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Green Cities? Urbanization, Trade and the Environment

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Urbanization, Trade and the Environment

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ABSTRACT

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This paper establishes a simple theoretical framework which comprises key forces that shape the structure and interrelation of cities to study the interdependencies between urban evolution and the environment. We focus on the potential of the unfettered market forces to economize on emissions. A key finding is that these forces alone may suffice to generate an urban Environmental Kuznets Curve. In particular, reducing trade costs increases per capita incomes and generates a U-shaped evolution of emissions in the process of agglomeration and redispersion. Another key result is that agglomeration per se is typically not a boon for the environment, as total emissions in the total city system are likely to rise.

JEL Classification: F18, Q50, R11, R12

Keywords: city structure, city systems, environmental pollution, global warming, Environmental Kuznets Curve, trade costs, commuting costs, housing

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1 Introduction

Urbanization is rapidly on the rise. The share of the population that lives in urban environments has increased from 37.6% to over 50% just between 1990 and today.[1] Cities are thought to be engines of growth and sources of structural change. They have recently been dubbed the greatest invention of humanity (Glaeser 2011). Is this 'triumph of the city' good or bad for the environment? In the face of global warming, the analysis of the effects of urbanization on the environment is of central sociopolitical relevance and one of the most pressing research questions in (environmental and urban) economics.

One prominent hypothesis holds that urban growth should ultimately be favorable for the environment since living in high density areas goes along with smaller housing lots and apartments and shorter driving distances to workplaces and for shopping (Glaeser 2011). Yet, pointing to the compactness of cities does not settle the issue, since increases in population density very likely go along with bigger cities and more commuting. More fundamentally, the issue necessitates to look at the entire city system and its emergence and at the trade relationship between cities and the associated emissions, not only at one city in isolation (Gaigné, Riou and Thisse 2012). The empirical evidence is inconclusive, too. The trend towards ever higher degrees of urbanization has been paralleled by an equally notorious upward trend in carbon dioxide emissions and other greenhouse gases ever since these have been recorded. However, there are also more benign developments. For example, in New York City, air pollution levels have increased from 1800 to 1940, but this trend has been reversed thereafter (Kahn 2006). The latter example suggests the possibility of an urban Environmental Kuznets Curve (EKC), an inversely U-shaped relationship between development and pollution (Copeland and Taylor 2003; Kahn 2006).

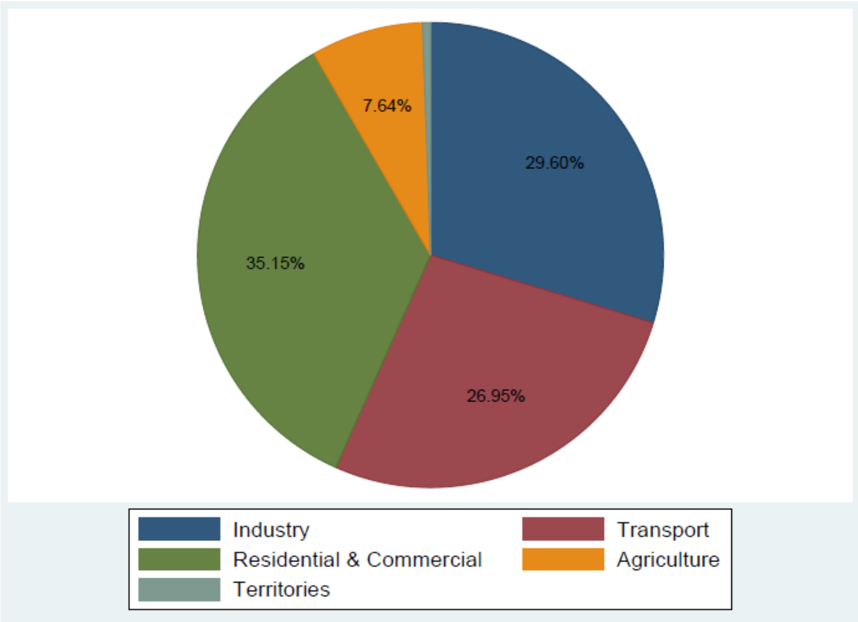
The literature on the environmental effects of urbanization is slim.[2] The contribution of this paper is to establish a simple theoretical framework which comprises key forces that shape the structure and interrelation of cities and which allows us to study fundamental interdependencies between urban evolution and the environment. This research is inspired by the seminal work of Copeland and Taylor (2003) who forcefully showed how fruitful it is to have a unifying model to address the interface between trade and the environment. Just as they faced the question 'is free trade good for the environment?', we ask 'is urbanization good for the environment?'.

[1] Starting with 9% around the year 1300 urbanization has almost doubled in the wake of the Industrial Revolution, and then increased to today's levels. Urban growth is expected to carry on, most spectacularly so in developing country megalopolises. See Bairoch (1988), Asian Development Bank (2012) and World Bank (2009).

[2] A lucid survey of important issues is provided in Kahn and Walsh (2014).

Copeland and Taylor (2003) identified key parameters (factor proportions, in particular) that drive (per capita) incomes and pollution in open economies. Our analysis brings in the urban perspective and traces the effects of parameters that are key for the evolution of city systems, such as the costs of transporting goods between cities, commuting costs within cities and the opportunity cost of land outside city boundaries.

Fig. 1: Emissions by sector, USA 2010 (EPA 2015)



In setting up our framework we make four important choices. First, we build on a version of the urban model of Alonso in which the lot size chosen by households and, hence, the population density in cities, is endogenously determined. This feature is crucial to address a potentially important source of pollution savings. Second, we go beyond a single city and look at an urban system consisting of two cities that trade goods and whose sizes evolve endogenously in response to market size effects established by the new economic geography (Fujita *et al.*, 1999). We consider a core-periphery model with two sectors, a farm sector and a modern sector which produces manufactures, and with mobile skilled workers who exhibit heterogeneous location preferences as in Tabuchi and Thisse (2002) and Murata (2003). Third, our model comprises the key sources of urban pollution, namely environmental externalities associated with housing, commuting, production of industrial and agricultural goods and the trade of goods across cities. Fourth, our analysis deliberately refrains from taking environmental policies and endogenous emission intensities into account. We are fully aware of the importance of government intervention to contain environmental pollution. However, we defer such an application of our framework to future work. This allows us to focus on the potential of unfettered market forces to economize on emissions. More specifically, it allows us to explore whether market forces alone suffice to generate an urban EKC as stipulated in Glaeser (2011).[3]

Even though we keep all specifications as simple as possible, endogenizing the internal city structure and the city interrelations throws up complexities that necessitate the use of numerical simulations at several parts of our analysis. Our calibration uses parameter values such that the greenhouse gas emissions sources witnessed in the USA shown in Fig. 1 are reproduced in the initial equilibrium ('baseline specification'). This illustrates that our model captures the most important pollution sources responsible for climate change.

Our analysis yields the following results. We first consider the case of two cities that maintain trade relations but whose size we exogenously keep at equal (fixed) size. We find that increasing the degree of trade freeness, aggregate population size and the share of expenditures devoted to manufacturing goods and to housing as well as decreasing the costs of commuting and the (exogenously fixed) agricultural land rent outside of cities raises per capita incomes and total emissions at the same time. Hence, no market-induced EKC is implied by any of these parameter changes. Things are different for the composition of the workforce: if the (exogenous) share of skilled workers is increased beginning at low levels, per capita incomes rise and total emissions fall. We also explore whether the city system is greener if we exogenously increase the size of one of the two cities. We find that all emissions in the emerging core increase and that, except for the emissions associated with imports, the opposite holds true in the emerging periphery. Total emissions of the entire city system rise in our baseline specification. Depending on the emission intensities of polluting activities, however, total emissions may also fall.

We then turn to the case where skilled labor is mobile so that the size of the two cities emerges endogenously. As trade freeness is successively increased, the model exhibits the location pattern with dispersion, partial agglomeration and redispersion known from Tabuchi and Thisse (2002). Remarkably, we now find that changes in any of the following four single parameters have the potential to lead to a market-induced EKC: the level of trade freeness, the share of skilled workers in the economy, the budget share devoted to manufactures and agricultural land rent. Consider trade freeness. As stressed in theories of new trade and economic geography and borne out in practice, trade cost reductions are important stimuli for increases in per capita

[3] Shibayama and Fraser (2014) is similar in spirit. They consider a closed economy and highlight nonhomothetic utility and thus abstract both from space and from trade.

incomes. We show that total emissions exhibit an inversely U-shaped behavior in the agglomeration-deglomeration process, because emissions from manufacturing, commuting and housing increase under agglomeration but decrease with redispersion. It is also interesting to note that, across the scenarios without and with mobile skilled labor, agglomeration per se is typically not a boon for the environment, as total emissions in the total city system are likely to rise. We also address the relationship between pollution and welfare and we find that the welfare maximizing allocation need not coincide with the pollution minimizing allocation.

Previous literature. Our paper is related to the following strands of previous research. First, there is a recent literature which has started to explore the nexus between urban growth and the environment both theoretically and empirically. Gaigné, Riou and Thisse (2012) develop a model of an urban system with two cities and extensions around a central business district in order to highlight that a compact city may not necessarily be environmentally-friendly when locations are endogenous and general equilibrium effects are taken into account. Our model is related to their model but differs in two key respects. First, the lot size is fixed in Gaigné et al. (2012) whereas we allow it to be endogenously determined. We see two advantages of our specification: it agrees with empirical evidence and it allows us to study how the compactness of cities responds to key parameters. Second, we follow the new economic geography in considering an increasing returns manufacturing industry which produces a variety of different goods whereas their model has a homogeneous good. Further, we study more pollution sources which makes our framework in principle useful for quantitative analysis of the relation between urbanization and pollution and for detailed policy analysis. Tscharaktschiew and Hirte (2010) develop a spatial general equilibrium model of a single polycentric city and calibrate it to an average German city in order to explore the effects of emission taxes and congestion charges on land-use and emissions. Their focus on a single city allows them to consider numerous urban details which we deliberately abstract from in order to zoom in on an urban system consisting of two cities of endogenous size. Glaeser and Kahn (2010) provide an important empirical study which obtains evidence supporting the view that American urban development is environmentally-friendly in the sense of being energy-efficient and carbon saving. Larson *et al.* (2012) provide related simulation analysis based on an Urban Energy Footprint Model which allows them to capture intricate and often unexpected feedback and rebound effects of energy policies that work through the urban land market.[4]

[4] See also Borck (2014) and Larson and Yezer (2014).

Second, a small literature has addressed the interface between the environment and agglomeration from the point of view of the new economic geography. Calmette and Péchoux (2007) set up a suitable extension of the core-periphery model and study the implementation of an emission quota. They show that the quota reduces the environmental externality in the aggregate but this comes with the unexpected side-effect that agglomeration is induced at higher trade costs, already, which drives up environmental damage. Elbers and Withagen (2004) study the non-cooperative strategic choice of an environmental policy within a similar model and find that this stabilizes the symmetric equilibrium. Lange and Quaas (2007) use a footloose entrepreneur version of the core-periphery model to analyze how the distribution of economic activity in space is affected by local environmental pollution. They find that the extent of environmental damages determines whether symmetry, partial or full agglomeration of economic activity in space obtains. Following standard practice in the new economic geography, these works ignore urban extensions and urban costs altogether, features that we highlight in our analysis. Another difference is that these works do not allow the environmental externalities to be global.

Third, our paper is related to the research on the Environmental Kuznets curve which was initiated with the empirical work by Grossman and Krueger (1993, 1995) and which is surveyed in Dasgupta et al. (2002). A systematic theoretical exploration and synthesis of the foundations of the EKC and its relation to international trade was then provided by Copeland and Taylor (2003). A recent strand of research has begun to explore the EKC from the point of view of cities and urban systems (Kahn 2006; Asian Development Bank 2012).

Finally, there are two recent works which highlight the interface between cities and the environment from altogether different angles. Cruz and Taylor (2013) explore the role of renewable energy sources which differ in the energy intensity for the size and density of urban agglomerations. Desmet and Rossi-Hansberg (2015) set up a dynamic spatial model which allows for trade costs, innovation and technology diffusion over space to study the impact of climate change on the spatial distribution of economic activity, trade and migration patterns as well as productivity and welfare.

The remainder of the paper is organized as follows. Section 2 sets up the model and characterizes the short-run equilibrium, where the allocation of labor across cities is given. Section 3 establishes the determinants of pollution and per capita income and explores the potential of an urban EKC in this short-run equilibrium. It also addresses the question whether big cities are desirable from an environmental point of view. The endogenous formation of the city system in the long-run where skilled labor is mobile across cities is explored in section 4. That section reexamines the determinants of pollution and per capita income and the ensuing potential of an urban EKC under these circumstances. The relationship between environmental pollution and welfare is also explored. Section 5 concludes.

2 The Model

The urban-geography setup. The economy consists of two ex-ante identical cities ($i, j = 1, 2$) with central business districts (CBDs) and spatial extensions as in Alonso (1964) and with inter-city interrelations as in the core-periphery model of Krugman (1991).[5] There are two production sectors, manufacturing indexed by M, and agriculture indexed by A, whose outputs are traded across cities. Trading the agricultural good is costless, while trade of manufactures is subject to iceberg costs. There are L workers with identical preferences and unit labor endowments. The fraction ρ of workers are skilled (denoted S) and λ denotes the share residing in city 1. We take λ as given in the short-run. In the long-run the skilled are mobile between cities and exhibit taste heterogeneity for the two locations as in Tabuchi and Thisse (2002) and Murata (2003). The skilled live around the CBDs and commute to work in manufacturing. Commuting costs are of the iceberg type. This implies that the effective labor supply of a skilled worker shrinks with the distance to the workplace.[6] The fraction $1-\rho$ of workers are (unskilled) farmers (denoted U). They are equally distributed among and immobile across cities and engaged in agricultural production. Farmers live outside the cities' boundaries and don't commute. They collect the land rent in each city.[7] The production of the two types of goods, the transport of goods across cities, commuting and housing consumption are associated with global environmental externalities, greenhouse gas (GHG) emissions, which harm households. We now characterize preferences and the equilibrium within and across cities.

Preferences and demand. Consumers of type $h = S, U$ in city i have utility

$$u_i^h = \mu \ln C_{M,i}^h + \gamma \ln C_{H,i}^h + \left(1-\mu-\gamma\right) \ln C_{A,i}^h - \kappa E^\theta \tag{1}$$

$$C_{M,i}^h = \left[\int_0^{N_i+N_j} c_i^h\left(v\right)^{(\sigma-1)/\sigma} dv \right]^{\sigma/(\sigma-1)} \tag{2}$$

[5] Our framework builds on Tabuchi (1998) and Krugman and Livas Elizondo (1996).
[6] This follows Krugman and Livas Elizondo (1996) and implies that the mass of firms and varieties is larger when economic activity is dispersed rather than agglomerated in space (see Murata and Thisse 2005).
[7] The reason for this assumption is that the land rent does not influence skilled workers' bid rents which makes the internal city equilibrium analytically solvable.

where $0<\mu,\gamma,\mu+\gamma<1$, $\kappa\geq 0$,$\theta>0$ are constants, $C_{M,i}^{h}$ is consumption of a manufacturing composite, $C_{H,i}^{h}$ is consumption of housing (lot size), $C_{A,i}^{h}$ is consumption of agricultural goods, and E is global pollution, the sources of which are described in detail at the end of this section. N_i and N_j denote the masses of varieties, $c_i^h(v)$ is consumption of variety v, and $\sigma>1$ is the elasticity of substitution between any two varieties.

The budget constraint of household h is given by

$$y_i^h = P_{M,i}C_{M,i}^h + P_{H,i}^h(r_i)C_{H,i}^h + C_{A,i}^h \tag{3}$$

$$P_{M,i} = \left[\int_0^{N_i+N_j} p_i(v)^{1-\sigma}\, dv\right]^{1/(1-\sigma)} \tag{4}$$

where y_i^h is the income (net-of-commuting cost if applicable), $P_{M,i}$ is the price index for manufactures and $p_i(v)$ is the consumer price of variety v which includes iceberg trade costs $\tau>1$ when goods are imported from city j. $P_{H,i}^h(r_i)$ is the price of housing at distance r_i from the CBD. The agricultural good is the numéraire. A skilled worker who lives r_i kilometers from the CBD incurs commuting costs which reduce her unit labor endowment by ψr_i, where $0<\psi<1/r_i$. Hence, $y_i^S=(1-\psi r_i)w_i^S$, where w_i^S is the skilled wage. Farmers live outside the city, don't commute, and collect proportionate shares of the city's land rent B_i. Hence, a farmer's income is $y_i^U = w_i^U + b_i$ where w_i^U is the unskilled wage and $b_i \equiv B_i \big/ \left[(1-\rho)L/2\right]$. Utility maximization implies demand functions and indirect utility V_i^h given by:

$$C_{M,i}^h = \frac{\mu y_i^h}{P_{M,i}}, \qquad c_i^h(v) = p_i(v)^{-\sigma} P_{M,i}{}^{\sigma-1}\mu y_i^h \tag{5}$$

$$C_{H,i}^h = \frac{\gamma y_i^h}{P_{H,i}^h(r_i)}, \qquad C_{A,i}^h = (1-\mu-\gamma)y_i^h \tag{6}$$

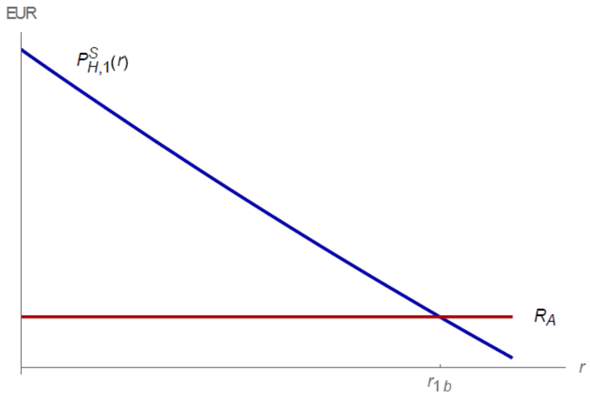
$$V_i^h = \log y_i^h - \mu\log P_{M,i} - \gamma\log P_{H,i}^h(r_i) - \kappa E^\theta \tag{7}$$

City structure. The city is linear and extends from the CBD to r_{ib}, the endogenous city border (we focus on the right side of the city only). Fig.2 depicts this border, the bid rent for land of skilled workers $P_{H,i}^S(r_i)$ (derived below) and the exogenous agricultural land rent, $R_A>0$. By assumption, R_A has to be paid per unit of land outside the city border by all farmers. Hence, farmers live on equal lots of size $\gamma\left(w_i^U + b_i\right)/R_A$ as implied by eq. (6). Using the redefinition $\log v_i^S \equiv V_i^S$ together with $y_i^S = \left(1-\psi r_i\right) w_i^S$ and solving eq. (7) gives a skilled workers' bid rent, the maximum amount a skilled worker living r_i km from the CBD would pay per unit of land:

$$P_{H,i}^S\left(r_i\right) = e^{-\kappa E^\theta/\gamma} P_{M,i}^{\ -\mu/\gamma} \left(v_i^S\right)^{-1/\gamma} \left[\left(1-\psi r_i\right) w_i^S\right]^{1/\gamma} \qquad (8)$$

This bid rent declines with distance from the CBD to compensate for higher commuting costs.

Fig. 2: Intra-city equilibrium, city 1



The city equilibrium is defined by two conditions which determine the spatial equilibrium value of indirect utility for the skilled v_i^S and the city border r_{ib} conditional on R_A and on skilled wages w_i^S, the manufacturing price index $P_{M,i}$, global environmental externalities E and the number of skilled workers in city i, $L_i^S = \lambda\rho L$, all of which are determined in the inter-city equilibrium (which we characterize in section 4):

$$P_{H,i}^S\left(r_{ib}\right) = R_A \quad \Rightarrow \quad e^{-\kappa E^\theta/\gamma} P_{M,i}^{\ -\mu/\gamma} \left(v_i^S\right)^{-1/\gamma} \left[\left(1-\psi r_{ib}\right) w_i^S\right]^{1/\gamma} = R_A \qquad (9)$$

$$L_i^S = \int_0^{r_{ib}} \frac{1}{C_{H,i}^S} dr_i = \frac{e^{-\kappa E^\theta/\gamma} P_{M,i}^{\ -\mu/\gamma} \left(v_i^S\right)^{-1/\gamma} \left[\left(w_i^S\right)^{1/\gamma} - \left[\left(1-\psi r_{ib}\right) w_i^S\right]^{1/\gamma}\right]}{\psi w_i^S} \qquad (10)$$

Eq. (9) states that at the city border, the bid rent of the skilled workers equals the agricultural rent R_A. Eq. (10) says that, given their housing demands, the skilled workers fit into the area between the CBD and r_{ib}. Solving these two equations gives

$$v_i^S = e^{-\kappa E^\theta} \cdot \frac{w_i^S}{P_{M,i}{}^\mu P_{U,i}{}^\gamma} \tag{11}$$

$$r_{ib} = \frac{1}{\psi}\left[1-\left(\frac{R_A}{P_{U,i}}\right)^\gamma\right] \tag{12}$$

where
$$P_{U,i} \equiv R_A + \psi L_i^S w_i^S \tag{13}$$

is a measure of urban costs which rises with the agricultural land rent and commuting costs and also with the number of skilled workers and the skilled wage, which drive up urban land rent. Utility of skilled workers in city i is increasing in skilled wages but decreasing in pollution, the manufacturing price index and urban costs, summarized by $P_{U,i}$. Eq. (12) reveals the repercussions on city structure. In line with the standard Alonso model, we find that cities expand spatially when agricultural land rent or commuting costs fall, and when the skilled work force and the wage of the skilled rise. In the following, we use $D_i(r_i) \equiv 1/C_{H,i}(r_i)$ to denote the density of skilled workers at distance r_i from the CBD.

Production and short-run inter-city equilibrium. The agricultural good is produced by farmers under perfect competition with a unit labor requirement, $X_i^A = L_i^A$. Since this good is the numéraire, the wage of farmers is equal to one, $w_i^U = 1$. The manufacturing sector uses skilled labor to produce differentiated goods under increasing returns and monopolistic competition. There is a fixed requirement of α units of skilled labor and a variable requirement of β units of skilled labor per unit of output. Total cost for a firm producing variety *v* is:

$$TC_i(v) = w_i^S\left[\alpha + \beta x_i(v)\right] \tag{14}$$

It is well-established that mill pricing applies in the Dixit-Stiglitz framework. Let $\hat{p}_i(v)$ denote the producer price at mill. Then we can write firm profits as:

$$\pi_i(v) = \left[\hat{p}_i(v) - \beta w_i^S\right] x_i(v) - \alpha w_i^S \tag{15}$$

Market clearing commands that production equals domestic and foreign demand inclusive of the indirect demand associated with the iceberg trade costs,

$$x_i(v) = d_{ii}(v) + \tau d_{ij}(v) \tag{16}$$

where $d_{ii}(v) = \hat{p}_i(v)^{-\sigma} P_{M,i}{}^{\sigma-1}\mu Y_i$ and $d_{ij}(v) = \left(\tau \hat{p}_i(v)\right)^{-\sigma} P_{M,j}{}^{\sigma-1}\mu Y_j$ from eq. (5).

City i's income comprises the land rent and the (net-of-commuting cost) wage incomes of the skilled and unskilled, $Y_i = w_i^S L_{i,eff}^S + (1-\rho) L/2 + B_i$ where $L_{i,eff}^S \equiv \int_0^{r_{ib}} D_i(r_i)(1-\psi r_i) dr_i$ is the effective supply of skilled labor. $L_{i,eff}^S$ falls short of L_i^S because of commuting costs. It is easily shown that $L_{i,eff}^S = \left[1-(R_A / P_{U,i})^{1+\gamma}\right] \cdot P_{U,i} / \left[\psi(1+\gamma) w_i^S\right]$ (see Appendix A1). Since consumers spend the share γ of their incomes on housing, we have $B_i = \gamma Y_i$. Solving for Y_i, city *i* 's income is:

$$Y_i = \frac{1}{1-\gamma}\left[w_i^S L_{i,eff}^S + (1-\rho)\frac{L}{2}\right] = \frac{1}{1-\gamma}\left\{\frac{P_{U,i}}{\psi(1+\gamma)} \cdot \left[1-\left(\frac{R_A}{P_{U,i}}\right)^{1+\gamma}\right] + (1-\rho)\frac{L}{2}\right\} \tag{17}$$

Normalizations. Following Fujita et al. (1999: 54f.) we normalize the units of measurement for output such that the marginal labor requirement satisfies $\beta = (\sigma - 1)/\sigma$ and we set the fixed input requirement at $\alpha = \mu / \sigma$.[8] Profit maximizing producer prices in city i then are

$$\hat{p}_i(v) = w_i^S \tag{18}$$

Imposing the condition of long-run zero profits implies that operating profits just equal fixed costs. Using producer prices (18) in eq. (15) entails that the equilibrium output is:

$$x_i(v) = \mu \tag{19}$$

The associated labor input is $l_i(v) = \alpha + \beta x_i(v) = \mu$. Labor market equilibrium requires that labor demand, $N_i l_i = N_i \mu$, is equal to the effective supply of skilled workers, $L_{i,eff}^S$. Hence, the number of firms is given by:

$$N_i = \frac{1}{\mu\psi(1+\gamma)}\left(\frac{P_{U,i}}{w_i^S}\right)\left[1-\left(\frac{R_A}{P_{U,i}}\right)^{1+\gamma}\right] \tag{20}$$

The number of firms feeds into the price index in city i which, using eq. (18), is:

$$P_{M,i} = \left[N_i \left(w_i^S\right)^{1-\sigma} + N_j \phi \left(w_j^S\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}} \tag{21}$$

where $0 \le \phi \equiv \tau^{1-\sigma} \le 1$ is a parameter of trade freeness. Using market clearing (16), demand (5) and pricing (18) we finally obtain two interdependent manufacturing wage equations

[8] This implies that when we change the parameter μ, we also change the fixed cost parameter α, due to our normalization. However, we have performed all ensuing comparative statics exercises also without this normalization and the results are qualitatively the same.

$$w_i^S = \left[Y_i P_{M,i}{}^{\sigma-1} + Y_j \phi P_{M,j}{}^{\sigma-1} \right]^{\frac{1}{\sigma}} \tag{22}$$

which, upon substituting price indices, firm numbers and incomes from (21), (20) and (17), implicitly pin down the wages of the skilled in the two cities, w_1^S and w_2^S, and then all other endogenous variables in the short-run equilibrium, where λ is given.

3 The city system and pollution in the short-run

This section characterizes the sources of pollution and studies their determinants in a system of two trading cities of exogenously given sizes, i.e. where λ is given.

3.1 Pollution

Global pollution E is due to local emissions E_i and E_j and takes the form

$$E = E_i + E_j \tag{23}$$

We consider five pollution sources. There are emissions from the production of manufacturing and agricultural goods. Intra-city commuting and shipping of goods across cities produces emissions from transport by cars, trucks etc. Finally, housing produces emissions from energy use due to electricity, heating and air conditioning. Total pollution generated in city i is:

$$E_i = \delta_1 X_i + \delta_2 X_i^A + \delta_3 \Psi_i + \delta_4 T_i + \delta_5 H_i \tag{24}$$

We take the emission intensities $\delta_1, \delta_2, \delta_3, \delta_4, \delta_5 > 0$ as exogenously given and uniform across cities. Since the output per manufacturing firm is constant (by eq. (19)), production of manufacturing goods, $X_i = N_i x_i$, is essentially determined by the number of manufacturing firms (20), which itself depends on the effective supply of skilled labor in the city. Hence, pollution from manufacturing production is a function of local skilled wages and urban costs:

$$X_i = N_i x_i = L_{i,eff}^S = \frac{1}{\psi(1+\gamma)} \cdot \frac{P_{U,i}}{w_i^S} \cdot \left[1 - \left(\frac{R_A}{P_{U,i}} \right)^{1+\gamma} \right] \tag{25}$$

Production of agricultural goods is determined by the local number of unskilled workers:

$$X_i^A = L_i^A = (1-\rho) L / 2 \tag{26}$$

Total commuting distance travelled in city i is $\Psi_i = \int_0^{r_{ib}} r_i D(r_i)\, dr$, hence (see Appendix A1):

$$\Psi_i = \frac{\gamma\left(P_{U,i} - R_A\right) - R_A\left(1 - P_{U,i}{}^{-\gamma} R_A{}^{\gamma}\right)}{(1+\gamma)\psi^2 w_i^S} \tag{27}$$

Pollution from commuting in a city depends on commuting costs, local skilled wages, and urban costs, all of which influence commuting through changes in urban structure.

Following the concept of the ecological footprint (e.g. Aichele and Felbermayr 2012) we count the externalities resulting from the *import of goods* as part of the emissions generated by the importing city. The goods that are transported to city i may consist of manufacturing imports, $N_j \tau d_{ji} = N_j \phi \hat{p}_j^{-\sigma} P_{M,i}^{\sigma-1} \mu Y_i$, and/or of imports of the agricultural good which amount to the excess of demand over local production, $(1-\mu-\gamma)Y_i - (1-\rho)L/2$. Even though trade in the agricultural good is costless, we assume that residents consume locally produced goods unless demand exceeds supply, so there is no trade of agricultural goods in a symmetric equilibrium. Using (18), (20), (21) and $N_i \mu = L_{i,eff}^S$, city *i*'s imports are:

$$T_i = \frac{\left(w_j^S\right)^{-\sigma} L_{j,eff}^S \phi \mu Y_i}{L_{i,eff}^S \left(w_i^S\right)^{1-\sigma} + L_{j,eff}^S \phi \left(w_j^S\right)^{1-\sigma}} + \max\left\{0, (1-\mu-\gamma)Y_i - (1-\rho)\frac{L}{2}\right\} \tag{28}$$

Finally, aggregate housing H_i in city i reflects the aggregate housing consumption of the skilled, $\int_0^{r_{ib}} C_{H,i}^S D_i(r_i)\,dr = r_{ib}$, plus the aggregate housing consumption of the unskilled, $C_{H,i}^U \cdot (1-\rho)L/2$. Substituting the city border, eq. (12), and $C_{H,i}^U$ from eq. (6) and using $b_i \cdot (1-\rho)L/2 = B_i = \gamma Y_i$ as well as (17) we obtain:

$$H_i = \frac{1}{\psi}\left[1 - \left(\frac{R_A}{P_{U,i}}\right)^{\gamma}\right] + \frac{\gamma}{(1-\gamma)R_A}\left[(1-\rho)\frac{L}{2} + \gamma w_i^S L_{i,eff}^S\right] \tag{29}$$

Pollution from housing depends on the incomes of the unskilled and skilled, on agricultural land rent, as well as on commuting costs and urban costs. Higher commuting costs ψ lead to lower housing consumption. The (seemingly counterintuitive) positive relationship between the measure of urban costs $P_{U,i}$ and aggregate housing consumption is explained by the fact that this measure of urban costs rises with wages and the skilled population.

Before proceeding, note that the five sources of local pollution characterized in eqs. (25) - (29) are fully determined by the distribution of skilled workers and the wages of the skilled, w_i^S and w_j^S, which by (22) themselves depend on λ.

3.2 The determinants of pollution and per capita-income

We now explore how the city equilibrium and the pollution sources are affected by key parameters. We consider the short-run equilibrium where skilled labor is immobile across cities and where their share in city 1 is fixed at symmetry, $\lambda = 1/2$. The model then implies that there is balanced intra-industry trade of manufactures and no trade of the agricultural good.[9]

Imposing this symmetry assumption on the wage equations (22) and using (13), (17), (20), and (21) we obtain an equation for the symmetric manufacturing wage $w_i^S = w_j^S = w^S$:

$$\left(R_A + \psi w^S \rho L/2\right)\left[1-\left(\frac{R_A}{R_A + \psi w^S \rho L/2}\right)^{1+\gamma}\right] = \frac{\mu\psi\left(1+\gamma\right)\left(1-\rho\right)L}{\left(1-\mu-\gamma\right)2} \qquad (30)$$

Eq. (30) is a non-linear equation in w^S which has no closed-form solution.[10] However, it is easily shown that it has a unique solution. We resort to numerical analysis to explore how the exogenous parameters affect the various pollution sources, total emissions and per capita incomes in the two cities and the city system. Here and below we use the following baseline parameters: $R_A = 0.275$, $\psi = 0.025$, $\mu = 0.475$, $\gamma = 0.22$, $\rho = 0.5$, $L = 4$, $\sigma = 4$, $\xi = 0.0975$, $\delta_1 = 0.84$, $\delta_2 = 0.81$, $\delta_3 = 1.48$, $\delta_4 = 1.48$ and $\delta_5 = 0.33$.[11]

We define city *i*'s real income per capita y_i^r as the weighted average of the real incomes of the skilled, $y_i^{r,S} = w_i^S / \left(P_{M,i}{}^{\mu} P_{U,i}{}^{\gamma}\right)$, and the unskilled, $y_i^{r,U} = 1/\left(P_{M,i}{}^{\mu} R_A{}^{\gamma}\right)$. Hence, $y_i^r = \left[L_i^S y_i^{r,S} + \left(1-\rho\right) L y_i^{r,U}/2\right] / \left[L_i^S + \left(1-\rho\right) L/2\right]$. Per capita real income in the total city system is $y^r = \left[L_i^S y_i^{r,S} + L_j^S y_j^{r,S} + \left(1-\rho\right) L \left(y_i^{r,U} + y_j^{r,U}\right)/2\right]/L$. Note that $L_i^S = \lambda\rho L = \rho L/2$ in the symmetric equilibrium that we consider here. We summarize our findings in Table 1.

An inspection of this table reveals that a number of key parameters impact on the various pollution sources either in the same qualitative way, or in a neutral way, so that the effect on total emissions (both per city and for the total city system) is unambiguous. Notice that the direct effect of the various parameters and the indirect effect stemming from the wage reaction obtained from eq. (30) is taken into account.

[9] Pflüger (2001) provides an early analysis of the trade-environment interface in the Krugman-Dixit-Stiglitz model.
[10] The urban sector is the reason why there is no closed-form solution. In fact, *without* this sector, the (effective) skilled work force is L_i, the number of firms is $N_i = L_i/\mu$ and we would have $R_A = 0$ and $B_i = 0$, so that the short-run equilibrium characterized in section 2 is identical to Krugman's CP-model. Under these circumstances and the normalization $\rho = \mu$, the wage equation can be solved to yield $w^S = 1$ (see Fujita et al. 1999, chapter 5).
[11] As noted in the Introduction, parameters are chosen to replicate the allocation of greenhouse gas emissions to pollution sources in Fig. 1.

For example, an increase in trade freeness ϕ leads to more trade (imports) and therefore to more emissions. An increase in commuting costs ψ reduces housing consumption, intra-city commuting distances, manufacturing production (through the reduction in effective labor supply) and imports, so that total emissions also fall. An increase in population affects all pollution sources and, hence, total pollution, in a positive way. Changes in the elasticity of substitution, σ, have no direct effect on pollution.

Table 1: Emissions and per capita incomes in the symmetric short-run equilibrium

	ϕ	ψ	R_A	L	ρ	μ	γ	σ
emissions of city i								
manufacturing production	0	-	+	+	+	-	-	0
agricultural production	0	0	0	+	-	0	0	0
intra-city commuting	0	-	-	+	-	+	+	0
housing	0	-	-	+	-	+	+	0
imports	+	-	+	+	+	-	-	0
total emissions per city	+	-	-	+	-	+	+	0
overall emissions	+	-	-	+	-	+	+	0
per capita incomes								
city i = city j = total system	+	-	-	+	∩	+	+	-

Note: The table documents the effects of an increase of the respective parameter on emissions and per capita incomes (+ = positive effect; - = negative effect; 0 = no effect; ∩ hump shape (non-monotonic); initial situation is the symmetric equilibrium of the two-city system. All effects are obtained from numerical simulations with parameters at their baseline level described in the text.

The other parameters affect the various pollution sources differently. For example, an increase in the share of the skilled population ρ raises manufacturing production and imports, but reduces pollution from agricultural production, intra-city commuting and housing. These latter forces dominate in our baseline scenario, so that emissions fall. The same holds true for an increase of R_A. The impact of both the parameter μ and the parameter γ is just the opposite. Apart from these differences, table 1 reveals a striking regularity between emissions and per capita incomes that we summarize in

Result 1 (pollution and per capita incomes in symmetric short-run equilibrium). *Consider the symmetric short-run equilibrium ($\lambda = 1/2$). Increases in the parameters ϕ, L, μ, and γ have a positive impact on total emissions and per capita incomes, whilst increases in ψ and R_A have a negative impact on both. Increasing σ reduces per capita incomes but has no impact on emissions. Increasing ρ reduces total emission and increases per capita incomes at low levels of ρ but impacts negatively on both at high levels.*

Importantly, result 1 implies that in this system of symmetric trading cities most parameter changes that induce increases in per capita incomes have a positive impact on total emissions, too. To put it differently, no market-induced Environmental Kuznets Curve is implied by any of these parameter changes. No EKC is borne out by changes in the substitution parameter either, since σ only affects per capita incomes but not emissions. An exception obtains for an increase in ρ which has a non-monotonic effect on per capita incomes but implies that total emissions fall unambiguously. Increasing the share of skilled workers drives down skilled wages, manufacturing prices and urban costs. Our simulations show that the latter two forces dominate at low levels of ρ whereas the fall in wages dominates at high levels. Hence for a range of low values of ρ per capita incomes rise as emissions fall. However, we show in sections 4.2 and 4.3, that, for a number of reasons, an urban EKC may appear in the long-run equilibrium where skilled labor is mobile and the city system evolves endogenously.

3.3 Big versus small cities

So far we have looked at cities of equal size ($\lambda = 1/2$). An important issue is whether big cities are desirable from an environmental point of view: can it be beneficial to shift part of the skilled population such that the city system has a large (core) city and a small peripheral city? This section explores how the various emission sources are affected by shifting λ beyond ½ such that city 1 exogenously becomes the core. Table 2 summarizes our findings.

Table 2: Evolution of emissions in growing/declining cities

	city 1 (emerging core)	city 2	total city system
emissions			
manufacturing production	+	-	-
agricultural production	0	0	0
intra-city commuting	+	-	+
housing	+	-	-
imports	+	+	+
total emissions	+	-	+

Legend: The table documents the effects of an increase in λ beyond ½ such that city i exogenously becomes the core; + : positive effect; - : negative effect; 0 : no effect.

Start by looking at *city 1*. Increasing its skilled population increases commuting distances and, hence, the emissions from commuter transit. Manufacturing production is raised even though the increase in the *effective supply* of skilled labor falls short of the increase in λ since part of this increase is absorbed by commuting costs. Hence, emissions from manufacturing production increase. Emissions from agricultural production are unaffected. Further, the population increase leads to an increase in total housing consumption in city 1, even though individual lot sizes become smaller. Hence, there is an increase in emissions associated with housing. Total emissions from goods transported to city 1 rise. At $\lambda = 1/2$ manufacturing trade is balanced and there is no agricultural trade. When λ increases, the emerging core becomes a net exporter of manufacturing goods and starts importing agricultural goods to keep trade balanced. Hence, city 1's manufacturing imports fall. However, while the value of net imports must equal the value of net exports, the increase in the quantity of agricultural imports exceeds the decrease in the amount of manufacturing imports so that total imports rise.[12] Taking stock of all pollution sources reveals that (except for agricultural production), all emission sources increase in city 1.

By the very nature of the exogenous shock that we analyze in this section, the effects on city 2, the emerging periphery, (typically) go in the opposite direction to those we just described for city 1.[13] The effect on total emissions of both cities taken together crucially depends on whether the emissions are concave, linear or convex in population. For our baseline parameters we find the following. Total emissions from commuting increase when the city system switches from symmetry to partial agglomeration since total commuting distance can be shown to be convex in population. Emissions from housing are lower, however, since housing consumption is concave in the size of the skilled workforce. Similarly, total emissions from manufacturing production across both cities are lower under partial agglomeration: production of each variety is unaffected (by eq. 19), but the number of goods falls as the effective aggregate labor supply of skilled workers falls. Emissions from agricultural production are unchanged. Overall emissions from goods transport increase.[14] Aggregating the emissions from all sources we find that total emissions across the two cities increase with partial agglomeration in our baseline scenario. Hence, we have:

Result 2. *Consider an increase in the share of the skilled in city 1 starting at symmetry ($\lambda = 1/2$). For the baseline parameters we obtain the following. (i) The emerging core has rising emissions from commuting, manufacturing production and housing. Its emissions from goods imports rise, its emissions from agricultural production are unaffected. Total emissions rise. (ii) The city system comprised of the two cities experiences increasing emissions associated with commuting and with imports. Emissions from housing and manufacturing production fall and the emissions from agricultural production remain constant. Total emissions increase in our baseline simulations.*

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[12] This holds true for small increases of $\lambda = 1/2$, starting from symmetry.

[13] An exception is goods transport: when λ rises above 1/2, city 2 – the emerging periphery – imports more manufacturing varieties and its total imports rise as well.

[14] Our findings differ from Gaigné et al. (2012) who find that total transport is (always) lower with agglomeration, since their model has no immobile workers to whom goods have to be shipped in the case of full agglomeration.

The significance of these results derives from the fact that they contradict popular arguments which maintain that living in big cities makes us greener by necessity. In fact, we find that the emerging core has rising emissions and that the emissions in the total city system increase as well. However, we should like to stress that the finding that agglomeration (one big city) produces more emissions than dispersion (two small cities) is not unambiguous: manufacturing production and housing are lower with agglomeration, whilst trade and commuting are higher (table 2), so that the effect of agglomeration on total emissions ultimately depends on the emissions intensities of these various pollution sources.

4 Endogenous city formation and pollution

We have so far addressed a system with two cities open to trade but with fixed population size. This section allows for the endogenous formation of cities.

4.1 Mobility and long-run spatial equilibrium

In the long-run skilled workers are mobile and, by assumption, exhibit heterogeneous location preferences as in Tabuchi and Thisse (2002) and Murata (2003). A skilled worker's utility of living in city i is $v_i^S + \varepsilon_i$, where ε_i is a random utility component which is identically and independently distributed across individuals according to a Gumbel distribution with mean zero and variance $\pi^2\xi^2/6$. The parameter $\xi \geq 0$ characterizes the dispersion of tastes. If ξ goes to zero, people choose their location based on the indirect utility attached to that location, whereas when ξ goes to infinity, they choose their location at random. Following the standards of discrete choice theory, the probability that a skilled worker chooses region i is

$$\text{Prob}_i(\lambda) = \frac{\exp\left[v_i^S(\lambda)/\xi\right]}{\exp\left[v_i^S(\lambda)/\xi\right] + \exp\left[v_j^S(\lambda)/\xi\right]} \tag{31}$$

where v_i^S is given by (11). The change in the skilled population is guided by the law of motion

$$d\lambda/dt = (1-\lambda)\,\text{Prob}_i(\lambda) - \lambda\,\text{Prob}_j(\lambda) \tag{32}$$

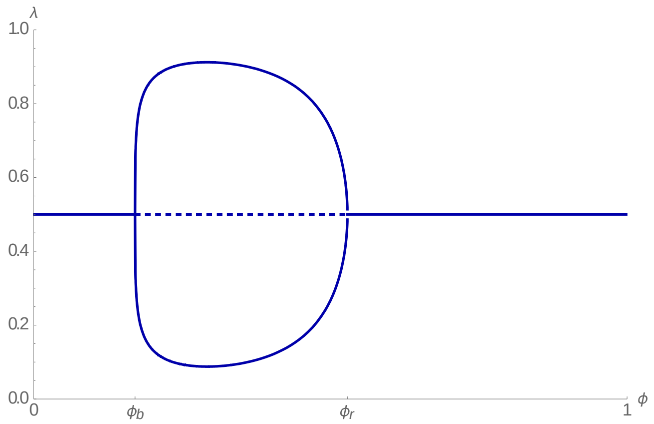
At an interior long-run equilibrium, $d\lambda/dt = 0$. Using (31) the equilibrium condition is

$$\Delta v^S(\lambda) - \xi \log\frac{\lambda}{1-\lambda} = 0 \tag{33}$$

where $\Delta v^S(\lambda) \equiv v_1^S(\lambda) - v_2^S(\lambda)$.

Our model exhibits seven agglomeration and dispersion forces which can be characterized with reference to (33) and indirect utility (11). Consider a symmetric equilibrium ($\lambda = 1/2$) and assume that a small amount $d\lambda$ of skilled workers is shifted from city j to city i. This raises market size and the skilled wage in i due to the demand linkage (market size effect), but it also depresses the skilled wage in i due to increased competition (crowding), as in Krugman (1991). The inflow of skilled workers drives down the manufacturing price level $P_{M,i}$, the supply linkage of the core-periphery model. Urban costs associated with commuting ($P_{U,i}$) act as a dispersion force, just as in Tabuchi (1998). By reducing effective labor supply, iceberg commuting costs have a further dispersive effect. This lowers the mass of firms in agglomerations and, hence, raises the manufacturing price index in city i. This also lowers overall income, and wages in i. Since the last term in (33) is decreasing in λ, taste heterogeneity (expressed by the variance of the preference parameter distribution) is a final dispersion force. Since we address a global externality, greenhouse gas emissions and global warming, environmental pollution plays no role for the economy's bifurcation pattern.[15] Due to the complexity of our model's urban sector which involves an endogenous lot size, no closed form solution can be derived for the bifurcation points.[16] We therefore continue to use numerical simulations to characterize the effects of the various parameters.

Fig 3: Bifurcation diagram



Note: Figure displays the bifurcation diagram for our benchmark parameter values (see section 3.2).

Raising trade freeness ϕ starting from autarky eventually induces agglomeration at ϕ_b, the break point, see figure 3. The taste heterogeneity of workers implies that this agglomeration process is smooth, stops before full agglomeration in one city is attained, and reverses as trade

[15] This is different when environmental externalities are at least partly local, see e.g. Lange and Quaas (2007).
[16] This is because there is no closed-form solution for the skilled wage in the symmetric city system (section 3).

freeness is continuously increased, as in Tabuchi and Thisse (2002). Symmetry is re-established at the redispersion point ϕ_r and continues to be the only spatial equilibrium until all trade costs are eliminated.[17] We summarize this finding in:

Result 3 (symmetry breaking). *Raising trade freeness ϕ successively from 0 to 1 yields an inversely U-shaped curve of stable location equilibria. Agglomeration emerges at the break point ϕ_b and symmetry attains again at the redispersion point, ϕ_r*

We use numerical simulations to describe how the break and redispersion points are affected by parameter changes. Our findings are summarized in:

Result 4 (comparative statics of the bifurcation points). *Using numerical analysis we find: there is less agglomeration (ϕ_b increases and ϕ_r decreases) when, (i) economies of scale decrease (σ rises), (ii) the expenditure share for manufactures μ falls, (iii) commuting costs ψ rise, (iv) taste heterogeneity ξ rises, (v) population size L increases, (vi) the skilled population share ρ rises, or (vii) agricultural land rent R_A falls; (viii) the effect of γ is ambiguous: more agglomeration (ϕ_b decreases and ϕ_r increases) for low values of γ and less agglomeration (ϕ_b increases and ϕ_r decreases) for high values.*

Results 4(i) - 4(iv) accord with previous findings. Reducing the elasticity of substitution σ (an inverse indicator of returns to scale in zero profit equilibrium), and raising the budget share devoted to manufactures (and hence both market size and trade cost savings) enlarges the range of trade costs where agglomeration is a spatial equilibrium, as in Krugman (1991). Increasing commuting costs ψ or the variance of the distribution of the taste parameter ξ, works in favor of dispersion, i.e. it raises the break point and reduces the redispersion point, as found by Tabuchi (1998) and Murata and Thisse (2005) for commuting costs, and by Tabuchi and Thisse (2002) and Murata (2003) for taste heterogeneity.

Results 4(v) - 4(viii) are novel and therefore deserve some comments. Increasing L works in favor of dispersion whereas it has no effect on the bifurcation pattern in standard core-periphery models (Fujita et al. 1999; Forslid and Ottaviano 2003; Pflüger 2004). This difference is due the urban extension in our model. Even though several of the agglomeration and dispersion

[17] This depends crucially on the taste heterogeneity of skilled workers. Without taste heterogeneity, we get the same agglomeration pattern as in Tabuchi (1998): dispersion for low or high trade freeness, catastrophic agglomeration with full agglomeration for intermediate values of ϕ. When ξ is very large, we get dispersion for all values of ϕ. Thus, we assume in the following that ξ is neither too small nor too large.

forces are affected by a change in population size (and partly so in opposite directions), the dominant effect is that an increase in L drives up the urban costs associated with a relocation of skilled labor.[18] This can be seen by noting that, at a given wage, $dP_{U,i} / d\lambda = \psi\rho L w_i^S > 0$ from (13). This effect corresponds to the finding in the standard urban model that an increase in population size causes single closed cities to expand spatially and to provide lower utility (e.g. Brueckner 1987). It implies that living in a small city becomes more attractive and more so, the larger total population. Result 4(v) shows that this direct dispersive force dominates even after all further general equilibrium repercussions on wages, prices, incomes, the city border and the amount of commuting have played out.

Increasing the share of the mobile (skilled) population, ρ, reduces the range of trade freeness where agglomeration is stable (result 4(vi)) - similarly to an increase of the overall population. The key mechanism that drives this result is the magnification of urban costs: the response of $P_{U,i}$ to λ is magnified by ρ just as by L (see above).

An increase in the agricultural land rent R_A leads to a larger range of trade freeness where agglomeration is stable (result 4(vii)). While urban costs $P_{U,i}$ rise with R_A, there is no direct effect from R_A on the agglomeration force implied by urban costs (i.e. $dP_{U,i} / d\lambda = \psi\rho L w_i^S$ is only indirectly affected by R_A via the wage). However, an increase in the exogenous land rent forces a city, ceteris paribus, to become smaller, just as in the standard urban model. Hence, there is less commuting and the loss in the effective labor supply that goes along with a relocation of skilled labor must then be smaller. This, in turn, implies that the agglomerative demand linkage (income shift) and supply linkage (trade cost savings) become stronger. Even though the competition effect is also strengthened and there are further general equilibrium effects, the magnification of the agglomeration forces dominates, as result 4(vii) reveals.

The literature usually finds that increasing the budget share devoted to housing γ works in favor of dispersion, i.e. it raises the break point and lowers the redispersion point (see e.g. Tabuchi (1998), Murata and Thisse (2005) and Pflüger and Südekum (2008). Our simulations

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[18] The other effects are the agglomerative supply linkage, ($dP_{M,i} / d\lambda < 0$), which is strengthened because, at given wages, the effective supply of labor $L_{i,eff}^S$ increases when L rises, so that the relocation of firms brings stronger cost savings. From (22) we can conclude that both the demand linkage, $\left(dw_i^S / dY_i\right)\left(dY_i / d\lambda\right) > 0$, and the competition (crowding) effect, $\left(dw_i^S / dP_{M,i}\right)\left(dP_{M,i} / d\lambda\right) < 0$ are also strengthened as L goes up.

show that in our present model this holds true only at high levels of γ whereas the inverse obtains for low levels.

4.2 The evolution of emissions and per capita incomes

We are now in a position to analyze how emissions and per capita incomes are affected by parameter changes when the city system is allowed to evolve endogenously. We characterize the effects assuming that city 1 becomes the core when an agglomerative process unfolds. Graphical illustrations of our numerical results are provided in tables 3, 4 and 5. We highlight the parameters that are particularly prone to exhibit secular changes, namely trade costs, commuting costs and population size. The effects of all other parameters are then discussed more briefly. No matter which parameter is concerned, we will see in the following that any parameter change that induces agglomeration, drives up total emissions of the city system whereas total emissions fall during redispersion, as shown above in Sec. 3.3.

[Table 3 about here]

Trade freeness. Increasing the degree of trade freeness ϕ from autarky to costless trade implies that the city system switches from dispersion to (partial) agglomeration and back to dispersion (see Fig.3 and Table 3). City sizes are equal under dispersion, $r_{1b} = r_{2b}$, but become increasingly different as agglomeration unfolds, $r_{1b} > r_{2b}$. *Real income per capita increases in city 1* for two reasons: falling trade costs imply that real income increases as long as economic activity is dispersed. When agglomeration is induced at the break point there is an additional boost to real income which increases strongly and then falls in the redispersion process. The ongoing reduction in trade costs causes city 1's real income to rise further, however. *City 2's real income per capita* develops in parallel with city 1 when there is symmetry, but exhibits a U-shaped development as agglomeration and redispersion take place. *Per capita income of the total city system* increases throughout the reduction of trade freeness. This reveals that the income losses of the periphery are dominated by income gains of the core. The behavior of real income per capita in the two cities can be traced back to its components. The manufacturing price level $P_{M,i}$ falls in both cities when symmetry is stable, but is inversely U-shaped (U-shaped) in city 1 (city 2) as agglomeration and redispersion occur. Urban costs $P_{U,i}$ and skilled wages w_i^S are only affected when the process of agglomeration and redispersion unfolds: urban costs exhibit an inversely U-shaped behavior in the core city and so do wages, after an initial dip at the break point, whereas the opposite applies for city 2.

Total emissions in both cities rise with ϕ under symmetry. The emissions in the core rise strongly as agglomeration unfolds, but the redispersion of economic activity brings back emissions, whereas city 2 experiences a U-shaped development of emissions. With our baseline parameters the total emissions of the city system increase continuously under dispersion, but exhibit an inversely U-shaped behavior in the agglomeration-deglomeration process. Total emissions reflect the behavior of its components: emissions from manufacturing, commuting and housing are constant in the symmetric allocation but increase as city 1 becomes the core and vice versa. Emissions from the transport of goods increase in both regions and overall. Emissions from the agricultural sector are not affected by trade costs.

Commuting costs. A steady *reduction* of commuting costs ψ induces agglomeration in city 1. This city expands at the bifurcation but it also experiences continuous per capita income growth before and after that. Per capita real income in the emerging periphery grows until the bifurcation occurs where it then strongly falls (see table 3). Overall, there is an expansion of real income per capita in the total city system. Key components of real income evolve as follows. Both the emerging core and the emerging periphery experience a secular fall in urban costs. There is a transitory hike in the city which becomes the core. The manufacturing price index in this city falls steadily, but strongly so at the bifurcation. The periphery experiences a strong increase in manufacturing prices after an initial period of slowly falling prices. Total emissions of the city system increase steadily as commuting costs fall but more strongly so at the bifurcation, which reflects the strong increase of emissions in the emerging core which dominates the decline of emissions in the peripheral city. The strong increase of emissions in the emerging core itself reflects strong increases of emissions from all sources except from agricultural production which is not affected by commuting costs.

Population size. Increasing total population L leads to dispersion of skilled workers (result 4(v)). As shown in table 3, when population increases, per capita real incomes increase, both for skilled and unskilled workers (whether skilled workers are agglomerated or dispersed). While urban costs increase, manufacturing prices fall strongly and skilled wages develop inversely U-shaped (U-shaped) in the core (the periphery). On net, real incomes per capita are increasing. The effects on pollution are straightforward. As population size increases, *total* pollution increases, as the production of goods increases, goods transport increases when industry is dispersed, people have longer commutes, and total housing consumption increases. With agglomeration, goods transport falls (the core imports less with rising population while the periphery imports more, and total imports fall). In summary, total pollution rises with population size. However, this does *not necessarily* imply that *per capita pollution* rises with population size. In our simulations, we find that commuting increases per capita, agricultural production stays constant, and goods transport, housing as well as manufacturing production decrease per capita with rising population.[19] For our benchmark parameters, total emissions per capita rise with rising population size, however.

[Table 4 about here]

Agricultural land rent. The agricultural land rent is an exogenous indicator of the opportunity cost of land. In one interpretation it can thought to be a policy instrument to control the boundaries of cities. Agglomeration is induced when R_A increases (result 4(vii)). Real per capita incomes in both cities fall, and more so in the emerging periphery (see table 4). This finding is due to the fact that higher R_A exerts direct pressure on urban costs (see eq. 13). There are also forces that stabilize real income in the emerging core (higher wages, lower manufacturing prices in the agglomeration process). However, these effects are dominated by the increase in urban costs, and even more so in the emerging periphery. Overall, the income per capita in the total city system falls steadily. Total pollution of the city system falls as R_A increases. This effect is due to decreasing emissions in both cities before the bifurcation takes place and it continues to hold as the steady fall of the periphery's emissions dominate the hike that the emerging core (initially) experiences when agglomeration unfolds. The benign development of emissions is in essence caused by decreasing emissions from housing consumption and commuting associated with smaller and more expensive cities, whereas emissions from manufacturing production and from the transport of goods work in the other direction.

Skilled worker share. Next, consider a *rise* in the share of skilled workers, ρ. This puts pressure on urban costs and induces redispersion of the city system (result 4(vi)). The concomitant change in per capita incomes in the core (periphery) is inversely U-shaped (U-shaped) until the two cities are of equal size and then exhibits an inversely U-shaped pattern (see table 4). The evolution of per capita income in the total city system is also inversely U-shaped. These outcomes reflect a nuanced interaction of components. A higher share of skilled workers implies lower wages both in the core and in the periphery, but also lower manufacturing price indices (reflecting the fact that the number of available varieties rises as ρ is increased) in both locations and falling (rising) urban costs in the core (periphery). Total emissions of the

[19] Goods transport per capita decreases with population size under symmetry, and first increases, then decreases in the range of partial agglomeration.

city system fall when the share of skilled workers rises since the fall of emissions in the emerging core is stronger than the rise of emissions in the periphery. When economic activity is fully dispersed, emissions in both cities fall as ρ is increased. These results are primarily due to lower emissions from transport, lower emissions from housing consumption in the core (which falls as urban costs rise) and due to a strong fall in emissions from agriculture due to the implied fall in the share of unskilled workers.

Budget share of manufacturing. An increase in the budget share of manufacturing boosts the importance of this sector and induces agglomeration (result 4(ii)). Real incomes evolve inversely U-shaped (U-shaped) in the core (periphery). The per capita income in the total city system develops in an inversely U-shaped way (see table 4). Our simulations reveal that skilled wages rise in the core and the periphery and so does the manufacturing price index. Moreover, urban costs rise strongly in the core and fall much less strongly in the periphery. Total emissions in the core (periphery) rise (fall) strongly at the break point and then fall (rise) when redispersion sets in at high values of μ. Overall, total emissions are increasing due to rising emissions from goods transport, production of manufactures and housing consumption and commuting in the core.

[Table 5 about here]

Location preferences. Parameter ξ expresses the dispersion of individual tastes for locations and it may also be interpreted as an inverse measure of labor mobility. Agglomeration is induced when ξ *falls* (result 4(iv)). Real per capita income in the core (periphery) rises (falls) and the effect in the core dominates so that per capita income in the total city system rises (see table 5). Emissions in the two cities and in the overall city system mimic the behavior of per capita income and, hence, also rise.

Elasticity of substitution. A *fall* in the elasticity of substitution σ implies that the economies of scale in manufacturing rise in zero-profit equilibrium and that agglomeration is induced (result 4(i)). Real per capita income in the core (periphery) rises (falls) and real per capita income in the total city system rises, since the effect in the core dominates (see table 5). Our simulation reveals that the fall in the manufacturing price index in the core is key for this result. The core (periphery) experiences increasing (decreasing) wages counteracted by an increase (fall) in urban costs. Total emissions in the emerging core increase in the agglomeration process but fall in the periphery. The first effect is stronger, so that emissions of the city system rise.

The strong rise in emissions in the emerging core are due to higher emissions from commuting, the transport of goods, manufacturing production and from housing.

Budget share of housing. The effect of an increase in the budget share of housing γ on the location pattern is non-monotonic (result 4(viii)). We focus on the case where the level of γ is high enough so that further increases induce dispersion. Then, real incomes per capita rise both in the core and the periphery but more strongly in the former (see table 5). Hence, real income per capita across the two cities is also steadily rising. Emissions are increasing in both cities (except for a dip at the break point in the emerging periphery) and the total city system.

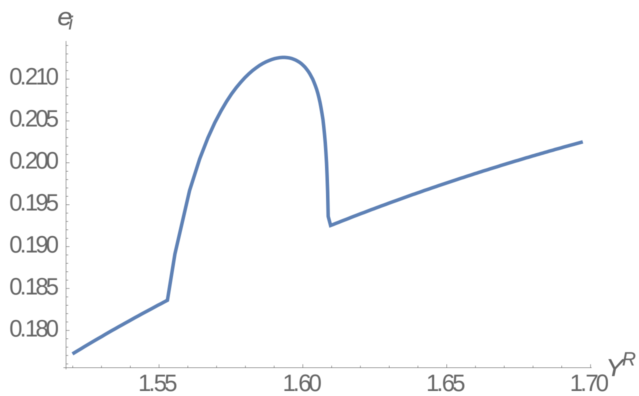
Taking stock of the effects of all parameter changes on total emissions and per capita income in the total city system we have

Result 5 (emissions and per capita incomes). *An increase in any parameter, except for the parameters ϕ, ρ and μ, induces parallel movements in total emissions and per capita incomes in the total city system, either positive (L, γ) or negative (ψ, R_A, ξ, σ). Increasing μ drives up total emissions and may increase or decrease per capita income. Increasing ϕ or ρ implies rising per capita income but falling emissions.*

4.3 The possibility of an urban Environmental Kuznets Curve

The large literature on the Environmental Kuznets Curve (EKC) considers the possibility that emissions might be inversely U-shaped in income. Here, we explore this hypothesis in the light of our model. We highlight the change of the trade freeness parameter ϕ. Fig. 3 shows how *national* real income per capita y^r and total emissions vary with changing trade freeness (ϕ moves from 0 to 1 generating rising incomes).

Fig. 3: An urban EKC with rising trade freeness



As can be seen, a purely market induced urban EKC arises as trade becomes freer over a certain range. The key to this result is the fact that as trade gets freer, national real income steadily rises, but emissions are inversely U-shaped due to the agglomeration and redispersion forces induced by the changing trade freeness. We summarize this finding as:

Result 6 (Urban EKC). *As trade freeness increases, a market-induced urban EKC emerges: total national emissions and national income increase for* $\phi < \phi_b$ *and* $\phi > \phi_r$ *, but emissions are inversely U-shaped in national real income for* $\phi \in [\phi_b, \phi_r]$.

Result 6 is of great significance, as it shows that an EKC may emerge in the city system without any policy intervention. Moreover, this EKC is based on increases in trade freeness which have been a very important driver for the connection of countries, regions and city systems and for the rise of incomes in the last decades, and which have therefore been highlighted by the New Economic Geography (Head and Mayer 2004).

Three further parameter changes have the potential to raise real incomes per capita and lower total emissions at the same time, but matters are more complicated (see table 4). A reduction in the agricultural land rent R_A is associated with increases in real per capita income for a small range of intermediate values of R_A. The connection between emissions and per capita incomes induced by changes in the parameters μ and ρ depends intricately on their starting values and directions, too. Reductions in μ starting at high levels and increases in ρ starting at low levels raise per capita incomes and lower total emissions at the same time. However, if μ is low enough or ρ is high enough, the considered changes affect per capita incomes and total emissions in the same direction.

Result 7. *Reductions in* R_A *starting at intermediate levels, reductions in* μ *starting at high levels and increases in* ρ *starting at low levels raise per capita incomes and lower total emissions at the same time.*

Even though these latter three parameters do not give rise to a full EKC story, their benign effect both on per capita incomes and on emissions makes them elements of explanation for an EKC that build on more than one parameter change. In concluding this section it is important to notice that a market-induced EKC is far more likely to obtain in long-run equilibrium where skilled labor is mobile and the city system evolves endogenously than when the allocation of skilled labor is fixed (as was assumed in section 3).

4.4 Pollution and welfare

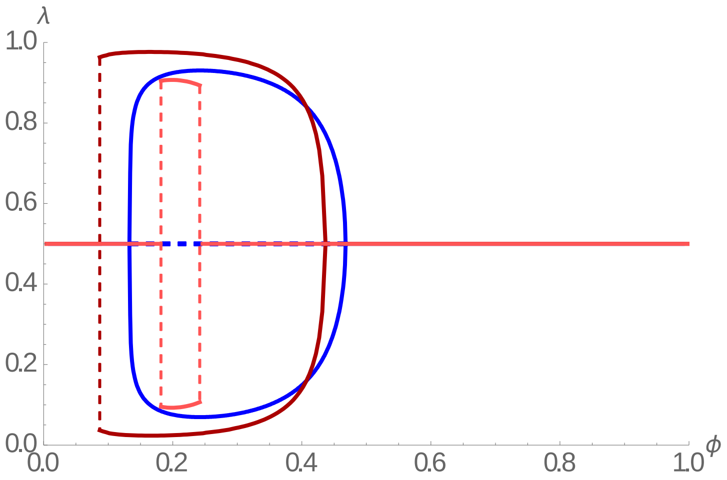
The social aims to keep emissions as low as possible and to maximize social welfare may very well lead to different recommendations concerning the structure of cities (e.g. Gaigné et al. 2012). In this section we explore how the market mechanism compares with the social optimum. Our model contains three potential sources of market failure: prices which differ from marginal costs, pecuniary externalities associated with the mobility of skilled workers in imperfectly competitive goods markets, and environmental externalities. We pursue a second-best approach, where markup prices are taken as given, but where the social planer chooses the allocation of skilled workers so as to maximize a social welfare function. Following Tabuchi and Thisse (2002), we take the unweighted sum of all skilled and unskilled workers' (expected) utility levels as our measure of social welfare:

$$W(\lambda) = \rho L\left\{\lambda v_1^S(\lambda) + (1-\lambda)v_2^S(\lambda) - \xi\left[\lambda \log\lambda + (1-\lambda)\log(1-\lambda)\right]\right\} + (1-\rho)L\left[v_1^U + v_2^U\right] \quad (34)$$

It is obvious from the indirect utility (11) that the comparison of the market equilibrium with the social optimum must strongly depend on the disutility associated with global (greenhouse gas) emissions. We use the parameter κ to highlight several cases. The case $\kappa = 0$ captures the situation where there are no negative environmental externalities. The dark red curve in Fig. 4 depicts the optimal choice of λ by the social planer as trade freeness varies from autarky to no trade costs to contrast it from the blue curve that depicts the location pattern associated with the market equilibrium (derived in section 4.1 and already depicted in Fig 3). The other light red curve shows how the social planer solution evolves as the parameter κ is increased to 0.5. As shown in Fig. 4, without externalities, the bubble depicting the social optimum does not coincide with the market equilibrium. This is a consequence of the various market failures immanent in economic geography models (see Pflüger and Südekum 2008). Moreover, the bubble shrinks the higher the disutility associated with environmental externalities. This is intuitive, since given our parameters, symmetry minimizes total pollution. Eventually, as κ becomes large enough the social planer chooses full dispersion, $\lambda = 1/2$, for all levels of trade freeness.

The discrepancy between the market equilibrium and the social optimum leaves a role for policies that control population flows directly or indirectly, e.g. through urban growth boundaries. However, these policies should be carefully designed, depending on various parameters which may be difficult to observe.

Fig. 4: Market equilibrium vs. social optimum



5 Conclusion

This paper establishes a simple theoretical framework which comprises key forces that shape the structure and interrelation of cities to study interdependencies between urban evolution and the environment. We focus on the potential of unfettered market forces to economize on emissions. A key finding is that market forces alone may suffice to generate an urban Environmental Kuznets Curve. One specific finding is that reducing trade costs increases per capita incomes and generates an inversely U-shaped evolution of emissions in the process of agglomeration and redispersion. We also find that agglomeration per se is typically not a boon for the environment, as total emissions in the total city system are likely to rise (although, as we have stressed, this depends on the emission intensities of various pollution sources).

We have made a number of limiting choices in setting up our framework. An interesting route to pursue in future work is to bring in environmental policies and to allow for abatement activities to endogenize the emission intensities. This may enhance the scope for a benign interaction between urbanization and the environment. Moreover, we have followed the economic geography and assumed that the 'modern sector' produces manufacturing goods only. Splitting this sector into manufactures and (cleaner) services is a second interesting extension. Finally, the internal city transport system could also be differentiated out in future work.

We believe that the simple model we have established proves useful to address these and further extensions.

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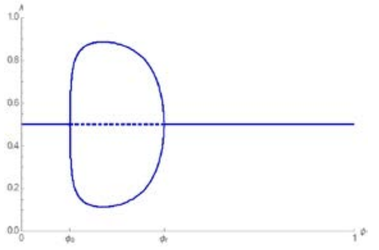
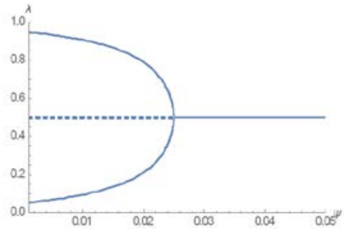
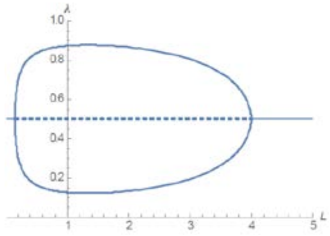
Appendix

Table 3: Emissions and per capita incomes I

	ϕ	ψ	L
location pattern			
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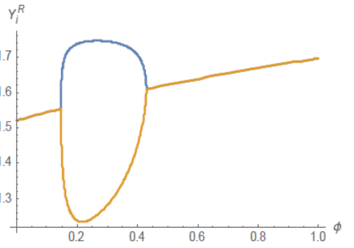
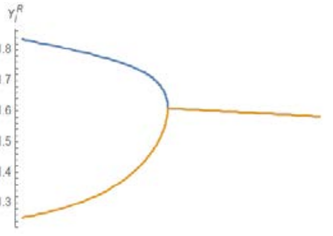
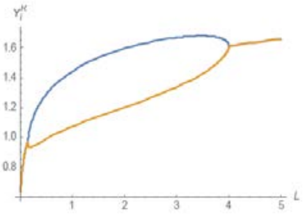
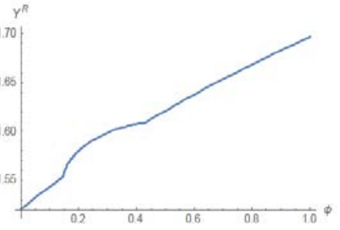
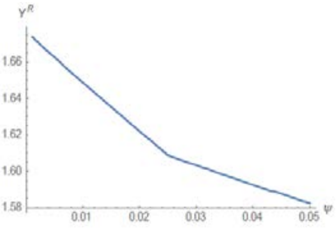
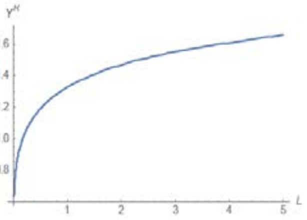
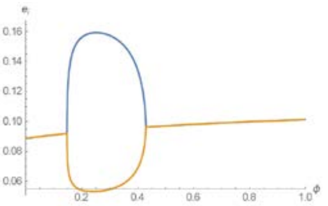
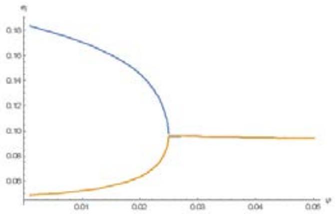
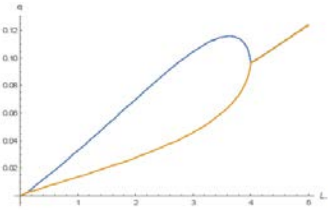
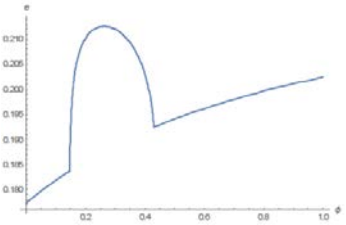
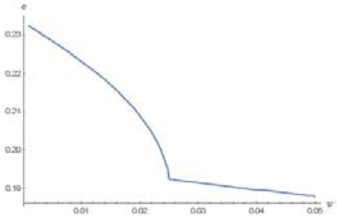
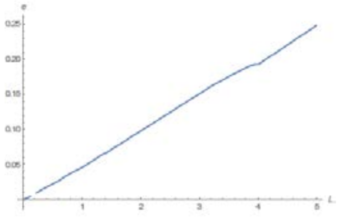
emerging core emerging periphery			
total city system			
emissions			
emerging core emerging periphery			
total city system			

Table 4: Emissions and per capita incomes II

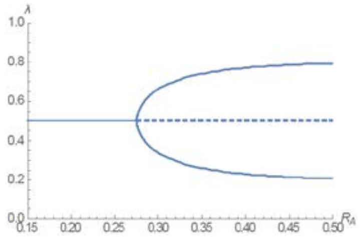
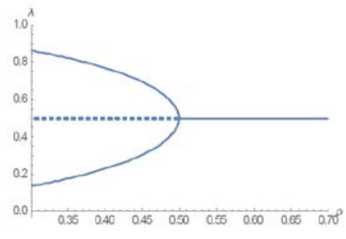
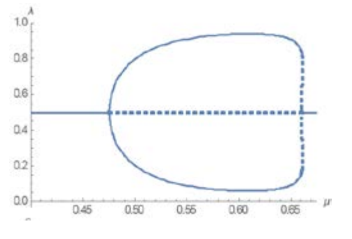
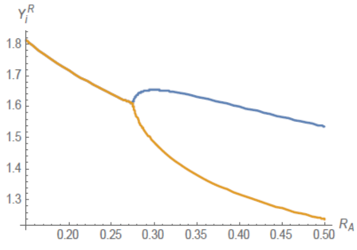
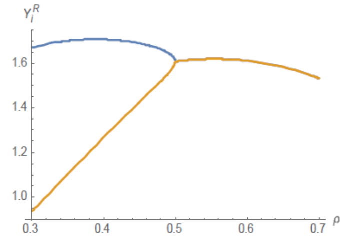
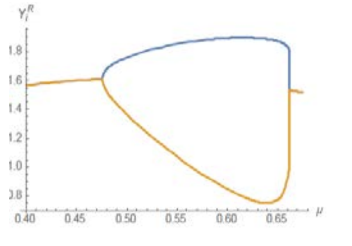
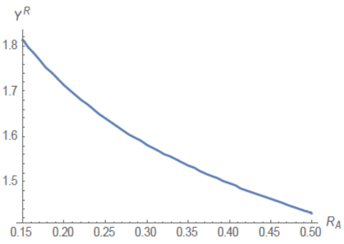
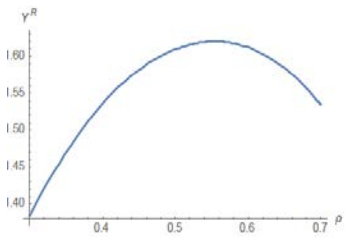
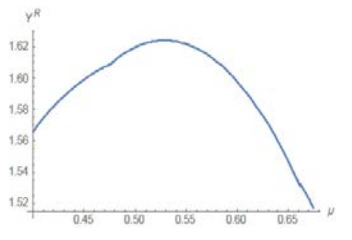
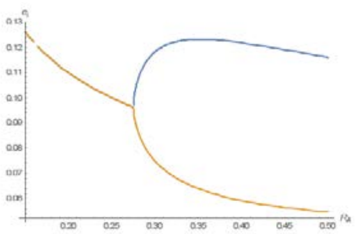
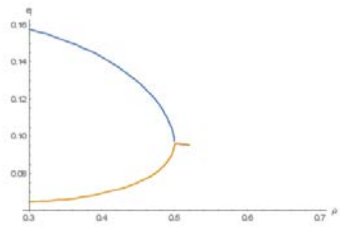
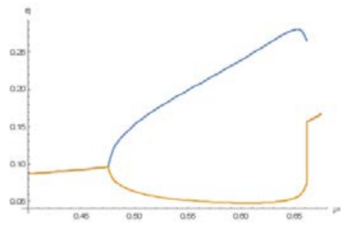
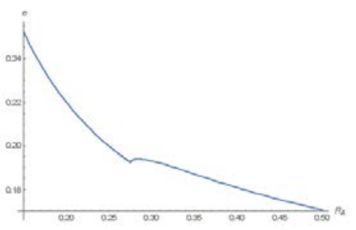
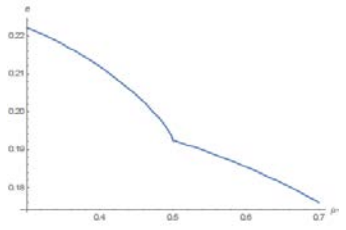
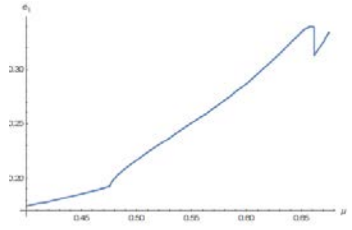
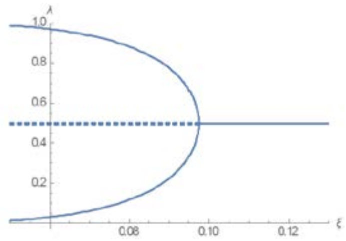
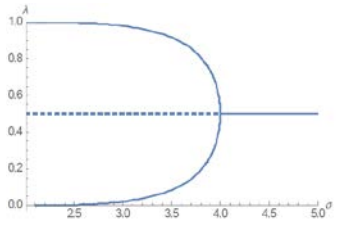
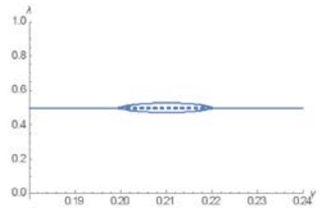
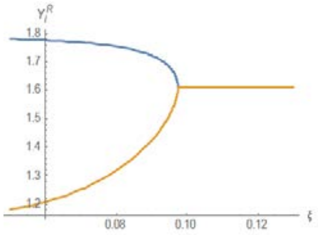
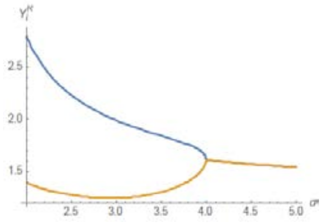
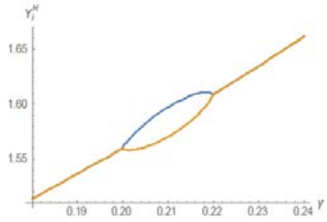
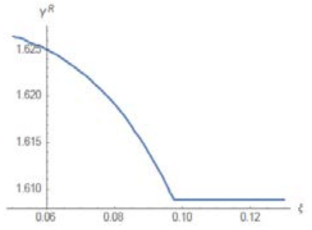
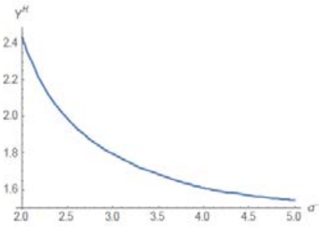
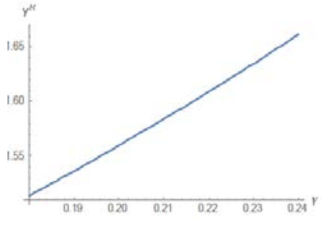
	R_A	ρ	μ
location pattern			
per capita income			
emerging core emerging periphery			
total city system			
emissions			
emerging core emerging periphery			
total city system			

Table 5: Emissions and per capita incomes III

	ξ	σ	γ
location pattern			
per capita income			
emerging core emerging periphery			
total city system			
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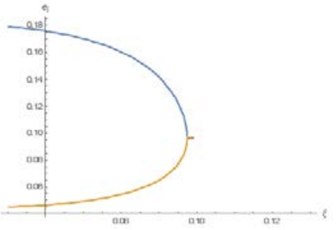
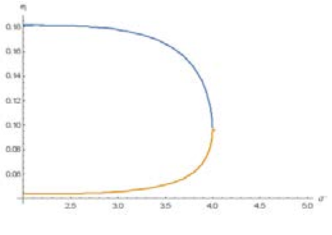
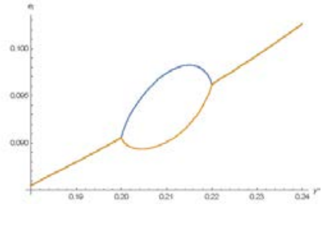
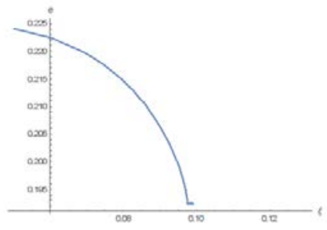
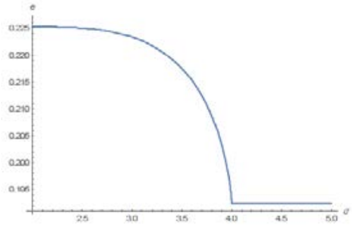
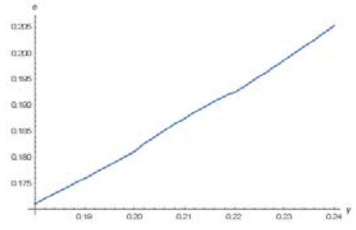
emerging core emerging periphery			
total city system			

Supplementary appendix - Not for publication

A1 Derivation of the effective labor supply in city i

In order to arrive at the effective supply of labor, the reduction of the total labor supply due to the iceberg commuting costs in accordance with the equilibrium location pattern of the skilled has to be taken into account: $L_{i,eff}^S \equiv \int_0^{r_{ib}} D_i(r_i)(1-\psi r_i)dr_i$. Using $D_i(r_i) \equiv 1/C_{H,i}^S(r_i)$ and the consumption of housing by the skilled given in eq. (6), $C_{H,i}^S(r_i) = \gamma(1-\psi r_i)w_i^S / P_{H,i}^S(r_i)$ this can be rewritten as $L_{i,eff}^S = \frac{1}{\gamma w_i^S}\int_0^{r_{ib}} P_{H,i}^S(r_i)dr_i$. The bid rent of skilled workers in the city equilibrium can be calculated from eqs. (8), (11) and (13) as $P_{H,i}^S(r_i) = (1-\psi r_i)^{1/\gamma} \cdot P_{U,i}$. Hence, $L_{i,eff}^S = \left(\frac{P_{U,i}}{\gamma w_i^S}\right)\int_0^{r_{ib}}(1-\psi r_i)^{1/\gamma} \cdot dr_i$. Solving the integral yields $\int_0^{r_{ib}}(1-\psi r_i)^{1/\gamma} \cdot dr_i = \left[-\frac{1}{\psi}\frac{\gamma}{1+\gamma}(1-\psi r_i)^{\frac{1+\gamma}{\gamma}}\right]_0^{r_{ib}} = \frac{1}{\psi}\frac{\gamma}{1+\gamma}\left[1-(1-\psi r_{ib})^{\frac{1+\gamma}{\gamma}}\right]$. Inserting the city boundary from eq. (12) we finally arrive at $L_{i,eff}^S = \frac{P_{U,i}}{\psi(1+\gamma)w_i^S}\left[1-\left(\frac{R_A}{P_{U,i}}\right)^{1+\gamma}\right]$.

A2 Derivation of total commuting distance in city i

Total commuting (distance) is given by $\Psi_i = \int_0^{r_{ib}} r_i D(r_i)dr_i = \int_0^{r_{ib}} \frac{r_i}{C_{H,i}^S}dr_i$. With $C_{H,i}^S(r_i) = \gamma(1-\psi r_i)w_i^S / P_{H,i}^S(r_i)$ and $P_{H,i}^S(r_i) = (1-\psi r_i)^{1/\gamma} \cdot P_{U,i}$ (see A1) this can be rewritten as $\Psi_i = \frac{1}{\gamma}\int_0^{r_{ib}} \frac{r_i P_{H,i}^S(r_i)}{(1-\psi r_i)w_i^S}dr_i = \frac{1}{\gamma}\frac{P_{U,i}}{w_i^S}\cdot\int_0^{r_{ib}} r_i \cdot (1-\psi r_i)^{\frac{1-\gamma}{\gamma}}dr_i$. Solving the integral yields $\int_0^{r_{ib}} r_i \cdot (1-\psi r_i)^{\frac{1-\gamma}{\gamma}}dr_i = \left[-\frac{\gamma(1-\psi r_i)^{\frac{1}{\gamma}}(\gamma+\psi r_i)}{(1+\gamma)\psi^2}\right]_0^{r_{ib}} = \frac{\gamma\left[\gamma-(1-\psi r_{ib})^{\frac{1}{\gamma}}(\gamma+\psi r_{ib})\right]}{(1+\gamma)\psi^2}$. Hence, total commuting distance is: $\Psi_i = \frac{\left[\gamma-(1-\psi r_{ib})^{\frac{1}{\gamma}}(\gamma+\psi r_{ib})\right]}{(1+\gamma)\psi^2}\cdot\frac{P_{U,i}}{w_i^S}$. Substituting for r_{ib} we get:

$$\Psi_i = \frac{\gamma(P_{U,i}-R_A)-R_A\left(1-P_{U,i}{}^{-\gamma}R_A{}^{\gamma}\right)}{(1+\gamma)\psi^2 w_i^S}.$$