Urban form and sustainable development

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Abstract

In this paper we study how the urban structure affects two environmental outcomes : greenhouse gas emissions from commuting and the conversion of agricultural/natural land ressources. The urban structure is characterized by its degree of polycentrism and by the share of urban and peri-urban dwellers. Polycentrism may lead to opposite effects on these indicators as lower commuting costs in secondary centers lead to lower land rents that may allow households to consume more residential land; furthermore commuting lenght may decrease, if workers commute to the closest business district, inducing less GHG emissions. The environmental impact of the urban structure is very dependant on residential lot sizes, fixed within zones but different between them. Then we address the implementation of two types of instruments to comply with an exogenous GHG target, a commuting tax/subsidy and a communication tax/subsidy for firms established in the secondary center.

Keywords: polycentrism, urban costs, communication costs, commuting costs, environmental policy, greenhouse gas emissions, land conversion.

JEL codes : Q54, Q58, R12, R21

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1. Introduction

Cities are home to an increasing share of the world population. It is therefore important to understand how urban development affects their environmental performance. Increasingly, jobs, hence households, are decentralized within cities : polycentrism is becoming a major feature of the urban landscape worldwide [3]. Despite a good understanding of the economic forces favoring the ermergence of polycentric structures, there is no real consensus on their environmental performance. This paper analyses how polycentrism affects two important environmental issues associated with urban development : the emission of greenhouse gases (GHG) by commuters and the conversion of surrounding agricultural/natural land.

The emergence of polycentric urban structures can be explained by the combination of three main factors: the increase in population, the increase in commuting costs and the fall in firms' communication costs between decentralized locations and the central business district (CBD). With increasing city size, urban costs (housing and commuting) tend to rise. This has to be compensated for by firms through higher wages. This creates an incentive for firms to locate outside the main center, in secondary centers where urban costs are lower. Indeed, Timothy and Weaton [34] report large variations in wages according to intra-urban location (15% higher in central Boston than in outlying work zones, 18% between central Minneapolis and the fringe counties). As they enjoy living on large plots and/or move along with firms, workers may also want to live in suburbia [16]. The relocation of firms is further facilitated by a fall in communication costs, costs related to the fact that the primary centers retain some specific services, such as high finance, so that firms established in secondary centers incur an access cost to these services. The development of new information and communication technologies in the last decades has greatly reduced these costs, without totally suppressing the need to access these services. Cavailhès et al. [8] analyze how the interplay between these various costs and the trade costs of the inter-regional shipment of commodities affects both the inter-regional and the intra-urban location of firms in a two-regions model. They show that under some conditions, polycentric agglomerations outperform monocentric cities on economic grounds : "*the emergence of subcenters within cities is a powerful strategy for large cities to maintain their attractiveness*" [8, p.384]. Absent from this analysis, though, are environmental concerns.

Urban development is associated with numerous damage to the environment : the transport of people and goods contributes to local air pollution and GHG emissions [20][17]; the increase in impervious surfaces alters the functioning of water ecosystems [25]; land fragmentation is detrimental to biodiversity [26]; etc. In this paper, we focus on two of the most pressing issues that are directly affected by the urban structure : the conversion of surrounding agricultural and natural land and the emission of GHG from the transport of people.

Indeed, urban spread, whether continuous or leagfrogging, implies high rates of conversion of agro-forested or natural land into developed land. Ahearn et al. [2] note that "*in large part, this new use of previously undeveloped land is for rural residences, often times on the fringe of urban areas, and often times with large lot sizes*". These large peripherical residential lots are explained by the fundamental trade-off of urban economics, between cost of land and cost of commuting to the central business district, or Clark's Law on density gradients [10]. These mechanisms operate in an actual world that is heterogenous, with natural or administrative boundaries and zoning, and positive or negative amenities. Urban growth boundaries that exist in many U.S. metropolises or greenbelts of U.K. cities constitute spatial discontinuities : before and beyond, the lot sizes are different, due to different supplies of urban public goods, zoning, etc. Instead of the negative exponential function [10], we prefer to use a non-smooth lot size gradient between urban and peri-urban areas. In France, for instance, the lot size of single-detached houses increases from 400 m^2 downtown to 600 m^2 in the suburbs and 900-1000 m^2 in the peri-urban belt[1]. The administrative limits create breaks, which may be due to a discontinuity in local public goods availability: in the city, inhabitants enjoy a lot of urban public goods (urban transport system, high-standard schools, etc.) that are not -or less- available in peri-urban areas.

The pressing importance of the second environmental variable we study is illustrated by the following quote from the former Executive Secretary of the United Nation Framework Convention on Climate Change : "*given the role that transport plays in causing greenhouse gas emissions, any serious action on climate change will zoom in on the transport sector*"[2]. Commuters are the main contributors to GHG emissions by the transport of people [13], and even if substantial reductions in polluting emissions might be warranted by technological innovation [20], these reductions will not suffice to stabilize the contribution of the transport sector to GHG emissions [12]. A large empirical literature is devoted to analyzing the impact of city size and structure on GHG emissions, via commuting [4, 20, 5, 17]. Among the theoretical contributions, Gaigné et al. [13] investigate the relevance of city compactness - understood as high-density urban areas - as a way to mitigate GHG emissions from the inter-regional shipping of commodities and the intra-regional commuting of workers. On the one hand, agglomeration in one region reduces the level of pollution from commodity shipping between regions; on the other hand, it increases the amount of commuting within the only metropolis, hence the associated polluting emissions. The authors advocate the combination of a density-increasing policy and of a policy encouraging polycentrism in order to achieve the best environmental outcome. Given our focus on a single metropolis, we analyse the GHG emissions from commuting only.

In this paper, we build on [8] and [13] to propose an investigation of the environmental performance of a metropolis made of a primary compact city surrounded by a residential peri-urban belt (where density is lower) and secondary cities and their peri-urban belts. More precisely, we look at how the degree of polycentrism, that is the share of inhabitants settled in the secondary centers, impact on both environmental variables of interest. We focus on this urban structure, leaving inter-regional trade issues aside, and consider two environmental impacts of urban development. We consider different lot sizes in the primary and secondary cities and in the peri-urban belts, to capture the stylized fact that lot sizes vary according to the location. In a second step, we study the efficient management of GHG emissions and undeveloped land preservation at the agglomeration level, by introducing environmental policies in this urban economics framework.

We describe our modeling strategy in Section 2 and derive the decentralized equilibrium in Section 3. Section 4 analyses the environmental outcomes of the equilibrium urban structure. In section 5 we discuss various policy instruments to ensure compliance with an exogenous GHG target. Section 6 concludes.

2. The Model

(i) The spatial structure. We consider a one-dimensional metropolis with mobile workers, one sector and two primary goods, labor and land. This metropolis is made of three *urban areas.* Its centre is a punctiform *central business district* (CBD); two punctiform *secondary business districts* (SBDs) - if any - are located towards the right and the left of the CBD. Jobs are located in the CBD and the SBDs. Workers are housed in *cities* that spread around the CBD and SBDs, and in *peri-urban belts* - if any - beyond. The settlement is

[1] Authors' calculation from the Housing surveys by the INSEE.

[2] Yvo de Boer, Speech to the Ministerial Conference on global Environment and Energy in Transport, 15 January 2009.

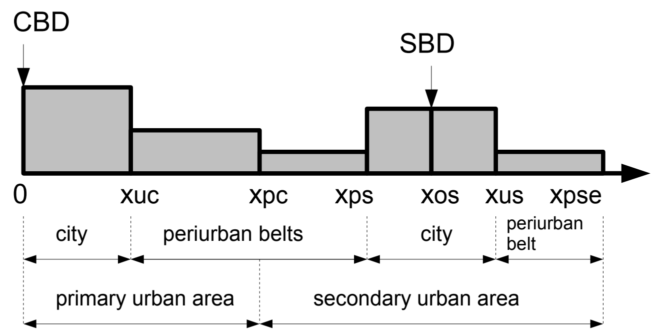

Figure 1: The metropolis

dense in cities, and scattered in the peri-urban belts. Without loss of generality, we focus on the right-hand side (RHS) of the metropolis (see Figure 1). Hereafter, subscript c refers to the CBD and subscript s to the SBD, while u and p denote, respectively, city and peri-urban belts. $x = 0$ is the center of the metropolis, x_{uc} the eastern limit of the city of the primary urban area and x_{pc} the eastern limit of the peri-urban belt of this primary urban area. Around the SBD (x_{os}) lies a city between x_{ps} and x_{us} surrounded by peri-urban belts. The eastern limit of the metropolis is x_{pse}. We denote $X_{uc} = [0, x_{uc}]$, $X_{pc} = [x_{uc}, x_{pc}]$, $X^L_{ps} = [x_{pc}, x_{ps}]$, $X_{us} = [x_{ps}, x_{us}]$ and $X^R_{ps} = [x_{us}, x_{pse}]$ the various segments of the metropolis.

(ii) Firms. Let M be the total number of workers and N the total number of identical firms. Technology in manufacturing is such that producing $Q(k)$ units of the composite good requires a given number ϕ of labor units. Firms do not consume land and are free to locate in either the CBD or the SBD. They pay a wage w_j, $j \in \{c, s\}$ depending on which business district they are settled in. To simplify notations, without loss of generality we assume $M = 1$. The profit of the CBD firms is Π_c, and Π_s the profit of the SBD firms. The latters bear a fixed communication cost $K > 0$ reflecting the fact that some high standard services or facilities (such as banking, airports, etc.) are only available in the CBD : firms located in the SBD have to visit those services periodically, at a cost. Profit functions for a firm k are set as follows, assuming that, within the metropolis, the output price does not vary and the cost of shipping the good is nul :

$$\Pi_c(k) = P_f Q(k) - \phi w_c, \tag{1}$$

$$\Pi_s(k) = P_f Q(k) - \phi w_s - K, \tag{2}$$

where P_f denotes the output price and $Q(k)$ the quantity of output. Since both types of firms face the same demand function, setting the profits to zero, we obtain the following equilibrium condition :

$$w_c - w_s = \frac{K}{\phi} \tag{3}$$

Hence, the equilibrium wage wedge increases with the communication costs faced by firms in the SBD (Appendix 4 illustrates this difference in the case of the metropolis of Toulouse).

(iii) Households. A proportion α ($\frac{1}{3} \leq \alpha \leq 1$) of households live in the primary urban area, among which $\alpha\beta_1$ live in the city and $\alpha(1-\beta_1)$ live in the peri-urban belt, with $0 < \beta_1 \leq 1$. The secondary urban area also comprises a city, where $(1-\alpha)\beta_2$ households live, and a peri-urban belt, where $(1-\alpha)(1-\beta_2)$ households reside, with $0 < \beta_2 \leq 1$.

Households are assumed to comprise a single worker. They enjoy a utility $U(q_{ij}, h_{ij}) = q_{ij} + v \ln h_{ij}$, $i \in \{u, p\}$ and $j \in \{c, s\}$, through the consumption of two goods : a quantity $q_{ij} > 0$ of an aspatial composite good at unitary price P and a residential good, with lot size $h_{ij}(x)$ and rent $R_j(x)$. The residential lot size depends on which segment of the city households reside in; typically we assume that peri-urban lot size h_{pc} is the same in all peri-urban zones, and that it is higher than urban lot sizes h_{uc} and h_{us}. We do not make a priori assumption on how urban lot sizes compare : in the standard urban economics case, $h_{us} > h_{uc}$ since the rent functions are lower in the secondary centers than in the primary ones (as illustrated in Figure 2). However, the case of $h_{us} < h_{uc}$ may arise in a heterogenous space with externalities (crime rate, pollution, congestion in the primary city, amenities in the secondary city, etc.), or when there exist limits to urban growth of the secondary cities that do not apply to the primary one. Appendix 4 illustrates a secondary urban lot size lower than that of Toulouse, a large and spread metropolis, and its satellites, attractive medium-sized cities.

To sum up, we assume the following : $h_{pc} = h_{ps} > h_{uc}, h_{us}$ and without loss of generality, we set $h_{uc} = 1$. With three different lot sizes, we only imperfectly account for the increase in lot size with distance from the city center and the decrease with population observed in the real world. However, this formalisation provides a richer depiction of this reality than the assumption of a fixed lot size over the entire urban system (see Appendix 4).

Households incur a cost of commuting between their residential location and the closest business district where they work, either CBD or SBD. Hence we assume no cross-commuting. However, we consider that commuting costs differ between urban and peri-urban areas because of network congestion in the former. Hence, distances travelled in a city have a unitary cost $t = 1$ while those travelled in a peri-urban area have a cost of $0 < \theta < 1$.

Absentee landowners allocate land to the highest bidder. Noting $\Psi_j(x)$ the bid rent of urban households and $\Phi_j(x)$ the bid rent of peri-urban households, $j \in \{c, s\}$, the rent function is :

$$R_j(x) = \max\{\Psi_j(x), \Phi_j(x), R_A\} \tag{4}$$

The opportunity rent, which is the agricultural land rent, R_A is set equal to 0 for simplicity.

Consequently, households' budget constraint depend on the location of their residence :

$$x \in X_{uc}\ ,\ w_c - x = Pq_{uc}(x) + h_{uc}R_c(x) \tag{5.uc}$$

$$x \in X_{pc}\ ,\ w_c - \theta(x - x_{uc}) - x_{uc} = Pq_{pc}(x) + h_{pc}R_c(x) \tag{5.pc}$$

$$x \in X_{us}\ ,\ w_s - |x_{0s} - x| = Pq_{us}(x) + h_{us}R_s(x) \tag{5.us}$$

$$x \in X_{ps}^L\ ,\ w_s - \theta(x_{ps} - x) - (x_{0s} - x_{ps}) = Pq_{us}(x) + h_{ps}R_s(x) \tag{5.psL}$$

$$x \in X_{ps}^R \, , \, w_s - \theta(x - x_{ps}) - (x_{ps} - x_{0s}) = Pq_{ps}(x) + h_{ps}R_s(x) \tag{5.psR}$$

The spatial equilibrium urban structure is analysed in the following section. To do so, we derive the equilibrium share of population in the primary urban area, α^*, and of urban/peri-urban population β_1^* and β_2^*, and assess how the parameters of the model impact on these equilibrium levels.

3. Equilibrium urban structure

Inside a zone ij the lot size h_{ij} is constant. Consequently, the equilibrium consumption of the aspatial good is the same within each zone. The bid rents are derived by equating the urban costs (housing plus commuting) within each area. Refer to Appendix 1 for the expressions of the bid rents and to Figure 2 for an illustration.

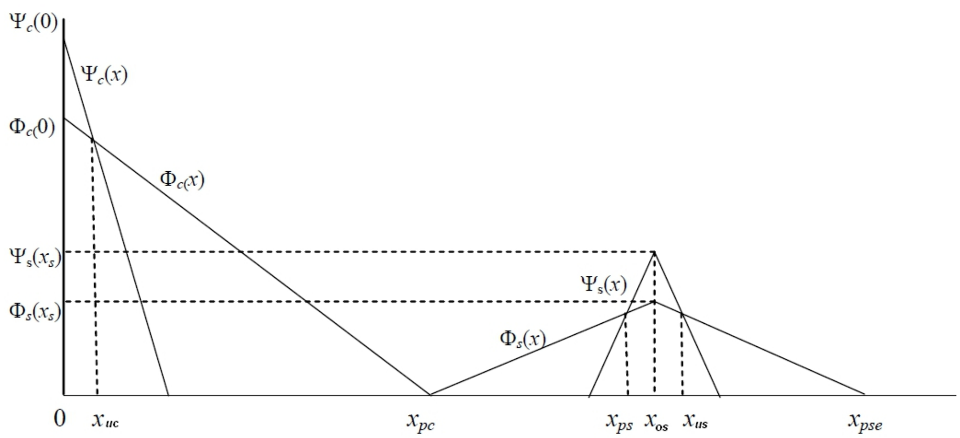

Figure 2: Urban and peri-urban bid rents

The worker located in x_{pc} is indifferent about her workplace. She pays a land rent $R_c(x_{pc}) = R_s(x_{pc}) = R_A = 0$ and she consumes a residential lot of size $h_{pc} = h_{ps}$. Consequently, she consumes the same level of composite good $q(x_{pc})$ whatever her workplace. Equating the budget equations (5.pc) and (5.psL) evaluated at $x = x_{pc}$, we obtain a condition on the wage difference between the CBD and the SBD :

$$w_c - w_s = \theta\left(2x_{pc} - x_{uc} - x_{ps}\right) + x_{uc} - x_{0s} + x_{ps} \tag{5}$$

The wage differential compensates for the gap in commuting costs. Combining Equations (5) and (3), we obtain a condition on the various segment limits for given θ, K and ϕ :

$$\frac{K}{\phi} = \theta\left(2x_{pc} - x_{uc} - x_{ps}\right) + x_{uc} - x_{0s} + x_{ps} \tag{U1}$$

The above expression ensures the equality of utilities between peri-urban households. To complete the spatial equilibrium, we also look for the following conditions :

$$U(q_{uc}, h_{uc}) = U(q_{pc}, h_{pc}) \tag{U2}$$

$$U(q_{us}, h_{us}) = U(q_{ps}, h_{pc}) \tag{U3}$$

From (U1)-(U2)-(U3), we can express the composite good consumption levels as functions of the residential lot sizes, or vice versa : either the residential lot size is exogenous, resulting from cadastral division or urban zoning policy, or the available quantities of the composite good are exogenous, for instance if they are local public goods. We adopt the former vision in the paper.

Solving for α, β_1 and β_2 in (U1)-(U2)-(U3) and replacing the zonal limits by their values (see Appendix 2) we obtain the equilibrium shares of population when $h_{pc} > \max\{1, h_{us}\}$:

$$\alpha^* = \frac{1}{h_{us}+2}[h_{us} + 4\frac{K}{\phi} - 4Pv\bar{V}] \text{ , with } \bar{V} = \frac{\ln(h_{pc})h_{pc}(1-\theta)(h_{us}-1) + \ln(h_{us})(h_{pc}-1)(\theta h_{pc} - h_{us})}{\theta(h_{pc}-1)(h_{pc}-h_{us})} \tag{6}$$

$$\beta_1^*(\alpha) = 1 - \frac{2Pv \ln h_{pc}}{\alpha^* \theta(h_{pc}-1)} \tag{7}$$

$$\beta_2^*(\alpha) = 1 - \frac{Pv \ln \frac{h_{pc}}{h_{us}}}{(1-\alpha^*)\theta(h_{pc}-h_{us})} \tag{8}$$

The following condition must apply to ensure that the primary center attracts at least one third of the population and not more that the total population :

$$\bar{V} - \frac{1}{6}\theta(h_{us}-1) < \frac{K}{\phi} < \frac{1}{2} + \bar{V} \tag{C1}$$

Given the importance of the communication costs in shaping the polycentric nature of the metropolis in our framework, we express the conditions necessary for the validity of $\alpha^* \in [0, 1]$ with respect to these costs. Not surprisingly, they need not be too high nor too low to ensure that the level of polycentrism, expressed as a share of the total population, is consistent. Note that setting $\theta = h_{us} = h_{pc} = 1$ in (U1)-(U2)-(U3), we obtain $\alpha^* = \frac{1}{3} + \frac{4}{3}\frac{K}{\phi}$. Consistent with previous studies [8][13], under the assumption of a constant lot size and of a constant transport rate, the primary city is home to at least a third of the total population, since two subcenters are considered. Furthermore, the higher the communication costs incurred by the secondary center firms, the larger the primary city.

Since $h_{pc} > \max\{1, h_{us}\}$, it can be easily shown that $\beta_1^*(\alpha), \beta_2^*(\alpha) \leq 1$. To ensure that both urban/peri-urban population shares are positive, the following conditions on the equilibrium polycentrism level must hold:

$$0 < \frac{2Pv \ln(h_{pc})}{\theta(h_{pc}-1)} < \alpha^* < 1 - \frac{Pv \ln(h_{pc}/h_{us})}{\theta(h_{pc}-h_{us})} \tag{C2}$$

To ensure that the equilibrium shares of urban/peri-urban populations are consistent, the polycentrism level should not be extreme, nor too low nor too high.

Proposition 1. *The impact of firm-related parameters on the urban form is non ambiguous : the system is more polycentric, the primary urban area is more compact and the secondary ones are more peri-urbanized when the communication costs between the CBD and the SBD are low. The impact of household-related parameters are not so clear-cut : an increase in commuting costs or in the preference for lot size may induce either a higher or a lower polycentrism level, and larger or smaller peri-urban belts, depending on the relative urban and peri-urban lot sizes.*

Proof. The impact of communication costs is straightforward :

$$\frac{\partial \alpha^*(\beta_1^*, \beta_2^*)}{\partial K} = \frac{4/\phi}{2 + h_{us}} > 0 \tag{9}$$

A high wage difference, that is a high communication cost between the primary and secondary centers, tends to be in defavor of polycentrism (remember that a high α^* denotes a low level of polycentrism). Communication costs impact first on the location of firms; but they also have an impact on the equilibrium urban/peri-urban repartition of population : rising communication costs increase the share of primary urban agents, and decreases that of secondary urban agents. Figure 2 provides the intuition behind this mechanism : more households need to accomodated in the primary city and/or the primary peri-urban blet. The bid rent function of the primary city and/or peri-urban belts rises, so that in all cases x_{uc} moves to the right. A similar reasoning applies to explain the decrease in β_2^*.

To assess the sign of the impact of the other parameters of the model on the equilibrium polycentrism level, (C3)-(C5) establish contidions on the ratio of lot size differences.

Commuting costs favor polycentrism if the following applies (see Appendix 3 for full derivation) :

$$\frac{h_{us} - 1}{h_{pc} - 1} < \frac{h_{us} \ln h_{us}}{h_{pc} \ln h_{pc}} \tag{C3}$$

They have both a positive direct impact on $\beta_1^*(\alpha)$ and $\beta_2^*(\alpha)$ and an indirect impact through α^* which sign depends on compliance or not with (C3). When (C3) holds, rising commuting costs increase the share of secondary urban agents and have an impact which sign cannot be derived on the share of primary urban dwellers; if (C3) does not hold they increase the share of primary urban agents, and their aggregate impact on secondary urban agents cannot be signed.

Preference for residential lot size and the commodity price have an impact of the same direction on the level of polycentrism. When $\theta > \frac{h_{us}}{h_{pc}}$, they always always favor polycentrism; otherwise they do so if :

$$\frac{h_{us} - 1}{h_{pc} - 1} > \frac{(h_{us} - \theta h_{pc}) \ln h_{us}}{h_{pc}(1 - \theta) \ln h_{pc}} \tag{C4}$$

As for transport costs, they have both a negative direct impact on $\beta_1^*(\alpha)$ and $\beta_2^*(\alpha)$ and an indirect impact through α^* which sign depends on compliance with (C4) : increasing preference for lot size decreases the share of primary urban dwellers if (C4) does no't hold and decreases that of secondary urban dwellers if it holds. As for above, in the other cases, the aggregate sign cannot be determined.

Finally, we look at the impact of residential lot size on the various components of the urban structure. We can establish that increasing h_{pc} favors polycentrism when the following applies :

$$\frac{h_{us} - 1}{h_{pc} - 1} < \frac{h_{us} \ln h_{us}(h_{pc} - 1) + (h_{us} - 1)(h_{pc} - h_{us})}{(h_{pc}^2 - h_{us}) \ln h_{pc}} \tag{C5}$$

The direct impact of the peri-urban lot size on the shares of urban dwellers can be shown to be positive. Then, as above, the aggregate impact depends on how lot size affects the level of polycentrism and is difficult to sign in some cases.

The case of the secondary urban lot size is more difficult to tract analytically - it can only easily be shown that it has no impact on β_1. □

4. The environmental impact of polycentrism

This section is devoted to analysing under which conditions the polycentric structure may be conducive to less land conversion and aggregate distances travelled. We focus on these two environmental variables as they capture important debates related to urban development and the same features of the urban structures impact on them : residential lot size, peri-urban belt width and polycentrism level. However, as we will show, these environmental features may still arise as conflicting objectives.

4.1. Land conversion

The first environmental criteria we analyse is the level of land conversion, noted S, which is the total width of the (half) city we study:

$$S = x_{pse} = \alpha[\beta_1 + h_{pc}(1-\beta_1)] + (1-\alpha)[h_{us}\beta_2 + h_{pc}(1-\beta_2)] \tag{10}$$

The higher S, the higher the detrimental impact of urban development on surrounding natural and agricultural land.

Proposition 2. *Polycentrism decreases the pressure of the metropolis on land ressources, if the secondary urban lot size is lower than unity.*

Proof. To sign the impact of the level of polycentrism on the total city width we proceed as follows :

$$\frac{dS}{d\alpha} = \frac{\partial S}{\partial \alpha} + \frac{\partial S}{\partial \beta_1}\frac{\partial \beta_1^*}{\partial \alpha} + \frac{\partial L}{\partial \beta_2}\frac{\partial \beta_2^*}{\partial \alpha} \tag{11}$$

that can be rearranged into :

$$\frac{dS}{d\alpha} = (h_{pc} - h_{us})\left(\beta_2^* - (1-\alpha)\frac{\partial \beta_2^*}{\partial \alpha}\right) - (h_{pc} - 1)\left(\beta_1^* + \alpha\frac{\partial \beta_2^*}{\partial \alpha}\right) \tag{12}$$

The above expression is positive, meaning that polycentricy reduces land conversion, if the following applies :

$$\frac{h_{pc} - h_{us}}{h_{pc} - 1} > 1 \Leftrightarrow h_{us} < 1 \tag{C6}$$

since it is easy to show that $\beta_2^* - (1-\alpha)\frac{\partial \beta_2^*}{\partial \alpha} = 1$ and $\beta_1^* + \alpha\frac{\partial \beta_1^*}{\partial \alpha} = 1$. □

The impact of polycentrism on land ressources depends on the relative difference in urban/peri-urban lot sizes : due to the assumptions that $h_{ps} = h_{pc}$ and $h_{us} = 1$, this amounts to comparing h_{us} to 1. Monocentrism entails more land conversion when (C6) holds, that is when the lot size is smaller in the secondary city than in the primary one.

Consequently, any alteration that increases the monocentric structure of the metropolis will be in favor of less land consumed when (C6) does not apply : higher communication costs, higher transport costs (if (C3) doesn't apply), and a lower preference for lot size (if (C4) doesn't apply). Conversely, if (C3)-(C4) and (C6) apply, less land consumed is obtained by favoring a more polycentric structure, through reduced communication costs, lower transport costs and a higher preference for lot size.

4.2. Commuting distances

The aggregate length of commuting L is the second environmental variable we study. Through this variable we capture the impact in terms of GHG emissions of the urban form. Hence we assume that there is a fixed linear relation between the distance travelled and the level of emission : we abstain from the consideration of the effect of congestion on the intensity of emissions, for instance.

$$L = 2\sum_i \sum_j \int_{x \in X_{ji}} \frac{1}{h_{ji}} x\, dx = \frac{h_{pc}}{4} - \frac{h_{pc} - h_{us}}{4}(1-\alpha)^2 \beta_2 - \frac{h_{pc} - 1}{4} \alpha\beta_1 (2 - \alpha\beta_1) \tag{13}$$

Proposition 3. *Increasing the level of polycentrism may induce a higher or a lower aggregate distance travelled by commuters, depending on the relative residential lot sizes.*

Proof. To study the impact of city structure on aggregate distance travelled, we consider the following :

$$\frac{dL}{d\alpha} = \frac{\partial L}{\partial \alpha} + \frac{\partial L}{\partial \beta_1}\frac{\partial \beta_1^*}{\partial \alpha} + \frac{\partial L}{\partial \beta_2}\frac{\partial \beta_2^*}{\partial \alpha} \tag{14}$$

Rearranging the above terms, accounting for the fact that $\beta_2^* - (1-\alpha)\frac{\partial \beta_2^*}{\partial \alpha} = 1$ and $\beta_1^* + \alpha \frac{\partial \beta_1^*}{\partial \alpha} = 1$, and replacing the β_i^* by their value in the remaining expression, we obtain :

$$\frac{1}{2}\frac{dL}{d\alpha} = (1-\alpha)(1-h_{us}) - 2\frac{pv}{\theta}[2\ln h_{pc} - \ln h_{us}] \tag{15}$$

If $h_{us} > 1$, monocentrism should increase distances travelled if $\alpha > 1 + 2\frac{Pv}{\theta(h_{us}-1)}[2\ln h_{pc} - \ln h_{us}] > 1$: this is not possible by definition of α. Monocentrism always decreases distances travelled.

If $h_{us} < 1$, monocentrism increases distances travelled if $\alpha < \bar{\alpha} = 1 - 2\frac{Pv}{\theta(1-h_{us})}[2\ln h_{pc} - \ln h_{us}]$. In other words, if the monocentrism level is low enough, reducing distances travelled is achieved by tending towards a more polycentric urban structure. Further note that $\bar{\alpha} > 0$ if $1 - h_{us} > \frac{2Pv}{\theta}[2\ln h_{pc} - \ln h_{us}]$: h_{us} has to be sufficiently smaller than 1 to ensure that the condition $0 < \alpha < \bar{\alpha}$ is achievable.

□

As for land conversion, the relative residential lot size difference plays a major role in assessing whether monocentrism or polycentrism encourages less kilometers travelled. Then again, any alteration of the exogenous parameters that impact on the urban structure can play in favor or in defavor of an environmental improvement.

4.3. The possibility of conflicting environmental objectives

Proposition 4. *Depending on the relative values of the lot sizes in the various segments of the metropolis, the impact of the urban structure on GHG emissions and land conversion can be characterized by three cases only : (i) polycentrism as the win-win solution, (ii) monocentrism as the win-win solution and (iii) polycentrism as a land preserving solution, at the expense of increased GHG emissions.*

Proof. Drawing from Propositions 2 and 3, the impact of the metropolis on the two environmental variables of interest can be assessed through the difference in urban residential lot sizes.

- for $1 - h_{us} < 0$ we have shown that $\partial S/\partial\alpha < 0$ and $\partial L/\partial\alpha < 0$: monocentrism is the win win solution (case A);
- for $0 < 1 - h_{us} < \bar{\alpha}$ we have shown that $\partial S/\partial\alpha > 0$ and $\partial L/\partial\alpha < 0$: polycentrism reduces land conversion but increases GHG emissions (case B);
- for $1 - h_{us} > \bar{\alpha}$ we have shown that $\partial S/\partial\alpha > 0$ and that $\partial L/\partial\alpha > 0$ if $\alpha < \bar{\alpha}$: polycentrism may appear arise as the win win solution (case C).

□

Both cases A and C are exemples of win-win situations where decreasing the distances travelled entails less land consumed. However the implication in terms of urban structure is different : in case A a more monocentric metropolis is the environmentally-friendly structure, while in case C, the polycentric metropolis is the sustainable solution. The mixed case B implies conflicting policy prescriptions in terms of urban structure to manage either S or L : while polycentrism reduces land conversion, it increases GHG emissions.

Figure 3 illustrates the three cases with the following numerical values for the parameters[3] : $p = 1$, $v = 0.1$, $wc = 1$, $w_c - w_s = 0.1$, $\theta = 0.9$ and for A : $h_{us} = 1.2$ and $h_{pc} = 2$, for B : $h_{us} = 0.7$ and $h_{pc} = 2$ and for C : $h_{us} = 0.85$ and $h_{pc} = 1.05$.

[3]The value of v of used in the simulations is lower than in standard empirical urban economics. Indeed, the surface and its exponent v in the utility function apply to the raw plot; while the structure is in the aspatial good because its price is footloose.

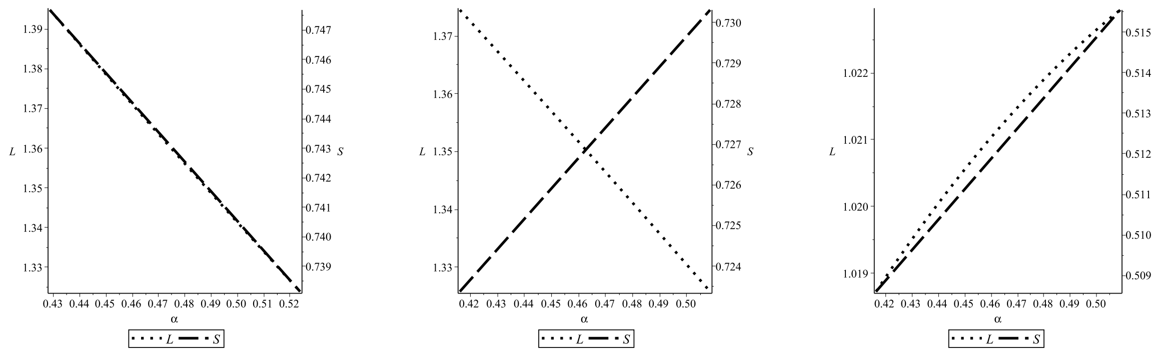

Figure 3 : Kilometers travelled and land conversion as function of the degree of polycentrism for, from left to right, cases A, B and C.

The implications in terms of public policy design are developped in the following section.

5. Public policies in a polycentric metropolis

In this section we address the design of public policies to induce compliance with an exogenously determined environmental target. We assume that the metropolis planner is constrained by an exogenous target on the aggregate level of GHG emissions, decided at a higher level of government. This constraint on GHG emissions is translated in our framework into a constraint on the aggregate commuting distance travelled, implying the same assumption of fixed emission rates as in the previous section. We analyse efficient tax/subsidy schemes that would allow the metropolis planner to comply with this target. Given the interplay between distances travelled, commuting costs and communication costs, we want to assess the effectiveness of two policy bases : commuting and communication costs. Due to the cumbersome nature of the analytical derivation of the tax schemes, we have recourse to numerical simulations. After deriving the efficient schemes, we assess how they impact the metropolis structure and hence the other environmental variable of interest in the model, land conversion. Remember that we look at an isolated metropolis, hence we do not account for how the urban form affects its competitiveness with respect to the rest of the world. Consequently, we are only interested in how different environmental objectives interplay, while Gaigné et al. [13] analyse the links between environmental and economic objectives.

Result 1. *A decrease of a given level of GHG emissions $L(K_{ini}) - \overline{T}$ is achievable by applying a communication tax/subsidy : $t^{com} = K^* - K_{ini}$. The resulting decrease in distances travelled may necessitate a more (cases B and C) or less (case A) polycentric urban structure and entail more (case C) or less (cases A and B) land conversion.*

Proof. We are looking for a value of K^* such that an exogenous GHG target $\overline{T}$ is respected. The simulations are undertaken as follows : for $K = K_{ini}$, we calculate the resulting $L(K_{ini})$. Then we randomly draw values of $\overline{T} < L(K_{ini})$ and derive the values of K^* that would lead the economy to that particular GHG emission target, respecting the definition domains of α^*, β_1^* and β_2^*. ◻

A tax/subsidy on communication costs proves an efficient GHG reduction strategy. Decreasing communication costs induce firms to settle in the SBD, attracting households and conducing to a more polycentric setting. In case C, this translates into lower commuting distances hence lower GHG emissions, but also into lower land conversion. In cases A and B, in order to comply with the GHG reduction target, it is necessary to go towards more monocentric urban structures, and this is achieved by taxing communication costs. However, the GHG reducing policy has opposite effects on land ressources : while it is also environmentally beneficial in case A, it increases land conversion in case B. This is due to the straightforward relation that exists between urban structure and communication costs : they affect positively the polycentrism level, and in an opposite fashion the urban/peri-urban population shares. As a consequence, relying on a communication costs based strategy to manage GHG emissions is a win-win solution in cases A and C, but in case B environmental objectives are still conflicting. This changes when commuting costs are the basis of policy-design.

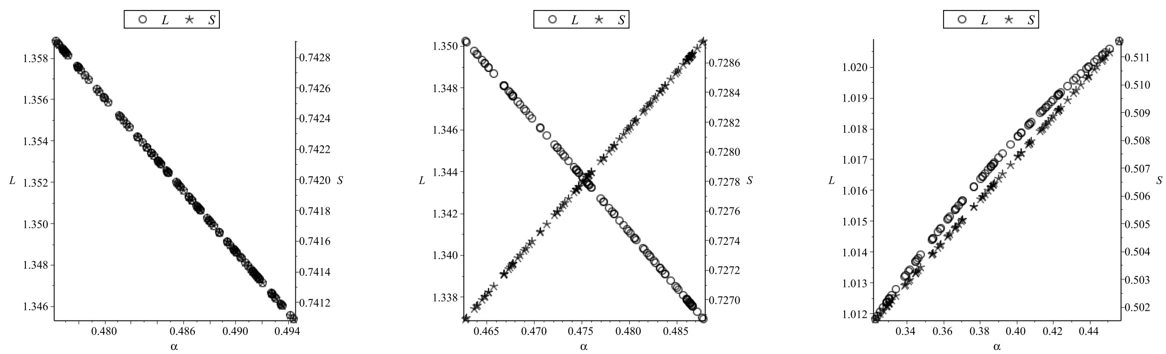

Figure 4 : Kilometers travelled and land conversion as function of the degree of polycentrism for, from left to right, cases A, B and C, with the efficient communication tax/subsidy scheme.

Result 2. *A decrease of a given level of GHG emissions $L(\theta_{ini}) - \overline{T}$ is obtained by imposing a transport tax/subsidy : $t^{tr} = \theta^{*} - \theta_{ini}$. The induced decrease in distance travelled may necessitate either a higher (cases B and C) or a lower (case A) level of polycentrism and it always entails less land conversion.*

Proof. We apply the same simulation strategy as for the transport tax analysis to the resolution of $L(\theta) = \bar{T}$. □

A tax/subsidy on peri-urban commuting costs proves an efficient urban planning strategy - within the restricted framework of our analysis, where the efficiency of a policy instrument is assessed by its capacity to induce a given level of GHG emissions. The way it impacts on the urban structure and, consequently, on land conversion, is different, though, from the communication tax/subsidy case. Indeed, due to the complex link between commuting costs and the two types of population shares, α and the β_is, there is no straightforward relation between how increasing or decreasing transport cost will affect aggregate distances and land conversion. As a matter of fact, cases A and C both remain win-win situations, with the same difference as above : polycentrism as a double environmental improvement for case A, monocentrism as the win-win solution in case A. However, case B is interesting since land conversion and aggregate distances travelled are no longer conflicting objectives when commuting is taxed : the urban structure is affected in such a way that both distances and land conversion are reduced by increasing transport costs - this translates into a more polycentric and more urban metropolis.

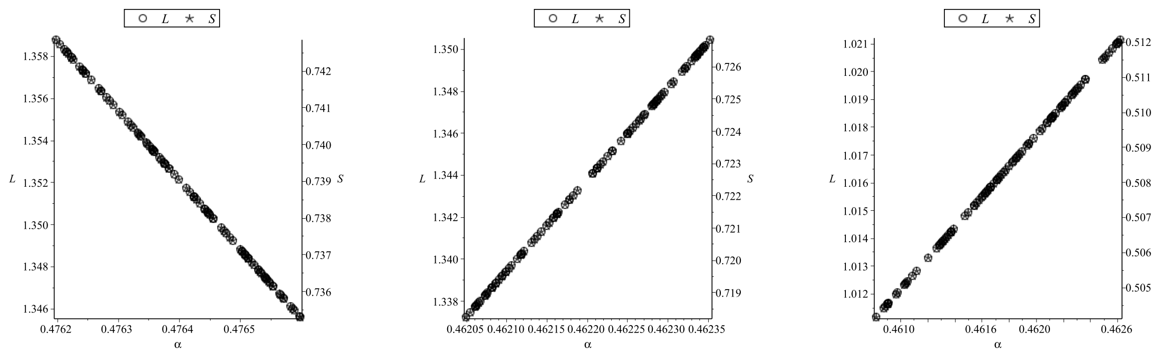

Figure 5 : Kilometers travelled and land conversion as function of the degree of polycentrism for, from left to right, cases A, B and C, with the efficient commuting tax/subsidy scheme.

Hence, the two policy strategies we have chosen to study induce different urban structures, hence different impacts on land conversion, to achieve the same GHG target.

6. Concluding remarks

In this paper we presented an urban economics model that allows for the development of secondary business districts, given a communication cost with the central business district, and of peri-urban belts where the population density is lower than that in compact city centers and where commuting to work is faster (hence its unitary cost is lower). Thus this model relaxes the assumptions that are often relied on of a monocentric city and/or of a unique residential lot size and/of a fixed transport cost. With this model we can analyse two environmental effects of the urban structure : the conversion of agricultural or natural land to urban uses and the emissions of GHG from commuting. The model also allows studying the effects of policy instruments on these two environmental variables : a commuting tax/subsidy and a communication tax/subsidy.

Polycentrism appears and increases when the communication costs decrease, which favors the decentralisation of firms. We show that the urban form has an impact on the two environmental variables we study. We show that there exist three polar cases of the environmental performance of the urban form : monocentrism as the win-win environmental solution, polycentrism as the win-win solution and monocentrism as the way to reduce GHG emissions at the expense of more land consumed. When polycentrism is a competitive economic equilibrium in inter-regional exchanges [8], it may also be environmentally beneficial.

These results suggest that a policy that modifies the structure of the metropolis can be used for environmental purposes; in this paper to limit the emissions of GHG. To restrain commuting-related GHG emissions, transport taxes are the usual suspects. We also analyse the efficiency of an instrument directly targeted at impacting on the development of secondary centers, a tax/subsidy on the communication costs that firms established in the secondary business district have to bear. These two instruments consist in reducing GHG by impacting on the urban form, but they have different impacts on the urban structure, hence on land conversion. The consideration of a budget-balanced scheme targeting both commuting and communication costs is under consideration for future developments.

The environmental attractiveness of the polycentric structure relies on the existence of attractive secondary urban areas, both for the firms (by reducing the commuting costs) and for the consumers. This motivates research in progress in two directions : theoretical to analyse how the differentiated availability of local public goods in the various zones may explain the residential lot size discrepancies; empirical, to estimate this relationship.

These developments also lead to public policy recommandations, in particular, in terms of regional planning. In France, the DATAR seeks to favor an urban network constituted of regional metropolises, with a national and international level of competitiveness, linked to secondary centers structuring rural areas. Such configurations may or not be environmentally sustainable according to the transport and communication costs and the LPG supplies - all of which constitute potential bases for public policies that allow - or not - to conciliate economic and environmental objectives.

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Appendix 1 : Bid rent functions

In each segment of the city, the fixed lot size assumption applies. Then the urban costs (housing plus commuting) are equated among the households in each segment. Consequently, in each segment the slope of the bid rent function is the opposite of the ratio between the commuting cost and the lot size prevaling in the segment.

The bid rent functions for urban and peri-urban households, respectively Ψ and Φ, are derived under the above assumption and accounting for the following conditions : $\Psi_c(x_{uc}) = \Phi_c(x_{uc})$, $\Psi_{sl}(x_{ps}) = \Phi_{sl}(x_{ps})$,

$\Psi_c(x_0) = \Psi_c(x_{pc})$, $\Psi_{sl}(x_{0s}) = \Psi_{sl}(x_{ps})$. c stands for central, s for secondary, l for left-hand side of the secondary city and r for its right-hand side.

$$\Psi_c(x) = x_{uc} + \frac{\theta}{h_{pc}}(x_{pc} - x_{uc}) - x \tag{16}$$

$$\Phi_c(x) = \frac{\theta}{h_{pc}}(x_{pc} - x) \tag{17}$$

$$\Psi_{sl}(x) = \frac{\theta}{h_{pc}}(x_{ps} - x_{pc}) + \frac{1}{h_{us}}(x - x_{ps}) \tag{18}$$

$$\Psi_{sr}(x) = \frac{\theta}{h_{pc}}(x_{ps} - x_{pc}) + \frac{1}{h_{us}}(2x_{0s} - x_{ps} - x) \tag{19}$$

$$\Phi_{sl}(x) = \frac{\theta}{h_{pc}}(x - x_{pc}) \tag{20}$$

$$\Phi_{sr}(x) = \frac{\theta}{h_{pc}}(2x_{0s} - x_{pc} - x) \tag{21}$$

Appendix 2 : Analytical expression of the zonal limits

Given the proportions of households living in each type of zone, and the lenght occupied by their residence, it is easy to provide an analytical definition of the limits of the zones :

$$x_{uc} = \frac{1}{2}\alpha\beta_1$$

$$x_{pc} = x_{uc} + \frac{1}{2}h_{pc}\alpha(1 - \beta_1)$$

$$x_{ps} = x_{pc} + \frac{1}{4}h_{pc}(1 - \alpha)(1 - \beta_2)$$

$$x_{0s} = x_{ps} + \frac{1}{4}h_{us}(1 - \alpha)\beta_2$$

$$x_{us} = x_{0s} + \frac{1}{4}h_{us}(1 - \alpha)\beta_2$$

$$x_{pse} = x_{us} + \frac{1}{4}h_{pc}(1 - \alpha)(1 - \beta_2)$$

Appendix 3 : impact of parameters on the population shares

$$\frac{\partial \alpha^*(\beta_1^*,\beta_2^*)}{\partial \theta} = \frac{4pv[h_{pc}(h_{us}-1)\ln h_{pc} - h_{us}\ln h_{us}(h_{pc}-1)]}{\theta^2(h_{us}+2)(h_{pc}-1)(h_{pc}-h_{us}))} \tag{22}$$

$$\frac{\partial \beta_1^*(\alpha^*,\beta_2^*)}{\partial \theta} = \frac{2pv\ln h_{pc}}{\alpha^*\theta^2(h_{pc}-1)} + \frac{\partial \beta_1^*}{\partial \alpha^*}\frac{\partial \alpha^*}{\partial \theta} \tag{23}$$

$$\frac{\partial \beta_2^*(\alpha^*,\beta_1^*)}{\partial \theta} = \frac{4pv\ln \frac{h_{pc}}{h_{us}}}{(1-\alpha^*)\theta^2(h_{pc}-h_{us})} + \frac{\partial \beta_2^*}{\partial \alpha^*}\frac{\partial \alpha^*}{\partial \theta} \tag{24}$$

$$\frac{\partial \alpha^*(\beta_1^*,\beta_2^*)}{\partial v} = \frac{-4p[\ln h_{pc}(h_{us}-1)h_{pc}(1-\theta) + \ln h_{us}(h_{pc}-1)(\theta h_{pc}-h_{us})]}{\theta(h_{us}+2)(h_{pc}-1)(h_{pc}-h_{us}))} \tag{25}$$

$$\frac{\partial \beta_1^*(\alpha^*,\beta_2^*)}{\partial v} = \frac{-2p\ln h_{pc}}{\alpha^*\theta(h_{pc}-1)} + \frac{\partial \beta_1^*}{\partial \alpha^*}\frac{\partial \alpha^*}{\partial \theta} \tag{26}$$

$$\frac{\partial \beta_2^*(\alpha^*,\beta_1^*)}{\partial v} = \frac{-4p\ln \frac{h_{pc}}{h_{us}}}{(1-\alpha^*)\theta(h_{pc}-h_{us})} + \frac{\partial \beta_2^*}{\partial \alpha^*}\frac{\partial \alpha^*}{\partial \theta} \tag{27}$$

Appendix 4. Stylized facts from France

As usual in urban economics, the outcomes of the foregoing model have been obtained at the cost of many simplifying assumptions. We have to assess the relevance of this model vis-à-vis the actual world. We present here, with empirical data from the French context, stylized facts that illustrate some theoretical assumptions (existence of peri-urban belts, absence of cross-commuting, variations in lot size), and some results that illuminate the main contrasting situations regarding the environnemental outcomes of the model.

As in many developed countries, the French urban structure is polycentric. The case of Toulouse and its satellites illustrates this pattern (see Figure 6). Toulouse, with more than 500,000 jobs and 1.2 million inhabitants is the fifth French urban area [21]. The city accommodates an international airport, a well-known university, high-tech industries and businesses (Airbus, banking, etc.). It is surrounded by satellites, medium-sized urban areas[4] that count around 75,000 people: Albi, Montauban, Auch, etc. Another key assumption of the model is no cross-commuting between the CBD and the SBDs. Daily commuting to Toulouse from the

[4] In the 2010 statistical zoning of aires urbaines, a French large or medium urban area is a densely built-up “pôle urbain” (city-center +suburbs) offering more than 5,000 jobs, and a peri-urban belt made up of communes where the built-up area is not adjacent to the pôle urbain (separated by agriculture, forests, etc.), and from which 40% or more of the working population commutes daily to another commune, generally to the "pôle urbain".

satellite urban areas is rare: the round-trip from the town hall of Albi to the town hall of Toulouse is 134 minutes (non-rush periods). Finally, firms of the satellites cities use the upper services located in Toulouse, bearing a communication cost, another key assumption of the model.

Regarding the urban structure, our modeling framework does not assume any geographical scale of analysis: scales of CBD/SBD interactions that differ from the Toulouse case are relevant within the framework of this model, provided that the SBDs are not to far from the CBD (so that SBDs' firms can interact with CBD's services) but far enough to exclude cross-commuting by workers. This situation occurs between medium-sized urban areas (several hundreds ot thousand inhabitants) and smaller satellite towns (several tens of thousands inhabitants). To illutrate this case, we use the example of Caen, a medium-sized metropolis (400,000 inhabitants), surrounded by urban areas that are smaller (40,000 inhabitants or so: Bayeux, St Lo, Vire, Flers, Lisieux, Dives-sur-mer).

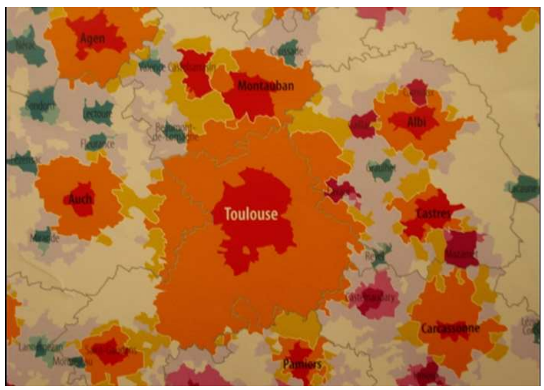

Figure 6 : The metropolis of Toulouse

In urban economics, it is usual to say that the lot size increases in the distance from the CBD, due to the trade off between land cost and commuting cost. We slightly modify this mechanism by assuming that this change in distance occurs in stages. The situation around Toulouse is illustrated by Table 1[5] : given the administrative borders, the mean lot size of single-detached houses in central Toulouse is 327 m^2; then in the suburbian communes of the 'pôle urbain' it varies according to the distance (from less than 20 minutes to more than 30 minutes) between 900 and 1,200 m^2, leading to a large mean lot size for all the communes of the 'pôle urbain' (the city of the model): 1,013 m^2. In the peri-urban belt, the lot sizes fluctuate around 2,000 m^2, a much higher level than in the pôle urbain, that is quite steady. Our assumption of an evolution in plateaus of the lot sizes is quite realistic regarding the suburbs and the peri-urban belt. Another break occurs between the inner city (300 m^2) and its suburbs (around 1,000 m^2); however the model would be untractable with three lot sizes in the primary urban area, and three other sizes in the secondary one. The individual data

[5]We use individual economic data from housing surveys conducted by the INSEE (Institut National de la Statistique et des Etudes Economiques) in 1984, 1988, 1992, 1996, 2002, and 2006. We thank the INSEE for providing us computing and technical equipments required for econometric treatments on its secured distant center.

from the housing surveys allows us to calculate that the mean salary in the urban area of Toulouse is 20,074 euros, and 16,664 euros in the satellite urban areas. A salary equation à la Mincer [28] allows estimating the $\frac{K}{\phi}$. We obtain for Toulouse : $w_c = 1298(\pm 900) + w_s (R^2 = 0.45)$. The wage wedge is significant at a 15% threshold, and is in favor of the primary urban area.

	number of obs.	mean lot size (m^2)
city of Toulouse	526	327
suburbs 0-20 mn from center	187	1245
suburbs 20-25 mn from center	357	921
suburbs 25-30 mn from center	385	1200
suburbs > 30 mn from center	312	1227
peri-urban belt < 30 mn	196	1935
peri-urban belt 30-35 mn	113	2435
peri-urban belt 35-40 mn	151	1876
peri-urban belt > 40 mn	100	1909

Table 1 : Residential lot size according to distance to center - Toulouse

Finally, we assume that the commuting cost is lower in the peri-urban belt than in cities. Using the Housing surveys data for all the French large and medium-sized urban areas, we calculate that the commuting speed is 39 km/h in the central city and its suburbs and 49.3 km/h in the peri-urban belt.[6]

For the following observed values of the lot sizes (h_{us}, h_{pc}), the following Corollaries illustrate Propositions 2-4 in the French cases of Caen ($h_{us} = 1.2$, $h_{pc} = 1.76$), Toulouse ($h_{us} = 0.81$, $h_{pc} = 2.16$) and Besançon ($h_{us} = 0.73$, $h_{pc} = 1.07$). Note that in the Toulouse and Besançon cases, the lot size in the secondary 'poles urbains' is much lower than in the 'pole urbain' of the primary city, leading to positive environmental outcomes of polycentrism.

With these values of the parameters, corollaries of Propositions 2, 3 and 4 are:

Corollary 1. *In Caen, monocentrism entails less land conversion : given the lot size differences, reducing sprawl would necessitate a more monocentric structure. Besançon and Toulouse are cases where the reverse applies : reducing the hold on land ressources goes with a more polycentric structure.*

Corollary 2. *Caen and Toulouse is a case where monocentrism entails less kilometers travelled : given the lot size differences, reducing commuting distances would necessitate a more monocentric structure. In Beançon, the reverse applies : polycentrism is compatible with a GHG reduction target.*

Corollary 3. *Caen and Besançon are examples of win-win situations where altering the urban structure induce a decrease in both GHG emissions and land conversion; however in Caen the structure has to be more monocentric, in Besançon polycentrism should be favored. Toulouse illustrates the mixed case where a more monocentric structure is needed to reduce GHG emissions, at the expense of increased land conversion.*

[6]Distances come from the software Odomatrix [23] which computes distances by the road network, expressed in kilometers and minutes during peak and off-peak traffic periods.