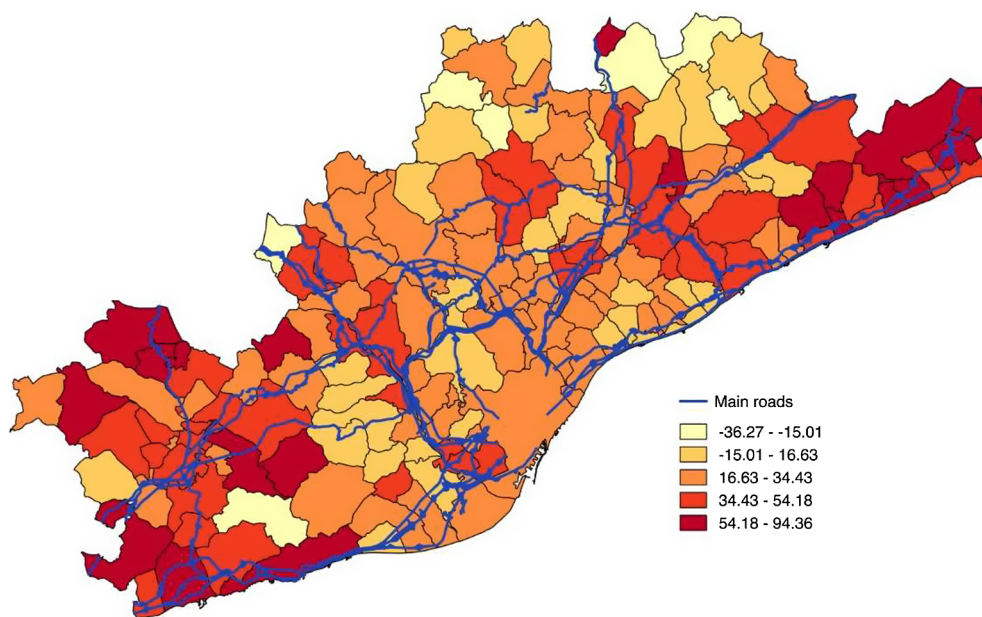


Fig. 5. Ecological footprint growth per worker 1991–2001.

Fig. 3 highlights the difference between the percentage of commuting trips in the subareas (Barcelona, first crown, new subcenters, old subcenters and the other small municipalities) and the percentage of total ecological footprint. Workers who live in the municipality of Barcelona represented 33.9% of trips in 2001, but the ecological footprint of the municipality of Barcelona accounted for only 19% of the total footprint. At the other extreme, the group of “other municipalities” accounted for 28.5% of total trips, while they accounted for 42.4% of the total ecological footprint.

Fig. 4 shows intra-metropolitan ecological footprint variation in 2001. Fig. 5, its increase between 1991 and 2001.

4.2. Urban form and spatial structure as determinants of the ecological footprint of commuting.

Table 6 shows the OLS models that estimate the impact of the built environment variables on the ecological footprint of commuting mobility for years 1991 and 2001. If the built environment variables are included separately, all parameters are significant

Table 7

The impact of built environment on the ecological footprint of commuting mobility per worker 1991 and 2001.

	1 1991	1' 2001	2 1991	2' 2001	3 1991	3' 2001	4 1991	4' 2001	5 1991	5' 2001
C	0.01 (0.4)	0.007 (0.5)	0.06* (4.7)	0.09* (7.1)	0.03* (2.0)	0.05* (3.3)	0.03* (2.9)	0.06* (4.5)	0.05* (2.1)	0.03 (1.8)
dBCN	0.0006* (3.2)	0.001* (6.5)							0.0001 (0.6)	0.0007* (3.6)
1/dSUB	−0.024* (−5.7)	−0.023* (−4.4)							−0.020* (−5.5)	−0.021* (−4.1)
dINFR	0.003* (2.3)	0.003* (2.2)							0.0022 (1.4)	0.0019 (1.37)
DEN			−0.0001* (−7.6)	−0.0002* (−8.4)					−0.0018 (−0.65)	0.0010 (0.37)
DISC					0.007* (2.3)	0.011* (3.6)			−0.0001* (−4.2)	−9.3e−5* (−3.14)
JOB RATIO							−0.01* (−3.3)	−0.02* (−4.5)	−0.011* (−2.9)	−0.013 (−3.2)
INCOME	3.8e−6* (2.9)	4.09e−6* (4.7)	2.7e−6* (3.4)	1.9e−6* (2.4)	3.4e−6* (3.4)	3.4e−6 (3.9)	3.3e−6* (3.8)	2.8e−6* (3.3)	2.9e−6* (2.6)	3.3e−6* (3.5)
R2 adjust	0.35	0.50	0.40	0.44	0.21	0.25	0.43	0.53	0.43	0.53
No Observations	164	164	164	164	164	164	164	164	164	164

"t" student in parenthesis: *p < 0.1; **p < 0.05; ***p < 0.01.

Errors are clustered at municipal scale.

and present the expected sign. The effect of living close to the CBD and close to a subcenter is a lower ecological footprint. Along the road infrastructure, corridors of economic activity emerge, so nearby municipalities present on average a low ecological footprint. The overlap of the road and train infrastructure on radial axes may explain this result (Table 7 columns 1 and 1'). The impact of density (Table 7, columns 2 and 2') is positive in terms of achieving a low ecological footprint. This result seems to confirm to a certain extent the beneficial environmental effect of high density, as argued by proponents of the Compact City Approach. The impact of discontinuity (Table 7, columns 3 and 3') is negative. Municipalities with more discontinuous urbanized land present on average a lower ecological footprint. The effect of a high job-ratio (Table 7, columns 4 and 4') is positive: in municipalities with a high job-ratio, workers are more likely to live and work in the same municipality, which shortens the average commuting distance, makes travel by car less likely and, consequently, reduces the ecological footprint per worker. As for the effect of household income per capita, the sign of the parameter is positive, which means that, all else being equal, wealthier municipalities present on average a larger ecological footprint per worker. The variables that exert the greatest effect on the variation in the ecological footprint per worker of a municipality are household income and the job-ratio. This result is coherent with most of the research that considers socio-economic influences as important as built environment variables (Handy, 1996; Dieleman et al., 2002; van Covering and Schwanen, 2006).

Separate models are presented for each urban form and spatial structure dimension to avoid multicollinearity issues. The problem with this way to proceed is that it can lead to the detection of spurious relationships. The most common solution is to include all urban spatial form and structure variables in the same model. The results of the complete model (all explanatory variables in a single model) presented in columns 5 and 5' are striking, since population density seems not to be significant. Besides, discontinuity exerts the opposite effect to that expected.¹⁵ The results of a respectable number of such studies would indicate the desirability of maintaining a compact and dense urban form as a strategy to reduce the global environmental impact of commuting mobility. Contrary, our results indicate that density is less relevant than location in terms of distance to the CBD, to subcenters and to the main road infrastructure.

It is worth noting that we have not estimated the models by applying logarithms, so the parameters obtained are not elasticities, but marginal effects. Related to this question, the parameters of spatial structure and structure may seem to have a very low value. This is because, as a dependent variable, the footprint value expressed in hectares is very low (if we used square meters instead of hectares, the parameters would be multiplied by 10,000). According to the results obtained, moving one km away from the center of Barcelona means that the footprint per worker is increased by 0.001 ha. Moving one km away from the nearest subcenter implies that the footprint increases 0.023 ha. Moving away from the main road infrastructure means an increase of 0.003 ha. In terms of density, despite the problems of significance of the variable, taking as reference a parameter −0.002, multiplying the density levels by two would mean that the footprint per worker is reduced by 0.02 ha.

Table 8 shows the effect of urban spatial form and structure variables, as well as its variation on the growth of the ecological footprint per worker between 1991 and 2001. The first column shows the effect of the urban spatial form and structure variables in 1991 on the variation in the ecological footprint between 1991 and 2001. The second column shows the effect of built environment indicators (excluding the variables expressed in distance - distance to the CBD, distance to the subcenter and distance to the nearest road access- since they do not vary) on the variation in the ecological footprint between 1991 and 2001. The third column addresses

¹⁵ To avoid multicollinearity issues in the general model that include all explanatory variables, it was checked that correlation matrix of explanatory variables. All correlations were always below 0.4.

Table 8

The impact of the built environment on the ecological footprint per worker growth 1991–2001.

	1	2	3
C	0.013 (1.29)	0.018 [*] (11)	0.01 [*] (2.0)
dBCN	0.0004 [*] (3.6)		0.0004 [*] (3.5)
1/dSUB	−0.0018 (−1.09)		0.0011 (0.4)
dINFR	−0.0005 (−0.5)		−0.0007 (−0.7)
DEN 1991	2.7e−6 (0.19)		0.003 (1.9)
DISC 1991	0.004 [*] (3.4)		1.3e−5 (0.9)
JOB RATIO 1991	0.0015 (1)		−0.003 (−1.5)
INCOME 1991	−5.6e−7 (−1.1)		−7.1e−7 (−1.9)
Δ DISC (91–2001)		−0.003 (−0.8)	−0.002 (−0.6)
Δ DEN (91–2001)		5.8e−5 (1.4)	3.3e−5 (1.1)
Δ RENTA (91–2001)		4.5e−07 (0.7)	8.6e−9 (0.01)
Δ Job Ratio (91–2001)		−0.014 [*] (−2.8)	−0.018 [*] (−2.9)
R ² Adj	0.22	0.08	0.25
No Observations	164	164	164

Standard error in parenthesis: ^{*}p < 0.1; ^{**}p < 0.05; ^{***}p < 0.01.

Errors are clustered at municipal scale.

the effect of the built environment variables, according to their values in 1991 and to their growth between 1991 and 2001. The adjustment capacity (adj R²) of the dynamic model is significantly lower than that of the static models. The significance of the parameters of the built environment variables is also noticeably lower. The results shown in column 3 indicate that the municipalities with the highest increase in ecological footprint are those that are more distant from the center of the region (Barcelona), and whose job-ratio has decreased the most.

5. Discussion

For those municipalities that have a residential profile, the ratio between jobs and workers at the municipal level increases seems to be a good strategy to reduce the ecological footprint per worker. Municipalities that are more specialized in residential functions tend to present a greater footprint than those with a more balanced mix of residences and spaces for economic activity.

Regarding subcenters' mobility model, we see differences depending on their specific nature. Traditional subcenters have been the destination of a large part of the commuting trips originating in the surrounding municipalities. However, we have detected that this structuring role of mobility flows is being lost, thus increasing trip distances and the use of the automobile. To preserve this structuring role, a public transport policy that connects subcenters efficiently should be implemented. The articulating role of subcenters has been modified to a great extent due to a process of decentralization of the population towards the urbanized suburban periphery, in conditions of low density. This process can be stopped by urban renewal policies at the scale of housing, building and neighborhood, and modernizing the public transport network. Regarding new subcenters deriving from the recent decentralization of employment, one way of containing emissions is to urbanize the residential space with medium/high densities and to improve the access of such spaces to public transport infrastructure.

The most surprising result is that corresponding to the parameter of the population density variable. Supporters of the Compact City Approach consider the main instrument to reduce the volume of GHG emissions to be land planning that maintains or grows density levels. Our results indicate that density probably has no significant effect on the ecological footprint per worker once distance to the CBD, to the nearest subcenters and to the nearest transport infrastructure are considered. This result stems from the estimation of the static model where all urban form and spatial structure variables are included to capture spurious relations. By incorporating the distance to the CBD, to the subcenters and to the road axes as regressors, as well as the job ratio and the discontinuity indicator, density ceases to be statistically significant. This result can be explained from a theoretical perspective. The monocentric (Alonso, 1964; Muth, 1969; Mills, 1967) and polycentric theoretical models (Fujita and Ogawa, 1982; Sullivan, 1986; White, 1999; Lucas and Rossi-Hansberg, 2002) consider that the intra-metropolitan variability of density responds to the proximity of each place to the elements that make up the spatial structure of the city. Therefore, if location determines density and not the other way around, parameters referring to the location of a municipality with respect to the elements that structure the metropolitan space are more significant than the parameter of the density variable.

The beneficial effects of a high density on commuting activity has been documented in hundreds of studies. Our study does not question this. Preserving an acceptable density level allows the adoption of transport-oriented policies and smart growth policies. Urbanism can act effectively by setting a minimum density for new urban developments and there is no reason for it to stop doing so. No anti-high-density discourse can be derived from the lack of significance of the density variable in some of the models.¹⁶ Besides, although high density does not imply a low footprint of commuting mobility, high density can be environmentally beneficial beyond its impact on mobility. For example, dense urban fabrics tend to have small apartments that consume less energy than the typical single-family dwellings of low-density neighborhoods, so high density can reduce residential GHG emissions (Ryu, 2005; Brown et al., 2008; Lee and Lee, 2014; Glaeser and Khan, 2010). Finally, perhaps we are measuring density at an inappropriate spatial scale (Næss, 2011). Therefore, it is important to emphasize the need for caution in assessing the relationship between density and ecological footprint.

The prevailing view in the field of urban studies is the appropriateness of taking measures that tend to compact cities. However, according to Glaeser and Khan (2010) and Gaigne et al. (2012) things may not be as simple if they are examined in the context of the national city system (Glaeser and Khan, 2010) or, at a theoretical level, within a spatial general equilibrium spatial model (Gaigne et al., 2012). Glaeser and Khan (2010) argue that location, not density, is the spatial dimension that is most correlated with the individual level of GHG emissions occurring in large cities in the United States. Cities with low GHG emissions per worker are in regions with a benign climate and with renewable energy sources. If these cities set limits on their growth, firms and workers will be redirected to other cities with less restrictions, worse climatology and without renewable energy sources. Although it is an interesting idea, and possibly true in the case of a society as mobile as the US, this type of behavior is not common in Europe, and even less so in Latin cities like Barcelona. There are other reasons for people leaving their home towns, such as economic and employment expectations in destination cities, and are usually flood processes, intense migrations in a brief period of time followed by long periods of stability. Even so, we believe this argument to make sense on a metropolitan scale. Firms and families can choose to locate to municipalities in the same metropolitan region where land rent is lower and there are possibilities for greater growth, although this implies a higher level of emissions. From this perspective, the results obtained in this study considerably agree with those of Glaeser and Khan (2010).

6. Conclusions

GHG emissions variability per worker associated with commuting in the Metropolitan Region of Barcelona present a spatial pattern. If there is a spatially recognizable pattern, it is therefore possible to alter the volume of emissions by acting on the built environment.

Results obtained on impact of density were not as expected. These seem to indicate that the density of a municipality *per se* does not affect the volume of emissions per worker. One of the most interesting results found is that recent and traditional subcentres articulate differentiated mobility flows around themselves, so that policies seeking to reduce emissions through actions on the built environment must also be different, in short, correctly adapted to the context. The most peripheral municipalities, less dense and more remote from the main transport infrastructure and major concentrations of employment are those with higher emissions per worker. This result supports anti-urban-sprawl policies aimed at reducing the volume of emissions.

The Barcelona Metropolitan Region faces three problems that deserve mention. The first is that the mobility model seems to become less predictable, that is, more random. The second is that the use of the automobile—outside Barcelona—has increased significantly. The third is that subcenters seem to be losing their structuring role of mobility flows. These trends are preoccupying and should be the focus of public administrations' attention.

One limitation of the study is that only the effect of urban form and spatial structure on commuting mobility has been examined. It would have been very interesting to have census information regarding other types of travel (leisure, vacations, shopping, business, etc.). The environmental impact of freight transport and mobility due to shopping, leisure, etc., could exceed that of mobility commuting. Contemplation of this type of mobility could affect the magnitude and significance of the parameters of the built environment variables. Another limitation of the study conducted is not having data for the period 2001–2011. This would have allowed to analyze how the changes occurred between 1991 and 2001 affect commuting mobility the following decade. Finally, one of the quantitative strategies of the study was, considering the diversity of conversion factors, to always take the lowest value as a rule. This criterion presents the problem of systematically underestimating ecological footprint values, but in turn, it allows us to sustain that the ecological footprint of commuting is at least equal to the estimated value.

Appendix A

See Tables A1–A5.

¹⁶ Ewing and Cervero (2010) present empirical evidence that indicates that, in some cases, density is one of the factors that least affect mobility patterns, especially commuting distance.

Table A1
Population statistics.

	1991	2001
Population	4,264,422	4,390,413
Worker Average distance to the CBD (km)	10.70	12.15
Density gradient)	−0.044 ^a	−0.040 ^a
Gini Index	0.837	0.798
Net density	126.9	96.2
Weighted Average distance to the closer access to road network	3.55	2.68
Weighted average distance to the closer subcentre	9.94	8.62

Table A2
Employment statistics.

	1991	2001
Place of work average distance to the CBD (km)	9.4	11.1
Density gradient	−0.02	−0.01
Gini Index	0.85	0.81
Net density	54.15	67.2
Weighted average distance to the closer access to road network	3.43	2.64
Subcentres identified	6 Granollers, Terrassa, Sabadell, Mataró, Rubí, Cerdanyola,	9 Granollers, Terrassa, Sabadell, Mataró, Rubí, Cerdanyola, Sant Cugat, Martorell, Vilanova
% employment in CBD	64.5	57
% employment in subcentres	13.5	18
% rest of municipalities	22.0	24.5
Weighted average distance to the closer subcentre	9.52	8.25

Table A3
Land statistics.

	1992	2002
Urbanized land	49,917.2	67,999.8
Rest of land	274,636.0	256,284.7
Residential land	33,604.9	45,623.2
Number of isolated urbanized areas	2,640	2,468

Table A4
Mobility 1991.

	Commuting distance	Self-sufficiency	Commuting distance of workers that live and work in different municipalities	(%) Displacements made by car (origin)	(%) displacements made by car (destination)
Barcelona	3.64	84.4	12.5	30.3	31.4
A1	5.88	35.0	7.9	38.5	43.8
Subcentres	5.13	67.9	11.7	52.3	52.3
Old subcentres	4.77	74.8	13.7	51.3	50.9
New subcentres	5.94	52.1	10.5	54.7	55.2
Resto of municipalities	7.15	45.8	11.5	55.0	53.7
Total BMR	5.15	62.6	10.4	41.3	41.3

Table A5
Mobility 2001.

	Commuting distance	Self-sufficiency	Commuting distance of workers that live and work in different municipalities	(%) Displacements made by car (origin)	(%) displacements made by car (destination)
Barcelona	4.07	82.4	13.8	29.4	13.9
A1	6.80	35.5	9.4	46.5	9.2
Subcentres	6.25	59.8	12.5	60.9	13.2
Old subcentres	6.03	67.1	14.2	59.6	13.2
New subcentres	6.68	45.6	10.6	63.4	13.1
Rest of municipalities	8.58	40.2	13.0	65.2	11.2
Total RMB	6.28	57.3	12.0	48.8	12.0

Appendix B. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.trd.2018.08.006>.

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