

Feeding the Cities and Greenhouse Gas Emissions: A New Economic Geography Approach

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Abstract

'Buying local food' is sometimes advocated as a means of reducing the 'carbon footprint' of food products. This statement overlooks the trade-off between inter- and intra-regional food transportation. We investigate this issue by using an m -region, new economic geography model. The spatial distribution of food production within and between regions is endogenously determined. We exhibit cases where locating a significant share of the food production in the least-urbanized regions results in lower transport-related emissions than in configurations where all regions are self-sufficient. The welfare-maximizing allocation of food production does not exclude the possibility that some regions should be self-sufficient, provided their urban population sizes are neither too large nor too small.

Key words: Agricultural location; Transport; Greenhouse gas emissions; Food miles; Local food

JEL classification: F12; Q10; Q54; Q56; R12

1. Introduction

More than half of the world population lives in cities. With this share expected to keep growing (United Nations, 2010), urbanization may have major consequences for the sustainability of food supply chains (Wu et al., 2011). In this context, the impact of urbanization on energy use and greenhouse gas (GHG) emissions from the food transportation sector has emerged as a growing concern for public authorities. Promoting alternative 'local-food' systems (Sonnino and Marsden, 2006) and reducing 'food-miles' (Paxton, 1994) have become recurring themes in Climate Change Action Plans (Kampman et al., 2010). The rationale is that food production should be located closer to consumption centers so as to reduce reliance on food imports from distant regions, and to mitigate GHG emissions due to food transportation.

The objective of this paper is to examine the validity of these recommendations from a social welfare perspective. An essential feature of the impact of food systems on the environment is the trade-off between intra- and inter-regional trade. This trade-off has been largely overlooked to date. Yet, intra-regional trade represents a significant share of food transportation (BTS and U.S. Census Bureau, 2010). If the relocation of agricultural production to the most populated regions reduces inter-regional trade but is accompanied by increased intra-regional flows, the net environmental impact remains unclear. To analyze this trade-off, an in-depth analysis is needed that includes each stage of the supply chain, is conducted at the level of the entire urban system rather than just the city level, and accounts for the land-market effects of urbanization on the location of agricultural production within and between regions. To the best of our knowledge, no such analysis is available in the literature.

We develop a new economic geography model that accounts for the damage caused by emissions from the food-transportation sector. This framework extends the model proposed by Gaigné et al. (2012) by including an agricultural sector and considering a more general m -region spatial configuration. Although the multi-region case adds some complexity, the model

remains analytically tractable. Our framework differs from the models proposed by Picard and Zeng (2005) and Daniel and Kilkenny (2009) since the location of agricultural production is endogenously determined by land rents, which in turn are affected by transport costs and the urban population distribution.

Our results show that analyses of environmental and welfare implications of the spatial allocation of food production cannot rely solely on the distance between food production areas and the location of end consumers. First, configurations in which all regions are self-sufficient –referred to as ‘pure local-food’– do not necessarily minimize emissions due to food transportation. In other words, interregional trade does not necessarily conflict with environmental objectives. Second, the analysis highlights that the economic consequences of the spatial allocation of food production extend beyond solely environmental impacts. The proposed model accounts for two effects on the utility of rural households: (i) farmers located in a more urbanized region benefit from access to a wider range of services, and (ii) larger urban areas generate higher land rents. The former effect favors location of farmers in the most urbanized regions, whereas the second tends to spatially separate urban and rural activities. We show that the resulting spatial-equilibrium allocation of rural population for a given distribution of the urban population does not match the pure local-food configuration except for very particular values of the parameters. Third, the welfare-maximizing spatial allocation of food production results from a combination of the various agglomeration and dispersion forces regarding both the environment and the utility of urban and rural households. The conditions under which the welfare-maximizing and pure local-food configurations coincide depend on the relative magnitude of these forces. If these conditions are not met, imposing that all regions be self-sufficient leads to a spatial misallocation of food production. Interestingly, this does not necessarily exclude the possibility that some regions should rely solely on local food. However, this possibility is restricted to regions with urban populations that are neither too large nor too small.

In order to disentangle these various effects on welfare, we proceed in three main steps. After presenting the model (Section 2), we analyze the emissions-minimizing spatial distribution of food production and highlight the trade-off between intra- and inter-regional trade related emissions (Section 3). In Section 4, we focus on the market forces driving farmers’ location choices and analyze the resulting spatial equilibrium. In Section 5, we examine the welfare-maximizing spatial food allocation by combining environmental damage and the impacts on urban and rural households’ surpluses.

2. A model

Consider an economy with two sectors (agriculture and services) and three goods (labor, land, and a composite good). The agricultural sector produces a homogeneous good using land and labor, while the service sector produces a differentiated good using only labor. The agricultural market is integrated across regions. The service sector is regionally segmented and operates under monopolistic competition. The total population is normalized to 1, and split into λ_u and λ_r urban and rural inhabitants, respectively. This economy comprises m regions, indexed by $j = \{1, \dots, m\}$ with an urban and rural population of λ_{uj} and λ_{rj} , respectively ($\sum_j \lambda_{uj} + \sum_j \lambda_{rj} = \lambda_u + \lambda_r = 1$). The spatial distribution of the urban population across regions is characterized by the m -vector $\boldsymbol{\lambda}_u = (\lambda_{u1}, \dots, \lambda_{um})$. Similarly, $\boldsymbol{\lambda}_r$ denotes the profile of the rural population.

Regions are ordered by decreasing urban population, so that $\lambda_{u1} \geq \lambda_{u2} \geq \dots \geq \lambda_{um}$. The largest city is located in the ‘core’ region ($j = 1$). The distance between any ‘peripheral’ region ($j = 2, \dots, m$) and region 1 is v . Each region is formally described by a one-dimensional

space. Locations are denoted x , and are measured from the center of each region. Without loss of generality, we focus on the right-hand side of the region, the left-hand being perfectly symmetric.

Each city has a central business district (CBD), located at $x = 0$, where firms in the service sector are located. All urban inhabitants work for these firms. The space used by the service sector is considered negligible, so that urban area is used entirely for residential purposes. Each urban inhabitant consumes a residential plot of a fixed size, normalized to unity for simplicity. Farmers live in rural areas (at the periphery of urban areas) and use $1/\mu$ units of land to produce one unit of the agricultural good, so that μ can be interpreted as the agricultural yield. The right endpoint of region j is thus $\bar{x}_j = \frac{\lambda_{uj}}{2} + \frac{\lambda_{rj}}{2\mu}$.

Agricultural goods are first shipped from the farm gate to a collecting point (e.g. an elevator), and then from the collecting point to the CBD. For simplicity, assume that there is one elevator at each side of the region, located at the center of the respective rural area. The right-hand side elevator in region j is located at $x_j^c = \frac{\lambda_{uj}}{2} + \frac{\lambda_{rj}}{4\mu}$. The agricultural good may then be exported to another region. Inter-regional trade is assumed to follow a ‘hub and spoke’ transportation/distribution method, whereby each peripheral region is connected to the ‘hub’ (located in the CBD of the core region) by a ‘spoke’ of length v . This system is frequent in the logistics and freight of commodities. As a modeling strategy, this assumption keeps the analysis of the m -region case tractable by reducing the number of trade flows to be considered.

To save on notation, we make the simplifying assumption that unit transport costs for the farm-to-elevator and elevator-to-CBD segments are both equal to t_a . Following Behrens et al. (2009), we assume also that the inter-regional transport market is not segmented. Inter-regional transportation and distribution involves a fixed fee (f) which does not depend on distance. This assumption is justified by the fact that, in practice, an important share of inter-regional transportation cost is related to distance-independent cost items (logistics, loading/unloading infrastructure, etc.). Thus, transport costs are given by:

$$C_{aj}(x) = t_a |x - x_j^c| + t_a x_j^c + f \quad (1)$$

Each farmer is assumed to supply inelastically one unit of labor, and to produce at constant returns to scale. For clarity, we assume that producing one unit of an agricultural good requires one unit of labor. A farmer located at x in region j bears the costs of transportation of his/her production to the end consumer and the (rural) land rent $R_j(x)$. This farmer’s profit is given by

$$\pi_{aj}(x) = p_a - \frac{R_j(x)}{\mu} - C_{aj}(x) \quad (2)$$

Preferences over the three consumption goods are the same across urban and rural households. The first good is homogeneous, can be traded costlessly, and is chosen as the numéraire. The second good is the agricultural product, which is homogeneous and can be shipped from one region to another. The third good (services), which is non-tradable across regions, is a differentiated good made available under the form of a continuum of varieties (v ranging from 0 to \bar{v}_j). We assume that the utility function is additive with respect to the quantity of the agricultural good (q_a) and services ($q_s(v)$ for variety $v \in [0, \bar{v}_j]$):

$$U(q_0, q_a, q_s(v)) = q_0 + \left(a - b \frac{q_a}{2}\right) q_a + \alpha \int_0^{\bar{v}_j} q_s(v) dv - \frac{\beta - \gamma}{2} \int_0^{\bar{v}_j} [q_s(v)]^2 dv - \frac{\gamma}{2\bar{v}_j} \left(\int_0^{\bar{v}_j} q_s(v) dv \right)^2 \quad (3)$$

To abstract from income effects, the marginal utility with respect to the numéraire is constant and each consumer’s initial endowment (\bar{q}_0) is sufficient to ensure strictly positive consumption (q_0) in equilibrium. As a consequence, as in e.g. Ottaviano et al. (2002), our modeling strategy

is akin to a partial equilibrium approach. Nevertheless, note that, due to equilibrium conditions on labor and regional land markets, this assumption does not remove the interactions between the agricultural and service sectors. As for services, we use the specification proposed by Vives (1990) as in Tabuchi and Thisse (2006). α , β , and γ are all positive parameters and $\beta > \gamma$ to ensure the quasi-concavity of the utility function. γ measures the substitutability between varieties, while $\beta - \gamma$ expresses the intensity of taste for variety.

To abstract from redistribution effects, we assume that land is owned by absentee landlords. Agricultural sector profits (2) are completely absorbed by farmers. The budget constraint faced by a rural household located at x in region j is thus:

$$q_0 + q_a p_a + \int_0^{\bar{v}_j} q_s(v) p_{sj}(v) dv = \bar{q}_0 + \pi_{aj}(x) = \bar{q}_0 + p_a - \frac{R_j(x)}{\mu} - C_{aj}(x) \quad (4)$$

Urban costs, defined as the sum of the commuting costs and land rents, are borne by urban households. The budget constraint faced by an urban household resident at x in region j is:

$$q_0 + q_a p_a + \int_0^{\bar{v}_j} q_s(v) p_{sj}(v) dv = \bar{q}_0 + w_j - R_j(x) - t_u x \quad (5)$$

where $p_{sj}(v)$ is the price of service v in region j , p_a is the price of the agricultural product, w_j is the service sector wage in region j , and t_u is the per-mile commuting cost. Maximizing utility (3) subject to budget constraints (4) and (5) leads to the inverse demand function for the agricultural good:

$$p_a(q_a) = \max \{a - b q_a, 0\} \quad (6)$$

and the inverse demand for service of variety v :

$$p_{sj}(v) = \max \left\{ \alpha \frac{\beta - \gamma}{\beta} - (\beta - \gamma) q_{sj}(v) + \frac{\gamma P_{sj}}{\beta \bar{v}_j}, 0 \right\} \quad (7)$$

where $P_{sj} = \int_0^{\bar{v}_j} p_{sj}(v) dv$ is the price index of services for the range supplied in region j .

Given our assumptions related to the farming sector, agricultural output in region j is equal to λ_{rj} . Combined with Eq. (6), the market clearing price for the agricultural good then is $p_a^* = a - b \sum_j \lambda_{rj} = a - b \lambda_r$. Note that the price received by all farmers is unique (p_a^*) regardless of the region of production and total agricultural output does not depend on the spatial allocation of food production. Food imports in region j are given by $(\lambda_{uj} + \lambda_{rj}) q_a - \lambda_{rj}$. Replacing q_a with its equilibrium value, imports in region j become $\lambda_{uj} \lambda_r - \lambda_{rj} \lambda_u$.

In the service sector, each variety is supplied by a single firm producing under increasing returns as in Tabuchi and Thisse (2006). Hence, \bar{v}_j is also the number of firms active in region j . Producing q_s units of service requires $1/\phi > 0$ units of labor so that ϕ is equivalent to the labor productivity in services. The profits of a services firm operating in region j are given by

$$\pi_{sj}(v) = q_{sj}(v) p_{sj}(v) - w_j / \phi \quad (8)$$

Each firm sets its price so as to maximize its profits taking into account the response of demand to the price of the service it supplies (Eq. (7)) and taking the price index P_{sj} as given. P_{sj} and w_j are treated as parameters (see, for instance, Ottaviano et al., 2002). Since all firms are identical, profit maximization leads to an equilibrium price for all varieties and regions:

$$p_s^* = \frac{\alpha(\beta - \gamma)}{\beta + (\beta - \gamma)} > 0. \quad (9)$$

The labor market clearing conditions imply that there are $\bar{v}_j = \phi \lambda_{uj}$ firms in region j (up to the integer problem). The equilibrium wage is determined by a bidding process in which firms

compete for (local) workers by offering them higher wages until no firm can profitably enter the market. Therefore, the equilibrium wage paid by service firms established in city j is equal to:

$$w_j^* = \frac{\phi}{\beta - \gamma} p_s^{*2} (\lambda_{uj} + \lambda_{rj}). \quad (10)$$

We next turn to the equilibrium land rent for both urban and rural households. Let $V_{uj}(x)$ and $V_{rj}(x)$ denote the indirect utility of urban and rural households, respectively, obtained by plugging the budget constraints (4) and (5) and equilibrium quantities and prices into (3):

$$V_{uj}(x) = p_a^* q_a(p_a^*) + \int_0^{\bar{v}_s} p_{sj}^*(v) q_{sj}(p_{sj}^*) dv + \bar{q}_0 + w_j^* - R_j(x) - t_u x \quad (11)$$

$$V_{rj}(x) = p_a^* q_a(p_a^*) + \int_0^{\bar{v}_s} p_{sj}^*(v) q_{sj}(p_{sj}^*) dv + \bar{q}_0 + p_a^* - \frac{R_j(x)}{\mu} - C_{aj}(x). \quad (12)$$

For urban workers, the equilibrium land rent must solve $\partial V_{uj}(x)/\partial x = 0$ or, equivalently, $\frac{\partial R_j(x)}{\partial x} + t_u = 0$, which solution is $R_j(x) = \bar{r}_{uj} - t_u x$, where \bar{r}_{uj} is a constant. Similarly, the equilibrium land rent for rural households must satisfy $\partial V_{rj}(x)/\partial x = 0$. As a consequence, the bid rents of rural workers are such that $R_j(x) = \bar{r}_{rj} - \mu t_a |x - x_j^c|$. Assuming that $t_u > \mu t_a$, the (right-hand side) urban workers reside around the CBD in the land strip $]0, \bar{x}_{uj}]$ where $\bar{x}_{uj} = \lambda_{uj}/2$ is the (right-hand side) city limit. Rural households live in $[\bar{x}_{uj}, \bar{x}_j]$. Because the opportunity cost of land is equal to zero, the land rent at the region limit is zero, i.e. $R_j^*(\bar{x}_j) = 0$. This implies that $\bar{r}_{rj} = t_a \lambda_{rj}/4$. In addition, urban and rural land rents at the city limit \bar{x}_{uj} must be equal, so that $\bar{r}_{uj} = t_u \bar{x}_{uj} + R_j(\bar{x}_{uj})$. As a result, the equilibrium land rent is equal to:

$$R_j^*(x) = \begin{cases} t_u \left(\frac{\lambda_{uj}}{2} - x \right) & \text{if } x \leq \bar{x}_{uj} \text{ (urban households)} \\ \mu t_a \left(\frac{\lambda_{rj}}{4\mu} - |x - x_j^c| \right) & \text{if } \bar{x}_{uj} < x \leq \bar{x}_j \text{ (rural households)} \end{cases} \quad (13)$$

Emissions from the food-transportation sector are due to both intra- and inter-regional trade. The distance traveled by agricultural goods within a region depends on the distance (i) from each farm gate to the elevator, and (ii) from the elevator to the CBD. The total ton-mileage traveled by agricultural commodities within regions (T_w) can be expressed as:

$$T_w(\boldsymbol{\lambda}_r, \boldsymbol{\lambda}_u) = \sum_{j=1}^m 2 \left[\int_{\bar{x}_{uj}}^{\bar{x}_j} \mu |x - x_j^c| dx + \frac{\lambda_{rj}}{2} x_j^c \right] = \sum_{j=1}^m \left(\frac{3}{8\mu} \lambda_{rj}^2 + \frac{1}{2} \lambda_{uj} \lambda_{rj} \right) \quad (14)$$

Because of the ‘hub-and-spoke’ assumption, total between-region ton-mileage (T_b) can be deduced from the sum of incoming and outgoing trade flows to and from peripheral regions:

$$T_b(\boldsymbol{\lambda}_r, \boldsymbol{\lambda}_u) = \sum_{j=2}^m v |\lambda_{rj} \lambda_u - \lambda_{uj} \lambda_r| \quad (15)$$

Notice that for a given λ_r , total intra-regional ton-mileage is minimized when $\lambda_{rj} = \frac{\lambda_r}{m} + \frac{2\mu}{3} \left(\frac{\lambda_u}{m} - \lambda_{uj} \right)$ for all j , while inter-regional trade flows are minimized when $\lambda_{rj} \lambda_u = \lambda_{uj} \lambda_r$ for all j . This underlines the trade-off between intra- and inter-regional flows.

The emission intensity generally differs for intra- and inter-regional trade transport modes. Without loss of generality, the units used to measure are scaled such that the emission factor associated with inter-regional transportation is normalized to 1. Let e_b denote the (relative) intra-regional emission factor of the agricultural product. Total emissions (E) are thus:

$$E(\boldsymbol{\lambda}_r, \boldsymbol{\lambda}_u) = T_w(\boldsymbol{\lambda}_r, \boldsymbol{\lambda}_u) + e_b T_b(\boldsymbol{\lambda}_r, \boldsymbol{\lambda}_u) \quad (16)$$

3. Emissions-minimizing spatial distribution of food production

What is the spatial distribution of food production that minimizes emissions due to food transportation? Three generic configurations can be envisaged: (i) a ‘pure local-food’ system where all regions are self-sufficient ($\lambda_u \lambda_{rj} = \lambda_r \lambda_{uj}$ for all j), (ii) a global food system where all regions export or import agricultural products ($\lambda_u \lambda_{rj} \neq \lambda_r \lambda_{uj}$ for all j), and (iii) a mixed system combining self-sufficient, importing and exporting regions. For a given distribution of the urban population across regions, the emissions-minimizing spatial allocation of food production is:

$$\hat{\lambda}_r \equiv \arg \min_{\lambda_r} E(\lambda_r; \lambda_u) \text{ subject to } \sum_j \lambda_{rj} = 1 - \lambda_u \text{ and } \lambda_{rj} \geq 0 \text{ for all } j \quad (17)$$

Let m_M , m_X , and m_S denote the number of importing, exporting, and self-sufficient regions, respectively. For interior solutions, the emissions-minimizing rural population located in any peripheral region is characterized¹ by:

$$\hat{\lambda}_{rj} = \begin{cases} \frac{\lambda_r}{\lambda_u} \bar{\lambda} + \frac{2\mu}{3} (\bar{\lambda} - \lambda_{uj}) & \text{if region } j \text{ imports, i.e. if } \lambda_{uj} > \bar{\lambda} \\ \frac{\lambda_r}{\lambda_u} \underline{\lambda} + \frac{2\mu}{3} (\underline{\lambda} - \lambda_{uj}) & \text{if region } j \text{ exports, i.e. if } \lambda_{uj} < \underline{\lambda} \\ \frac{\lambda_r}{\lambda_u} \lambda_{uj} & \text{if region } j \text{ is self-sufficient, i.e. if } \underline{\lambda} \leq \lambda_{uj} \leq \bar{\lambda} \end{cases} \quad (18)$$

where $\underline{\lambda}$ and $\bar{\lambda}$ are defined as (for $m_M + m_X \neq 0$):

$$\underline{\lambda} \equiv \frac{1}{m_M + m_X} \left(\sum_{k \in M} \lambda_{uk} + \sum_{k \in X} \lambda_{uk} - \frac{4\lambda_u^2 \mu v e_b}{3\lambda_r + 2\lambda_u \mu} (2m_M - 1) \right) \quad (19)$$

$$\bar{\lambda} \equiv \frac{1}{m_M + m_X} \left(\sum_{k \in M} \lambda_{uk} + \sum_{k \in X} \lambda_{uk} + \frac{4\lambda_u^2 \mu v e_b}{3\lambda_r + 2\lambda_u \mu} (2m_X + 1) \right) \quad (20)$$

As a trade hub, region 1 plays a special role and either imports or is self-sufficient. The emissions-minimizing rural population in region 1 (for interior solutions) is:

$$\hat{\lambda}_{r1} = \begin{cases} \frac{\lambda_r}{\lambda_u} \left(\frac{\underline{\lambda} + \bar{\lambda}}{2} \right) + \frac{2\mu}{3} \left(\frac{\underline{\lambda} + \bar{\lambda}}{2} - \lambda_{u1} \right) & \text{if region 1 imports, i.e. if } \lambda_{u1} > \frac{\underline{\lambda} + \bar{\lambda}}{2} \\ \frac{\lambda_r}{\lambda_u} \lambda_{u1} & \text{if region 1 is self-sufficient, i.e. if } \lambda_{u1} \leq \frac{\underline{\lambda} + \bar{\lambda}}{2} \end{cases} \quad (21)$$

Note that, in Eqs. (18)-(21), $\hat{\lambda}_{rj}$ depends on $\underline{\lambda}$ and $\bar{\lambda}$, which depend on the sets of importing and exporting regions at the optimum which, in turn, are determined by the values taken by the cumulative distribution function of the urban population at $\underline{\lambda}$ and $\bar{\lambda}$ (inequalities in (18)). Therefore, Eqs. (18)-(21) do not provide a closed-form characterization of the emissions-minimizing rural population profile. Nevertheless, notice that:

$$\bar{\lambda} - \underline{\lambda} = \frac{8\lambda_u^2 \mu v e_b}{3\lambda_r + 2\lambda_u \mu} \quad (22)$$

This difference embeds the terms of the trade-off between intra- and inter-regional trade related emissions. Based on Eq. (22), it can be readily shown that $\bar{\lambda} - \underline{\lambda}$ is increasing with respect to e_b , v , μ , and λ_u . Hence, the larger $\bar{\lambda} - \underline{\lambda}$, the greater the weight of inter-regional transportation relative to intra-regional transportation in total emissions.

Proposition 1 *A ‘pure local-food’ configuration minimizes emissions due to food transportation if and only if $\lambda_{u1} - \lambda_{um} \leq \frac{\bar{\lambda} - \underline{\lambda}}{2} = \frac{4\lambda_u^2 \mu v e_b}{3\lambda_r + 2\lambda_u \mu}$.*

¹The mathematical resolution of (17), although straightforward, is somewhat lengthy. Due to space constraints, it is not shown here. The same applies to the proofs of Propositions 1–3.

The intuition behind Proposition (1) is as follows. Consider a pure local food configuration ($\lambda_r \lambda_{uj} = \lambda_u \lambda_{rj}$ for all j). If the difference in urban population between the most ($j = 1$) and the least ($j = m$) urbanized regions is larger than the ratio of the corresponding marginal effects on emissions due to inter- relative to intra-regional flows, it is possible to reduce total emissions by shifting some food production from region 1 to region m . In this case, the decrease in within-region ton-mileage (distances are shorter within region m) more than offsets the increase in interregional trade flows (region m becomes an exporter).

Proposition (1) conveys two important messages. First, contrary to the ‘food-miles’ argument, a pure local-food system does not necessarily minimize the emissions due to food transportation. Second, the proposition underlines the role played by the distribution of the urban population across regions. The wider the range of the urban population ($\lambda_{u1} - \lambda_{um}$), the less likely that a pure local-food system minimizes emissions. Unless the urban population is uniformly distributed across regions, locating a significant share of food production in the least urbanized regions may lower emissions relative to the pure local-food configuration.

The above configuration is depicted in Figure 1. Consider an example with $m = 50$ regions and assume that the distribution of the urban population follows a (generalized) Zipf law. The parameter values² chosen for this example are such that the condition given in Proposition 1 is not met. In the example, the emissions-minimizing distribution of agricultural production implies that 68% of the regions are such that $\lambda_{uj} < \underline{\lambda}$ (see Figure 1, right axis). These regions export food to the five most urbanized regions (such that $\lambda_{uj} > \bar{\lambda}$, signaled by triangles in Figure 1). Self-sufficiency is limited to the remaining eleven regions (signaled by squares) characterized by urban populations that are neither too small nor too large ($\underline{\lambda} \leq \lambda_{uj} \leq \bar{\lambda}$). In this example, imposing that all regions be self-sufficient would significantly increase emissions (by 67%, see Table 1) compared to the emissions-minimizing configuration.

4. Spatial-equilibrium distribution of food production

We next analyze the spatial-equilibrium allocation of food production for a given distribution of the urban population. Such an equilibrium occurs if no farmer is better off by moving to another region (see for instance Fujita and Thisse, 2002). Using the number of varieties defined by the labor market-clearing condition ($\bar{v}_j = \phi \lambda_{uj}$), Eq. (12) becomes:

$$V_{rj}(\lambda_{rj}, \lambda_{uj}) = \bar{q}_0 + \frac{b}{2} \lambda_r^2 + \frac{\alpha^2 \beta}{2(2\beta - \gamma)^2} \phi \lambda_{uj} + (a - b\lambda_r) - f - t_a \left(\frac{\lambda_{uj}}{2} + \frac{\lambda_{rj}}{2\mu} \right) \quad (23)$$

An interior spatial equilibrium arises at $0 < \lambda_{rj}^* < 1$ (see e.g. Tabuchi et al., 2005), when:

$$\Delta V_{rj}(\lambda_r^*, \lambda_u) \equiv V_{rj}(\lambda_{rj}^*, \lambda_{uj}) - \frac{1}{m} \sum_{k=1}^m V_{rk}(\lambda_{rk}^*, \lambda_{uk}) = 0 \text{ for all } j \quad (24)$$

An interior equilibrium is stable if and only if the slope of the indirect utility differential is strictly negative in the neighborhood of the equilibrium (i.e. $\partial \Delta V_{rj} / \partial \lambda_{rj} < 0$ at λ_{rj}^*). Combining

²Although the parameter values were chosen mostly for illustrative purposes, they capture some essential stylized features of current global land use. Based on World Bank (2013), we set $\lambda_u \approx 0.53$ and $\lambda_r \approx 0.47$. The same dataset indicates that 15.1% of urban inhabitants live in the largest city in their respective countries. The exponent of the Zipf distribution is calibrated to approximately 0.79 so that $\lambda_{u1} = 0.151 \times 0.53$. The world agricultural area is about 4.9 Gha (World Bank, 2013), and the world urban area is 0.066 Gha (Schneider et al., 2009). Thus, the average area needed to feed one person is approximately 39 times larger than average urban plot size ($(4.9/0.066) \times 0.53$). We thus set $\mu = 1/39 \approx 0.026$. The value of e_b is based on the figures reported by Weber and Matthews (2008) for water and truck transportation : $e_b = 14/180 \approx 0.08$. v is set at a large enough for regions not overlap.

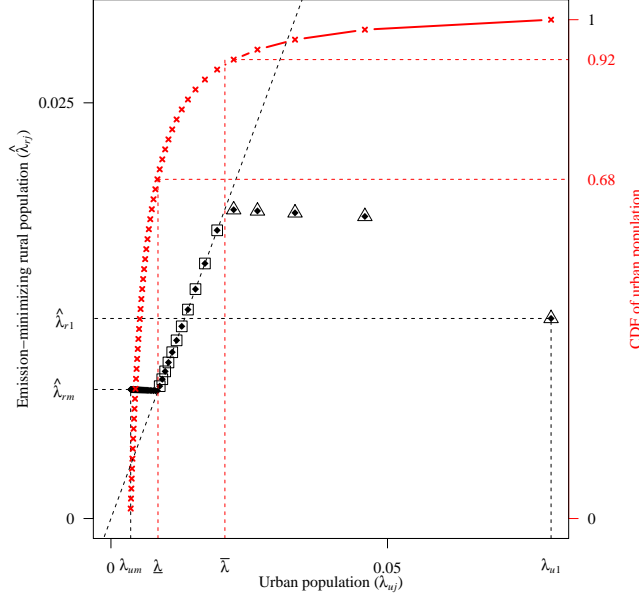


Figure 1. Emissions-minimizing distribution of the rural population (diamonds, left axis) and cdf of the urban population across regions (red crosses, right axis). Parameter values (see text): $m = 50$, $\lambda_u \approx 0.53$, $\lambda_r \approx 0.47$, $\lambda_{uj} = 0.0796/(j^{0.79})$ for all j , $\mu \approx 0.026$, $e_b \approx 0.08$, $v = 4$.

Eqs. (23) and (24), the indirect utility differential becomes:

$$\Delta V_{rj}(\boldsymbol{\lambda}_r, \boldsymbol{\lambda}_u) = \left(\lambda_{uj} - \frac{\lambda_u}{m} \right) \phi \delta - \frac{t_a}{2} \left(\lambda_{uj} - \frac{\lambda_u}{m} + \frac{\lambda_{rj}}{\mu} - \frac{\lambda_r}{\mu m} \right) \quad (25)$$

where $\delta \equiv \frac{\alpha^2 \beta}{2(2\beta - \gamma)^2}$. Since ΔV_{rj} is decreasing with respect to λ_{rj} , the interior equilibrium is stable. Solving $\Delta V_{rj}(\boldsymbol{\lambda}_r^*, \boldsymbol{\lambda}_u) = 0$ leads to:

$$\lambda_{rj}^*(\lambda_{uj}) = \frac{\lambda_r}{m} + \mu \left(\lambda_{uj} - \frac{\lambda_u}{m} \right) \left[\frac{2\phi \delta}{t_a} - 1 \right] \text{ for all } j \quad (26)$$

The equilibrium defined by Eq. (26) results from the interactions between various agglomeration and dispersion forces. On the one hand, farmers have an incentive to locate near larger cities so as to enjoy a wider range of services. On the other hand, a larger urban population induces fiercer competition over land and higher agricultural land rents. The spatial equilibrium results from the comparison between the marginal increase in the utility of rural households ($\phi \delta$) and the marginal increase in the land rent ($t_a/2$) due to one additional urban worker. When these two effects are balanced, the rural population is evenly distributed across regions.

Proposition 2 *A pure local-food configuration emerges as a spatial equilibrium if and only if at least one of the following two conditions is met: (i) $\lambda_{uj} = \frac{\lambda_u}{m}$ for all j , and (ii) $t_a = \frac{2\phi \delta \lambda_u \mu}{\lambda_r + \lambda_u \mu}$.*

The proposition indicates that the spatial-equilibrium allocation coincides with a pure local-food configuration only under very specific conditions. Moreover, whether food production tends to locate in the most or in the least urbanized regions depends on the comparison between inter-sectoral agglomeration and separation forces. For very low values of intra-regional transport cost (i.e. $0 < t_a < \frac{2\phi \delta \lambda_u \mu}{\lambda_r + \lambda_u \mu}$), the food production locates predominantly in the most-urbanized regions. In this case, the most-urbanized regions export food to the least-urbanized

ones, leading to large intra-regional transportation flows. As t_a rises, food production relocates to less urbanized regions, thus simultaneously reducing intra- and inter-regional flows, and therefore emissions until $t_a = \frac{2\phi\delta\lambda_u\mu}{\lambda_r+\lambda_u\mu}$, the value at which a pure local-food configuration emerges. For $\frac{2\phi\delta\lambda_u\mu}{\lambda_r+\lambda_u\mu} < t_a < 2\phi\delta$, inter-regional trade resumes but now, from the least- to the most-urbanized regions. Finally, for any transportation cost higher than $2\phi\delta$, food production locates mainly in the least-urbanized regions, inducing a substantial increase in inter-regional trade flows. The role of t_a on the spatial-equilibrium distribution of food production is depicted in Figure 2 for two values of t_a .

5. Welfare-maximizing spatial distribution of food production

In addition to the previously mentioned effects, the welfare analysis should integrate the impacts on the utility of urban households. Let $W(\boldsymbol{\lambda}_r, \boldsymbol{\lambda}_u)$ be a measure of the social welfare:

$$W(\boldsymbol{\lambda}_r, \boldsymbol{\lambda}_u) \equiv \sum_j \lambda_{rj} V_{rj}(\lambda_{rj}, \lambda_{uj}) + \sum_j \lambda_{uj} V_{uj}(\lambda_{rj}, \lambda_{uj}) - dE(\boldsymbol{\lambda}_r, \boldsymbol{\lambda}_u) \quad (27)$$

where $d > 0$ measures the marginal environmental damage (taken constant for simplicity). Plugging the values of \bar{v}_j and w_j at the equilibrium of the urban labor market into (11), we obtain:

$$V_{uj}(\lambda_{rj}, \lambda_{uj}) = \bar{q}_0 + \frac{b}{2}\lambda_r^2 + \phi\delta\lambda_{uj} + \frac{2\phi\delta(\beta - \gamma)}{\beta}(\lambda_{uj} + \lambda_{rj}) - t_u \frac{\lambda_{uj}}{2} \quad (28)$$

The fourth term in Eq. (28) reflects the effect of market size on service sector wages. This effect reinforces inter-sectoral agglomeration. The welfare-maximizing distribution of agricultural production across regions for a given distribution of the urban population is defined as:

$$\boldsymbol{\lambda}_r^o \equiv \arg \max_{\boldsymbol{\lambda}_r} W(\boldsymbol{\lambda}_r, \boldsymbol{\lambda}_u) \text{ subject to } \sum_j \lambda_{rj} = 1 - \lambda_u \text{ and } \lambda_{rj} \geq 0 \text{ for all } j \quad (29)$$

The resolution of (29) closely follows that of (17). Welfare-maximizing rural populations in peripheral regions are given by:

$$\lambda_{rj}^o = \begin{cases} \frac{\lambda_r}{\lambda_u} \bar{\lambda}^o + \frac{2\mu}{3d+4t_a} \left[d + t_a - 2\phi\delta \frac{3\beta-2\gamma}{\beta} \right] (\bar{\lambda}^o - \lambda_{uj}) & \text{if region } j \text{ imports} \\ \frac{\lambda_r}{\lambda_u} \underline{\lambda}^o + \frac{2\mu}{3d+4t_a} \left[d + t_a - 2\phi\delta \frac{3\beta-2\gamma}{\beta} \right] (\underline{\lambda}^o - \lambda_{uj}) & \text{if region } j \text{ exports} \\ \frac{\lambda_r}{\lambda_u} \lambda_{uj} & \text{if region } j \text{ is self-sufficient} \end{cases} \quad (30)$$

Again, $\bar{\lambda}^o$ and $\underline{\lambda}^o$ (not shown here due to space constraint) depend on the set of importing and exporting regions. Although a general closed-form solution cannot be derived, it is possible to characterize the welfare-maximizing configuration by examining:

$$\bar{\lambda}^o - \underline{\lambda}^o = \frac{8\lambda_u^2 \mu v e_b d}{(3d + 4t_a)\lambda_r + 2\lambda_u\mu \left(d + t_a - 2\phi\delta \frac{3\beta-2\gamma}{\beta} \right)} \quad (31)$$

This difference summarizes the net social-welfare effect of all the aforementioned trade-offs (intra- vs. inter-regional trade related emissions, within-region transport costs vs. access to services, and market-size effect on urban wages). The difference is unambiguously increasing with respect to the emission factor (e_b) and distance (v). Note that if marginal damage is low (if $d \rightarrow 0$), then $\bar{\lambda}^o - \underline{\lambda}^o$ also tends to zero. Standard calculations show that, in this case, $\bar{\lambda}^o$ and $\underline{\lambda}^o$ both tend to λ_u/m implying that only the regions with an urban population sufficiently close to the overall average urban population should be self-sufficient. Note also that $\bar{\lambda}^o - \underline{\lambda}^o$ is not necessarily positive. In particular, if the inter-sectoral agglomeration forces related to

the service sector are sufficiently large (e.g. if δ is sufficiently large), cases where $\bar{\lambda}^o < \underline{\lambda}^o$ are possible. In such cases, rural areas in the most urbanized regions should be large enough for these regions to export to the least urbanized ones. Last, note that for a specific value of the transport costs ($t_a = \frac{\lambda_u \mu}{2\lambda_r + \lambda_u \mu} \frac{2\phi\delta(3\beta-2\gamma)}{\beta}$) agglomeration and dispersion forces cancel out, implying that welfare-maximizing and emissions-minimizing configurations coincide.

Proposition 3 *A pure local-food configuration maximizes welfare if and only if $\lambda_{u1} - \lambda_{um} \leq \frac{|\bar{\lambda}^o - \underline{\lambda}^o|}{2}$.*

The proposition underscores that the welfare-maximizing spatial allocation of food production depends on the relative magnitude of various agglomeration and dispersion forces that extend beyond the sole effect of the distance traveled by food items. The proposition also emphasizes the role of heterogeneity in the urban population distribution across regions. In particular, the wider the range of the urban population ($\lambda_{u1} - \lambda_{um}$), the less likely that a pure local-food configuration maximizes welfare. As in the emissions-minimizing case, the optimal allocation of food production may require that some regions engage in trade while others remain self-sufficient. The size of the urban populations in the latter regions should be neither too large nor too small.

The spatial equilibrium differs from the welfare-maximizing allocation of food production because of the presence of two types of externalities (affecting the environment and urban wages). The discrepancy between the two situations is depicted in Figure 2. If t_a is high (right panel), the spatial-equilibrium tends to allocate relatively more (less) food production in the least (most) urbanized regions than in the welfare-maximizing configuration. In this case, only five regions should be self-sufficient. This number rises to eleven for the smaller value of t_a (left panel). In both examples, the welfare-maximizing emission level is close to the emissions-minimizing one. If t_a is large, emissions in the spatial-equilibrium configuration are slightly larger than in the welfare-maximizing case but still significantly lower than in the pure local-food configuration (See Table 1).

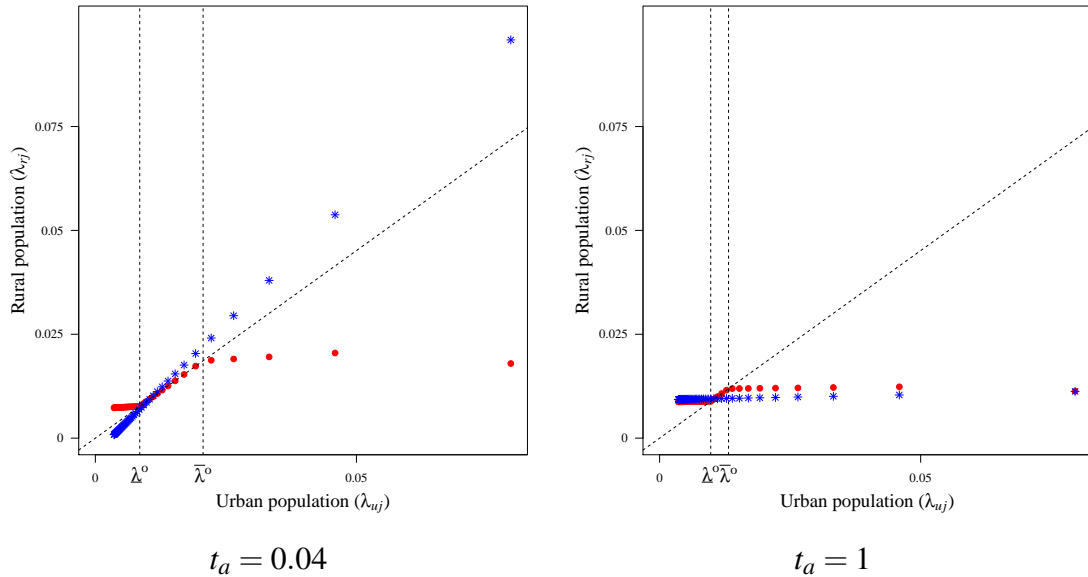


Figure 2. Welfare-maximizing (dots) and spatial equilibrium (asterisks) for two values of t_a . Same parameter values as in Figure 1 with, in addition, $\phi = \delta = 1$, and $d = 0.5$.

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Table 1. Summary of the simulation results in the various spatial configurations and for two values of within-region transport costs (t_a). Same parameter values as in Figure 2.

Spatial configuration	Number of regions			Relative change in emissions w.r.t. emissions-minimizing [%]		
	Importers m_M	Self-suff. m_S	Exporters m_X	Within T_w	Between $e_b T_b$	Total E
Pure local food	0	50	0	+118	-100	+67
Emissions-minimizing	5	11	34	-	-	-
Spatial equilibrium						
$t_a = 0.04$	38	0	12	+235	-28	+174
$t_a = 1$	12	0	38	-11	+81	+10
Welfare-maximizing						
$t_a = 0.04$	5	11	34	+4	-10	+1
$t_a = 1$	9	5	36	-10	+51	+4

6. Concluding remarks

Should local food be promoted on the basis that it contributes to the reduction of the distance traveled by food items, and therefore, transport-related emissions? Even from a strictly environmental perspective, the answer to this question is not as straightforward as might be expected. It depends on the extent to which emissions savings permitted by less inter-regional trade are offset by potentially larger intra-regional transportation flows. Thus, food trade does not necessarily conflict with the mitigation objectives. Besides, social welfare analyses that examine this question should integrate interactions with other agglomeration and dispersion economic forces, including those affecting non-agricultural markets. The conditions for a pure local-food system to be socially optimal derived in this paper combine some of these elements. If these conditions are not met, the relocation of some food production closer to the most populated cities may deteriorate both the environment and welfare.

Food transportation flows depend strongly on the spatial distribution of the urban population. In the limit case of an urban population evenly distributed across regions, the spatial equilibrium coincides with the pure-local food configuration, and, simultaneously minimizes emissions and maximizes welfare. However, as soon as there is some heterogeneity in the distribution of the urban population, market outcome and the optimal configuration may diverge. Our findings indicate that the greater the difference in the populations of the largest and the smallest cities, the less likely that pure-local food configurations will maximize welfare and minimize emissions. These findings offer a fair level of generality since they do not require additional specifications for the number of regions or the distribution of the urban population.

Proximity on its own is not an appropriate basis for policies aimed at improving the sustainability of food-supply chains. By focusing solely on food-miles, fundamental effects that affect social welfare are ignored. Ultimately, this may distort the economic and environmental assessment of the consequences of the spatial allocation of food production. However, local-food systems should not be systematically ruled out. Indeed, the welfare-maximizing allocation of food production might correspond to a configuration that combines trade between some regions and self-sufficiency for other regions. In this case, the size of the urban population in the self-sufficient region should be neither too large nor too small. Last, environmental and other

spatial externalities may justify the use of policy instruments targeting for example emissions, transport costs, and/or land-use. Our findings suggest that such instruments should focus on the multi-regional level rather than the level of individual regions. The analysis proposed in this text lays the groundwork for further investigation of the design and properties of these instruments.

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