Urban environmental externalities, agglomeration forces, and the technological ‘deus ex machina’

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Received 24 October 2005; in revised form 15 June 2006; published online 11 February 2008

Abstract. The aim of this paper is to analyze and depict urban equilibrium from the perspective of a complex force field between (positive) agglomeration economies and (negative) environmental externalities. Based on a simplified representation of a linear urban economy, a general-equilibrium model is designed and its properties are investigated by using numerical simulations. The model includes a spacious industrial centre, in which agglomeration externalities are differentiated over space, and a residential area that suffers from pollution, which is also differentiated over space. For the sake of simplicity urban environmental externalities are analyzed as being proportional to fossil fuel use, so that energy taxes would be a logical instrument. Environmental technology choice by firms is used as a tool for coping with environmental externalities, and is endogenized. Using this model we are able to generate interesting and sometimes surprising results for the city under consideration.

1 Towards an urban world

The historical evolution of our world is marked by a continual shift from a rural society to urban modes of living. According to UN estimates, the urban population worldwide has grown from approximately 15% in 1900 to 55% in 2000 (with large differences between the developing and the developed world). Also, even though in a recent book O’Sullivan (2000) points at uneasy, ambiguous, and sometimes controversial views on the benefits of urbanization, the worldwide trend towards further urbanization is undeniable. A growth in urbanization may manifest itself in two ways: a growth in existing cities (up to the level of megacities exceeding 10 million inhabitants, such as Mexico City and São Paulo) and the emergence of new cities (with a rapid population growth, either planned in a new town context or unplanned or spontaneous). Nowadays, both types of urbanization occur in parallel, with the result that in many countries the urbanization rate exceeds 70%.

Is there any reason why urbanization should come to a standstill? In the past, urban economists have tried to derive the optimal size of cities by minimizing the overall urban costs per inhabitant, and have tried to identify the conditions under which a city would face negative marginal net benefits from further growth. But reality has been rather harsh in that modern cities have never stopped growing. Of course, there have been temporary slowdowns and declines, but from a structural perspective it is noteworthy that urban areas (including suburban areas) have shown a remarkably stable growth pattern to the detriment of rural areas. Even the deurbanization (or counterurbanization) hypothesis has never exhibited a strong trend toward a global decline of cities (albeit with a few exceptions).

The city as a nucleus of human activity has generated many economies of density, most of them positive, but also some of them very negative (eg organized crime, environmental decay, traffic congestion). As a consequence we witness nowadays an increasing concern about the urban environment as part of the global sustainability debate (eg Stanners and Bourdeau, 1995). In the literature we find many debates about

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counterurbanization versus urban sprawl, and this reflects the fact that positive and negative externalities are preponderant forces with varying degrees of dominance. This ambiguity in the urban economics literature calls for a solid analytical economic framework that should comprise the essential characteristics of the urban economy, with particular emphasis on the forces that shape (dis)economies in urban activity patterns (see also Capello and Nijkamp, 2004). A prominent place should here be given to environmental externalities which may erode or even overrule agglomeration economies in the city.

Against this background we aim in this paper to present the fundamentals of an urban economic model encapsulating both scale economies and environmental externalities. The conditions for a more sustainable equilibrium can then be derived. A new element in the model is the inclusion of an energy-saving, and therefore pollution-reducing (ie environmental), technology, which might act as a remedy against urban environmental decline. Because environmental decline may also be reduced by adjusting input mixes in the urban economy, the model allows for complex (spatial) interactions between urban density, technology choice, environmental quality, and agglomeration effects. A further extension of this model might imply that scale economies in the abatement sector may also emerge, suggesting that city size offers an appropriate platform for increasing returns to scale in abatement activities. This phenomenon may affect the conditions for sustainable urban development towards a larger city size. Our model will be illustrated by some sample numerical simulations. Before outlining the contours and the specifications of our model, we will offer in the next section a concise overview of recent contributions to the analysis of the urban environment.

2 In search of sustainable cities

Urban environmental problems are not a policy concern exclusive to modern times, but have played a role ever since the emergence of human settlements (see Banister et al, 1999). The scale and intensity of environmental decay is, however, increasingly recognized as a major threat to a healthy urban future. In particular, after the publication of the Brundtland Report (see WCED, 1987) we have witnessed an increasing interest in environmental (and climatological) policy issues, not only worldwide but also locally. The avalanche of sustainability studies (for example, see Van den Bergh, 1996 for an overview), has also called for a renewed interest in urban environmental quality (see, for example, Banister et al, 1997; Breheny, 1992; Capello et al, 1999; Finco and Nijkamp, 2000; Haughton and Hunter, 1994; Nijkamp and Perrels, 1994; Selman, 1996; Pearce, 1999; Satterthwaite, 1997; 2000).

At present, two strands of literature on urban sustainability may be distinguished. The first class of contributions stems from urban ecology and looks at sustainable cities from the perspective of a multidimensional set of environmental, social, and cultural quality indicators of cities. In this category one also finds such concepts as the green city, the garden city, and the eco-city. Often, reference is made to the compliance with a priori specified threshold values (such as carrying capacity, noise levels, critical emission levels etc). These ideas have gained much interest in such policy circles as the Local Agenda 21 and OECD. Admittedly, urban sustainability is often a vaguely defined concept, so that its actual meaning in a policy context remains inconclusive. In general, the concept refers to a city with a sufficient degree of broadly defined environmental quality under conditions of economic efficiency.

Another class of interest in urban sustainability originates from the urban economics literature. Most emphasis is laid here on efficiency principles in a rather abstract way. There are, however, some notable exceptions. For example, almost two decades ago, Orishimo (1982) had already demonstrated that city size is related to urban

environmental qualities, while the actual externalities are determined by urban land use, the urban transport systems, and the urban way of life. It should be noted that cities are not the sole sources of environmental decay. In fact, cities provide a wide range of promising possibilities for energy-efficiency activity patterns (eg district heating, public transport, and shortened travel distances), environmentally benign modes of production (eg combined heat and power and waste water treatment), and consumption (eg solar energy and insulation of apartment buildings). From this perspective a city may be seen as an efficient way of spatially organizing human activity. Any other spatial organization of our world is likely to be less efficient from economic, environmental, and energy angles.

Clearly, the negative externalities are most visible to the public, and it is therefore no surprise that a 'flight to the suburbs' (urban sprawl or a movement to green areas) has taken place. But, nevertheless, cities have tried to turn the tide by various rehabilitation and recovery programmes, and surprising successes have been achieved in various cases. In an interesting article entitled "Are cities dying?" Glaeser (1998) raises the question of whether cities will survive, not only from an economic perspective but also from social and environmental perspectives, and emphasizes the importance of agglomeration economies (for example, in the urban labour market and in the urban ICT sector) as a natural key force for continued urbanization. The city is the place 'par excellence' for spillovers of communication and information and hence for learning economies (see Cohen and Paul, 2005). Clearly, there are also diseconomies (such as congestion, pollution concentration, diseconomies of density, crime, urban anonymity etc). It is a challenge of urban policy to strike a balance between such conflicting forces. For the time being there is no reason to believe that cities will vanish, but such a belief ought to be substantiated by a firmer economic and less anecdotic foundation. The role of modern technology—and perhaps that of network organization—ought especially to be given more prominent attention (see, for example, Evans and Wurster, 2000; Mokyr, 1990; Wigand et al, 1997). An important concern is, however, that not all cities will survive to the same extent and not all will flourish in terms of equal economic and environmental opportunities. The attention and public investment that is needed for furthering promising agglomeration economies are, together, a *sine qua non* for urban sustainability. But mapping out all the forces at work in a consistent economic way is a major challenge, particularly because each model of the urban economy tends to become immediately extremely complex, so that its analytical properties can hardly be traced anymore. Therefore, there is a need for a simple yet rich model that is able to offer a somewhat representative mapping of a complex sustainable city. Such a model will be presented in the next section.

3 A spatial general-equilibrium modelling framework for studying agglomeration and environmental externalities in an urban context

3.1 Introduction

It is clear from the discussion above that the analysis of the sustainability of cities—and of environmental policies for cities—requires a rather complex conceptual framework. Not only are there different, often counteracting, forces at work (eg positive external effects such as agglomeration externalities and technological spillovers versus negative ones such as environmental externalities), but, in addition, these typically vary in intensity over space. Indeed, if this were not the case, an important *raison d'être* for cities would be eliminated. For instance, if agglomeration advantages did not fall somewhat with the distance to other producers, there would be less or even no reason for firms to cluster together and pay high land rents in a dense city centre. The conceptual framework should therefore be capable of dealing with the spatial dimension.

Furthermore, as sustainability (typically) refers to a long-term goal, a partial-equilibrium analysis may be problematic because it would ignore long-term indirect effects of environmental policies on, for instance, land rents, on urban labour-market conditions, and on the resulting repercussions on input choice in the sector considered. A general-equilibrium approach seems preferable, especially if the environmental externalities caused by firms are directly related to one or more of the inputs used—as will be assumed in our model.

The analytic framework for formalizing the issues raised in the previous sections, which will be presented in this section, therefore concerns a continuous-space urban general-equilibrium model. Given the inherent complexity of this type of model, we will have to make many simplifying assumptions merely to keep the exercise manageable and the results interpretable. We therefore emphasize here that the key purpose of the model is to describe a continuous-space system that captures what we consider to be essential aspects of the problem at hand—environmental externalities, agglomeration externalities, input substitution, environmental technology choice, and general equilibrium, all from a spatial perspective—in the most basic form, and to map out the possible consequences of environmental policies in such a system. The model is not intended to describe a realistic city—it is intended only to describe and analyze economic principles that would be relevant in a realistic city, in a coherent framework. The inclusion of multiple externalities in an urban general-equilibrium setting is not new; for example, Anas and Kim (1996) and Anas and Xu (1999) consider agglomeration externalities versus congestion externalities.

The model builds upon the earlier work of Verhoef and Nijkamp (2002; 2004) and Verhoef (2005).⁽¹⁾ In the first of these the trade-off between agglomeration economies and environmental externalities was investigated extensively. In the present model we have a considerably richer representation of the production sector, especially because we drop the assumption of a spaceless industrial district, we consider agglomeration externalities as a spatially differentiated phenomenon, and because we introduce endogenous technology choice of firms in modelling their energy-saving behaviour. At the same time, the model described in this paper has a much simpler representation of the residential sector and households' decision making; here we will assume fixed labour supply and also assume that residential lot sizes are given. The second paper cited above (Verhoef and Nijkamp, 2004) combines the simpler production structure and spaceless central business district from Verhoef and Nijkamp (2002) with environmental externalities that do not arise from production, as in this paper, but instead from commuting. Finally, Verhoef (2004) considers congestion externalities, instead of environmental externalities, from commuting in an otherwise similar analytical setting, focusing especially on second-best policies such as flat kilometre charges and cordon pricing. Because these models are closely related, our exposition in section 3 closely follows those in Verhoef and Nijkamp (2002; 2004) and Verhoef (2005).

Some introductory remarks are needed. First, z will be used to denote a one-dimensional continuous urban space. Our model will produce a symmetrical city. Unless otherwise explicitly stated we will be considering only one half of this city in the knowledge that the other half will be identical. The (endogenously determined) centre of the central industrial district (CID) defines $z = 0$ (without loss of generality), and the CID stretches to the endogenously determined boundary with the suburban residential district (SRD), denoted as $z^\#$ (the spatial demarcation of industrial production and the residential area is thus not assumed beforehand, but will follow endogenously). At the separation point, $z^\#$, the equilibrium industrial and residential

⁽¹⁾ The exposition of the model in this section therefore follows those in Verhoef and Nijkamp (2002; 2004) and Verhoef (2005).

'bid rents'⁽²⁾ r_I and r_R must be equal and must cross each other, following the standard rule that, in a competitive equilibrium situation, land should go to the highest bidder. The SRD stretches from $z^\#$ to z^* , with z^* being the a priori unknown endogenous city boundary. At z^* the equilibrium residential bid rent, r_R , must be equal to the exogenous and constant agricultural bid rent, r_A , for the same reason as above. In equilibrium no household would have an incentive to move beyond z^* , as this would increase commuting costs without reducing land rent. Neither would a firm or household have an incentive to move to the SRD or CID, respectively, as the prevailing rent would be higher than their bid rent. Moreover, within the CID, profits must be constant over space in equilibrium, and equal to zero because of our assumption of perfect competition. Within the SRD, utility must be constant over space. Both imply that the actual equilibrium rent r should be equal to the bid rents r_I in the CID and r_R in the SRD. These conditions, too, reflect the idea that, in a spatial equilibrium with endogenous land prices, no economic actor would have an incentive to relocate and could benefit from outbidding another actor occupying a certain lot. The equilibrium land rent is therefore given by $r(z) = \max\{r_I(z), r_R(z), r_A\}$.

It is assumed that all excess urban land rents above r_A are redistributed among the city's population. Alternatively, we could have used the 'absentee landlord assumption', which would seem less realistic because it assumes that none of the land rents generated in the city would be used for consumption in the city. It would also be implausible to assume that *all* land rents generated in the city are redistributed among the population, as this would imply that the endogenous city size can be expanded costlessly from the overall city's perspective. The present representation would correspond to a situation where the public authority of the city buys the urban land against the relatively low rural land price, implying an equivalent per-unit-of-time price of r_A , and redistributes all excess rents generated in the city among its population. This is a convenient assumption in the sense that it easily allows us to consider households with identical initial endowments. Similarly, it is assumed that all (environmental) tax revenues generated in the city, X , are redistributed in a uniform, lump-sum way among the population.

Next, we turn to the resource and environmental sector in the city. Pollution in the CID is assumed to result proportionally from the use of one of the inputs—energy. We thus assume that urban pollution is the result of fossil fuel use, so that energy consumption is a critical variable. Doing so is the simplest way of allowing consideration of both technology choice and input choice as sources of environmental improvement, where the latter is expected to have a more direct impact on urban land use than the former, insofar as land is another input in the production process. Like land, energy is also bought against a given price on a competitive market with a perfectly elastic supply. The same holds for environmental technologies, which are assumed to be of a pure energy-saving nature and thus to simultaneously affect both the internal (energy) costs of a firm and—via the proportional relation—the external costs resulting from the pollution emitted. These technologies are assumed not to be produced within the city itself, but to be offered against an exogenous price in the 'rest of the world'. Some share of the urban production will therefore not be consumed in the urban area, but will be exported in exchange for the energy input, environmental technologies, and for the purchase of urban land—both industrial and residential—against the agricultural rent. Some final assumptions and remarks are to be made: all consumers and producers are assumed to be 'price takers'; households are identical, and so are firms;

(2) The bid rent is defined as the maximum rent a firm or household can pay per unit space at different locations in order to obtain the maximum profit level (for firms, typically zero) or utility level (for households) that is achievable in the city.

the industrial product can be transported costlessly; the price of the industrial good can be used as the numéraire. However, since the ‘terms of trade’ for agricultural land, the energy input, and environmental technologies are also assumed to be exogenous, four prices can be set beforehand. We will now turn to the various actors in the city and the resulting equilibrium issues.

3.2 Consumers

Our closed city has N households, which we will treat as a continuum of single economic entities. A household’s utility U depends on the consumption of the industrial good, y , on the consumption of space or the size of the residence, s , and on the environmental quality, q . A household’s financial budget consists of the endogenous wage rate multiplied by the fixed amount of labour supplied per household (which we set at unity), plus the redistributed excess urban land rents. In equilibrium this budget is fully spent on the consumption of y and s . All prices are treated parametrically by the (price-taking) households; w denotes the wage rate, p denotes the price of the industrial good, and $r(z)$ denotes the rent. Commuting does not require financial outlays, but it does cost time at a given rate t (there is no congestion). We make this simplifying assumption to avoid having to include a market for commuters’ transport in our general-equilibrium framework. Also, strictly for convenience, we will ignore differences in commuting distance to firms whose locations within the CID actually differ (also, wages will be assumed to be equalized within the CID). We simply assume that all commuters travel to the centre of the CID, so that the total commuting time $T_c(z)$ is equal to tz . Finally, we assume that residential lot sizes s_R are given, so that there is no substitution between the consumption of space and other consumption goods. This is, of course, also a simplification, but it is not unprecedented: Mun et al (2003), for example, made a similar simplification in a monocentric model.

The fact that labour supply and space consumption are exogenous leads to a trivial household’s optimization problem, which we present here only because we need it for the determination of equilibrium rents in the SRD. The household’s maximization problem is dependent on the residential location z , and can be written as follows:

$$\underset{y(z)}{\text{maximize}} U[y(z), s, T_c(z), q(z)], \quad (1)$$

such that

$$\frac{R + X}{N} + w - py(z) - r(z)s_R = 0,$$

where the excess urban land rents R are:

$$R = \int_0^{z^*} [r(z) - r_A] dz. \quad (2)$$

A spatial equilibrium requires that $U(z)$ is constant over z for all $z^\# \leq z \leq z^*$ (and is lower for all other z). Given the structure of the utility function and the spatial pattern of environmental quality $q(z)$, this implies a particular equilibrium pattern of land rents. We can be more explicit about this when postulating a specific form for the utility function. In the numerical model used below, we will be using a very convenient linearly additive structure (which can be used because all consumed quantities except y are determined exogenously):

$$U(z) = \alpha_y y(z) + \alpha_s s_R - \alpha_t tz + \alpha_q q(z), \quad (3)$$

where each α is a parameter. Note that, because of the assumed constancy of s_R , the term $\alpha_s s_R$ is a constant that could be dropped without loss of generality. The conditional demand for y follows directly from the constraint in equation (1):

$$y(z) = \left[\frac{R+X}{N} + w - r(z)s_R \right] / p, \quad (4)$$

and the indirect utility $V(z)$ —the maximum utility achievable under given prices and wage—can be written as:

$$V(z) = \alpha_y \left\{ \left[\frac{R+X}{N} + w - r(z)s_R \right] / p \right\} + \alpha_s s_R - \alpha_t t z + \alpha_e q(z). \quad (5)$$

The condition that $V(z)$ be constant over space implies that:

$$V'(z) = \alpha_y \frac{-r'(z)s_R}{p} - \alpha_t t + \alpha_e q'(z) = 0, \quad (6a)$$

which implies that the slope for the residential bid-rent gradient is:

$$r'_R(z) = \frac{p[-\alpha_t t + \alpha_e q'(z)]}{\alpha_y s_R}, \quad (6b)$$

With a linear decay function for the effect of CID pollution on environmental quality $q(z)$, as we are assuming for the sake of convenience, equation (6b) will be constant over z , implying that the equilibrium rent gradient must be linear in the SRD. A 'compact' city requires equation (6b), and hence its numerator, to be smaller than zero; the per-unit-of-distance change in commuting disutility should outweigh the change in environmental disutility. The location and size of the SRD, given $r_1(z)$ and r_A , is then defined by the solution of the following two equations in $z^\#$ and z^* :

$$\frac{z^* - z^\#}{s_R} = N, \quad (7a)$$

and

$$r_A + r'_R(z^\# - z^*) = r_1(z^\#). \quad (7b)$$

Equation (7a) secures that the SRD, between $z^\#$ and z^* , is just sufficiently large enough to provide room for N households that each use s_R units of space. Equation (7b) stipulates that, at $z^\#$, the residential bid rent on the left-hand side will be equal to the industrial bid rent on the right-hand side. Given this solution for $z^\#$ and z^* from equation (7a) and equation (7b), the equilibrium rent in the SRD is most easily written as:

$$r(z) = r_R(z) = r_A + r'_R(z - z^*), \quad \forall z^\# \leq z \leq z^*. \quad (8)$$

Labour supply is fixed at the population size:

$$L^S = N. \quad (9)$$

The total consumption of the industrial product Y should satisfy

$$Y = \int_{z^\#}^{z^*} \frac{y(z)}{s} dz. \quad (10)$$

Finally, we define environmental quality such that a virgin state corresponds to $q = q^V$. Denoting the environmental quality at the edge of the CID as $q(z^\#)$, to be defined as a function of emissions in equation (20) below, a spatially differentiated externality can be represented by making $q(z)$ an increasing function of both $q(z^\#)$ and z .

We will be using the following piecewise linear relation:

$$q(z) = \min\{q^V, q(z^\#) + q^0(z - z^\#)[q^V - q(z^\#)]\}, \quad \forall z > z^\#, \quad (11)$$

where q^0 is a parameter. We thus assume a linear distance-decay relation for the impact of every unit of pollution that appears at the edge of the CID upon environmental quality as long as this is below the virgin-state quality. The impact of every such unit upon utility will therefore have vanished completely at a distance $1/q^0$ from $z^\#$, which is independent of $q(z^\#)$, and at which the virgin state is therefore always reached. Throughout the paper—including the derivation of equation (7a)—equation (8)—we will assume that $q(z^*) < q^V$ and therefore $z^* - z^\# < 1/q^0$, so that a strictly linear function $q(z)$ can be used.

3.3 Firms

There is a continuum of firms, each of which is infinitesimally small relative to the market and takes all prices as given. The industrial output is homogeneous, and agglomeration externalities in our model thus arise from a more efficient production that occurs when the scale of aggregate production increases. The agglomeration benefits enjoyed are assumed to be dependent on the firm's location relative to that of others, and are summarized in an efficiency measure $a(z)$. An individual firm takes the equilibrium pattern of $a(z)$ as given, but $a(z)$ is endogenous on the city level, which represents the existence of external agglomeration economies.

Firms have a constant elasticity of substitution (CES) production technology with three inputs (labour, energy, and space), which allows us to consider input substitution. Because a firm's production function is assumed to exhibit constant returns to scale it qualifies for application of Euler's theorem. The proof would follow that found in Chiang and Wainwright (2005, page 385–386), with the production function multiplied by $a(z)$, which is treated as given by the price-taking firm. Therefore, when the urban aggregate production function exhibits increasing returns to scale due to agglomeration externalities, but these increasing returns are entirely external to the firms, we can model the firms' behaviour using a 'derived production function' with constant returns to scale, in which the efficiency measure $a(z)$ is treated parametrically. The following derived aggregate production function $\theta(z)$ applies:

$$\theta(z) = a(z) \{ [\delta_L l(z)]^\rho + [\delta_E g(z)]^\rho + [\delta_S s(z)]^\rho \}^{\frac{1}{\rho}}, \quad (12)$$

where $l(z)$ is the labour input, $g(z)$ is the generalized energy input (a bundle of pure energy and energy technology—see below), and $s(z)$ is the land input; δ_L , δ_E , δ_S and ρ are parameters (at least at the firm level), where ρ ($\rho \neq 0 \leq 1$) defines the elasticity of substitution σ according to $\sigma = 1/(1 - \rho)$. In particular, $\rho = -\infty$ corresponds to a Leontief production function, $\rho = 1$ corresponds to a linear production function, and the limit of $\rho \rightarrow 0$ would reproduce a Cobb–Douglas production function. A convenient parameter often used when working with CES production functions is $\pi = \rho/(\rho - 1)$, which we too will be using below.

Verhoef and Nijkamp (2002) consider two different types of agglomeration economies for the nonspatial CID that they examine: one in which the nonlocalized efficiency measure A increases in aggregate production Q ('type- Q agglomeration economies') and one in which it increases in aggregate labour supply L ('type- L agglomeration economies'). Both formulations have been used in the literature. Sullivan (1986), for instance, uses type- Q agglomeration effects, whereas Arnott (1979) and Fujita (1989, section 8.2) use type L .

In our present model we will consider ‘type- Q agglomeration economies’ only. As stated we will assume that these depend on a firm’s location relative to that of others. Specifically, the agglomeration economies enjoyed are assumed to increase in proximity-weighted total production, which we represent by using the following specification:

$$a(z) = a^0 + a^1 \left[\int_0^{z^\#} \frac{\theta(x)}{(a^2 + |z - x|)^{a^3}} dx + \int_0^{z^\#} \frac{\theta(x)}{(a^2 + |z - x|)^{a^3}} dx \right],$$

with $a^0 = a_0^0 + a_{\text{CID}}^0$, (13)

where $a^0 - a^3$ are parameters. The first of these, a^0 , represents the efficiency that would be obtained by a firm producing in the CID when agglomeration externalities were absent, and thus reflects the efficiency that would be obtained by a firm that would produce in complete isolation (a_0^0), in addition to factors such as the quality of the CID’s transport and communication infrastructures, (not formally modelled) service sectors etc (a_{CID}^0). The parameter a^1 gives the relative importance of proximity-weighted production, given by the terms enclosed by the square brackets in equation 13). These two terms distinguish between firms on one’s own side of the CID (the first term) and those on the other side (the second term). Note that this is an instance where one has to consider the second half of our city as well, or one would identify the wrong location as that with the highest $a(z)$. Otherwise, these two terms reveal that production elsewhere in the CID is weighted by the inverse of distance raised to some power a^3 to determine the impact on $a(z)$.

The function $a(z)$ therefore, in a simple but conceptually appealing way, reflects spatially differentiated production-dependent agglomeration externalities as occurring in the CID, which may be the result of all sorts of technology and knowledge spillovers as they may occur between firms that cluster in space. For reasons of analytical and numerical simplicity, these spillovers are lumped together in a single, one-dimensional space-varying efficiency measure. Despite the resulting artificial and conceptual nature of the resulting measure $a(z)$, we believe this is a meaningful way of endogenizing agglomeration externalities in a spatial general-equilibrium model of perfect competition.

The following conditional input demand functions can be derived when solving the firms’ cost minimizing problem under the constraint implied by the production function in equation (12):

$$l(z) = w^{\pi-1} \delta_L^{-\pi} \left\{ \left[\frac{w}{\delta_L} \right]^\pi + \left[\frac{p_g}{\delta_E} \right]^\pi + \left[\frac{r(z)}{\delta_S} \right]^\pi \right\}^{-\frac{1}{\pi}} \frac{p(z)}{a(z)}; \quad (14a)$$

$$g(z) = p_g^{\pi-1} \delta_E^{-\pi} \left\{ \left[\frac{w}{\delta_L} \right]^\pi + \left[\frac{p_g}{\delta_E} \right]^\pi + \left[\frac{r(z)}{\delta_S} \right]^\pi \right\}^{-\frac{1}{\pi}} \frac{p(z)}{a(z)}; \quad (14b)$$

$$s(z) = r(z)^{\pi-1} \delta_S^{-\pi} \left\{ \left[\frac{w}{\delta_L} \right]^\pi + \left[\frac{p_g}{\delta_E} \right]^\pi + \left[\frac{r(z)}{\delta_S} \right]^\pi \right\}^{-\frac{1}{\pi}} \frac{p(z)}{a(z)}; \quad (14c)$$

where p_g gives the price of the generalized energy input. As stated, the generalized energy input is composed of a ‘pure energy’ part, denoted E , and a technology part, denoted T . We assume that these two inputs are purchased against given prices p_E and p_T on the world market, and that they can be combined in a constant-returns-to-scale Cobb–Douglas production function to produce the generalized energy input g . This gives us an intuitive formulation that enables us to study substitution between pure energy and energy saving technologies that may occur in response to regulatory policies. Note that this formulation makes sure that the overall bilayered production

function still exhibits constant returns-to-scale, as required for our assumptions of perfect competition and zero profits.

The generalized energy input is thus produced according to

$$g(z) = E(z)^\varepsilon T(z)^{1-\varepsilon}. \quad (15)$$

The conditional demand functions for E and T can again be derived from the cost-minimization problem, and read

$$E(z) = \frac{\varepsilon}{p_E + \tau_E} \left(\frac{p_E + \tau_E}{\varepsilon} \right)^\varepsilon \left(\frac{p_T}{1-\varepsilon} \right)^{1-\varepsilon} g(z); \quad (16a)$$

$$T(z) = \frac{1-\varepsilon}{p_T} \left(\frac{p_E + \tau_E}{\varepsilon} \right)^\varepsilon \left(\frac{p_T}{1-\varepsilon} \right)^{1-\varepsilon} g(z); \quad (16b)$$

where τ_E denotes the (uniform) energy tax that the urban regulator will be assumed to use to affect energy consumption and hence pollution in the CID. The total tax revenues generated with this tax τ_E are given by

$$X = \int_0^{z^\#} \tau_E \frac{E(z)}{s(z)} dz. \quad (17)$$

From equations (16a) and (16b), it can be inferred that the generalized energy price p_g perceived by a firm—given that it selects the cost-minimizing input combination $E(z)$ and $T(z)$ —is indeed independent of its location z [as used in equations (14a)–(14c) above], and can be written as

$$p_g = \left(\frac{p_E + \tau_E}{\varepsilon} \right)^\varepsilon \left(\frac{p_T}{1-\varepsilon} \right)^{1-\varepsilon}. \quad (18)$$

In a similar way, the average costs that can be derived from equations (14a)–(14c), in combination with the zero-profit condition and the constancy of prices over the CID, imply that the following condition should hold:

$$p = \frac{1}{a(z)} \left\{ \left[\frac{w}{\delta_L} \right]^\pi + \left[\frac{p_g}{\delta_E} \right]^\pi + \left[\frac{r(z)}{\delta_S} \right]^\pi \right\}^{\frac{1}{\pi}}, \quad \forall 0 \leq z \leq z^\#. \quad (19)$$

Equation (19) shows that $r(z)$ cannot be constant over space in the CID in equilibrium when $a(z)$ is not constant—which it generally will not be by equation (13).

From equation (16a), assuming that pollution is proportional to the use of the pure energy input with a factor e and that from the point of emission the decay of the environmental externality immediately sets in, $q(z^\#)$ can be written as

$$q(z^\#) = q^V - \int_0^{z^\#} e \frac{E(z)}{s(z)} [1 - q^0(z^\# - z)] dz. \quad (20)$$

Note that we assume that pollution moves only one way in our one-dimensional model, namely from the point of emission to the SRD. This is not an essential assumption, but it does imply that we ignore the impact of emissions from the implicit ‘other half of the CID’ for the SRD we have modelled. For a fully symmetric ‘complete’ city this assumption would correspond with the situation where the emitted pollutant would disperse exclusively by flowing from a point with a high concentration ($z = 0$) to points with lower concentrations, so that emissions from the one side of the CID would, indeed, never reach the SRD on the other side of the city. Clearly, other assumptions on the nature of dispersion and decay of pollutants could be made just as well in our model.

Total production Q , total labour demand L^D , total energy use G and its components E and T , and total land use S by the industrial sector can be written as

$$Q = \int_0^{z^\#} \frac{\theta(z)}{s(z)} dz; \quad (21a)$$

$$L = \int_0^{z^\#} \frac{l(z)}{s(z)} dz; \quad (21b)$$

$$G = \int_0^{z^\#} \frac{g(z)}{s(z)} dz; \quad (21c)$$

$$E = \int_0^{z^\#} \frac{E(z)}{s(z)} dz; \quad (21d)$$

$$T = \int_0^{z^\#} \frac{T(z)}{s(z)} dz; \quad (21e)$$

$$S = \int_0^{z^\#} \frac{s(z)}{s(z)} dz \equiv z^\#. \quad (21f)$$

Finally, equilibrium on the labour market requires that

$$L^D = L^S = N. \quad (22)$$

3.4 General spatial equilibrium

It will not come as a surprise that the system described above has no easily manageable closed-form analytical solutions. There are fourteen unknown scalar variables ($z^\#, z^*, Y, q(z^\#), X, p_g, w, Q, L^S, L^D, g, E, T, S$) for which an equal number of (linearly independent) equations are available (7a–7b, 10, 20, 17, 18, 22, 9, 21a–21f); and there are twelve unknown functions of z [$(y(z), V(z), r_R(z), q(z), \theta(z), a(z), l(z), g(z), s(z), E(z), T(z), r_I(z))$] in the same number of equations (4), (5), (8) [after substitution of (6b)], (11), (12), (13), (14a)–(14c), (16a)–(16b), (19)]. Finding a general equilibrium requires a solution for the above twenty-six unknowns, satisfying the set of twenty-six equations mentioned (note that, of course, neither the existence nor the uniqueness of an equilibrium is guaranteed by the equality of equations and unknowns).

The constant-returns-to-scale assumption in the bilayered production function furthermore guarantees that Euler's theorem applies, which means that all inputs can indeed be paid their marginal value productivity without running into economic losses or profits for the firms. As the tax revenues and excess rents (above r_A) are redistributed among the population, the trade balance condition and exhaustion of income for consumptive purposes will also be satisfied. To see why, first observe that a balance of trade would require

$$p(Q - Y) = r_A z^* + p_E E + p_T T, \quad (23a)$$

and that the aggregate zero-profit condition implies:

$$pQ = \int_0^{z^\#} [r(z) - r_A] dz + r_A z^\# + wN + p_E E + p_T T + X. \quad (23b)$$

Households spend the total wage sum wN plus the sum of tax revenues and excess rents on the consumption of the industrial product and on the consumption of

residential land:

$$wN + \int_0^{z^*} [r(z) - r_A]dz + X = pY + \int_0^{z^*} [r(z) - r_A]dz + r_A(z^* - z^\#).$$

(23c)

Substitution of equation (23c) into equation (23b) immediately yields equation (23a). One condition for a spatial equilibrium with a compact city was already discussed in section 3.1: the residential bid rent should be negatively sloped. for the assumed monocentric city to be stable, the profits attainable for production outside the CID must be negative. Because we want to maintain focus on a monocentric city, we will simply assume that this is the case; that is, that the equivalent of a^0 applying outside the CID (for instance, ‘only’ a_0^0) is sufficiently low to prevent profits from being positive in absence of agglomeration externalities at equilibrium land rents. It is clear that endogenization of this condition in the current model would allow us to study the formation of subcentres in the same modelling framework—an issue that we do not want to include in the present exposition, but wish to postpone until future work. We will not engage in a further inquiry into the existence, uniqueness, and properties of equilibria of the formal model, but instead turn to a discussion of the results of a simulation model that was built fully consistent with the above model, and that allows a more insightful exposition of the properties of the model.

4 A numerical simulation model

4.1 Parametrization and base-case equilibrium

The numerical simulation model represents a fully imaginary city that operates exactly according to the model developed in section 3. The set of equations defining equilibrium was solved using the rather intuitive economic logic of starting with an exogenously defined disequilibrium and then equilibrating markets one by one (sometimes in loops) until the convergence criteria were met. The appendix describes the solution method in somewhat more detail. Table 1 shows the parameter values chosen. These were set such that the interpretation of results is made as easy as possible, by creating as much ‘balance’ as possible in the parametrization of the utility and production functions.

The base case of our model concerns the market equilibrium in absence of environmental taxation (that is, $\tau_E = 0$). Table 2 shows the equilibrium values of the main endogenous (scalar) variables for the parametrization in table 1. Given the conceptual character of the model, most of these equilibrium values have no particular meaning for a single equilibrium considered in isolation, but will become relevant only when performing comparative static analyses, for instance, when comparing the base-case equilibrium to one that results with environmental taxation. The only variables that do have some meaningful interpretation as characteristics of the base case are the following: income shares, showing that 74% of the available money income is spent on industrial goods and the rest is spent on land rents; factor shares, showing that 30% of the total

Table 1. Parametrization of the numerical model.

Prices	Utility function	Upper layer production function	Lower layer production function	Environmental externalities function	Agglomeration externalities function	Other
$p = 1$	$\alpha_y = 1$	$\rho = -0.35$	$\varepsilon = 0.5$	$q^V = 1$	$a_0^0 = a_{CID}^0 = 0.5$	$N = 250$
$p_E = 0.1$	$\alpha_s = 1$	$\sigma = 1/(1 - \rho) = 0.74$		$q^0 = 0.005$	$a^0 = 1$	$s_R = 0.5$
$p_T = 0.1$	$\alpha_t = 1$	$\pi = \rho/(\rho - 1) = 0.26$		$e = 0.001$	$a^1 = 0.15$	$t = 0.001$
$r_A = 0.1$	$\alpha_c = 1$	$\delta_L = 10$			$a^2 = 1$	
$\tau_E = 0$		$\delta_E = 10$			$a^3 = 1.5$	
		$\delta_S = 10$				

Table 2. Some key variables in the illustrative base-case equilibrium.

Prices	Utility	Upper layer production function	Lower layer production function	Agglomeration externalities	Size of the city
$w = 0.134$	$Y = 51.2$	$Q = 114$	$E = 186$	$a^{\text{av}} = 1.50$	$z^{\#} = 123$
$p_g = 0.200$	$q(z^{\#}) = 0.873$	$S = 123$	$T = 186$		$z^* = 248$
$r(z^{\#}) = 0.191$	$q(z^*) = 0.952$	$L = 250$			
$\tau_E = 0$	$U^{\text{av}} = 1.43$	$G = 186$			
Income shares: industrial goods (74%); housing (26%)					
Factor shares: labour (30%); energy (33%); space (37%)					
Factor shares (in energy): pure energy (50%); tax (0%); technology (50%)					

production costs concerns labour, 33% concerns the polluting input (energy), and 37% concerns land rents; the factor shares within the generalized energy input, showing an equal distribution between pure energy and technology; the fact that the average efficiency level a^{av} (averaged over production, not space) is 1.5, which is one-and-a-half times as much as the level that would be obtained without agglomeration externalities ($a^0 = 1$); and the fact that around 50% of the land is used for production and 50% is used for residential purposes.

The solid lines in figure 1 depict the space patterns of some of the model's key variables. Figure 1(d), for instance, shows the equilibrium pattern of $a(z)$, which reflects the efficiency-enhancing impact of proximity-weighted production. The intuitive feature that $a(z)$ obtains the highest value in the centre of the CID at $z = 0$, is reflected in the spatial pattern of land rents, which also reach a maximum at $z = 0$ [figure 1(a)]. The CID extends to the intersection with the residential bid-rent function. As required for

Figure 1. (a) Land rents (r), (b) utility (U) and profits (π), (c) environmental quality (q), and (d) the efficiency indicator (a) as a function of space (z) in the base-case equilibrium (solid lines) and the second-best optimum (dashed lines).

equilibrium, the industrial bid rent intersects the residential one from above at $z^\#$ (not shown in the figure, but easily identifiable), and the same again holds for the residential and agricultural bid rents at z^* (again not shown in the figure).

Two other important spatial-equilibrium conditions are depicted in figure 1(b); as required, utility U is constant over space (at the level $U^{\text{av}} = 1.43$ shown in table 2) within the SRD, and profits π are zero and (hence) constant over space within the CID. Finally, figure 1(c) shows that, as could be expected, environmental quality indeed increases over space, but nowhere in the city reaches the ‘virgin’ quality $q^V = 1$.

4.2 A second-best optimum: energy taxation

Evidently, our conceptual model is particularly useful for comparative static analyses, comparing the base-case equilibrium to equilibria as they would arise under some form of policy intervention, taking spatial general-equilibrium interactions fully into account. In this paper we consider one such policy, namely one that figures predominantly in the environmental economics literature: energy taxes. From the outset we emphasize that a tax on energy use is a second-best instrument in the current setting for two reasons. First, the model has two important externalities: apart from the environmental externality there is the agglomeration externality which means that the free market would most likely fail to achieve a Pareto efficient (spatial) equilibrium. Verhoef and Nijkamp (2002) studied the simultaneous regulation of environmental and agglomeration externalities. Second, due to the decay of pollution, a unit of energy used in the centre of the CID would lead to lower external costs in the SRD than a unit used near $z^\#$. Optimal pollution taxes would thus vary over space. Because we assume that the polluting input is taxed, and this can freely be traded within the CID, such spatial tax differentiation is impossible, and therefore a second type of second-best distortion enters the picture.

The value added by using a spatial-general equilibrium model for the analysis of the effects of such a policy instrument in an urban setting is justified particularly convincingly if even a simple conceptual model would lead to qualitatively different results than would be anticipated on the basis of ‘logical reasoning’, or simple partial-equilibrium models, be they spatial or not. Therefore we first give an intuitive reasoning of the qualitative effects of an energy tax in the present setting, which will next be proven wrong—or at least not necessarily correct—using the simulation model.

One would expect that a tax on the pure energy input would lead to a substitution away from pure energy to technology in the lower level production function (which indeed will be the case), and in the upper level production function away from the generalized energy input (which has become more expensive) to the other inputs—land and labour. The use of more land per unit of output for production would imply that the density in the CID decreases, leading to a reduction in beneficial agglomeration externalities. Moreover, the higher energy price would lead to a negative impact on total output, which would lead in turn to a reduction in the size of the CID. This would reduce agglomeration externalities even further. As in Verhoef and Nijkamp (2002), there would thus be a conflict between optimizing environmental externalities and agglomeration externalities, where the pursuit of the former goal would be at the expense of the latter.

Now, which are the ‘true’ effects of an energy tax in the present model? To that end, we first find the optimal level of the second-best energy tax. As there is no closed-form solution for the second-best energy tax, we found this by numerical search, namely by considering the equilibrium utility level as a function of the energy tax. Figure 2 shows that the optimal value is near $\tau_E = 0.09$ (visible irregularities in this and subsequent figures are due to numerical imprecision). Table 3 shows the same equilibrium levels of

Figure 2. Utility as a function of environmental taxation (τ_E) (normalized in base-case equilibrium).

Table 3. Some key variables in the second-best optimum.

Prices	Utility	Upper layer production function	Lower layer production function	Agglomeration externalities	Size of the city
$w = 0.069$	$Y = 35.3$	$Q = 72.2$	$E = 65.4$	$a^{av} = 1.69$	$z^\# = 53.3$
$p_g = 0.276$	$q(z^\#) = 0.944$	$S = 53.3$	$T = 124$		$z^* = 178$
$r(z^\#) = 0.280$	$q(z^*) = 0.979$	$L = 250$			
$\tau_E = 0.09$	$U^{av} = 1.49$	$G = 90.2$			
Income shares: industrial goods (60%); housing (40%)					
Factor shares: labour (24%); energy (35%); space (41%)					
Factor shares (in energy): pure energy (26%); tax (24%); technology (50%)					

endogenous variables for the second-best optimum as table 2 did for the base case, while the dotted curves in figure 1 depict the pattern of some key spatially differentiated variables in the second-best optimum. We reemphasize that parameters were not chosen to represent any realistic situation, but much more to create sufficient differentiation between equilibria so that, for instance, the curves in figure 1 lie sufficiently far apart. Note that this implies differences between the free-market and second-best optimal equilibria that would be considered unrealistically large by most readers (including ourselves).

The results show that in the second-best optimum, the use of pure energy has indeed been reduced, which is partly the result of a shift from pure energy towards energy-saving technologies, partly the result of using less of the generalized energy input per-unit-of-production, and partly the result of a lower equilibrium output level. We emphasize that this is not as obvious as might be expected, since the second-best tax could have been negative if the indirect effect on agglomeration externalities were negative and would have outweighed the beneficial direct impact on the environmental externality.

Figure 3 shows that as τ_E is raised the proportional decline in the pure energy input is the strongest among all inputs and outputs. The decline in the use of the generalized energy input is significantly smaller, which is consistent with the fact that

Figure 3. Inputs and outputs as a function of environmental taxation (τ_E) (normalized in base-case equilibrium).

the use of energy-saving technologies has a smaller decrease than that of overall output. The absolute use of the labour input has remained constant, which is the result of the general-equilibrium nature of the model in combination with the assumption of fixed labour supply. Consistent with a relative increase of labour per unit of output, the endogenous wage rate has decreased; see also figure 4 (recall that p , p_E , and p_T are exogenous).

Probably the greatest surprise in the results is that—contrary to expectation but consistent with the decrease in average land input per unit of product implied in figure 3, and the resulting increase in density in the CID (the average output per unit of space rises from 0.93 in table 2 to 1.35 in table 3)—the average-efficiency parameter a^{av} , as well as the levels of $a(z)$ shown in figure 1, increase. Intuitively, one might

Figure 4. Inputs as a function of environmental taxation (τ_E) (normalized in base-case equilibrium).

expect the opposite, namely a substitution of energy towards land, implying less dense land use in the CID instead, which, coupled with the reduction in the size of the CID due to the reduced output, would lead to a lower value of a^{av} . Also, if the substitution effect were dominated by the contraction in total output, so that a net reduction in land consumption remained, one would still expect this reduction to be smaller in relative terms than that in generalized energy—one would not expect the reduction to be larger, as shown in figure 3.

The explanation for the paradox is not so difficult in hindsight, but illustrates in a nice way the importance of using a spatial general-equilibrium framework for studying the type of questions under consideration here. What happens is the following. The improved environmental quality implies that the residential bid rent should become steeper for household equilibrium to hold. This reflects that more central housing locations have become relatively more attractive, as the benefits of reduced emissions increase when approaching the CID due to the assumed decay function. With a given agricultural land rent and a relatively inelastic demand for housing per household (perfectly inelastic in our model), this implies that $r(z^\#)$ must increase compared to the initial equilibrium—even before knowing the new equilibrium value of $z^\#$. As the general shape of $r_1(z)$ will not change, this in turn implies an upward shift of the $r_1(z)$ function. This will subsequently lead to a lower conditional demand for land for production, which increases density in the CID leading to higher agglomeration benefits (due to the assumed distance decay). This in turn will drive up CID land rents even further until a new equilibrium is reached. Also note that the wage rate has decreased by a large amount in the new equilibrium, so the anticipated initial substitution away from energy to land is more than compensated for by a substitution away from land towards labour.

Combined with the results from Verhoef and Nijkamp (2002), we may thus conclude that the question of whether pollution taxes reduce or stimulate agglomeration externalities in a monocentric city depends on the specific circumstances. Some key determinants include the following: the question of whether it is aggregate production or employment that determine the strength of agglomeration externalities; the substitution possibilities for consumers between land and other consumption goods that, together with the consumers' sensitivity to pollution, will codetermine the extent to which land rents near the CID's boundary will increase when environmental externalities are limited; the question of whether agglomeration externalities are more sensitive to the density of urban production or to its sheer scale; the output elasticity for the city's production; and the substitutability between various inputs in urban production.

5 Retrospect

We have presented above a conceptual spatial general-equilibrium model, and a numerical-simulation model based on this, for the purpose of demonstrating a number of points that we consider important for the study of the sustainability of cities. The conceptual nature of the model is an important aspect to be emphasized: the developed model is not intended to describe a realistic city—it is intended only to describe and analyze in a coherent framework the economic principles that would be relevant in a realistic city. The exposition above offered an example of how such a model could be built, and a discussion of the type of analysis that one could carry out with it.

We argued that a rather complex conceptual framework is required, and discussed the reasons why that is so. Not only are different, often counteracting, forces at work (eg positive external effects such as agglomeration externalities and technological spillovers *versus* negative ones such as environmental externalities), but these, in addition, typically vary in intensity over space. The conceptual framework should thus at least be

capable of dealing with the spatial dimension. Furthermore, as sustainability (typically) refers to a long-run goal, a partial-equilibrium analysis may be problematic—it would ignore long-run indirect effects of environmental policies on, for instance, land rents and on urban labour-market conditions, and also ignore the resulting repercussions on input choice in the sector that we have considered. Especially if the environmental externalities caused by firms are directly related to one or more of the inputs used—as assumed in our model—a general-equilibrium approach seems preferable.

The numerical example demonstrated the importance of using such a modelling framework for the analysis of environmental pollution in cities and associated policies. It is as simple as that—the more complex the real system one is dealing with, the less predictable its behaviour becomes. This implies that ‘loose reasoning’ only on the basis of intuitive arguments may cause one to make inferences that are opposite to what may happen in reality, when all mutual interactions between the system’s elements are taken into account. In our example it was found to be that environmental policies would not necessarily lead to a reduction in (average) agglomeration benefits, but that, in fact, the opposite may occur.

We have also tried to show that one can, in fact, get quite far in modelling spatial systems according to general-equilibrium principles. Despite the model’s simplicity, it is notable that it is seemingly not too difficult to construct a general-equilibrium framework for an urban economy in which both agglomeration and environmental externalities exist and vary over continuous space. Three inputs are used, including labour, which is supplied by households competing for the same land as producers. Also, (energy) technology choice is endogenous.

At the same time we are well aware of the limitations of the conceptual model presented here. For example, barriers to substitution in the production function were not considered. Among the long list of possible extensions, we would, for instance, list dynamics and heterogeneity (of firms and households, but also multisectoral urban economies, possibly with an R&D sector) high on our research agenda. Pollution by mobile sources, either within the city centre or from commuting (as in Verhoef and Nijkamp, 2004), would be interesting to include. Another interesting topic would be the spatial layout of ‘free-market’ versus ‘optimal’ cities, especially if multiple production (sub)centres are allowed for. In the same vein we might look into the question of multiple cities in a national system. Agricultural rents and cities’ populations might then become endogenous. Such spatial interactions would be very interesting but would lead to a rather complex multicity system. An entirely different strand of research would look into empirical evidence to try to identify the key economic forces that explain the existence of cities, to determine to which extent these forces are externalities, and, if they are, to see what the existence of such externalities would imply for the expected efficiency and desirability of environmental policies in cities. This would also call for a more precise and operational definition of urban sustainability, measured along several dimensions.

Acknowledgements. Part of the research of Erik Verhoef for this paper was made possible by a fellowship of the Royal Netherlands Academy of Arts and Sciences. We thank two anonymous referees for constructive and insightful comments.

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Appendix

Solution method

The numerical model was solved using a nested loop algorithm.

The inner loop solves the endogenous variables for the CID by taking its size and $r(z^\#)$ as given, and then calculating the derived input demands, then the implied $q(z)$, then $a(z)$, and then average production costs $ac(z)$. It then updates $r(z)$ to bring $ac(z)$ closer to p . It then returns to the calculation of derived input demands, and repeats this until convergence is reached. The criterion is that the relative change in labour demand should be less than 10^{-6} between successive iterations.

The outer loop calculates the environmental quality from the inner loop, then calculates the implied $r'(z)$, the implied $r(z^\#)$, and then the implied $z^\#$ and z^* . Next it adjusts the size of the SRD such that the cumulative labour supply becomes closer to its exogenous level. This is repeated until convergence is reached, which is defined by the condition that the relative deviation of the number of households, from its exogenous value, should be less than 10^{-6} .

The algorithm is slow, but convergent as long as it is not led into negative values for quantities and prices. It appeared to be robust for our model for changes in starting values so long as these avoided such negative values. No problems of multiple solutions were encountered.

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