ECOLOGICAL SUSTAINABILITY AND URBAN FORM

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One controversial idea present in the debate on urban sustainability is that urban sprawl is an ecological stressing problem. We have tested this popular assumption by measuring the ecological footprint of commuting and housing of the 163 municipalities of the Barcelona Metropolitan Region and by relating the estimated values with residential density and accessibility, the fundamental determinant of residential density according to the Monocentric City Model.

1.INTRODUCTION

Professors Mathis Wackernagel and William E. Rees have introduced the concept of *Ecological Footprint* as a strong sustainability indicator.

The Ecological Footprint of a population is estimated by calculating how much land and water area is required on a continuous basis to produce all the goods consumed, and to assimilate all the wastes generated, by that population (Rees and Wackernagel (1996), p. 61)

The measures of per capita ecological footprints for countries and regions present a great variability. For the case of the rich countries and regions, once controlled the effects of medium income and climate, a residual variation still persists, which is probably picking up the effect of the urban form. The ecological footprint of food and services consumption don't seem to keep any relationship with urban form, but the ecological footprint of transportation and housing are probably determined by residential density. Those studies where the relation between energy consumption and residential density is tested validate this idea. In Rees and Wackernagel (1996) this intuition is also emphasised[1].

"*In many cases, housing type and location are the chief determinants of the ecological footprint as they influence house size and the household's transportation requirements. Living in densely populated urban areas leads to a smaller per capita footprints because more efficient land-use and*

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[1] In Nijkamp and Finco (2001) the relation between ecological footprint and urban sustainability is critically reviewed.

infrastructure and reduced transportation and residential heating requirements" (Rees and Wackernagel (1996), p. 103)

The purpose of this paper is to present a case-study of the Barcelona Metropolitan Region where per capita ecological footprint of housing and commuting are calculated, and to explore the relationship between the estimated ecological footprint and urban form by introducing de *Monocentric City Model* developed by Alonso (1964), Muth (1968) and Mills (1973).

The paper is structured as follows. Section 2 presents the ecological footprint of commuting procedure. Section 3 discusses the alternative methods for calculating the ecological footprint of housing. Section 4 briefly describes the spatial structure of the Barcelona Metropopolitan Region. In section 5 we present the per capita commuting and housing ecological footprint estimations for the 163 municipalities of the Barcelona Metropolitan Region. Section 6 explores the relationship between the estimated per capita ecological footprints, residential density variations and accessibility by introducing the exponential residential density function derived from the Monocentric City Model, the classical urban economics theoretical outcome. Section 7 discusses how suburbanization of population may generate an increase in per capita ecological footprint. Finally, section 8 summarises the main results and gives some methodological and analytical conclusions.

2.DETERMINING THE ECOLOGICAL FOOTPRINT OF COMMUTING: CALCULATION PROCEDURE

The ecological footprint of transportation includes: a) forestry land area required to sequester all the CO_2 direct emissions[2], b) energy and forest land area associated to energy and materials used in the production, construction and maintenance of vehicles and transportation infrastructures, and c) land occupied by the communication roads. Only the first component can be calculated strictly for commuting. In calculating only the first component, we are underestimating the real value. We leave for a later study to establish the proportion of components b) and c) that should be computed to commuting.

[2] "*Virgin forest ecosystems whose harvest would lead to a massive net CO_2 release that would be recovered only after 200 years of subsequent ecological production on this land*" (Rees and Wackernagel (1996) p. 70).

$$EFCOMpc_i = \frac{\left[\sum_i \sum_z \left(d_{ij} E_z T_{Ez,HEz} N_{ijz}\right)\right]}{POP_i} \qquad (1)$$

E.F $COMpc_i$: Per capita Commuting Ecological Footprint of municipality (*i*).
D_{ij}: (163x163) Distance matrix between municipalities (*i*) and (*j*).
E_z: The energy cost per traveller, km and mode of transport (Estevan and Sanz (1996))
N_{ijz}: Number of commuters of each municipality (*i*) toward the same municipality, as well as to the rest of municipalities (*j*) of the region by mode of transport (*z*)
POP_i: Population of municipality (*i*).
$T_{EZ,HEZ}$: Conversion factors from energy consumption to ecological footprint by mode of transport (Rees ang Wackernagel (1996)).

To calculate the per capita ecological footprint of commuting the following information is required: 1) distance between each one of the municipalities, 2) energy cost per traveller, km and mode of transport, c) number of travels of each municipality toward the same municipality, as well as to the rest of municipalities of the region, d) municipal population, and d) conversion factors from energy consumption values to ecological footprint values.

3.DETERMINING THE ECOLOGICAL FOOTPRINT OF HOUSING: CALCULATION PROCEDURE

The ecological footprint of housing includes: a) directly consumed land in housing uses, b) the ecological footprint of current energy consumption in heating, illumination, appliances and refrigeration, and c) the ecological footprint of materials and energy used in the construction of housings.

Although components a) and b) are easily calculable, the ecological footprint of construction presents serious difficulties. There are two alternative procedures. The first one consists on using data base on annual consumption of materials and annual energy of the construction sector (flow methodology), while the second consists on calculating the discounted value of energy and materials of the stock of housings and current residential energy consumption (stock methodology). The first methodology can be used in national and regional estimation, while for local estimations the required data is not available in most cases. The second methodology requires of a previous study on the consumption of materials and energy of the more common types of housing in the Barcelona Metropolitan Region. Recently, we collaborated with architects Daniel Calatayud and Jordi Sala, from the Department of Urbanism of the UPC School of

Architecture to estimate the ecological footprint of Sant Cugat, a medium sized municipality of the Barcelona Metropolitan Region[3].

In this study we found out that the ecological footprint of housing depends negatively on the number of floors of the building and positively on the residential unit dimension, an available information 1991 Housings Census 1991. Taking both sources of information, we have estimated by the ecological footprint of housing by using the stock procedure for all the municipalities of the RMB extrapolating baseline data for particular housing types to the entire municipality in a something rudimentary way.

The housing type analysis proportioned the following coefficients once the estimated medium per capita ecological footprint for all types are determined by the surface of the residential unit and the number of floors of the building.

$$E.F.MedHou = 20.14 + 0.16(MedHouSurface) - 1.4(N^{o}\,ofFloorsMedBuild) + \varepsilon$$

E.F.MedHou: Ecological Footprint of the Medium residential unit type
(MedHouSurface): Surface of the Medium residential unit type
(Nºof FloorsMedBuild): Number of floors of the Medium residential unit type
ε: The residual includes the rest of factors determining ecological footprint

$$\varepsilon = f(MaterialConsump, ConstrTechn, SunOrient, ...)$$

MaterialConsump: Material Consumption.
ConstrTechn: Technology of construction.
SunOrient: Solar Orientation.

Maintaining such coefficients for medium data of residential surface and number of floors of each municipality, the ecological footprint of housing is estimated.

$$PCEFHous_i = \frac{E.F.MedHou_i * NumRsidUnits_i}{Pop_i} \qquad (2)$$

PCEFHous$_i$: Per capita Ecological Footprint of Housing of municipality (*i*).
E.F.MedHou$_i$: Ecological Footprint of Medium House on municipality (*i*).
NumResidUnits$_i$: Number of residential units at municipality (*i*).
POP$_i$: Population of municipality (*i*).

[3] Total embodied energy consumption cal also be calculated by the software ARCHISUN developed by a research team conduced by Rafael Serra (UPC) under the Thermie-B European Comission Program in collaboration with il Politecnico di Milano, Hannover University and Tombazis & Associates.

4.THE BARCELONA METROPOLITAN REGION

The Metropolitan Region of Barcelona (RMB) is a conurbation with a big, diverse and compact centre (the municipality of Barcelona), a extremely dense first metropolitan ring urbanised by massive housing buildings, agricultural land and metropolitan parks discontinuities, seven subcentres and an extensive area that combines rural and low density residential uses. The net of transportation is radial. All subcentres are communicated with the centre through diverse railroad lines and metropolitan highways. The RMB is a complex, diverse, discontinuous, policentric and also partly dispersed metropolitan region. A city of cities with more than 160 municipalities that occupies near 4000 km^2 in a radius of approximately 45 km. (**table 1**)

Table 1
The Barcelona Metropolitan Region

METROPOLITAN RINGS	NUMBER OF MUNICIPALITIES	MEDIUM DISTANCE FROM THE CITY CENTRE	NET DENSITY RESIDENTIAL LEVELS (POPULA TION/HA)	PER CAPITA RESIDENTIAL ENERGY CONSUMPTION (KWH)	PERCENTAGE OF PUBLIC TRANSPORT COMMUTING TRAVELS	PERCENTAGE OF RESIDENTIAL UNITS IN BUILDINGS WITH MORE THAN 3 FLOORS	MEDIUM POPULATION
Barcelona	1	2,5	366	0.77	41	94	1,6 millions
First ring	10	12,2	378	0.55	29	86	88230
Second ring	23	20,3	241	0.70	19	69	23289
Subcentres	7	38,1	169	0.71	15	68	85283
Subcentres commuting area	20	41,3	54	0.93	13	33	5391
Metropolitan Corridors	101	41,2	69	1.01	16	46	5830

5.ECOLOGICAL FOOTPRINT ESTIMATES

The ecological footprint of commuting

The per capita ecological footprint of commuting in the RMB was in 1996 0.0372 hectares, that is to say, to absorb the emissions of CO_2 would be necessary 372 m^2 per capita The RMB has 197.721 hectares of forest land, 470 m2 per capita. Keeping in mind that total mobility probably triplicates commuting mobility, the global ecological deficit must be around 200%. Comparative to other metropolitan regions, it is a low deficit level. Urban residential land in the Barcelona Metropolitan Region is relatively scarce (a fifth part of forestry land) due to its relief (**Table 2**).

Table 2.a
TOTAL COMMUTING ECOLOGICAL FOOTPRINT1996

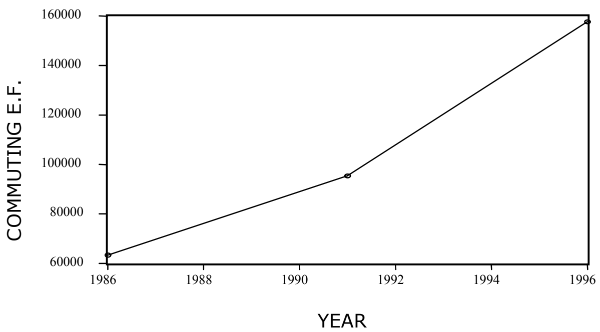
METROPOLITAN RING	E.F BUS	E.F TRAIN	E.F SUBWAY	E.F CAR	E.F MOTORCICLE	H.E. BIKE	H.E. FOOT	TOTAL E.F.
Barcelona	1639	2940	2335	18517	1042	16	292	**26784**
FIRST RING	1900	1530	3789	17430	709	13	1794	**27168**
SECON RING	2024	2987	73	22679	648	19	1928	**30361**
SUBCENTRES	1042	3294	0	17041	496	18	1262	**23156**
COMMUTING SUBCENTRES AREAS	378	558	0	7266	247	5	238	**8695**
METROPOLITAN CORRIDORS	2056	4076	18	33315	941	39	104	**41490**
TOTAL	**9042**	**15388**	**6217**	**116251**	**4086**	**114**	**6558**	**157657**

Table 2.b
PER CAPITA COMMUTING ECOLOGICAL FOOTPRINT 1996

METROPOLITAN RING	E.F BUS	E.F TRAIN	E.F SUBWAY	E.F CAR	E.F MOTORCICLE	H.E. BIKE	E.F FOOT	TOTAL PC E.F.
Barcelona	0.00109	0.00195	0.00155	0.01227	0.00069	0.00001	0.00019	**0.01775**
FIRST RING	0.00215	0.00173	0.00429	0.01976	0.00080	0.00002	0.00203	**0.03079**
SECOND RING	0.00366	0.00541	0.00013	0.04103	0.00117	0.00004	0.00349	**0.05493**
SUBCENTRES	0.00175	0.00552	0.00000	0.02855	0.00083	0.00003	0.00211	**0.03879**
COMMUTING SUBCENTRES AREA	0.00351	0.00518	0.00000	0.06739	0.00230	0.00005	0.00221	**0.08065**
METROPOLITAN CORRIDOR	0.00355	0.00704	0.00003	0.05750	0.00163	0.00007	0.00180	**0.07161**
TOTAL	**0.00214**	**0.00364**	**0.00147**	**0.02750**	**0.00097**	**0.00003**	**0.00155**	**0.03729**

The evolution of the measured ecological footprint of commuting during the last 10 years reveals an stressing ecological problem. The ecological footprint of commuting was 63356 hectares (0.014 hectares per capita) in 1986, 95338 in 1991 (0.022 hectares per capita) and 157657 hectares in 1996 (0.037 hectares per capita). Total and per capita ecological footprint has more than doubled during the last 10 years. (see **figure 1**).

Figure 1
TOTAL COMMUTING ECOLOGICAL FOOTPRINT 1986-1996



The ecological footprint of housing

The estimates obtained applying the methodology proposed by Calatayud, Sala and Muñiz (2001) indicates that the per capita ecological footprint of housing construction, direct occupied land and energy land required to sequester annual residential energy consumption, increases as we move away from the city centre. In the less dense metropolitan environment (metropolitan corridors) the per capita ecological footprint is 70 % higher than in the municipality of Barcelona and 117 % higher than in the densest environment (first ring) mainly urbanised by massive housing buildings. (**table 3**)

Table 3
THE PER CAPITA ECOLOGICAL FOOTPRINT IN HOUSING

METROPOLITAN RING	TOTAL ECOLOGICAL FOOTPRINT	PER CAPITA ECOLOGICAL FOOTPRINT
Barcelona	151436	0.0921
First Ring	67123	0.0729
Second ring	46899	0.0962
subcentres	55802	0.0943
Commuting subcentres area	12654	0.1386
Metropolitan corridos	78068	0.1565
total	**411984**	**0.0966**

6.ACCESSIBILITY AND ECOLOGICAL FOOTPRINT

The purpose of this paper is to relate the measured ecological footprint with accessibility.

Table 4.
From energy consumption and residential density relation to ecological footprint and accessibility relation

Energetic consumption = F (residential density) Newman and Kenworthy (1988)
Per capita Ecological Footprint= G (residential density) Rees and Wackernagel (1996)
Residential Density = R (accessibility) Alonso (1964), Muth (1969), Mills (1973)
Per capita Ecological Footprint = Z (accessibility) Muñiz and Galindo (2001)

The first step consists in establishing the relationship between energy consumption and the percentage of private commuters, and net residential density by applying the methodology of Newman and Kenworthy (1988) among others. We have also included as a control variable municipal medium income. We have tested diverse functional forms, being the log-lineal the better one (**table 5**)

$$Ln\,\mathrm{Re}\,sidEnerConsum_i = a + bLnDEN_i + cLnINC_i \qquad (3)$$

$$Ln(\%)\,\mathrm{Pr}\,ivTransTrav_i = a' + b'LnDEN_i + c'LnINC_i \qquad (4)$$

$LnResidEnerConsum_i$: Logarithm of the residential energy consumption of municipality (*i*).
$Ln(\%)PrivTransTrav_i$: Logarithm of the percentage of travels in private mode of transport over total travels in municipality (*i*).
$LnDEN_i$: Logarithm of population density (population per hectare) in municipality (*i*).
$LnINC_i$: Logarithm of municipal medium income.

Table 5
Net residential density and Residential Energy consumption and Private Transportation Travels percentage Relationship

Estimated Coefficients	Dep Variable: Energy Consumption	Dep Variable: (%) private Transportation travel
a	4.83* (3.78)	2.92* (3.71)
b	-0.09* (-3.86)	-0.08* (-5.48)
c	0.31 (1.89)	0.18 (1.83)
R^2	0.09	0.16
Number of observations	163	163

t values are in parentheses
(*) statistically significant variable.
R^2 of the ordinary least squares regression.

The explanatory power overall of regressed equations (3) and (4) is poor, but all coefficients present the expected sign and are statistically significant. Once controlled for income, residential density significantly determine per capita residential energy consumption and % private transportation travels. In other words, less dense areas present higher per capita residential energy consumption and % private transportation travels beyond the effect of Medium Income.

Figure 2.a.
Net residential density and residential energy consumption (1991)

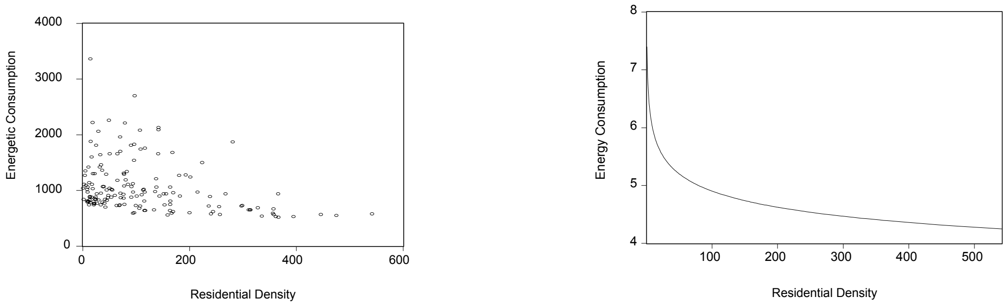


Figure 2.b.
Net residential density and % of private transport travels (1996)

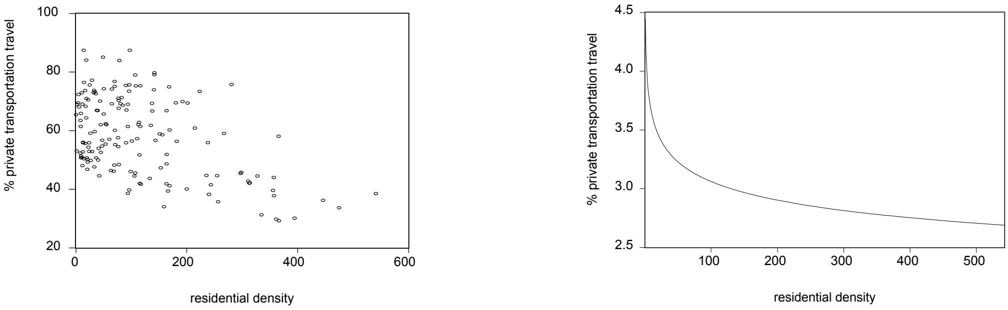


Figure 3.a.
Net residential density and per capita commuting ecological footprint

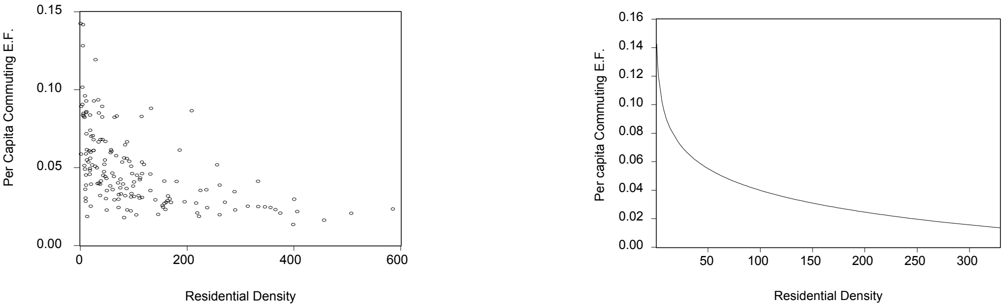
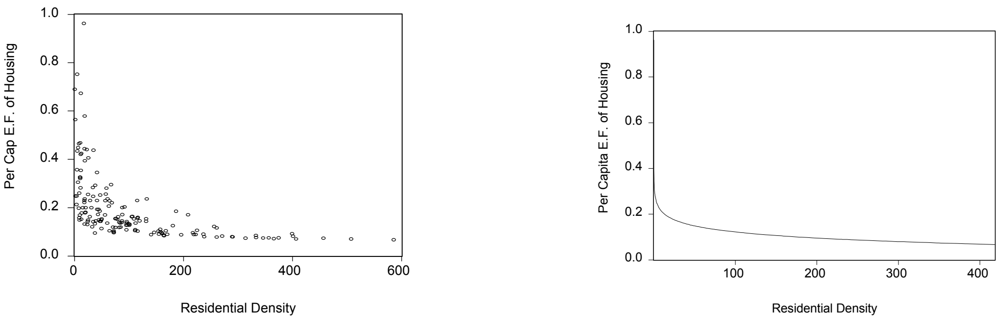


Figure 3.b.
Net residential Density and per capita ecological footprint of housing



The second step consists in evaluating the relationship between total per capita ecological footprint (the sum of housing and commuting ecological footprint) and net residential density.

Table 6 shows the results of the estimated ecological footprint functions taking density as a dependent variable. Using the criteria of explanatory power overall, the estimated exponential function was considered better as we can intuitively check in the scatter diagram (figures 3a and 3.b). The estimated coefficient b for the exponential function represents the constant percentage decline in ecological footprint per unit of residential density.

$$b = \frac{dEF(DEN) \big/ dDEN}{EF(DEN)} \tag{5}$$

Table 6
Per capita ecological footprint and net residential density
Alternative functional forms

Dependent variable	**Functional form**	**Estimated coefficients and R^2 (*t* values in parentheses)**
EFpc	$EF_0 - bDEN$	EF_0= 0.38 (23.9) b= -0.0008 (8.7) R^2 = 0.32
Ln EFpc	$LnEF_o - bDEN$	Ln EF_0 = -1.01 (24.9) b = -0.0034 (-13.35) R^2 = 0.53

The measured total ecological footprint for commuting and housing falls exponentially with residential density level. This relationship has been sustained by most of works where residential and transportation energy consumption are related to the density levels[4]. We pretend next to go further in the exploration of the determinant of the structural factors determining ecological footprint variation by introducing the residential density function associated to the Monocentric City Model.

According to the Monocentric City Model, residential density exponentially declines with distance to the city centre.

[4] Banister (1992), Breheny (1992), Khan (2000), Kenworthy and Newman (1990), Newman and Kenworthy (1988), Mogridge (1985), Prevedouros and Schofer (1991), Webster and Bly (1987).

$$DEN(x) = D_0 e^{-\gamma x} \quad (6)$$

D (X) is the residential density at a distance (X) from the city centre, D_0 is the theoretical density in downtown and γ the population density gradient.

If

$$EFpc(x) = EF_0 e^{-bDEN} \quad (7)$$

then:

$$EFpc(x) = EF_0 e^{-bD_0 e^{-\gamma x}} \quad (8)$$

When incorporating the exponential density funtion (6) in the function linking ecological footprint and density (7), the ecological footprint passes to depend on the accessibility (8), measured as distance to downtown.

One of the criticisms to the standard exponential density function is that the measure of accessibility is too simple, since cities expand on a limited number of communication axes and therefore it should also be included the distance to the axis as an additional gradient (9).

$$EFpc(x, Daxis) = EF_0 e^{-bD_0 e^{-\gamma_1 x - \gamma_2 Daxis}} \quad (9)$$

According to the fundamental equation, the ecological footprint should increase in a doubly exponential way as we move away from the city centre and from the nearest axis of transport. The estimates that appear in **table 7** are very similar to those estimated for the extended residential density function in Muñiz and Galindo (2001).

Table 7
EQUATION (11) ESTIMATION
Dependent variable: Ln Efpc

Coefficient	
Ln EF_0	**-0.83 (6.29)**
BD_0	**-1.64 (10.14)**
γ_1	**-0.028 (4.12)**
γ_2	**-0.18 (2.75)**
R^2	**0.50**
Number observations	**163**

t values are in parentheses
(*) statistically significant variable.
R^2 of the ordinary least squares regression.

The percentage variation in ecological footprint per unit of distance from the city centre is[5]:

$$\hat{\gamma}_1 = \frac{dEFpc(x, Daxis)/dx}{EFpc(x, Daxis)} = \gamma_1 bD_0 e^{-\gamma_1 x - \gamma_2 Daxis} \qquad (10)$$

while the percentage variation in ecological footprint per unit of distance from the nearest axis is:

$$\hat{\gamma}_2 = \frac{dEFpc(x, Daxis)/dDaxis}{EFpc(x, Daxis)} = \gamma_2 bD_0 e^{-\gamma_1 x - \gamma_2 Daxis} \qquad (11)$$

Table 8 summarises the indexes results for different distances to the city centre and transport axis. The percentage variation in ecological footprint per unit of distance from the city centre oscillates among 0.045 for a city centre distance zero and 0.011 for a city centre distance of 50 km. The percentage variation in ecological footprint per unit of distance from the nearest axis is more than six times higher than the one for the distance to the centre zero, and only 41 % higher when axis transport distance and city centre distance is 10 km.

[5] In a double exponential function the gradient (percentage variation of dependent variable per unit of the independent variable) is not constant for all distances.

Table 8
PERCENTAGE E.F. VARIATION PER UNIT OF DISTANCE

x	D axis	PERCENTAGE E.F. VARIATION PER UNIT OF DISTANCE (X) $\hat{\gamma}_1$
0	0	0.045
10	0	0.034
50	0	0.011
X	**D axis**	**PERCENTAGE E.F. VARIATION PER UNIT OF DISTANCE (D axis)** $\hat{\gamma}_2$
0	0	0.295
0	5	0.119
0	10	0.048

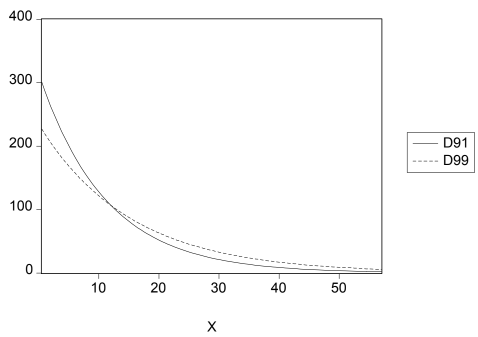
The ecological footprint increases proportionally more with distance from the axis of transport than with distance from downtown. In other words, less accessible and dispersal areas present higher ecological footprints than central and compact areas. It implies that urban sprawl has important costs in terms of sustainability.

7.SUBURBANIZATION AND SUSTAINABILITY

Figure 3 shows different residential density functions (exponential, extended exponential with distance to the axis and cubic-spline) variation between 1991 and 1999. In all cases the absolute value of the slope decreases (a flatter gradient in terms of the exponential function) and therefore the functions intersect for a distance to the centre of 12 km.

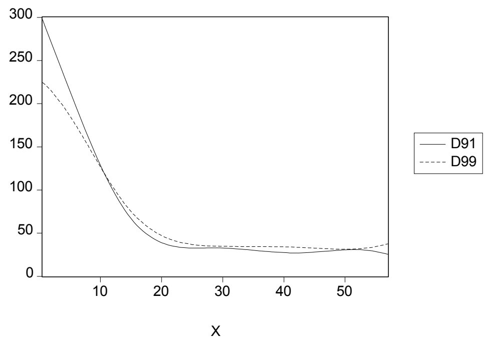
Figure 4
SUBURBANIZATION

4.A. EXPONENTIAL

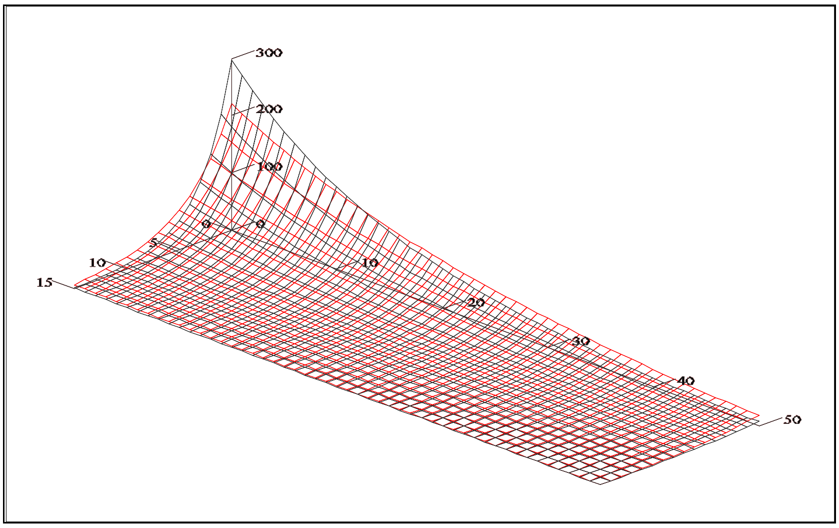


gradient 91: -0.0901
gradient 99: -0.0657

4.B. CUBIC-SPLINE



4. C. EXTENDED EXPONENTIAL WITH DISTANCE FROM THE TRANSPORT AXIS



X gradient 91: -0.0726
X gradient 99: -0.0498
D axis gradient 91: -0.3524
D axis gradient 99: -0.2319

Spatial integration and suburbanization results in a reduction of the density levels of the municipality of Barcelona, the first ring and the subcentres, and an increase in the less accessible and disperse areas. It implies a spatial redistribution of densities which balance supposes a higher per capita land consumption, a smaller medium density level and a great increase of private mobility.

8.CONCLUSIONS.

As a first conclusion, our results seems to indicate that the urban economics theoretical tools can be successfully integrated into a urban sustainability framework. Our second conclusion is that, although taking very seriously the limitations of the concept of ecological footprint, it is still a naïve, funny, controversial and very popular tool that helps to visualise the global implications of our current energy consumption and transportation patterns.

Suburbanization and metropolitan integration have created a new European city without precise limits (Koolhaas (2001)). It is articulated by monofunctional pieces tied by infrastructures of transportation and separated for "holes." A city that doesn't grow only by aggregation, but also by means of the integration of small and medium cities that they had been developed in an endogenous way in the past.

The ecological problem of spatial integration and suburbanization is that the relocation of the activity and the progressive occupation of the outlying space for new residence forms imply a higher consumption of materials, energy and floor, that which probably feeds the ecological footprint of the city beyond a reasonable level.

The urban structure of the Barcelona Metropolitan Region constitutes its main active in sustainability terms. According to Rogers (2001), a sustainable urban conurbation should: a) have a mixed great centre, b) a policentric structure, c) green belts and d) a radial and traverse public transportation system. The Barcelona Metropolitan Region completes with almost all the requirements. However, the tendency of the last years can already destroy what makes of the Barcelona Metropolitan Region a model urban sustainability.

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