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## Abstract

This paper develops a model with an endogenous number of cities to explore whether local governments establish the optimal city size when key activities in the city are associated with emissions that harm consumers. In contrast to extant research, our model is fully micro-founded with respect to the urban sector and the agglomeration mechanism as well as the modelling of pollution and pollution abatement. We derive two key insights. First, if the national government implements a permit system (equivalently, pollution taxes) that allow for emissions as in the first-best, cities chosen by local governments are too small. Second, if no emission scheme is implemented, or if emission policies are too lax, cities steered by local governments may become too large. The tractability of the model also allows us to uncover the determinants of optimal city sizes, emissions, emission intensities and determinants of locally chosen city sizes, as well as to address the second-best emission policy and extensions to city asymmetries, a fiscal externality, local pollution, generalized commuting costs and further pollution sources.


JEL-Codes: H730, R120, Q500.

Keywords: city systems, environmental pollution, emission policies.

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# 1 Introduction

Are cities too small or too big? It is often voiced in the public debate that the world's large cities are oversized and prone to sprawl further. A classic line of economic reasoning indeed holds that free migration of people causes cities to become inefficiently big. This argument has been challenged by an influential recent line of research which points out that cities may actually be too small (e.g. Albouy et al. 2019; Au and Henderson 2006; Desmet and Rossi-Hansberg 2013; Hsieh and Moretti 2019). A key argument in these analyses is that mobility restrictions imposed by local governments may keep city sizes too small so that countries forego large welfare benefits.

This paper contributes to this debate by establishing theoretical arguments why city sizes may be distorted away from the optimum (where city dwellers' utility is maximized). The circumstances highlighted in this paper arise when activities in cities are associated with emissions that cause environmental pollution on the national ('global') level, the key example being CO2-emissions and global warming.[1] First, if the national government implements a permit system (equivalently, pollution taxes) that allow for emissions as in the first-best, cities chosen by local governments are too small. Second, if no such national emission policy is implemented, or if the policy is too lax, as is quite likely the case in practice for political economy reasons, cities steered by local governments may become *too large*, and their overall number is too small.

We develop a parsimonious, yet rich, theoretical framework and impose a number of simplifications to make the analysis tractable and transparent. The key assumption is to build on Henderson's (1974) city systems model with an *endogenous* number of cities. We build on a well-known version of this model whose micro-foundations comprise monocentric cities and agglomeration economies due to the sharing of inputs (Duranton and Puga 2004; 2014). We extend this model with a micro-founded pollution process with emission abatement as in Copeland and Taylor (1994; 2003). For the sake of tractability, we focus on two important sources of pollution in the main analysis, emissions associated with production and commuting.[2] Emissions are controlled with permits or, equivalently in this model, with emission taxes. We focus on comparing the social planner allocation (as implemented by a benevolent national government) with the allocation chosen by local governments. Of course,

[1] The Economist (2018) has recently put local government and global warming in the focus.
[2] The key pollution sources besides production and commuting activities are emissions from housing and from trade (see Borck and Pflüger 2019). We discuss these further pollution sources in the extensions in section 4.

the evolution of cities and urban systems is shaped by various forces. Mobile people are attracted to locations that satisfy their pecuniary and non-pecuniary needs best, and local and national governments directly and indirectly influence cities and city sizes. However, there is a growing perception, if not a consensus, that governments, notably local ones, play the crucial role in determining city sizes today.[3] A further reason for our focus is to highlight the interplay between policies chosen by local governments and by a (benevolent) national government.

The key results of the paper, the mentioned city biases that arise in the micro-founded model with an endogenous location number and with pollution abatement under global environmental pollution, reveal a surprising discrepancy. Cities are too small when the national government fixes emissions at a level as in the first-best, but may become too large when such an emission policy is absent or too lax. The first result is due to a positive externality associated with city size on global pollution. Global pollution depends on the product of emissions of a city and the number of cities. Increasing city size reduces their number and, hence, global pollution. The benevolent planner takes this into account and, hence, apart from choosing an optimal emission policy, economizes on the creation of new cities. Local governments, in contrast, maximize city dwellers per-capita income without regard to global pollution and, hence, ignore this positive externality in choosing city size. The second result follows from the fact that emissions, apart from harming consumers, also have a positive effect on productivity and wages so that local governments' choice of city size depends on the emission level set by the national emission scheme. If national governments do not regulate emissions properly, city sizes may easily grow beyond the optimal level.

In addition to deriving these key results, we use the micro-founded model to uncover the determinants of optimal city sizes, emissions and emission intensities as well as the determinants of locally chosen city sizes. We also address extensions of the analysis to multiple city outputs and city asymmetries, to a fiscal externality which arises when the proceeds from the national emission scheme are wasted, to local rather than global pollution, and to generalized commuting costs and we discuss how further pollution sources fit into the analysis.

[3] Glaeser (2013) provides a lucid review of the institutions of local governments and urban political economy stressing the important role of local councils, strong mayors etc. Desmet and Henderson (2015) argue that "(…) while much of what we see is driven by market forces, the role of governments in economies has grown" and "Government policies and institutions strongly influence the structure of urban hierarchy." Hsieh and Moretti (2019 ) show that "… the constraints on housing supply in the most productive US cities effectively limit the number of workers who have access to such high productivity." Local governments are also highlighted in recent theoretical work, e.g. Duranton and Puga (2014; 2017) and Albouy et al. (2019).

**Related Literature.** Our analysis relates to two strands of research. First and foremost, we contribute to the theoretical research on the optimal distribution of population across cities. This research started with the insight that cities are too big under self-organization due to a coordination failure that results from local increasing returns at small city size (Henderson 1974). Efficiency can be restored by competitive land-developers or by allowing for the formation of autonomous local governments which act on behalf of the atomistic agents, however (Henderson 1974; Becker and Henderson 2000; Abdel-Rahman and Anas 2004). Albouy et al. (2019) provide a contrast by showing that inefficiently low city sizes are chosen in the presence of positive fiscal externalities or when there are Ricardian differences in land (heterogeneous production amenities). Despite recognition that global environmental pollution, global warming in particular, is one of the most important problems for humanity, the interrelation between city size and pollution is only rarely addressed. Borck and Tabuchi (2019) develop a city systems model with separate black-box mechanisms for the processes of agglomeration and pollution, which they assume to be independent iso-elastic functions of city size. The lack of micro-foundations and the separability assumption stand in sharp contrast to our model. As a result, the workings of the city economy in Borck and Tabuchi (2019) are independent of the pollution process, whilst emissions (and their abatement) play a key role for productivity, wages, commuting, emission intensities, and per-capita emissions in our model. Whilst we are able to identify microeconomic determinants as well as the emission policy as drivers of per-capita emissions, they simply assume that per-capita emissions either rise or fall with city size. One implication of this agnostic treatment of the pollution process in Borck and Tabuchi (2019) is that the city bias (deviation from the optimum) in a symmetric city system may go either way under global pollution.[4] Moreover, in contrast to the present paper, there is no room for an emission policy distinct from the choice of city size in their model. This also rules out the possibility that city sizes may become too big when the national emission policy is too lax, our second key result. Our micro-founded model also allows us to scrutinize further dimensions of the interplay between policies chosen by local governments and policies by a (benevolent) national government, notably a second-best emission policy and political economy circumstances where the proceeds from an emission policy are wasted. It should also be pointed out that we extend our analysis to a setting with trade across cities (see section 4) whereas the

[4] They also consider an economy with asymmetries as in Albouy et al. (2019) yet with an exogenous number of cities. For that version they provide a calibration which implies that the largest US cities may be undersized in the range of 3-4%.

cities in the city systems considered by Albouy et al. (2019) and Borck and Tabuchi (2019) are autarkic, i.e. there is no trade across cities in their models.

There is also a more general literature that addresses the nexus between cities and the environment, largely inspired by Glaeser's (2011) hypothesis that large cities may make us not only richer, smarter and more productive, but also greener (see also Kahn and Walsh 2015; Kahn 2006). Gaigné et al. (2012) use a new economic geography oligopoly model to show that Glaeser's hypothesis needs to be qualified when intra- and intercity interactions, such as longer commutes and the transport of goods are taken into account. This finding is reinforced in Borck and Pflüger (2019) using a Krugman-type new economic geography model which allows for endogenous lot sizes. There are also important contributions with a different focus than our analysis. A theoretical literature studies pollution in monocentric or polycentric cities without looking at the city system. Examples of these works are the analysis of carbon and congestion policies by Tscharaktschiew and Hirte (2000), the studies on land-use by Kyriakopolou and Xepapadeas (2016) and Schindler et al. (2017), the studies on various aspects of urban structure by Borck (2016) and Borck and Brueckner (2018) and the study on land-use and transportation policies by Larson et al. (2012).[5] There is also an empirical literature exemplified by Glaeser and Kahn (2010) who study carbon dioxide emissions by households in American metro areas. They find that denser cities and city parts have lower emissions and they also find a negative correlation between land-use controls and CO2-emissions. Another example is Blaudin de Thé et al. (2020) who look at the impact of urban form on household fuel consumption and car emissions in France. One of their key findings is that, contrary to the findings for the US, the relationship between the metropolitan population and car emissions in France is bell-shaped. Finally, there are quantitative simulation studies. One key example is Desmet and Rossi-Hansberg (2015) who address global warming within a flexible new quantitative spatial model which highlights the role that mobility frictions play for the adaption to climate change.

The structure of the rest of the paper is as follows. Section 2 introduces the model. Section 3 compares the social planner solution with the allocation chosen by local governments when environmental pollution is global. Section 4 addresses extensions and section 5 concludes.

[5] See also Larson and Yezer (2015) who extend the simulation model (urban energy footprint model) used in Larson et al. (2012) for the analysis of a closed city to an open city environment, yet also without taking the workings of the total city system into account.

## 2 The model

A key aspect of this paper is to build the analysis on a fully micro-founded model with respect to the urban sector, the agglomeration mechanism, and, crucially also, the modelling of pollution and emission abatement. We draw on a well-known model of city systems in the tradition of Henderson (1974) with micro-foundations in terms of input sharing following Ethier (1982) and Abdel-Rahman and Fujita (1990), as e.g. laid out in Duranton and Puga (2014). This micro-founded agglomeration mechanism has the merit to be simple and intuitive and to be widely known and used in the literature.[6] We amend this model in the spirit of Copeland and Taylor (1994; 2003) by assuming that intermediate inputs are produced with labor and emissions (rather than just labor), and that emissions harm consumer-workers. The overall number of consumer-workers in the total city-system is exogenously given by $N$, the number of cities $n$ is endogenously determined.

**Preferences.** Consumer-workers are homogeneous. They live in cities (indexed by $i$), supply 1 unit of working time and consume 1 unit of housing, each. Preferences are linear in consumption $X_i$ of a homogeneous and freely tradable final good, the numéraire, and additively separable in the disutility associated with pollution $\Omega_i$ in the city, $U_i = X_i - \eta \cdot \Omega_i$, where $\eta > 0$ .[7] Consumer's gross income $I_i$ consists of her wage $w_i$, a proportionate share of total land rents, $TLR_i/N_i$, where $N_i$ is the endogenous number of city residents, and a proportionate share of the proceeds from an emission policy, $TET_i/N_i$. Let $R_i(0)$ denote average urban costs in spatial equilibrium in the city, a convenient summary measure of housing and commuting costs (detailed below). Consumer's income net of urban costs (spent on the final good) is $c_i = I_i - R_i(0)$ and her indirect utility is $V_i = c_i - \eta\Omega_i$.

**Pollution and spatial equilibrium across cities.** Pollution in city $i$ is the result of emissions of intermediate firms. If pollution is purely local, $\Omega_i = m_i e_i = E_i$, where $m_i$ is the mass of intermediate firms in city $i$, $e_i$ denotes the emissions of a single firm and $E_i$ denotes aggregate emissions in the city. If pollution is purely global, $\Omega_i = nE_i$.

Consumers are mobile across cities. Spatial equilibrium in the city systems commands that utility is equalized at a common level, $V_i = \bar{V}$ .

[6] See Duranton and Puga (2004) for a critical evaluation and for a comprehensive review of other agglomeration mechanisms.

[7] The analysis extends to more than one final output, see section 4. I thank discussants of this paper for urging me to cast the main analysis in terms of one output in conformance with Occam's razor, however.

**Production and the wage equation.** (Gross) final output $Y_i$ in the city is produced with the CES-technology $Y_i = B\left\{\int_0^{m_i}[y_i(h)]^{\frac{1}{1+\sigma}}dh\right\}^{1+\sigma}$, where $y_i(h)$ is the quantity of intermediate input $h$, $m_i$ is the mass of intermediates, $B$ is a productivity shifter, and $0 < \sigma < 1$ so that $\varepsilon \equiv (1+\sigma)/\sigma$ is the elasticity of technological substitution between any two intermediates. Intermediates are non-tradable and produced with labor $l_i$ and emissions $e_i$ under increasing returns and monopolistic competition with the cost function $C_{y_i}[y_i(h)] = w_i{}^{1-\rho}t_i{}^{\rho}\ [y_i(h)+\alpha]$, where $t_i$ denotes the (shadow) price of emissions associated with the emission policy, $\alpha > 0$, $0 \leq \rho \leq 1$ is the cost share of emissions in variable and fixed output and $1-\rho$ is the respective cost share of labor. This technology extends the standard specification where labor is the only input ($\rho = 0$, see Duranton and Puga 2004; 2014) along the lines of Krugman and Venables (1995) and Tabuchi and Pflüger (2011). Our specification with emissions as a production factor can be understood to be supported by an explicit abatement technology as in Copeland and Taylor (1994; 2003).[8] Following these authors we impose the condition $e_i \leq \kappa\, l_i$, where $\kappa > 0$ limits the substitution possibilities between labor and emissions to ensure that output is bounded above for a given labor input. The quantities of intermediates are chosen to minimize the costs to produce final output. Conditional input demand is $y_i(h) = \frac{[q_i(h)]^{-(1+\sigma)/\sigma}}{\left\{\int_0^{m_i}[q_i(h')]^{-1/\sigma}dh'\right\}^{1+\sigma}}\frac{Y_i}{B}$, where $q_i(h)$ denotes the price of intermediate $h$. Hence, firm $h$ faces own-price demand elasticity $-(1+\sigma)/\sigma$ and the profit-maximizing price is a constant mark-up on marginal costs, $q_i = (1+\sigma)\ w_i{}^{1-\rho}t_i{}^{\rho}$. Since all variables take on identical values for all intermediate firms due to symmetry, we drop the index $h$ from now on. Free entry drives intermediates' profits to zero, $\pi_i = q_i y_i - C_{y_i} = 0$. Hence, break-even output is $y_i = \alpha/\sigma$. Aggregate labor input and emissions of intermediate firms comprise constant and variable components and are calculated as $L_i = \alpha(1-\rho)\varepsilon\, m_i(t_i/w_i)^{\rho}$ and $E_i = \alpha\rho\varepsilon m_i(t_i/w_i)^{\rho-1}$, respectively. Hence, a higher ratio $w_i/t_i$ lowers the demand for labor and raises the demand for emissions. This equation for emissions reveals the equivalence of emission policies: a permit system fixes emissions at some level $E_i$ so that their shadow price $t_i$ is then implied; if an emission tax $t_i$ is chosen, the level of emissions is implied.

[8] Emissions (pollution) is a joint and undesirable side-product in the production of intermediates. We assume that these emissions can be contained by devoting a part of labor to abatement as in Copeland and Taylor (1994; 2003). There is then an equivalent technology where emissions can be included as an input into production. The cost function used in this paper extends their analysis to the circumstances of our model.

Under symmetry, final output is $Y_i = B\, m_i^{1+\sigma} y_i$. Using the break-even output for intermediates $y_i = \alpha/\sigma$, the mass of intermediate firms $m_i = [L_i/(1-\rho)]^{(1-\rho)}[E_i/\rho]^{\rho}[\sigma/\alpha(1-\sigma)]$ implied by the aggregate input of labor and emissions, and the normalization $(\alpha/\sigma)^{-\sigma}(1+\sigma)^{-(1+\sigma)}\ \rho^{-\rho(1+\sigma)}\ (1-\rho)^{-(1-\rho)(1+\sigma)} = 1$ (in analogy to Duranton and Puga 2014), the aggregate production function (gross output) in city $i$ can be written as:

$$Y_i(L_i, E_i) = B\ E_i^{\rho(1+\sigma)}\ L_i^{(1-\rho)(1+\sigma)} \tag{1}$$

Perfect competition implies that revenue equals cost in final output production, $Y_i = w_i L_i + t_i E_i$. Employing $t_i E_i = w_i L_i\, \rho/(1-\rho)$ implied by the demand for labor and emissions at the city level, we have $w_i = (1-\rho)\, Y_i/L_i$. Using (1) the wage in the city follows as:

$$w_i = (1-\rho)\ B\ E_i^{\rho(1+\sigma)}\ L_i^{(1-\rho)(1+\sigma)-1} \tag{2}$$

Eqs. (1) and (2) deserve two comments. First, emissions have a positive impact on aggregate output and the wage in the city as do productive amenities $B$ (the former, of course, also harm consumers). Second, when aggregate output is produced with labor and emissions, the elasticity of production with respect to labor is given by $(1-\rho)(1+\sigma)$. Hence, the sharing externality is weaker with emissions as an additional production factor. We impose the condition $(1-\rho)(1+\sigma) > 1$, i.e. $\rho$ may not be too large, to ensure that aggregate output exhibits increasing returns to labor, the wage in the city rises with $L_i$, so non-degenerate cities exist.

It is worth noting that per-capita emissions in the city are endogenously determined in the model. This can be seen by combining the cost-minimization condition $t_i E_i = w_i L_i\, \rho/(1-\rho)$ with the wage equation (2) to obtain $E_i/L_i = (B\rho L_i^{\sigma}/t_i)^{1/[1-\rho(1+\sigma)]}$.[9] Hence, per-capita emissions in the city are positively related to $L_i$ (and to $B$ and $\rho$) but, crucially, they also depend on the policy stance as expressed by the (shadow-) price of emissions $t_i$.[10] It is an important advantage of our micro-founded model over the black-box approaches in the extant literature (e.g. Borck and Tabuchi 2019) that we are able to identify both microeconomic determinants and emission policy as drivers of per-capita emissions in the cities.

**The urban sector.** Cities are monocentric, one-sided and stretch out linearly from the CBD at $r_i = 0$ where production takes place, to the residences located at distance $r_i$ from the CBD. The opportunity cost of land at the city border $\bar{r}_i$ is normalized to zero. Since workers consume 1 unit of floor-space, the city border is at $\bar{r}_i = N_i$. Workers commute from their residences to the

[9] This derivation anticipates that city population and labor force are the same $N_i = L_i$ (see the next paragraph).
[10] We discuss this further in section 3.2.

CBD and back at a cost. We follow Duranton and Puga (2014) in assuming that the commuting cost of a resident living at distance $r_i$ from the CBD is incurred in terms of local output and given by $\tau\, r_i{}^{\gamma}\,(1+\gamma)/\gamma$ where $\gamma > 0$ is the mentioned elasticity, $\tau > 0$ is a commuting cost parameter, and the term $(1+\gamma)/\gamma$ is introduced to simplify expressions to be derived below.[11] Population and the labor force coincide under these circumstances, $N_i = L_i$. Total commuting costs are $TCC_i = \tau N_i{}^{1+\gamma}/\gamma$, land rent at $r_i$ is $R_i(r_i) = \tau\big(L_i{}^{\gamma} - r_i{}^{\gamma}\big)\,(1+\gamma)/\gamma$, total land rent is $TLR_i = \tau N_i{}^{1+\gamma}$, and average urban costs in spatial equilibrium in the city are $R_i(0) = \tau N_i{}^{\gamma}\,(1+\gamma)/\gamma$ as shown in Duranton and Puga (2014). The city's net output $Y_i^{net}$ is the difference between potential output (1) and commuting costs:

$$Y_i^{net}(N_i, E_i) = B\, E_i{}^{\rho(1+\sigma)}\, N_i{}^{(1-\rho)(1+\sigma)} - \frac{\tau}{\gamma} N_i{}^{1+\gamma} \tag{3}$$

Equation (3) makes it clear that production and commuting are associated with emissions in the model. The share $TCC_i/Y_i(L_i, E_i)$ of gross output and the associated emissions are devoted to commuting in the city, the remaining share $1 - TCC_i/Y_i(L_i, E_i)$ is devoted to production (net output) which is consumed by households. We characterize these shares below.

# 3 Global environmental pollution

This section addresses global pollution and derives the social planner allocation ($SP$) and the allocation chosen by local governments ($LG$), which we will call 'market equilibrium'. We also uncover the determinants of city sizes and emissions chosen by the social planner and by local governments and we address a second-best emission policy where the national government takes into account that city size is chosen by local governments.

**3.1 Social planner vs. local governments.** When pollution is purely global, as with global warming, each city resident is faced with the pollution of the total city system, $\Omega_i = n\, E_i$.

The *social planner* chooses city size, local emissions and the number of cities to maximize $U_i = X_i - \eta n E_i$, taking into account that demand in the city system equals supply, $n\, N_i X_i = n\, Y_i^{net}(N_i, E_i)$, and that the population fits into the cities, $n\, N_i = N$. Hence, $U_i = Y_i^{net}/N_i - \eta N E_i/N_i$. The first order conditions with respect to $N_i$ and $E_i$, $dU_i/dN_i = \left(N_i \frac{dY_i^{net}}{dN_i} - Y_i^{net}\right)/N_i{}^2 + \eta N E_i/N_i{}^2 = 0$ and $dU_i/dE_i = \frac{dY_i^{Net}}{dE_i}/N_i - \eta N/N_i = 0$ imply:

[11] Early literature assumed linear commuting costs (e.g. Becker and Henderson 2000; Duranton and Puga 2004). It is now common to generalize this specification by assuming that commuting costs are iso-elastic with respect to distance (Duranton and Puga 2014; 2017; Albouy et al. 2019; Behrens and Robert-Nicoud 2015), Combes et al. (2019) provide the seminal empirical analysis which builds on this specification. See also section 4.4.

$$\frac{dY_i^{net}}{dN_i}\frac{N_i}{Y_i^{net}} + \frac{dY_i^{net}}{dE_i}\frac{E_i}{Y_i^{net}} = 1 \tag{4}$$

$$\frac{dY_i^{net}}{dE_i} = \eta N \tag{5}$$

Eq. (4) commands that the production elasticity of labor in the city $\varepsilon_{Y_i^{net},N_i} \equiv \frac{dY_i^{net}}{dN_i}\frac{N_i}{Y_i^{net}}$ and the production elasticity of emissions in the city $\varepsilon_{Y_i^{net},E_i} \equiv \frac{dY_i^{net}}{dE_i}\frac{E_i}{Y_i^{net}}$ sum up to unity. Eq. (5) requires the marginal product of emissions at the city level to be equal to the marginal damage inflicted on the total population. The number of cities follows as $n = N/N_i$.

*Local governments* take the disutility term $\eta\Omega_i$ to be a constant under global pollution.[12] They choose city size to maximize per-capita income net of urban costs of their residents $c_i$, and hereby they take the national emission policy as given. Let us assume that the national government implements an emission policy which fixes total emissions $nE_i$ in the city system through a permit system (or, equivalently, through an emission tax) and that the associated revenue is rebated to local governments who redistribute it lump-sum to city residents. City dwellers' capita income net of urban costs is then $c_i = w_i + TET_i/N_i + TLR_i/N_i - R_i(0)$. Substituting the wage, total land rent, average urban costs, and the proceeds from the emission scheme $TET_i = t_iE_i = w_iN_i\,\rho/(1-\rho)$, it follows that $c_i = Y_i^{net}/N_i$. Maximizing $c_i$ with respect to city size yields the condition

$$\varepsilon_{Y_i^{net},N_i} = \frac{dY_i^{net}}{dN_i}\frac{N_i}{Y_i^{net}} = 1 \tag{6}$$

which shows that local governments choose city size such that the marginal product of labor equals the average product of labor in the city.

A comparison with the social planner solution proves our first key result: *when pollution is purely global cities are too small under local governments*. This holds true because the marginal and the average product of labor in the city coincide under local governments, eq. (6), whereas the marginal product of labor in the city is smaller than the average product in the optimum, eq. (4). The intuition for this result is a positive externality from city size on global pollution and the associated welfare loss, $\eta nE_i = \eta NE_i/N_i$. Increasing city size reduces the number of cities and, hence, global pollution. The benevolent planner takes global pollution into account and, hence, apart from choosing an optimal emission policy, economizes on the creation of new cities. Local governments, in contrast, maximize city dwellers income without regard to global

[12] Technically, this argument commands that we think of a continuum of cities.

pollution and, hence, ignore the positive externality associated with their choice of city size. This discrepancy between local governments, who focus on city size but ignore the associated positive externality, and benevolent national governments, who are able to optimally and separately choose city size and emissions in the city system which arises in our micro-founded model under global pollution, is one hallmark of our analysis which sets it apart from extant research.[13]

**3.2 Determinants of city size.** The analysis is so far conducted in terms of a general net output function, i.e. without using the specifics of the micro-foundation of agglomeration economies and the specifics of the urban sector embedded in eq. (3). In order to establish the determinants of city size in closed-form we now use eq. (3) in the *social planner solution* (4) and (5). This delivers two interdependent conditions

$$N_i = \left[\frac{B\,\sigma\, E_i^{\rho(1+\sigma)}}{\tau}\right]^{\frac{1}{\gamma-\sigma+\rho(1+\sigma)}} \quad \text{and} \quad E_i = \left[\frac{B\,\rho(1+\sigma) N_i{}^{(1-\rho)(1+\sigma)}}{\eta N}\right]^{\frac{1}{1-\rho(1+\sigma)}} \tag{7}$$

which indicate that city size rises in emissions and emissions rise in city size. Solving these conditions yields:[14]

$$N_i^{SP} = \left[B\ \left(\frac{\sigma}{\tau}\right)^{1-\rho(1+\sigma)}\ \left(\frac{\rho(1+\sigma)}{\eta N}\right)^{\rho(1+\sigma)}\right]^{\frac{1}{\gamma-\sigma-\gamma\rho(1+\sigma)}} \tag{8}$$

$$E_i^{SP} = \left[B^{1+\gamma}\left(\frac{\sigma}{\tau}\right)^{(1-\rho)(1+\sigma)}\ \left(\frac{\rho(1+\sigma)}{\eta N}\right)^{\gamma-\sigma+\rho(1+\sigma)}\right]^{\frac{1}{\gamma-\sigma-\gamma\rho(1+\sigma)}}$$

An inspection of (8) shows that optimal city size and emissions are negatively related to the marginal disutility from emissions, $\eta$, to overall population $N$ and to commuting costs $\tau$ and positively related to the productivity shifter $B$. Optimal city size can be shown to be rising in the agglomeration measure $\sigma$ and falling in the elasticity of commuting costs with respect to distance $\gamma$ under similar conditions as in the baseline model of Duranton and Puga (2014).[15] Using (3) and $N_i$ from (7), the share of resources (gross output) devoted to commuting in a city of optimal size is calculated as $TCC_i/Y_i = \sigma/\gamma$. The optimal emission intensity in a city of optimal size follows as $E_i/Y_i = \rho(1+\sigma)/\eta N$. Intuitively, the optimal emission intensity is

[13] See our discussion of the related literature in section 1.
[14] We impose the condition $\gamma > \sigma/[1-\rho(1+\sigma)]$ to obtain economically meaningful solutions. This replaces the standard condition $\gamma > \sigma$ when labor is the only production factor (cf. Duranton and Puga 2014).
[15] This follows from differentiation with respect to the parameters and noticing that the resulting terms approach the terms in Duranton and Puga (2014) if $\rho$ is not too large. The derivative of optimal city size with respect to $\rho$ is typically negative which corresponds with the intuition that the sharing externality is reduced, the higher is $\rho$.

positively related to the production elasticity of emissions and negatively related to the marginal disutility of emissions and the overall population in the city system.[16]

Turning to *local governments,* and using (3) in (6) implies:

$$N_i^{LG} = \left[\frac{B\,[\sigma-\rho(1+\sigma)]E_i^{\rho(1+\sigma)}}{\tau}\right]^{\frac{1}{\gamma-\sigma+\rho(1+\sigma)}} \tag{9}$$

Section 3.1 has already proved that $N_i^{LG}$ falls short of the optimal city size $N_i^{SP}$. In the specification considered here this is immediately seen by comparing (9) with the first condition in (7): for given emissions – as specified by $E_i = E_i^{SP}$ – the downward city size bias rises in the importance of emissions in the production process, $\rho(1+\sigma)$. The determinants of city size chosen by local governments correspond to those of the social planner solution in qualitative terms. In particular the marginal disutility parameter $\eta$ (which appears in $E_i^{SP}$) works qualitatively as in the social planner solution.

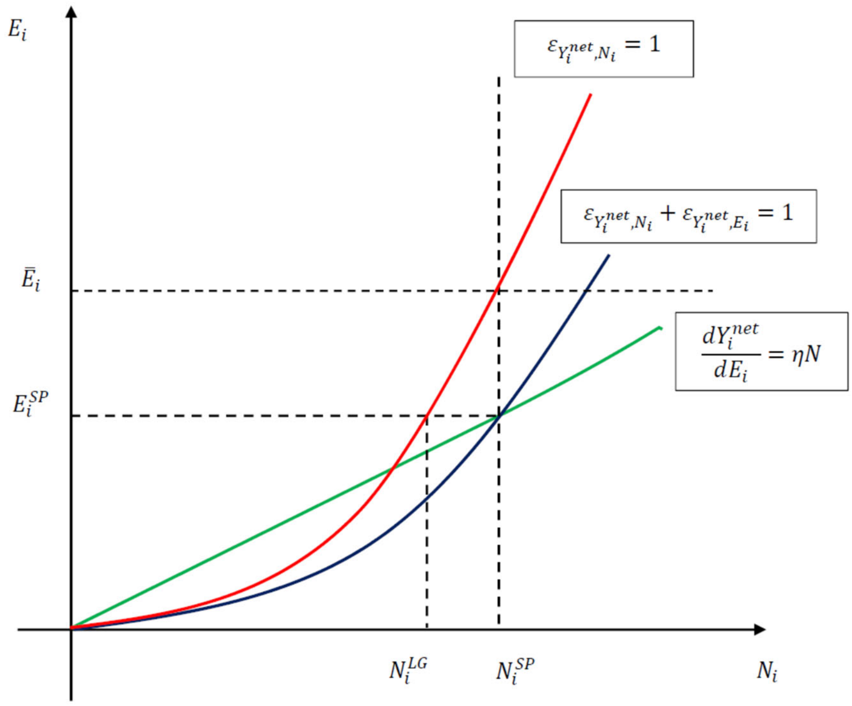


Figure 1: City size and emissions: social optimum and local government allocation

Figure 1 provides a graphical representation of this comparison in a diagram with city sizes and aggregate emissions on the horizontal and vertical axes. The green upward-sloping curve

[16] The assumption that commuting costs are in terms of local output implies that production and commuting exhibit the same emission intensity. The evidence speaks in favor of different emission intensities, of course (see e.g. Borck and Pflüger 2019). We maintain this assumption since the purpose of the present paper is a conceptual one and we want to keep the analysis tractable.

depicts the condition for optimal emissions (5) as solved out in the second condition in (7). The blue upward-sloping locus depicts condition (4) as solved out in the first condition in (7). The red upward-sloping curve depicts condition (6) as solved out in (9). City size and emissions in chosen by a benevolent national government (social planner) arise at the intersection of (4) and (5). Local governments choose city size at the intersection of the horizontal line through $E_i^{SP}$ with the red curve.

**3.3 Second-best.** The comparison that we have undertaken in sections 3.1 and 3.2 compares city sizes chosen by benevolent national governments and local governments under the assumption that national governments can dictate both city size $N_i^{SP}$ and emissions $E_i = E_i^{SP}$. If city size were in fact determined by local governments it is no longer optimal to keep emissions at $E_i^{SP}$. To put it differently, a constellation $N_i^{LG}$ and $E_i^{SP}$ would only arise, if the national government were to choose the national emission scheme without taking into account the choice of city size by local governments. Such a myopic choice of a national emission policy may well accord with political practice. A benevolent non-myopic national government faced with the situation that city size is chosen on the local level, would go for a second-best solution, however. The second-best solution of the national government commands to choose emissions to maximize $U_i = Y_i^{net}/N_i - \eta N E_i/N_i$ subject to the constraint that $N_i$ is chosen by local governments according to equation (9). This second-best level is readily derived to be given by $E_i^{SecB} = \left[B^{\gamma+1}\left(\frac{\sigma-\rho(1+\sigma)}{\tau}\right)^{(1-\rho)(1+\sigma)}\left[\frac{\rho(1+\sigma)[\gamma-\sigma+\rho(1+\sigma)]}{(\gamma-\sigma)\eta N}\right]^{\gamma-\sigma+\rho(1+\sigma)}\right]^{\frac{1}{(\gamma-\sigma)-\gamma\rho(1+\sigma)}}$. A comparison with the first-best emissions as given by equation (8) shows that this second-best emission level falls short of $E_i^{SP}$.[17] This implies that the associated city size chosen by local governments is even smaller than the one that obtains with the "myopic" level $E_i^{SP}$ as portrayed in figure one (the second-best solution is to the left of ($E_i^{SP}$, $N_i^{SP}$) along the red-curve which depicts equation (9). This is a typical second-best result: taking the decision of local governments into account, the second-best emission level chosen by the national government compromises on emissions and thereby reduces city size below the level that these would choose if they faced $E_i^{SP}$.

**3.4 Improper regulation of emissions.** The first-best solution characterized by equations (4) and (5) would be implemented by a benevolent national government with control over city sizes

[17] Relating the two emission levels yields $E_i^{SecB}/E_i^{FB} = \left[\frac{\sigma-\rho(1+\sigma)}{\sigma}\right]^{\frac{(1-\rho)(1+\sigma)}{(\gamma-\sigma)-\gamma\rho(1+\sigma)}}\left[\frac{\gamma-\sigma+\rho(1+\sigma)}{\gamma-\sigma}\right]$. Whilst the rightmost bracket is greater than one, this effects is swamped by the first-term (the bracket of the first term is smaller than one and the exponent is much larger than one, making the first term very small).

(and, hence, the number of cities) and over emissions, where the latter could be steered through a national permit system (or an optimal emission tax). Rather than following benevolent motives (or a second-best strategy as characterized in 3.3) national governments may be guided by political economy considerations (Glaeser 2013). In particular, they may abstain from implementing an optimal environmental policy, say because of lobby activities on part of producers. We refrain from specifying a political economy game to keep the analysis simple. We also suppose that firms' rents associated with emissions accrue to local residents. Income net of urban costs is then given by $c_i = Y_i^{net}/N_i$ and this is the relevant maximand for local governments, so that eq. (6) applies and we have $N_i^{LG} = \left[\frac{B\,[\sigma-\rho(1+\sigma)]E_i{}^{\rho(1+\sigma)}/\tau}{\tau}\right]^{\frac{1}{\gamma-\sigma+\rho(1+\sigma)}}$ by eq. (9). This indicates that the level of emissions (permits) chosen by the (non-benevolent) national government feeds into city size chosen by local governments with positive elasticity $[\rho(1+\sigma)]/[\gamma-\sigma+\rho(1+\sigma)]$. It also follows immediately that cities exceed the first-best optimum, $N_i^{LG} > N_i^{SP} = \left[\frac{B\,\sigma\,E_i^{\rho(1+\sigma)}}{\tau}\right]^{\frac{1}{\gamma-\sigma+\rho(1+\sigma)}}$ if $E_i > \{\sigma/[\sigma-\rho(1+\sigma)]\}^{1/\rho(1+\sigma)}E_i^{SP} \equiv \bar{E}_i$ which is readily possible if the national emission policy is so lax that this condition is met. This proves the second key result, which is of arguably bigger policy relevance, in practice, than the bias established in section 3.1: rather than being biased downwards, *cities chosen by local governments may become excessively large when pollution is global and a national emission policy is either not in place or not stringent enough*. Figure 1 visualises this case in the quadrant which opens up to the right of $N_i^{SP}$ and above $\bar{E}_i$: the red curve which characterizes the choice of city size by local governments shows how city sizes expand as emission policies get laxer.

# 4 Extensions

This section considers five extensions. We first address a fiscal externality that arises when the proceeds from the emission policy are wasted. Then we turn briefly to the case of purely local pollution. Next, we consider an extension to multiple city outputs and city asymmetries. Fourth, we study alternative specifications of commuting costs. Fifth, we take up further pollution sources. We develop each of these extensions against the background of the main model that we established in section 2 and applied in section 3.

**4.1 No rebate of the proceeds from the emission policy.** We maintain the assumption of global pollution in this part of the analysis. In contrast to section 3 we now stipulate that the national government implements an emission policy that fixes emissions at the first-best level but does not rebate the proceeds of this policy to city residents. Rather, the proceeds are assumed to be used to satisfy the aims of government bureaucrats or in other wasteful ways. This implies that there is a positive fiscal externality from local authorities to the national government. A city dweller's income net of urban costs is then $c_i = w_i + TLR_i/N_i - R_i(0)$ which, upon substitution, can be written as $c_i = (1-\rho)(Y_i^{net}/N_i) - \rho\,\tau\,N_i^{\gamma}/\gamma$. Local authorities' maximization of $c_i$ implies the first-order condition $(dY_i^{net}/dN_i) - (Y_i^{net}/N_i) = \rho\,\tau\,N_i^{\gamma}/(1-\rho)$. This result shows that, under this positive fiscal externality, local governments choose city size such that the marginal product of labor in the city exceeds the average product of labor. This implies that city size is (even) lower than in the case where the proceeds from the emission policy are rebated to city residents (cf. eq. (6)), and this additional downward bias compared to the first-best is the stronger, the larger is $\rho$.[18]

**4.2 Purely local pollution.** For the sake of comparison we now turn to purely local pollution such that $\Omega_i = E_i$. The first-best optimum commands to choose $N_i$ and $E_i$ to maximize $U_i = Y_i^{net}/N_i - \eta E_i$. Benevolent local governments choose city size and emissions to maximize city residents' indirect utility $V_i = c_i - \eta\Omega_i$. They use a local permit system (or an emission tax) to regulate $E_i$. We assume that they rebate the proceeds to city residents on a per capita basis. Per capita income net of urban costs is then $c_i = Y_i^{net}/N_i$. Hence, local governments face an identical problem as the social planner and they therefore implement the social optimum as characterized by $\varepsilon_{Y_i^{net},N_i} = \frac{dY_i^{net}}{dN_i}\frac{N_i}{Y_i^{net}} = 1$ and $\frac{dY_i^{net}}{dE_i} = \eta N_i$.[19] The first of these conditions commands the marginal and the average product of labor in the city to be equal, the second condition requires the marginal product of emissions in the city to equal marginal damage.[20]

Of course, local governments may - for similar political economy arguments as those stipulated in sections 3.3. and 4.1 - not act in the best interest of city residents, opening up discrepancies to the first-best optimum. First, a discrepancy arises when local governments do not or not stringently enough address environment pollution. City sizes then become excessively large. Second, if the proceeds from the emission scheme are wasted, rather than rebated to consumer-workers, city size is downward-biased relative to the optimum. The derivation and intuition of these results parallel the analyses in sections 3.3 and 4.1, so we omit them here.

**4.3 Multiple city outputs and city asymmetries.** In accord with the ideal of parsimonious modelling our basic framework was set up in terms of one final output (see also footnote 9).

[18] This result can be related to Albouy et al. (2019) where it is shown that city size is scaled down when there are positive fiscal externalities on the local level.

[19] There is no longer a positive externality associated with city size that drove the solutions apart under global pollution.

[20] Closed-form solutions for city size and emissions are immediately derived. They are omitted for brevity.

The key results carry over to a setting with multiple city outputs and city asymmetries, however. To see this consider a generalization of the setting to two final goods $(i, j)$ which are assembled at no cost in monocentric cities under constant returns and perfect competition using local non-tradable intermediates as in the benchmark model but allow for differences in productive amenities $B_i$ and in the technical elasticities of substitution $\sigma_i$ such that net output in equation (3) is generalized to $Y_i^{net}(N_i, E_i) = B_i\, E_i^{\rho(1+\sigma_i)}\, N_i^{(1-\rho)(1+\sigma_i)} - N_i^{1+\gamma}\, \tau/\sigma$. It is well-known that cities specialize on one type of output under our assumptions (cf. Duranton and Puga 2014). Assume that consumers in cities of type $i$ have Cobb-Douglas preferences over the two final outputs with expenditure share $0 < \theta < 1$ devoted to the final output of cities of type $i$. Let $X_{ii}$ and $X_{ij}$ denote consumption levels of a consumer who lives in city $i$ (first index) and who consumes goods produced in $i$ and $j$ (second index). The allocation of the social planner under global pollution is found my maximizing utility of a citizen in city $i$, $X_{ii}{}^{\theta} X_{ij}{}^{1-\theta} - \eta\, \{n_i E_i + n_j E_j\}$ subject to the constraints that utility is equalized across cities, $X_{ii}{}^{\theta} X_{ij}{}^{1-\theta} = X_{ji}{}^{\theta} X_{jj}{}^{1-\theta}$, that total demands equal total supplies for both types of outputs, $n_i N_i X_{ii} + n_j N_j X_{ji} = n_i Y_i(N_i, S_i)$ and $n_i N_i X_{ij} + n_j N_j X_{jj} = n_j Y_j(N_j, S_j)$, and that the total population fits into the cities, $n_i N_i + n_j N_j = N$. The optimal program is easily shown to yield equations (4) and (5) as in the benchmark model. Local governments maximize per capita income net of urban costs and this yields equation (6) just as in the benchmark which can be solved out as in equation (9) with $B_i$ replacing $B$ and $\sigma_i$ replacing $\sigma$. This proves that our two key results (cf. sections 3.1 and 3.2) carry over to a setting with more than one output and with city asymmetries.

**4.4 Alternative specification of commuting costs.** In line with current research, our modelling of the urban sector (section 2) assumed that commuting costs are in terms of local output (e.g. Combes et al. 2019; Duranton and Puga 2014; Behrens and Robert-Nicoud 2015). In practice, commuting costs also involve the opportunity cost of time. The key conclusions derived in section 3 are robust to a generalization of commuting costs which comprise both time and monetary costs, however. To see how generalized commuting costs affect the results it is instructive to assume that commuting costs are only in terms of time ('iceberg costs'). This extreme case is often chosen in theoretical treatments in order to include an urban sector in the simplest way. It is well-established that this extreme case of pure time costs comes with unsatisfactory implications, notably that an increase in the city productivity shifter $B$ does not affect city size (e.g. Duranton and Puga 2004).[21] This unsatisfactory implication carries over to our model extension involving the micro-founded pollution process considered in this paper.

[21] I have benefited from communication with Gilles Duranton concerning this point.

Moreover, it is immediately shown that a number of further and related unsatisfactory implications would emerge, notably that optimal city size is independent of the marginal disutility associated with pollution $\eta$.[22] The origin of these unsatisfactory implications lies in the fact that a city's net aggregate output is proportional to labor supply in the city when commuting costs are pure time costs (in contrast to the case where commuting costs are in monetary terms, cf. eq. (3)). However, this proportionality under pure iceberg commuting costs breaks when there are both time and monetary commuting costs. Hence, the logic of our main framework applies and we can conclude that the results derived in section 3 are robust to the case where commuting costs comprise both components, as is the case in practice (Duranton and Puga 2004).

**4.5 Other pollution sources.** The purpose of this paper is a conceptual one - to show that novel circumstances of city size distortion arise under (global) environmental pollution. To achieve this end it sufficed to use a parsimonious framework which was still rich enough to comprise two key sources of pollution in cities, production and commuting activity. It is nonetheless instructive to address further pollution sources. Start with emissions associated with households' good consumption. Fitting these into the analysis requires little more than a re-interpretation of the main framework. Models based on Ethier's (1982) micro-foundation can not only be cast in terms of final goods being assembled from specialized productive intermediates as in section 2. Final outputs have alternatively been framed as CES-goods baskets consisting of a variety of consumer goods (e.g. Egger and Kreickemeier 2012). Seen from the latter angle our analysis can immediately be understood as a case where consumption is associated with emissions. A further pollution source are emissions associated with housing through energy use for heating and electricity, as highlighted by Glaeser and Kahn (2010). The benchmark model owes much of its tractability to the assumption that households inelastically consume 1 unit of housing and that housing services do not consume other resources than land.[23] One conceivable extension would be to bring in the Muth-Mill competitive construction sector that uses land and emissions (possibly in addition to capital, see Brueckner 1987). If formalized with the abatement technology inspired by Copeland and Taylor (2003), see section 2, we would expect that the mechanics driving the results in section 3 are simply reinforced, however, the

[22] A standard specification assumes that a commute to and back from the CBD reduces a consumer's unit working time by $2\,\psi\,r_i$, where $\psi > 0$ is a commuting cost parameter. The effective labor supply in the city with $N_i$ consumer-workers is then $L_i = N_i(1-\psi N_i)$ (cf. Duranton and Puga 2004) and the city's net aggregate output becomes $Y_i^{Net}(N_i, E_i) = B\,{E_i}^{\rho(1+\sigma)}\,[N_i(1-\psi N_i)]^{(1-\rho)(1+\sigma)}$. The optimal city size and the local government solution are then $N_i^{SP} = \frac{\sigma}{\psi[(2\sigma+1)-\rho(1+\sigma)]}$ and $N_i^{LG} = \frac{\sigma-\rho(1+\sigma)}{\psi[(2\sigma+1)-2\rho(\sigma+1)]}$, respectively (see Pflüger 2018).

[23] Borck and Pflüger (2019) consider an extension to endogneous lot sizes.

reason being that the positive externality associated with city choice still prevails. Undoubtedly, a final important source of pollution in city systems are emissions associated with transport across cities. This trade is assumed to be costless in our analysis in conformance with the research building on Henderson (1974) up to the most recent seminal extensions of that model, and this assumption has for long been identified to be a 'weakness' of that model.[24] The present analysis is similarly stuck with this assumption. We have addressed such trade costs squarely in other work, however.[25]

## 5 Conclusion

Are cities too small or too big? A popular current line of thought views cities as rather being too small than too big, in particular in countries such as China, but also in the USA (e.g. Au and Henderson 2006; Desmet and Rossi-Hansberg 2011; Albouy et al. 2019). We focus the analysis on the case that activities in cities involve 'global' environmental pollution. National governments address this externality with permits or emission taxes, local governments care (only) about the size of cities. We use a model of city systems in the tradition of Henderson (1974) with an endogenous number of cities and micro-foundations for urban structure, for the agglomeration process, and, crucially so, for the process of pollution and pollution abatement. Our analysis delivers two key insights. First, if the national government implements a permit system (equivalently, pollution taxes) that allow for emissions as in the first-best, cities chosen by local governments are too small. Second, if no emission scheme is implemented, or if emission policies are too lax, cities steered by local governments may become too large. Our micro-founded model also allows us to scrutinize further dimensions of the interplay between locally and nationally chosen policies, in particular a second-best policy and political economy circumstances where the proceeds from a national emission policy are wasted, and we consider extensions to city asymmetries, generalized commuting costs and further pollution sources. Avenues for future research include the heterogeneity of agents (consumer-workers), the competitive choice of environmental policies and extensions of the model to a dynamic setting.

[24] Duranton and Puga (2000) elaborate on this point. Behrens et al. (2014) and Albouy et al. (2019) are important recent extensions of the Henderson (1974) framework that exemplify this no trade cost assumption.
[25] Trade costs are key in the new economic geography, in contrast, and Borck and Pflüger (2019) highlight emissions associated with trade across locations in such a new economic geography framework.

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