Feeding the Cities and GHG Emissions Beyond the Food Miles Approach

Stéphane De Cara[*], Anne Fournier[†], Carl Gaigné[‡]

February 2012

Abstract

In this paper, we study the relationship between urbanization, agricultural location, and GHG emissions related to food transportation within and between regions. We develop an economic geography model of rural-urban systems where the location of agricultural activities is endogenous. We show that a local food system is desirable only if this system is adopted by medium-sized cities and agricultural yields are high enough. Otherwise, a global food system yields less GHG emissions. Second, we find that market mechanisms yield too much inter-regional trade in agricultural products when urban population is sufficiently dispersed and agricultural transport costs are high enough. Third, we highlight that a carbon tax on intra-regional transportation helps reducing GHG emissions as long as transport costs and agricultural yields remain low enough. If not, then it may raise transport-related emissions because of the relocation of food production. Finally, we get that, starting from the spatial equilibrium, a marginal change in the location of agricultural production improves the welfare of farmers and decreases transport-related emissions, except when agricultural transport costs reach intermediate values.

Keywords: Urbanization; Agricultural location; Transport; Greenhouse gas; Food miles
JEL Classification: F12; Q10; Q54; Q56; R12

1 Introduction

More than half of the world population lives in cities. In the coming years, this share is expected to keep growing worldwide, reaching 84% in developed countries and about 65% in Africa and Asia by 2050 (United Nations, 2010).

This rising trend, resulting in both inter-urban concentration and urban sprawl, implies significant consequences for the future of food supply chains. Indeed, urban expansion is threatening the sustainability of the current food systems in at least two ways. First, at a given location of agricultural production, increasing quantities of food commodities have to be brought into cities.

---

[*] INRA-AgroParisTech, UMR 210 Economie Publique, Thiverval-Grignon (France)
[†] EconomiX-CNRS, UMR 7235, University of Paris Ouest (France). Email: anne.fournier@u-paris10.fr
[‡] INRA, UMR1302 SMART, Rennes (France) and Université Laval, CREATE, Québec (Canada).

Second, urbanization induces land-use changes and thus, a spatial reallocation of the agricultural production. We incidentally observe that the spatial extension of residential areas occurs at the expense of agricultural land.[1] In the most urbanized regions, due to agglomeration economies, land competition is so tougher that only firms with high value-added per unit of land may profitably operate there (Fujita and Thisse, 2002). As a result, urbanization yields the dispersion of low value-added activities such as food and agricultural sectors (Bagoulla et al., 2010).

In the end, these two structural changes involve larger volumes of agricultural goods transported and more energy used in the process. Data over the past few years already show this tendency. Hence, from 1997 to 2002, ton-miles for cereal grains rose by 37% in the US, and the average mileage per shipment for agricultural commodities grew by 10%. Similar evolutions have been observed in the richer EU countries. In France for instance, the average kilometers per shipment for agricultural products has increased by 33% for all transportation modes over the period 1975-1995, and by 66% for road transport only (Savin, 2000). With increasing food demand and global trade, freight-traffic growth is expected to strengthen in the future.

This may explain why agricultural and food transportation is a significant and growing source of GHG emissions (IPCC, 2007).[2] In 2006, over 4 million tons of fresh fruits and vegetables were imported into France, leading to emissions of nearly one million teq CO2 (BioIS, 2007). Beyond the geographical origin of goods, the environmental impacts of food transport are also highly dependent on the mode used: One ton of food shipped over one kilometer would emit from 15 to 30 grams of CO2 when the transportation is performed by water or rail while this figure rises to 210-1.430 gCO2/t.km when commodities are carried by truck and may even go up to 1580 gCO2/t.km for air freight (DEFRA, 2002). These large differences between mode justify that, although air freight accounts for only 1% of fruits and vegetables imports into France, it is still responsible for a quarter of GHG emissions (BioIS, 2007).

Feeding the cities in a sustainable way has truly emerged as a growing concern for public authorities. Adjustments in the location of production are now regularly mentioned in Climate-Change Action Plans to mitigate transport-related emissions (OECD, 2008; EPA, 2010a; Kampman et al., 2010). The relocation of agricultural production in the highly-populated regions is even sometimes advocated as one means of lowering the negative environmental impacts of food supply chain. This argument usually revolves around the ‘food-miles’ concept (Paxton, 1994): reducing the distance food is transported from the producer to the end consumer may contribute to the mitigation of transport-related greenhouse gas (GHG) emissions. In BioIS (2007) for instance, authors show that

---

[1] As an illustration, residential land use in the US grew 47.5% between 1976 and 1992, while population only rose by 17.8% over the same period (Overman et al., 2008). Europe faces a similar trend; between 1990 and 2000, built-up areas increased by 12% whereas population grew just 2% (EEA, 2004).

[2] More generally, transportation is one of the main source of GHG emissions (IPCC, 2007). In the US, this sector is the second largest and fastest-growing source of GHG emissions (27% of 2008 US GHG emissions and +22% between 1990 and 2008, EPA, 2010b). The overall rise in transportation emissions reflects both continued growth in passenger and commodity flows, increasing travel distances and shifts to energy-intensive modes. As for freight activities, the ton-miles of goods shipped by truck domestically increased 56% between 1993 and 2002 (USDOT, 2006).

emissions stemming from the transportation of one ton of apples consumed in France are 14 times higher when imported from Chile than when locally grown. Regarding melons, the consumption of local fruits would result in 40 kg of CO2 against 145 kg for the same volume of goods imported from Spain.

However, different studies also reveal that reducing food miles is not necessarily good for the environment when the transport mode and production technologies differ greatly according to the location. For example, lambs raised in New Zealand and shipped to Europe would emit less carbon dioxide emissions per ton than lambs produced in Europe because lambs from New Zealand is imported by boat and raised by using much less industrial feed (Saunders et al., 2006).

In this paper, we argue that, *even though transport and production technologies do not vary in space, buying local is not necessarily beneficial for the environment from a transport-related emissions standpoint*. When assessing the impact of buying local on GHG emissions, the existing literature does not address two major issues. First, *the intra-regional trade in agricultural or food products reaches high values*. Indeed, agricultural shipments are generally characterized by short distances. In the US, they are primarily within-state haulages and they represent a significant share of the value and tonnage of truck shipments. For example, US cereal grains (the largest consumer of transportation services) are generally shipped short distances (139 miles in average) and are primarily handled by truck. More broadly, if we focus on the top trade partners for each state, data show that with few exception, freight flows occur predominantly within the same state or with immediate neighboring states; for nine states out of ten, within-state haulages account for at least 50% of total flows and local ones (i.e., when including the commodity freight flows with the surrounding states) represent at least 78% (FHWA, 2011). We do not know *a priori* whether reducing inter-regional trade by relocating agricultural production in the most populated regions may increase in higher proportion intra-regional trade. GHG emissions have to be evaluated at each stage of the supply chain.

Second, the ecological assessment of food systems should be implemented at the entire urban system level and not only at the city level. Due to *the relocation of agricultural activities in the long run in response to urbanization*, the ecological gains within a region may induce ecological losses in other ones. Hence, a full-fledged analysis should be conducted within a framework in which the location of agricultural production within and between regions is endogenous.

In what follows, we develop an economic geography model with multiple regions where the spatial allocation of agricultural production within and between regions depends on land prices that are affected by transport costs and city size. Such a framework allows us to evaluate GHG emissions related to the transportation of food products within rural areas and from rural areas to cities. Our framework extends that proposed by Gaigné et al. (2011) by including an agricultural sector and by considering a richest distribution network of commodities. By introducing more than two regions, we can consider a hub and spoke distribution system[3] which is the dominant distribution system.

---

[3] Hub and spoke distribution consists in a few large distribution centers located in urbanized regions which receive products from suppliers located in different regions and then, send the products to customers located in different

Contrary to Fujita et al. (1999) and Picard and Zeng (2005), the location of agricultural production is not exogenously treated but determined through bid rent. Our approach differs from Daniel and Kilkenny (2009) too, in several dimensions. First, we consider that land is also used by the urban population so that the spatial allocation of land between urban activities and agricultural production is endogenously determined. Second, we assume that each region has a spatial extension and that transportation costs for both agricultural commodities and individuals working in the city occur within each region. Third, we derive a complete analytical characterization of the location equilibrium and we provide comparative statics. Because results are not based on numerical simulations, the paper offers a fair level of generality. Fourth, a welfare analysis is developed which allows us to compare the location equilibrium and the spatial pattern minimizing pollution with the first best allocation of agricultural production.

Our analysis reveals that there is a trade off between curbing GHG emissions stemming from intra- or inter- regional transportation. We show that the gains associated with local food systems (inducing no inter-regional trade) relatively to a global food system (inducing inter-regional trade) depends on the city size distribution, agricultural yields, and transport costs. More precisely, we find that the development of local food systems reduce the total GHG emissions only if this system is applied by medium-sized cities and if agricultural yields are high enough. In contrast, global food systems yield lower transport-related emissions than local systems when the economy is dominated by few large cities even though there is no land constraint in the most urban-crowded regions. Hence, in highly urbanized economies, the excess of pollution due to freight transportation does not arise from inter-regional trade but from the existence of very large agricultural areas, entailing high levels of intra-regional trade flows (like in mid-western states in the US or in Great West in France).

Further, because agricultural transportation costs and land-use changes do not reflect the environmental damages caused by the delivery of food commodities, market failures occur. However, the relationship between the total distance traveled by food products and the location of agricultural production is complex: we do not know a priori if transportation costs are too high or too low, and if the market yields too much inter-regional trade flows. We highlight that the market yields too much inter-regional food trade provided that the urban population is sufficiently dispersed and agricultural transport costs are high enough. In addition, our analysis suggests that, from a transport-related emissions standpoint, a carbon tax may hurt the environmental situation. Indeed, we show that a rise in transport costs (due to a carbon tax for example) may raise the emissions when transport costs and agricultural yields are relatively high because of the mis-allocation of agricultural production. Finally, we find that a centralized regional policy controlling land use could be more efficient; starting from the equilibrium, we get that all changes in the location of agricultural production that would shrink GHG emissions would also enhance the total welfare. In other words, farmers' welfare and environmental situation may go hand in hand.

It is worth stressing that the differentials across space in the pollution caused by agricultural

---

cities.

production itself and in land productivity are left aside. Although these dimensions are admittedly significant in the relation between agricultural location and GHG emissions, this allows us to focus on the important economic trade-offs at play in the transport-related emissions. Even without accounting for these two dimensions, we exhibit cases where, for large metropolitan areas, food can be sourced from remote locations whilst reducing total transport-related GHG emissions.

The rest of the paper is organized as follows. The next Section presents the analytical framework. Section 3 examines the link between the location of agricultural activities and GHG emissions. In Section 4, we determine whether market mechanisms yield too inter-regional trade and we discuss the policies to be implemented to correct market failures. We extend the analysis by studying urban population location choices and discussing the potential consequences of a differential in yields between regions in Section 5. Finally, Section 6 summarizes our findings and suggests some directions for further research.

2 The Model

Our economy consists in two sectors (agriculture and services). The population is divided into $L > 0$ workers used in the services sector and $A > 0$ farmers working in the agricultural sector. This economy provides three primary goods (labor, land and the numéraire) and two consumption goods (the agricultural good and the services). Services are non-tradable goods while the numéraire is traded costlessly and agricultural transportation is costly.

(i) Spatial structure and transportation/distribution network Consider an economy with m regions indexed by $r = \{1, 2, .., m\}$. Each of them encompasses both a city and a rural hinterland. We define a central region (or a core region) hosting the largest city (labeled by region 1) and $m-1$ peripheral regions. The size of cities may differ between peripheral regions.

Each region is formally described by a one-dimensional space where the city and the rural area have a spatial extension.[4] The city hosts services firms and workers while farmers live and produce in rural areas. Whenever a city is formed, it has a business district (BD) located at $x = 0$, where region-r firms are set up.[5] Without loss of generality, we focus on the right-hand side of the region, the left-hand side being perfectly symmetrical. Distances and locations are expressed by the same variable x, measured from the city center. Our purpose being to highlight the interactions between transportation and the location of activities, we assume that the supply of natural amenities is the same in all regions.

Urban inhabitants consume a residential plot of fixed size $s > 0$, regardless of their location. For simplicity, we assume s to be normalized to unity. Denoting by L_r the urban population living

---

[4] We could develop a more realistic spatial pattern as a bi-dimensional space. However, moving to two dimensions increases the complexity while the gains in term of results are very limited.

[5] See the survey by Duranton and Puga (2004) for the reasons explaining the existence of a CBD.

in city r (with $\sum_{r=1}^{m} L_r = L$), the right endpoint of this city is then given by

$$\bar{x}_r = \frac{L_r}{2}.$$

Hence, the spatial extension of the residential area in region r is given by $[-\bar{x}_r, \bar{x}_r]$ if $L_r > 0$. In each region, the rural population settles at the periphery of the urban area. Every rural dweller uses $1/\mu$ units of land to produce the agricultural good. The right endpoint of region r is then given by

$$x_r^a = \frac{L_r}{2} + \frac{A_r}{2\mu}$$

where A_r stands for the rural population located in region r. There are two agricultural areas in each region and their spatial extensions are given by $x_r^a - \bar{x}_r$ if $A_r > 0$. Note that the mass of land units is assumed to be high enough in each region to host all agricultural activities at the equilibrium. However, our findings hold even if we consider that there is a constraint in land availability in each region. This point will be discussed below.

The transportation/distribution network is conceived as follows. Peripheral regions are located along a circle and the central region is located in the circle's center. Each region is connected to the central one by a spoke, representing a transport route, with a distance v. We assume that peripheral regions are not directly connected among them, implying that all agricultural products which are not locally consumed are assembled in the central region and then shipped to importing regions. Hence, the physical flows of products follow the *hub and spoke distribution method* which is a key feature of distribution networks for commodities: agricultural goods traded between peripheral regions move from the originating region to the center of the circle through the corresponding spoke, and then to the city of destination through another spoke.

In addition, within each rural areas, agricultural goods are collected by elevators and, further, shipped from elevators to the city[6]. Thus, the city is the connection point between agricultural areas within a region but also between that region and the other ones.

(ii) Consumers. Urban and rural populations consume three types of good: a numéraire, an agricultural good and a bundle of non-tradeable *services* locally produced (trade costs are prohibitive). Each individual is initially endowed with $\bar{q}_0 > 0$ units of the numéraire which is supposed to be large enough for the individual consumption of the numéraire to be strictly positive at the equilibrium outcome.[7] Preferences are the same across individuals and a consumer's utility is given by:

$$\begin{aligned} U_r(q_0; q_r(\omega), \omega \quad &\in \quad [0, n_r]) = q_0 + \left(\alpha_a - \beta_a \frac{q_r^a}{2}\right) q_r^a + \\ &\alpha \int_0^{n_r} q_r(\omega) d\omega - \frac{\beta - \gamma}{2} \int_0^{n_r} [q_r(\omega)]^2 d\omega - \frac{\gamma}{2n_r} \left(\int_0^{n_r} q_r(\omega) d\omega\right)^2 \end{aligned} \tag{1}$$

---

[6] The number and the location of elevators are specified below.

[7] For simplicity, we assume that land is owned by absentee landlords.

where q_0 refers to the quantity of the numéraire, q_r^a, the consumption of the agricultural good, and $q(\omega)$, the quantity of variety ω of services. All parameters α, β and γ are positive; $\gamma > 0$ measures the substitutability between varieties, whereas $\beta - \gamma > 0$ expresses the intensity of the taste for variety. This utility function is used in Tabuchi and Thisse (2006) and Gaigné and Thisse (2009) where we consider only the services sector.

Urban dwellers work in the services sector and commute to the CBD where jobs are located. They pay a unit transport cost $t > 0$, so that a worker located at $x > 0$ bears a commuting cost equal to tx. The budget constraint faced by a urban household settled at x in region r is then given by

$$q_r^a p_r^a + \int_0^{n_r} q_r(\omega) p_r(\omega) \mathrm{d}\omega + q_0 + R_r(x) + tx = w_r(x) + \bar{q}_0 \tag{2}$$

where $p_r(\omega)$ stands for the price of service ω, p_r^a, the price of agricultural product, $R_r(x)$, the land rent at x and w_r, the wage paid by firms in region r's CBD.

The rural population works in the agricultural sector. Their workplace and their residential location are identical so that, the budget constraint faced by a rural household living at x in region r is given by

$$q_r^a p_r^a + \int_0^{n_r} q_r(\omega) p_r(\omega) \mathrm{d}\omega + q_0 = y_r(x) + \bar{q}_0 \tag{3}$$

where $y_r(x)$ is the earning received by a farmer in region r's.

Utility maximization leads to the inverse demand for the agricultural product, $p^a = \alpha_a - \beta_a q^a$, so that region r's inverse demand for this good is

$$p^a = \max\left\{\alpha_a - \beta_a Q_r^a/(L_r + A_r), 0\right\} \tag{4}$$

where Q_r^a is the total quantity of the agricultural good sold in region r. Similarly, utility maximization leads to the inverse demand for a service,

$$p_r(\omega) = \max\{\alpha(\beta - \gamma)/\beta - (\beta - \gamma) q_r(\omega) + \gamma P_r/(n_r \beta), 0\}$$

where $P_r = \int_0^{n_r} p_r(\omega) d\omega$ is defined only over the range of services produced in city r because this good is non-tradable.

(iii) The agricultural sector. Agricultural products move from the farm to an elevator and, further, to a local intermediary located in the city center ($x = 0$). The local demand is satisfied by the local intermediary. The surplus is exported to the central region where a national intermediary is established.

Farms produce at constant returns to scale and are price-takers. The mass of labor working in the agricultural sector is given by A and each farmer supplies inelastically one unit of labor. We assume that producing one unit of the agricultural good requires one unit of labor A and $1/\mu$ units of land. Thus, variable μ captures the agricultural yields. In order to sell their produce, farmers have to convey their goods to the city which induces transportation costs. Hence, the net income of a farmer located at x in region r is given by

$$y_r(x) = p^a - \frac{R_r^{a^*}(x)}{\mu} - C_a(x) \tag{5}$$

where $R_r^{a^*}(x)$ is the equilibrium land rent paid by a farm located at x and $C_r(x)$ stands for the total cost incurred by the farmer associated with the distribution of his output. The profit is assumed to be completely absorbed by farmers.

The equilibrium agricultural price. The market clearing condition for the agricultural good is such that $A = Q^a$, with $Q^a = (\alpha_a - p^a)(L + A)/\beta_a$ so that

$$p^a = \alpha_a - \frac{\beta_a A}{L + A}$$

Observe that, because of the perfect competition condition, p^a is common to all farmers, regardless of the region where their activity takes place. Therefore, we can straight away notice that the agricultural price will not play any role in the farmers' location choice. In addition, notice that the total production of agricultural commodities does not vary with respect to its spatial allocation. In other words, GHG emissions related to the agricultural production activity are supposed to be constant whatever its location.

The agricultural transport cost. Shipping food commodities to end consumers involves transportation costs including the cost of shipping goods from the agricultural estate to elevator k (with $k = 1, ..., K$) located at x_r^k, the cost of transportation from the elevator to the city center, and the trade cost between regions. We consider that intra-regional transport costs vary with distance while the impact of distance on inter-regional transport costs are negligible. Hence, we have

$$C_a(x, k) = f + t_a \left| x - x_r^k \right| + t_a^k x_r^k$$

where f is a fixed fee (including transportation and distribution costs), t_a represents the unit cost of agricultural transportation between a farm and elevator k and t_a^k is the unit cost of agricultural transportation between elevator k and the CBD. We assume that $t_a^k = \tau t_a$ with $0 < \tau < 1$ where τ captures the fact the marginal cost in transportation is lower between the elevator and the city because more volume can be hauled. In other words, τ measures the elevator's capacity to reduce the number of shipments from its location to the city: if $\tau = 1$, then the production of each farmer is shipped directly to the city and when $\tau \to 0$ then all agricultural production received by a collector can be stored and carried with a single shipment[8].

It is worth noting that, although the individual transport demand for agricultural commodities by farmers is inelastic, the regional transport demand for agricultural goods varies with the freight price (as we will see in the next section).

---

[8] In practice, τ close to one means that the agricultural goods would be vegetables or fruits while low values of τ would correspond to cereals.

The location and the number of elevators. Let K_r be the number of elevators within each agricultural area of region r (thus $2K_r$ elevators in region r). We assume that there are equally spaced along the agricultural area[9] and located at $x_r^k = \{x_r^1, x_r^2, ..., x_r^K\}$. Without loss of generality, we suppose $\bar{x}_r < x_r^1 < x_r^2 < ... < x_r^K$ so that the location of elevator k is given by:

$$x_r^k = \bar{x}_r + \frac{x_r^a - \bar{x}_r}{2K_r} + (k-1)\frac{x_r^a - \bar{x}_r}{K_r} = \frac{L_r}{2} + \frac{A_r}{4\mu K_r} + (k-1)\frac{A_r}{2\mu K_r}. \tag{6}$$

For a same distance to an elevator, the transport cost is higher for a farmer located far away from the city than a less distant farmer. We also take into account that K_r varies with A_r since the number of elevators reacts positively to a change in agricultural production. For simplicity, we assume that

$$K_r = \kappa A_r/2 \tag{7}$$

with $0 < \kappa < 1$. Hence, increasing agricultural production in a region induces a rise in the number of elevators in that region. The cost of an elevator is assumed to be a fixed cost f_e equally paid by farmers which implies that the cost incurred by a farmer is equal to $2f_e K_r/A_r = f_e\kappa$.

The equilibrium agricultural land rent. At given prices and location of the urban population, each farmer chooses his location within his agricultural area so as to maximize his utility. An *equilibrium* is such that no farmer wants to change his location so that $V_i^a(x,1) = ... = V_i^a(x,k) = ...V_i^a(x,K)$. Knowing $V_i^a(x)$ and given that the consumption of the other goods does not depend on the location within the agricultural area, the bid rent at the equilibrium verifies $\partial V_i^a(x,k)/\partial x = 0$ or equivalently $R_i^{a\prime}(x,k)/\mu + t_a = 0$ and $R_r^a(x,1) + C_a(x,1) = ... = R_r^a(x,K) + C_a(x,K)$ where $R_r^{a^*}(x,k)$ is the bid rent of a farmer producing at x and carrying his output to elevator k. As a consequence, land rent capitalizes not only the cost of the distance between farmers and the elevator but also the transport cost between the latter and the city. Then, the equilibrium agricultural land rent is given by $R_r^{a^*}(x) = \max\{R_r^a(x,1), ..., R_r^a(x,k), R_r^a(x,k+1), ...R_r^a(x,K_r)\}$. Because at the endpoint of the agricultural areas we must have $R_r^a(x_r^a) = R_a = 0$, $R_r^{a^*}(x,k)$ is equal to:

$$R_r^{a^*}(x,k) = \mu t_a \left[\frac{A_r}{4\mu K_r} - \left|x - x_r^k\right| + \tau\frac{A_r}{2\mu K_r}(K_r - k)\right] \tag{8}$$

By plugging (8) and (7) into (5), the income received by a farmer becomes:

$$y_r(x) = p^a - f - f_e\kappa - t_a\tau\left(\frac{A_r}{2\mu} + \frac{L_r}{2}\right) - \frac{(1-\tau)t_a}{4\mu\kappa} \equiv y_r. \tag{9}$$

Note that according to (9), agricultural wages differ across regions; in particular, the more the region-r is spatially extended, the more the cost of agricultural transportation is high, which implies the equilibrium wage y_r to be cut down.

---

[9] Note that we consider unit freight prices per unit of distance between the elevator and the city is identical regardless of the elevator and is treated as a parameter. Ideally, we would consider a game in which the elevators act strategically to maximize their profits. Such a configuration makes the analysis more complex without adding new significant results.

(iv) The services sector. Firms of the services sector produce a differentiated good under monopolistic competition. They are located in the CBD and are assumed to use no land. Producing q units of the differentiated service requires $1/\phi > 0$ units of labor so that ϕ is equivalent to the labor productivity in services. The profits of a region r service firm are consequently given by

$$\pi_r(\omega) = q_r(\omega)p_r(\omega) - w_r/\phi$$

Each service firm treats the price index P_r and the wage w_r as parameters so that the equilibrium price of a good 2-variety in city r is

$$p_r^* \equiv p^* = \frac{\alpha(\beta-\gamma)}{\beta+(\beta-\gamma)} > 0$$

The labor market-clearing conditions imply that there are $n_r = \phi L_r$ (up to the integer problem) service firms. Urban labor markets are local and the equilibrium wage is determined by a bidding process in which firms compete for workers by offering them higher wages until no firm can profitably enter the market. In other words, operating profits are completely absorbed by the wage bill. This implies that the equilibrium wage paid by service firms established in city r is equal to

$$w_r^* = \varphi(L_r + A_r) \tag{10}$$

where $\varphi \equiv \phi p^{*2}$.

3 Local vs. global food system

We analyze the impact of spatial organization of food system on GHG emissions stemming from the transportation of agricultural commodities. Let λ_r and θ_r be the share of rural and urban population located in region r. Given our framework, three food systems can be envisaged: (i) a local food system where there is no inter-regional food trade ($\lambda_r = \theta_r$ regardless of region r); (ii) a global food system where all regions export or import agricultural products ($\lambda_r \lesseqgtr \theta_r$ regardless of region r); and a mixed system which combines cases (i) and (ii) ($\lambda_r = \theta_r$ and $\lambda_s \lesseqgtr \theta_s$ with $r \neq s$). The purpose of the further analysis is to determine the spatial patterns that would be best suited to curb transport-related emissions. In order to make the discussion clearer, we distinguish between the inter- and intra-regional transportation. We first start by exploring the impact of farms' distribution on each GHG emissions flow (due to inter- and intra-regional transportation). In a second step, we account for these two flows simultaneously.

(i) Inter regional transport of agricultural goods (T) The first flow we consider refers to trade in agricultural commodities between core and peripheral regions. The sector being treated as operating in perfect competition[10], flows of agricultural goods are consequently unidirectional;

---

[10] Agricultural market is a common market where supplies from every region gather to balance out the overall demand.

everything happens as if the region that has an excess of food supply exports its surplus to the neighboring region - which, by definition, is short of agricultural goods - in order to bridge the gap between local supply and demand. Hence, a region exports food commodities if $A_r - Q_r^a > 0$. Let $X_r = \max\{A_r - Q_r^a, 0\}$ be the volume of agricultural goods exported by region r, with

$$A_r - Q_r^a = \frac{(\lambda_r - \theta_r)AL}{A+L} \tag{11}$$

As mentioned before, the physical flows of food commodities follow the hub and spoke distribution method. Thus, $\Sigma_r X_r$ is the total exports from peripheral regions assembled in the central region. Let $M_r = \max\{Q_r^a - A_r, 0\}$ be the imports of region r from the central region. We assume that the central region does not export food products, what will be checked at the equilibrium.

The sum of trade flows T is then given by

$$T = \Sigma_r X_r + \Sigma_r M_r \text{ with r} \neq 1.$$

Clearly, T is minimized when there is no inter-regional trade or, when urban and rural populations are equally spatially distributed ($\theta_r = \lambda_r$). In this case, food is locally grown and consumed in each region.

(ii) Intra regional transport of agricultural goods (D) The second flow refers to the transportation of agricultural goods within regions, i.e., from the farms' gate to the central market located in the CBD *via* the elevators. In each region, the route is made up of an agricultural area - which is more or less long according to the location of farmers within this area - and the entire urban area ($\bar{x}_r$). To evaluate the distance traveled by commodities, we need to know the allocation of farmers between elevators. Since farmers choose the elevator minimizing his total cost, the farmer who is indifferent between elevator k and $k+1$ is given by:

$$\widehat{x}_r^{k,k+1} = \frac{x_r^k + x_r^{k+1}}{2} + \frac{\tau(x_r^{k+1} - x_r^k)}{2} = \frac{L_r}{2} + \frac{A_r k}{2\mu K_r} + \frac{\tau A_r}{4\mu K_r}.$$

Our spatial framework implies that the elevators are heterogeneous: their distance from the city is not the same, which induces different transport costs. Hence, farmers cannot be equally shared among the elevators. The mass of farmers shipping their output to elevator 1 (which has the location closest to the city) and to elevator K (which is the most remote from the city) are respectively given by:

$$\widehat{x}_r^{1,2} - \bar{x}_r = \frac{A_r(2+\tau)}{4\mu K_r} \quad \text{and} \quad x_r^a - \widehat{x}_r^{K,K-1} = \frac{A_r(2-\tau)}{4\mu K_r}$$

while for the other $K-2$ elevators we have

$$\widehat{x}_r^{k,k+1} - \widehat{x}_r^{k,k-1} = \frac{A_r}{2\mu K_r} \quad \text{with } k \in (1, K)$$

It appears the relative majority of farmers uses the least distant elevator while the furthest one has the lowest fraction of farmers. As expected, a rise in τ induces a higher share of agricultural products collected by the least distant elevator at the expense of the most distant one. The other elevators have the same share of farmers. The sum of distances traveled by agricultural commodities within each region is finally given by:

$$D_r = 2\sum_{k=1}^{K} \int_{\widehat{x}_r^{k,k-1}}^{\widehat{x}_r^{k,k+1}} \left| x - x_r^k \right| \mathrm{d}x + 2\sum_{k=1}^{K} x_r^k \left(\widehat{x}_r^{k,k+1} - \widehat{x}_r^{k,k-1} \right) \tau$$

where the first term of RHS represents the total distance traveled by commodities between farms and elevators whereas the second term of RHS is the total quantity of agricultural products carried per shipment from the elevator to the city.

In Appendix A, we show that:

$$D_r = \frac{\tau A_r^2}{4\mu^2} + \frac{A_r(1-\tau^2)}{8\kappa\mu^2} + \frac{\tau^2}{2\kappa^2} + \frac{A_r L_r}{2\mu}\tau$$

with $\mathrm{d}D_r/\mathrm{d}\mu < 0$. Under the constraint $\Sigma_r \lambda_r = 1$, $\Sigma_r D_r$ is minimized when λ_r reaches

$$\frac{1}{m} - \left(\theta_r - \frac{1}{m} \right) \frac{L\mu}{A} \equiv \lambda_r^D.$$

$\lambda_r^D > \theta_r$ if and only if $\theta_r < 1/m$ (and vice-versa). As a consequence, intra-regional flows are minimized under sectoral separation, that is to say, when agricultural production clusters mainly in the least-urbanized regions. Indeed, in these regions, the urban area is less extensive and agricultural estates are consequently based on locations closer to the city, so that shipping routes are in average shorter. Hence, except when urban population is equally split between cities, *local food system is not desirable from the intra-regional emissions standpoint.*

(iii) Spatial patterns and the environment. The total GHG emissions stemming from agricultural goods transportation are given by:

$$E = e_T \nu T(\lambda_r, \theta_r) + e_D \sum_{r=1}^{m} D_r(\lambda_r, \theta_r)$$

where e_T is the amount of GHG emissions generated by one unit of distance traveled by a good shipped to the neighboring region and e_D represents the amount of GHG emissions generated by one unit of distance traveled by an agricultural good within a region. The value of these parameters basically depends on the technology used for transportation. To be consistent with the reality of freight, we define two different emission factors, depending on the stage of transport we consider. This reflects the fact that, during its delivery trip, a commodity is often carried by several successive modes of transport. In practice, intra-regional transportation is more likely to be inland (trucking or rail) whereas inter-regional one is usually either air or water freight. Therefore, carbon intensity is not uniform throughout the shipment travel and then, emission factors have to be differentiated in order to account for this feature.

E describes a convex parabola in λ_r. As a consequence, there is a single spatial allocation of agricultural production minimizing the total emissions for a same set of parameters. Let us denote

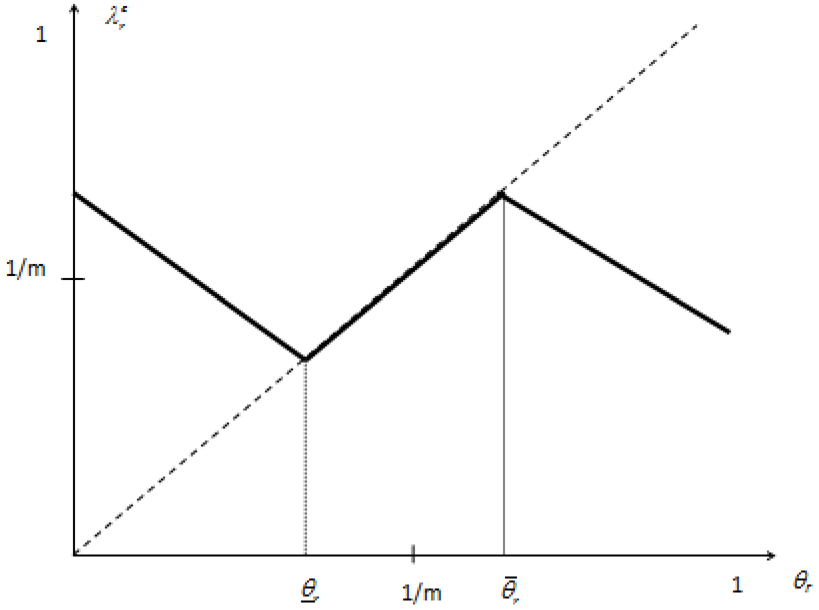

Figure 1: *The pollution minimizing locations and urbanization*

by λ_r^e the share of the rural population settled in region r that allows to minimize the emissions. By minimizing E under the constraint $\Sigma_r \lambda_r = 1$ (see Appendix B), we get

$$\lambda_r^e = \begin{cases} \frac{1}{m} + \frac{L\mu}{A}\left[\frac{1}{m} - \theta_r + \frac{2e_T \nu\mu(2m - m\mathbf{d} - 2\overline{m}+1)}{e_D(A+L)m\tau}\right] & \text{if } \theta_r > \overline{\theta} \\ \theta_r & \text{if } \overline{\theta} > \theta_r > \underline{\theta} \\ \frac{1}{m} + \frac{L\mu}{A}\left[\frac{1}{m} - \theta_r - \frac{2e_T \nu\mu(2\overline{m}-1)}{e_D(A+L)m\tau}\right] & \text{if } \theta_r < \underline{\theta} \end{cases} \tag{12}$$

where $\mathbf{d}$ is a dummy variable which is equal to 1 for the central region and 0 for the other regions, $\overline{m}$ is the number of region importing agricultural products (i.e. with $\lambda_r^e > \theta_r$), and where[11]

$$\overline{\theta} \equiv \frac{1}{m} + \frac{L\mu}{L\mu + A}\frac{2e_T\nu\mu(m - m\mathbf{d} - 2\overline{m} + 1)}{e_D(A+L)m\tau} > \frac{1}{m} \quad \text{and} \quad \underline{\theta} \equiv \frac{1}{m} - \frac{L\mu}{L\mu + A}\frac{2e_T\nu\mu(2\overline{m} - 1)}{e_D(A+L)m\tau} < \frac{1}{m}.$$

The first line in (12) refers to the importing regions. In this case, $\lambda_r^e < \theta_r$ is checked if and only if $\theta > \overline{\theta}$. The third line of (12) refers to the exporting regions where $\lambda_r^e > \theta_r$ holds if and only if $\theta_r < \underline{\theta}$. Because $\overline{\theta} > \underline{\theta}$, there are regions where λ_r^e must be equal to θ_r to minimize the transport-related emissions. In other words, any city verifying $\overline{\theta} > \theta_r > \underline{\theta}$ should adopt a local food system to reduce GHG emissions. However, it appears that $\overline{\theta} - \underline{\theta}$ decreases as the urban population (L) increases from high values ($L > \sqrt{\mu}A$). Hence, when the economy is sufficiently urbanized, a global food system is more likely to be more desirable than local food systems from an ecological standpoint.

---

[11] Note that $\overline{m}$ depends on the spatial distribution of urban population. More exactly, $\overline{m}$ is the number of regions with an urban population higher than $\overline{\theta}_r$.

Referring to (12), we can notice that the location of urban activities has an impact on the distribution of agricultural production leading to the lowest pollution; its effect can be either attractive or repulsive depending on the level of urban agglomeration.

If the urban population is highly gathered in the largest regions (i.e. $\theta_r > \overline{\theta}$ or $\theta_r < \underline{\theta}$ regardless of r) then it is beneficial to locate the agricultural activity mostly in the least urbanized regions. Hence, *when the economy is dominated by few large cities and numerous very small cities, a global food system leads to less transport-related emissions.* Even though there is no land constraint in the most urbanized regions, inter-regional trade is preferable than a configuration with no inter-regional trade (local food systems). Indeed, with no inter-regional trade and big cities, the agricultural areas would be very large, inducing high levels of emissions due to intra-regional transport. As a consequence, when urban population is unequally distributed among cities, the ecological benefit of the agricultural agglomeration in the least urban-crowded regions rises with the growth of the largest cities. In other words, *the environmental benefit of inter-regional food trade increases with the growth of the largest cities.*

In contrast, if urban population is sufficiently dispersed between core and peripheral regions (i.e. $\overline{\theta} > \theta_r > \underline{\theta}$ regardless of r), then we find results in line with recommendations that are made when adopting a "food miles" approach. Stated differently, we get that supporting the development of a local food system is beneficial from the environmental standpoint. However, when the size distribution of cities is not too unequal, medium-sized cities should implement a local food system while trade in agricultural cities should occur between regions with a big city and rural regions (with small cities). To sum-up,

Proposition 3.1 *For the sake of the transport-related emissions,*

1. *global food system is desirable when the urban population is highly agglomerated (so that $\theta_r > \overline{\theta}$ or $\theta_r < \underline{\theta}$ regardless of region r).*
2. *local food system is preferable if the urban population is sufficiently dispersed (so that $\overline{\theta} > \theta_r > \underline{\theta}$ regardless of region r).*
3. *Mixed food system combining local food networks and a global food network is desirable when the urban population is not too much agglomerated ($\theta_{\max} > \overline{\theta} > \theta_r > \underline{\theta} > \theta_{\min}$).*

Focusing on parameter μ, (12) reveals that $\overline{\theta} - \underline{\theta}$ increases with agricultural yields. Increasing yields provide an incentive to relocate some of the agricultural activity from the least urbanized regions to the most urbanized ones. High values of μ reinforce the ecological interest to gather agricultural estates; as farms take up little land, the concentration of agricultural production within the core regions allows to reduce the inter-regional transport-related emissions without inducing a substantial spatial expansion. Hence, a full sectoral separation would strongly increase the trade emissions by exacerbating the imbalance between local supply and demand.

In addition, the degree of agricultural concentration characterizing the lowest-emissions pattern is determined by the value of the last term in the RHS of (12) (when $\theta_r > \overline{\theta}$ or $\theta_r < \underline{\theta}$). This ratio can be construed as a comparison between the harmfulness of the intra-regional transportation flow ($e_D m$) and that of the inter-regional trade in food commodities ($e_T \nu (\overline{m} - 1)$). It determines the conditions under which, promoting local consumption and relocation is environmentally beneficial. Hence, if shipping one unit of agricultural good from a peripheral region to a core region is more GHG-emitter than intra-regional collection (i.e. $e_T \nu / e_D$ high), the environmental benefit of localization is large. In this case, switching from a global to an "almost local" food supply chain allows to curb the emissions. On the contrary, supposing that delivering goods from farms to the city within the same region is highly pollutant, it is then interesting to minimize intra-regional flows. The benefit of relocation fades and it is desirable to locate agricultural production mostly in the least-sprawled regions and retain - or even enhance - inter-regional trade in food commodities.[12] In other words, if the objective pursued is to limit the emissions due to food transportation, then a sectoral separation implying that peripheral regions are specialized in agricultural production is recommended when (i.e. $e_T \nu / e_D$ low).

Proposition 3.2 *No inter-regional trade in food commodities is more likely to be desirable from an ecological standpoint when agricultural yields (μ) and $e_T \nu / e_D$ increase.*

Findings from this section lead us to make the following observation. Based on the "standard" food miles approach, recommendations usually consist in limiting agricultural trade by supporting the development of a local food system. According to this literature, a regional food system – that is to say, a full relocation of agricultural production – is often preferable from an environmental standpoint (Norberg-Hodge et al., 2002; Garnett, 2003; Stephens et al., 2003; Pretty et al., 2005). Instead, the result that localization minimizes emissions related to intra-regional transportation only holds in specific cases, i.e., when the urban population is sufficiently dispersed among central and peripheral regions. In all other cases, urban growth tends to increase the length of food haulage (and hence emissions) in the largest region relatively more than it diminishes in the smallest ones. Therefore, the full relocation of agricultural activities leads to raise the total emissions due to intra-regional transportation. As the studies based on the food-miles approach do not account for the role of urban growth and intra-regional transport, this point is generally missed.

4 Market, agricultural location and ecological outcome

The following analysis aims at defining the conditions under which the market outcome matches with the spatial distribution of agricultural production that minimizes GHG emissions.

4.1 The market outcome

First, we have to determine the long-run spatial equilibrium. We follow the standard approach in economic geography (see Fujita and Thisse (2002)). In the long run, the spatial allocation of

---

[12] In this situation, the core region would have to import larger quantities of agricultural goods in order to feed its inhabitants.

production is driven by the inter-regional distribution of the urban population. In our case, a spatial equilibrium occurs when no farmer may get a higher utility level by moving to another region. In other words, the location of agricultural production is such that farmers settle in the region that provides the highest indirect utility.

The indirect utility of a region r farmer is given by

$$V_r^a = y_r + n_r S + S^a \tag{13}$$

where S and S^a are the consumer surplus evaluated at the equilibrium prices of a differentiated service and the agricultural good respectively with

$$S = \frac{\alpha^2\beta^2}{[\beta + (\beta-\gamma)]^2 + \beta} \quad \text{and} \quad S^a = \frac{\beta_a}{2}\left(\frac{A}{A+L}\right)^2 \tag{14}$$

Note the individual surplus varies among regions due to the number of services available in each region. Because V_r^a is continuous in $\lambda_r \in [0,1]$ and $\partial V_r^a/\partial\lambda_r < 0$, a spatial equilibrium always exists and this equilibrium is stable. We follow a well-established tradition in migration modeling when there are more than two regions by focusing on adjustment processes in which individuals locate themselves among several regions (see Tabuchi et al. (2005)). A spatial equilibrium arises at $0 < \lambda_r^* < 1$ when

$$\Delta V^a(\theta_r, \lambda_r^*) \equiv V_r^a(\theta_r, \lambda_r^*) - \frac{1}{m}\sum_{r=1}^{m}[V_r^a(\theta_r, \lambda_r)] = 0,$$

or at $\lambda_r^* = 1$ when $\Delta V^a(\theta_r, 1) \geq 0$. In addition, an interior equilibrium is stable if and only if the slope of the indirect utility differential ΔV^a is strictly negative in the neighborhood of the equilibrium, i.e., $\partial \Delta V^a(\theta_r, \lambda_r)/\partial\lambda_r < 0$ at λ_r^*. Whenever it exists, an agglomerated equilibrium is stable.

By replacing y_r and n_r by their expression, we get:

$$\Delta V^a(\theta_r, \lambda_r) = -t_a\tau\left(\frac{\lambda_r A}{2\mu} + \frac{\theta_r L}{2}\right) + \lambda_r L\phi S + \frac{t_a\tau}{m}\left(\frac{A}{2\mu} + \frac{L}{2}\right) - \frac{L\phi S}{m}. \tag{15}$$

The above expression reveals that ΔV^a decreases with λ_r. Thus, the interior equilibrium is always stable and takes the following form:

$$\lambda_r^*(\theta_r) = \frac{1}{m} + \left(\theta_r - \frac{1}{m}\right)\left(\frac{\bar{t}_a}{t_a} - \tau\right)\frac{L}{A}\frac{\mu}{\tau} \tag{16}$$

with $\bar{t}_a \equiv 2\phi S$ and $\Sigma_r \lambda_r^* = \Sigma_r \theta_r = 1$.

It appears from Eq.(16) that the relation between urbanization and the location of agricultural production is ambiguous. In the one side, increasing city size raises agricultural land rents and induces a reallocation of agricultural production to less urbanized regions. The positive impact of urbanization on agricultural land rents is stronger when agricultural transport costs are higher. On the other side, a larger city allows farmers to consume a larger set of services. As a consequence, the impact of urbanization on location of agricultural production depends on how farmers value the services supplied in their region and transport costs in the agricultural sector. For instance, when farmers value weakly the urban services or when agricultural transport costs are high, $\bar{t}_a/t_a - \tau$ is more likely to be negative. As a result, λ_r and θ_r vary in opposite directions, suggesting that the agricultural production tends to locate in the least-urbanized regions to enjoy lower land rent. By contrast, when farmers strongly value the urban services and/or when food collection costs are low, agricultural production settles mainly in the most-urbanized region. In this case, parameter $\bar{t}_a/t_a$ is relatively high, implying that $\bar{t}_a/t_a - \tau$ is positive.

The impacts of t_a and μ on λ_r^* depend on the sign of $\theta_r - 1/m$. Higher food transport costs or lower agricultural yields increase the agricultural production in the least urbanized regions at the expense of the most urbanized ones. When t_a is low, the inter-regional differences in the net income (y_r) are low so that the incentive to move to the region with a larger set of available varieties is stronger. When t_a increases, farmers are more sensitive to the inter-regional differences in the net income (y_r). Because land rents are higher in the most populated regions, agricultural production reallocates to the least urban-crowded regions. Note that the incentive to produce in the most populated regions vanishes when the farmer's surplus arising from the consumption of urban services is weak.

Concerning the effect of agricultural yields on location, remember that low yields are equivalent to high land requirements.[13] Hence, from the perspective of farmers, a low value of μ involves that the spatial extension of their estate is relatively large and, consequently, the cost they have to pay to settle in a region (i.e., $R_r^a(x)/\mu$) are high. As a result, a significant need in land promotes spatial dispersion of agricultural production so as to reduce the cost of the land rent.

Proposition 4.1 *Higher food transport costs and lower agricultural yields induce a reallocation of agricultural production from the most urbanized regions to the least ones and, in turn, more inter-regional trade.*

4.2 Does market yield too much inter-regional trade?

Assessing the ecological impact of market requires that we explicit the spatial distribution of urban population. For simplicity, we consider that the economy consists in one large city (located in the core region) and several small cities (the peripheral regions).[14] Formally, the share of urban population in the core region, say region 1, is given by $\theta_1 \equiv \theta > 1/m$ and the size of the urban population living in peripheral regions is identical so that $\theta_2 = ... = \theta_m \equiv \theta_p$. As a result, we have $\theta_p = (1-\theta)/(m-1)$ where $\theta_p < 1/m$. In this case, the share of agricultural production located

---

[13] Note that this relation stems from the way we define the size of agricultural plots.

[14] We could use the well-established rank size rule (or the Zipf's law) in urban economics (see Duranton, 2010). Indeed, there are many empirical studies showing that the distribution of city size can approximated with a Pareto distribution. In our case, we can consider region 1 has the largest city and region r has the r-th largest city. Hence, according to the rank size rule, we have $r = L_1 L_r^{-\zeta}$ where ζ is the exponent of the Pareto distribution. If $\zeta = 1$, we get $L_r = L_1/r$ or, equivalently, $\theta_r = \theta/r$. Hence, $\theta_{r+1} = r\theta_r/(r+1)$. For example, the expected size of the second largest city is half the size of that of the largest. Using such a distribution of city size leads to similar results.

in the core region is given by $\lambda(\theta)$ and by $[1-\lambda(\theta)]/(m-1)$ in each peripheral region. Such a configuration implies whether the core region imports, the other regions export (and vice-versa). However, we can show that $\lambda^e < \theta$ and, in turn, $\lambda_p^e > \theta_p$ so that we have $\overline{m} = 1$.[15] Hence, the situation where the core region is exporting food can not match with a lowest-emissions pattern. Hence, under this spatial distribution of urban population, the spatial allocation of agricultural production minimizing GHG emissions is given by

$$\lambda^e = \begin{cases} \frac{1}{m} + \frac{L\mu}{A}\left[\frac{1}{m} - \theta + \frac{2e_T\nu\mu(m-1)}{e_D(A+L)m\tau}\right] & \text{if } \theta > \overline{\theta} \\ \theta & \text{if } \frac{1}{m} < \theta < \overline{\theta} \end{cases} \tag{17}$$

$$\overline{\theta} \equiv \frac{1}{m} + \frac{L\mu}{L\mu + A}\frac{2e_T\nu\mu(m-1)}{e_D(A+L)m\tau} > \frac{1}{m}$$

When $\theta > \overline{\theta}$, we have $\lambda^e < \theta$ so that the core region imports agricultural products. Otherwise, when $\theta < \overline{\theta}$, $\partial E/\partial\lambda < 0$ as long as $\lambda < \theta$ so that $\lambda^e = \theta$.

We are now equipped to compare the lowest-emissions patterns with the spatial equilibrium. Our purpose in doing this comparison is to exhibit cases where the market leads to a spatial pattern where food freight emissions are minimized. From (16), we have $\lambda^* > \theta$ when $\frac{L\mu}{A+L\mu} > \frac{\tau t_a}{\bar{t}_a}$. Under these circumstances, $\lambda^* > \lambda^e$. Hence, when collection costs are low enough or high agricultural yields, market leads too much agricultural production in the core region from an ecological standpoint. When $\frac{L\mu}{A+L\mu} < \frac{\tau t_a}{\bar{t}_a}$, assessing the difference between the spatial equilibrium (λ^*) and the lowest-emissions pattern (λ^e) leads to

$$\lambda^* - \lambda^e = \begin{cases} \frac{L\mu}{A\tau}\frac{\bar{t}_a}{t_a}\left(\theta - \widetilde{\theta}\right) & \text{if } \theta > \overline{\theta} \\ \left(\theta - \frac{1}{m}\right)\frac{L\mu}{A\tau}\left(\frac{\bar{t}_a}{t_a} - \tau\right) & \text{if } \overline{\theta} > \theta \geq \frac{1}{m} \end{cases} \tag{18}$$

with

$$\widetilde{\theta} \equiv \frac{1}{m} + \frac{\tau t_a}{\bar{t}_a}\frac{2e_T\nu\mu(m-1)}{e_D(A+L)m} > \overline{\theta}$$

It appears a highly dispersed urban population (θ close to $1/m$) and very low values of agricultural yields (μ close to zero) allows the spatial equilibrium to meet a lowest-emission pattern. In other words, the market mechanisms lead to a spatial organization which corresponds to the lowest-emissions pattern whether full dispersion of agricultural production prevails. Otherwise, *market induces a spatial pattern in agricultural supply with excess pollution.*[16] However, we do not know whether there is too much or too little agricultural activities in the core region.

(i) When $\theta > \overline{\theta}$, high agricultural transport costs make more likely the fact that market induces too much dispersion in agricultural production or, equivalently, too inter-regional trade ($\widetilde{\theta}$ is relatively high). Stated differently, *if the economy is dominated by a large city, there is too much*

---

[15] If the core region exports agricultural products ($\lambda^e > \theta$), the location of agricultural production minimizing the GHG emissions is given by $\frac{1}{m} + \frac{L\mu}{A}\left[\frac{1}{m} - \theta - \frac{2e_T\nu\mu(m-1)}{e_D(A+L)m\tau}\right] < \theta$ which is incompatible with the fact the core exports agricultural goods. As E is convex, $\lambda^e < \theta$.

[16] Except that it exists a particular value of food collection cost t_a involving a lowest-emission spatial pattern. This value is not the same when $\theta > \overline{\theta}$ and when $\theta < \overline{\theta}$.

agriculture trade provided that agricultural transport costs are high enough. Farmers tend to settle in the peripheral regions in order to reduce their transportation cost, so that the share of the agricultural production located in the core region is not large enough to allow the emissions to be minimized.

(ii) When urban population is relatively dispersed ($\theta < \overline{\theta}$), we obtain similar results. There is too agriculture trade when agricultural transport costs are high enough ($\bar{t}_a/t_a - \tau < 0$). Hence, high values of t_a entail an excess of agricultural dispersion. The share of the food production located in the peripheral regions is too high. When $\bar{t}_a/t_a - \tau > 0$, more agricultural trade is required to reduce excess pollution. When transport costs of agricultural products are high enough, additional GHG emissions stemming from inter-regional trade flows would be more than offset by the decrease of emissions at the intra-regional scale. Consequently, one may expect that any measure involving a drop in food collection cost would contribute to mitigate transport-related emissions by readjusting the location of agricultural activities.

The following proposition summarizes our main findings:

Proposition 4.2 *Market mechanisms yield too much inter-regional trade provided that agricultural transport costs are high enough or the largest city size is low enough. Otherwise, market induces too much agricultural production in the most urbanized region.*

Hence, when we take into account the total intra-regional distance traveled by food products, urbanization does not induce too much food miles between regions.

4.3 Agricultural transport costs, location and GHG emissions

Because the agricultural transportation cost does not reflect the environmental damages caused by the delivery of food commodities, market failures occur. We do not know a priori if t_a is too high or too low. The effect of agricultural transport costs on GHG emissions is given by

$$\frac{\mathrm{d}E}{\mathrm{d}t_a} = \frac{\partial E}{\partial \lambda}\frac{\mathrm{d}\lambda^*}{\mathrm{d}t_a}$$

where $\mathrm{d}\lambda^*/\mathrm{d}t_a < 0$ whereas $\partial E/\partial \lambda > 0$ if and only if $\theta > \widetilde{\theta}$ or $\bar{t}_a/t_a - \tau > 0$. Because $\widetilde{\theta}$ decreases with t_a, rising t_a induces lower GHG emissions if t_a remains low enough. Remember that E is convex with λ and λ^* is convex in t_a. As a result, when t_a is low, excess pollution due to the misallocation of agricultural production reaches high values ($\lambda^* - \lambda^e$ is positive and is relatively high). There are too much agricultural activities in the most populated region from an ecological standpoint. Hence, starting from very low values of t_a, a marginal increase in t_a favors the dispersion (λ^* falls in high proportion) so that GHG emissions shrink. However, from a threshold value of transport costs $\widehat{t}_a$, given by $\lambda^*(\widehat{t}_a) = \lambda^e(\widehat{t}_a)$ with

$$\widehat{t}_a \equiv \frac{\bar{t}_a}{\tau}\frac{\left(\theta - \frac{1}{m}\right) e_D(A+L)m}{2e_T\nu\mu(m-1)}$$

GHG emissions increase when t_a rises. It also follows that the interval over transport costs in which higher transport costs involves lower emissions ($t_a \in [0, \widehat{t}_a)$) increases with the city size in the core region and decreases with agricultural yields. As a consequence, *any measure involving a drop in food collection cost would contribute to mitigate transport-related emissions provided that agricultural transport costs and agricultural yields are not too high.*

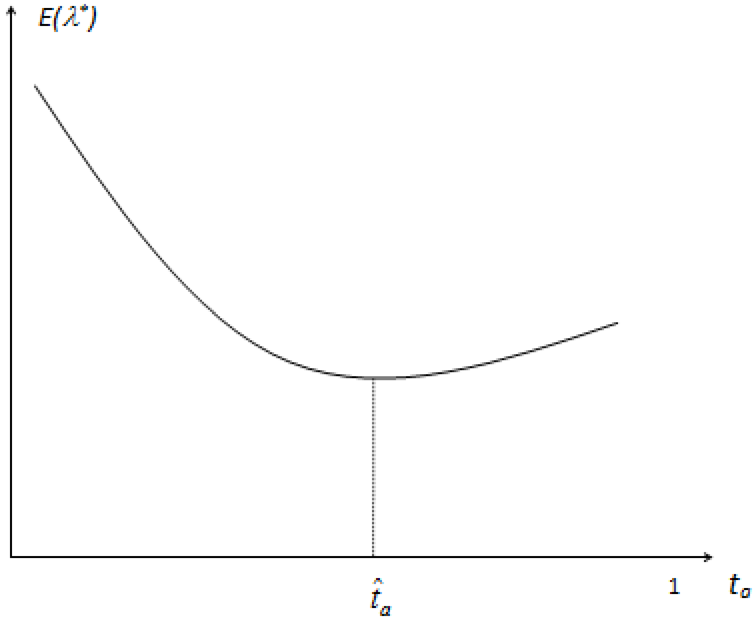

Figure 2: *Agricultural transport costs and transport-related emissions*

Two additional comments are in order. First, when t_a is low, *increasing freight rates in the agricultural sector induce a higher decline in transport-related emissions when agricultural yields are high.* Indeed, in this case, the dispersion effect of higher transport costs is stronger when agricultural yields are high and $|\lambda^* - \lambda^e|$ increases with μ.[17] Second, when t_a is high, $\lambda^e - \lambda^*$ and $d\lambda^*/dt_a$ achieve low values. In other words, the excess of pollution due to trade in agricultural products is low when agricultural transport costs are high while it reaches higher values when the food collection cost is lower.

Proposition 4.3 *A higher agricultural transport costs reduces excess pollution if the agricultural transport costs and agricultural yields remain low enough.*

4.4 Welfare

We have shown that market does not induce the spatial allocation of agricultural production minimizing transport-related emissions. A centralized policy controlling land use could be implemented to regulate GHG emissions. However, we do not know a priori whether such a policy may hurt

---

[17] When $\theta > \overline{\theta}$, $d(\lambda^* - \lambda^e)/d\mu \propto (\theta - \widetilde{\theta}) + \mu d\widetilde{\theta}/d\mu = \theta - 1/m > 0$. In addition, when $\theta < \overline{\theta}$, higher μ increases $|\lambda^* - \lambda^e|$.

farmers welfare. Since the market outcome and the lowest-emissions pattern involve different agricultural land rents, it is important to figure out how social welfare is affected by spatial allocation of agricultural production. Note that the welfare level of the urban population is not affected when the inter-city distribution of urban activities is given. This implies that we must determine the inter-region allocation of agricultural production (λ^o) that maximizes the welfare level of farmers given by $W^a \equiv \lambda V_1^a(\lambda) + (m-1)\lambda_p(\lambda)V_p^a(\lambda)$. Some standard calculations show that W^a is maximized when $\lambda = \lambda^o$ with

$$\lambda^o \equiv \frac{1}{m} + \frac{1}{2}\left(\theta - \frac{1}{m}\right)\left(\frac{\bar{t}_a}{t_a} - \tau\right)\frac{L\mu}{A\tau}.$$

Hence, $\lambda^* \gtreqless \lambda^o$ if and only if $\bar{t}_a/t_a - \tau \gtreqless 0$. The market induces an excess of agricultural agglomeration from a welfare viewpoint when the unit cost of food collection is low, and vice-versa. Hence, *there is no conflict between the ecological and welfare criteria when the location of agricultural production changes marginally* (except under particular configurations where $\theta > \overline{\theta}$ and $0 < \bar{t}_a/t_a - \tau < 1$). To summarize,

Proposition 4.4 *Starting from the spatial equilibrium, a marginal change in the location of agricultural production improves the welfare of farmers and decreases transport-related emissions, except when agricultural transport costs reach intermediate values.*

5 Discussion

We finally discuss the robustness of our results. We first discuss the consequences that the introduction of land heterogeneity across space may have on both agricultural location and GHG emissions. Further, we abandon the assumption that the location of the urban population is exogenously given in order to see what changes this entails.

5.1 Heterogeneous crop yields and GHG emissions

For simplicity, we have assumed that peripheral and central regions both enjoy the same quality of land, designated by the variable μ. The purpose is to review the significant changes that would result from the consideration of land heterogeneity between regions in our framework. As we will see, our main results do not depend on the spatial dispersion of agricultural yields.

The first modification associated with the heterogeneity of crop yields concerns the space consumption by farmers. The differences in land productivity across regions would inevitably alter the spatial footprint of the agricultural activity. At identical population levels, the spatial extension of the region benefiting from the highest yields is smallest. As a result, GHG emissions stemming from the intra-regional transportation of agricultural commodities in the "most productive" region because the food-mileage is shorter. From a transport-related emissions standpoint, there would be an environmental interest in gathering the agricultural activity in this region.

The second comment relates to the impact of market mechanisms on the spatial allocation of agricultural production. Agricultural yields positively the net income of farmers (see (9)). Because the farmers settled in the region with the best-quality land enjoy a higher income, the incentives to produce in this region are strengthened. It is easy to check that when, agricultural yields are heterogeneous, (16) becomes:

$$\lambda_r^* = \frac{\mu_r}{\sum\limits_{r=1}^{m} \mu_r} + \left(\theta_r - \frac{1}{m}\right)\left(\frac{\bar{t}_a}{t_a} - \tau\right)\frac{L}{A\tau}\frac{m\prod\limits_{r=1}^{m} \mu_r}{\sum\limits_{r=1}^{m} \mu_r}$$

where μ_r ($r \in \{1, m\}$) stands for the level of agricultural yields in region r. It appears that the allocation process of agricultural production across regions is similar to the case with homogeneous yields. The difference lies in the fact the region with higher yields has an advantage and attracts more agricultural production *ceteris paribus*. For example, the agricultural activity does not evenly disperse anymore when all cities are similar in size (i.e., $\theta_r = 1/m$). Emissions stemming from agricultural production. Hence, the specialization of the regions with highest agricultural yields in the agricultural sector allows farmers to increase their income and to reduce their transport-related emissions.

Last, when accounting for land heterogeneity, enlarging the environmental assessment to agricultural emissions would requires to consider spatially-differentiated emission factors. Indeed, in our framework with homogeneous yields, aggregate agricultural production is constant and does not depend on its spatial distribution. By considering heterogeneous agricultural yields, total production is affected by its spatial allocation across regions. Consequently, in order to accurately capture the relation between yields and the level of emissions due to agricultural production, one must probably refine the inclusion of the variable μ in our model. Henceforth, the latter has to encompass factors that can explain the origin of the differential in crop yields across the regions. This notably involves to consider two dimensions: the soil properties and the input use (in particular, nitrogen fertilizer). However, such an extension is beyond the scope of our analysis. This is an area for future research

5.2 Endogenous location choices

So far, we have assumed that the spatial distribution of urban population was given and fixed. This made the analysis more tractable and enabled us to focus solely on the agricultural sector. We now relax this assumption. The location decisions of urban and rural populations are related to each other as rural households are also potential consumers. To make the analysis more readable, we consider that $K = 1$ and the number of regions is given by $m = 2$.

Within each region, a urban worker chooses his location so as to maximize his utility (1) under the budget constraint (2). Because of the fixed lot size assumption, the value of the consumption of the non-spatial goods $q_r^a p_r^a + q_r(\omega)p_r(\omega) + q_0$ at the residential equilibrium is the same regardless of the urban worker's location. Because $R_r^a(\bar{x}) = 0$, the equilibrium urban land rent can be written as follows:

$$R_r^*(x) = t\left(\frac{L_r}{2} - x\right) \qquad \text{for } x < \bar{x}_r. \tag{19}$$

In the following, we successively determine the locational equilibrium of the manufacturing activity and highlight the link between the spatial organization of the economy as a whole and GHG emissions due to agricultural transport flows. The indirect utility of a urban worker living in region r is given by

$$V_r(\lambda, \theta) = n_r S + S^a + w_r^* - UC_r + \bar{q}_0 \tag{20}$$

where UC_r are the urban costs borne by this worker. Using Eq.(19), it is readily verified that

$$UC_r \equiv R_r^* + tx = \frac{tL_r}{2}. \tag{21}$$

As for the rural population, urban households residing in region r have an incentive to migrate to region s if the level of the utility they would receive in s is higher than in r. Thus, the migration process can be described by the utility differential $\Delta V(\theta, \lambda^*) \equiv V_1(\theta, \lambda^*) - V_2(\theta, \lambda^*)$ where θ is the share of urban population living in region 1. Replacing each term by its expression and substituting λ^{a^*} by its equilibrium expression (16), we get:

$$\Delta V(\theta) = \frac{L}{2}\left(\theta - \frac{1}{2}\right)(\bar{t} - t) \tag{22}$$

where

$$\bar{t} \equiv \bar{t}_a + \frac{4\phi\mu p^{*2}}{1+\tau}\left[\frac{\bar{t}_a}{t_a} + \frac{1-\tau(2\mu-1)}{2\mu}\right]$$

According to Eq.(22), $\Delta V(\theta)$ can be either decreasing or increasing with θ, depending on the sign of $\bar{t} - t$. Thus, for high values of t ($t > \bar{t}$), the only stable equilibrium is the symmetrical dispersion of urban workers ($\theta^* = 1/2$). Referring to Eq.(21), urban costs rise with t. As a consequence, when commuting is expensive, urban costs become so high that they can not be offset by any surplus enhancement. In contrast, for low values of t ($t < \bar{t}$), the urban population tends to concentrate, so that an agglomeration pattern occurs ($\theta^* = 1$). In this case, the low cost allows urban population to gather in the core region in order to enjoy greater consumption surplus, without having to suffer from high urban costs.

Knowing how urban households choose their location, we can finally replace θ in the expression of λ^* in order to define the overall spatial patterns. When the spatial pattern consists in a symmetrical dispersion of both agricultural production and urban population, we have $\theta^* = \lambda^* = 1/2M$. When urban population is agglomerated, we have $\theta^* = 1$ and $\lambda^* = \frac{1}{2} + (\frac{\bar{t}_a}{t_a} - \tau)\frac{L\mu}{A(1+\tau)}$. Using the results obtained in Section 4.2, we finally have $\lambda^* = \lambda^e = 1/2$ when $t > \bar{t}$ and, when $t < \bar{t}$,

$$\lambda^* - \lambda^e = \frac{L\mu}{A(1+\tau)}\left(\frac{\bar{t}_a}{t_a} - \tau\right) + \frac{L}{A}\left[\frac{\tau}{1+2\tau} - \frac{2\nu e_T \mu}{(A+L)(1+2\tau)e_D}\right]$$

Hence, when commuting costs are high enough, the market leads to the spatial organization that allows to minimize transport-related emissions. However, when commuting costs are low, market and lowest-emissions outcome are unlikely to match; large values of collection costs entail too much dispersion while small values induce an excess of agricultural agglomeration.

6 Conclusion

In this paper, we have studied the relationship between the spatial distribution of agricultural production and GHG emissions due to food transportation. The analytical framework we used allows to account for endogenous location of agricultural activities, trade-offs between competing land uses (residential and agricultural) and relationships between spatial patterns and transport-related emissions. Our spatial framework is richer than standard economy models because, on the one side, we consider several regions and each region has a spatial extension and, on the other side, we are explicit on the network of transportation and distribution of products. However, it is sufficiently simple to obtain definite interpretable results instead of distracting complexity.

This paper sheds new lights on the food-miles debate. Special attention must be paid on the impacts of urban growth on the localization of agricultural production *between* regions and *within* regions. By focusing only on the food-mileage between regions, fundamental effects are left aside which may distort the environmental assessment of local food systems. Indeed, our results reveal that local food systems may be desirable only if this system is adopted by medium-sized cities and if agricultural yields are high enough. In contrast, a global food system with a hub and spoke distribution system induce less GHG emissions related to agricultural transport when the economy is sufficiently urbanized or dominated by few large cities.

Additionally, our analysis reveals the conditions under which market failures occur. We show that the market induces too much inter-regional trade flows for agricultural products provided that urban population is sufficiently dispersed and agricultural transport costs are high enough. In other words, in highly urbanized economy, the excess of pollution due to transport does not arise from inter-regional trade but from the very large size of agricultural areas in rural regions, inducing high levels of intra-regional trade flows. Finally, while a carbon tax may raise transport-related emissions because of a relocation of agricultural production, we show that a centralized regional policy controlling land use may both reduce transport-related emissions and improve farmers' welfare.

This work could be extended in several directions. In our framework, we have exclusively focused on transport-related emissions. We have left aside the emissions stemming from production. According to Weber and Matthews (2008), they are responsible for a vast majority of total GHG emissions associated with food chain. Including emissions stemming from manufactured goods shipments, agricultural production itself and land use change would enrich the environmental analysis of the spatial organization of the economy. In this respect, the discussion initiated in Section 5 provides a brief overview of the issue and may serve as a basis for further research.

References

Bagoulla, C., Chevassus-Lozza, E., Daniel, K., and Gaigné, C. (2010). Regional Production Adjustement to Import Competition: Evidence from the French Agro-Industry. *American Journal of Agricultural Economics*, 92:1040–1050.

BioIS (2007). Impact environnemental du transport de fruits et légumes frais importés et consommés en France métropolitaine. Technical report, ADEME. `http://www.ale08.org/IMG/pdf/Fruits_Legumes.pdf`.

Cavailhès, J., Gaigné, C., Tabuchi, T., and Thisse, J.-F. (2007). Trade and the Structure of Cities. *Journal of Urban Economics*, 62:383–404.

Daniel, K. and Kilkenny, M. (2009). Agricultural Subsidies and Rural Development. *Journal of Agricultural Economics*, 60(3):504–529.

DEFRA (2002). National Atmospheric Emissions Inventory. Technical report. `http://naei.defra.gov.uk/`.

Duranton, G. and Puga, D. (2004). *Handbook of Regional and Urban Economics*, chapter 48: Micro-Foundations of Urban Agglomeration Economies, pages 2063–2117. Elsevier.

EEA (2004). EEA Signals 2004. Technical report, European Environment Agency.

EPA (2010a). Analysis of the Transportation Sector: Greenhouse Gas and Oil Reduction Scenarios. Technical report, EPA.

EPA (2010b). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2008. Technical report, U. S. Environmental Protection Agency.

FHWA (2011). Freight Analysis Framework. `http://faf.ornl.gov/fafweb/FUT.aspx`.

Fujita, M., Krugman, P., and Venables, A. (1999). *The Spatial Economy: Cities, Regions, and International Trade*. MIT Press.

Fujita, M. and Thisse, J.-F. (2002). *Economics of Agglomeration*. Cambridge Books.

Gaigné, C., Riou, S., and Thisse, J.-F. (2011). Are Compact Cities Environmentally Friendly?

Gaigné, C. and Thisse, J.-F. (2009). Aging Nations and the Future of Cities. *Journal of Regional Science*, 49(4):663 – 688.

Garnett, T. (2003). Wise Moves. Exploring the relationship between food, road transport and CO2. Technical report, Transport2000.

IPCC (2007). The Fourth Assessment Report: Climate Change. Technical report. `http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html`.

Kampman, B., Van Essen, H., Van Rooijen, T., Wilmink, I., and Tavasszy, L. (2010). Infrastructure and Spatial Policy, Speed and Traffic Management. Technical report, European Commission.

Norberg-Hodge, H., Merrifield, T., and Gorelick, S. (2002). *Bringing the food economy home: Local alternatives to global agribusiness.* Zed Books.

OECD (2008). OECD Environmental Outlook to 2030. Technical report, OECD.

Overman, H., Puga, D., and Turner, M. (2008). Decomposing the Growth in Residential Land in the United States. *Regional Science and Urban Economics*, 38:487–497.

Paxton, A. (1994). The Food Miles Report: The Dangers of Long Distance Food Transport. Technical report, SAFE Alliance.

Picard, P. M. and Zeng, D.-Z. (2005). Agricultural Sector and Industrial Agglomeration. *Journal of Development Economics*, 77(1):75–106.

Pretty, J., Ball, A., Lang, T., and Morison, J. (2005). Farm Costs and Food Miles: An Assessment of the Full Cost of the UK Weekly Food Basket. *Food Policy*, 30:1–19.

Saunders, C., Barber, A., and Taylor, G. (2006). Food Miles: Comparative Energy/Emissions Performance of New Zealand's Agriculture Industry. Technical report, AERU Research Report No. 285. Lincoln , New Zealand : Lincoln University.

Savin, J.-M. (2000). L'évolution des distances moyennes de transports des marchandises. *Notes de Synthèse du SES*, 129:17–20.

Stephens, P. A., Pretty, J. N., and Sutherland, W. J. (2003). Agriculture, transport policy and landscape heterogeneity. *Trends in Ecology and Evolution*, 18:555–556.

Tabuchi, T. and Thisse, J.-F. (2006). Regional Specialization, Urban Hierarchy, and Commuting Costs. *International Economic Review*, 47(4):1295–1317.

Tabuchi, T., Thisse, J.-F., and Zeng, D.-Z. (2005). On the Number And Size of Cities. *Journal of Economic Geography*, 5:423–448.

United Nations (2010). World Urbanization Prospects: The 2009 Revision. Technical report, United Nations, Department of Economic and Social Affairs, Population Division. `http://esa.un.org/unpd/wup/Documents/WUP2009_Highlights_Final.pdf`.

USDOT (2006). Freight In America: A New National Picture. Technical report, U.S. Departement of Transportation, Bureau of Transportation Statistics. `http://www.bts.gov/publications/freight_in_america/pdf/entire.pdf`.

Weber, C. and Matthews, H. (2008). Food-Miles and the Relative Climate Impacts of Food Choices in the United States. *Environmental Science & Technology*, 42:3508–3513.

Appendix A: The Sum of Distance

$$\begin{aligned}
\sum_{k=1}^{K_r}\int_{\widehat{x}_r^{k,k-1}}^{\widehat{x}_r^{k,k+1}} \left|x - x_r^k\right| \mathrm{d}x &= \left(\frac{A_r}{4\mu K_r}\right)^2 + \frac{K_r-1}{2}\left\{\left[\frac{A_r(1+\tau)}{4\mu K_r}\right]^2 + \left[\frac{A_r(1-\tau)}{4\mu K_r}\right]^2\right\} \\
&= \left(\frac{A_r}{4\mu K_r}\right)^2 + (K_r-1)\left(\frac{A_r}{4\mu K_r}\right)^2(1+\tau^2) \\
&= \left(\frac{A_r}{4\mu K_r}\right)^2\left[K_r + (K_r-1)\tau^2\right]
\end{aligned}$$

and

$$\begin{aligned}
\sum_{1}^{K_r} x_r^k\left(\widehat{x}_r^{k,k+1} - \widehat{x}_r^{k,k-1}\right) &= \frac{L_r}{2}\frac{A_r}{2\mu} + \left(\frac{A_r}{4\mu K_r}\right)^2(2+\tau) + \frac{K-2}{2}\frac{A_r}{2\mu K_r}\frac{A_r}{2\mu K_r} \\
&\quad + \frac{(K_r-2)(K_r-1)}{2}\frac{A_r}{2\mu K_r}\frac{A_r}{2\mu K_r} + \left[\frac{A_r}{4\mu K_r} + 2(K-1)\frac{A_r}{4\mu K_r}\right]\frac{A_r(2-\tau)}{4\mu K_r} \\
&= \frac{L_r}{2}\frac{A_r}{2\mu} + \left(\frac{A_r}{4\mu K_r}\right)^2(2+\tau) + 2(K_r-2)K\left(\frac{A_r}{4\mu K_r}\right)^2 \\
&\quad + (2K_r-1)(2-\tau)\left(\frac{A_r}{4\mu K_r}\right)^2 \\
&= \frac{L_r}{2}\frac{A_r}{2\mu} + \left(\frac{A_r}{4\mu K_r}\right)^2\left[2K_r^2 - 2\tau(K_r-1)\right]
\end{aligned}$$

Hence,

$$D_r^a = \frac{A_r^2}{4\mu^2}\left[\frac{\tau^2 + K_r(1-\tau^2) + 2\tau K_r^2}{2K_r^2}\right] + \frac{L_r}{2}\frac{A_r}{\mu}\tau.$$

Because $K_r = \kappa A_r/2$, we get

$$D_r^a = \frac{4A_r^2\tau}{\mu^2} + \frac{A_r(1-\tau^2)}{4\kappa\mu^2} + \frac{\tau^2}{2\kappa^2\mu^2} + \frac{L_r}{2}\frac{A_r}{\mu}\tau$$

Appendix B: Emission Flows

$$\begin{aligned} E(\lambda_r,\theta_r) &= e_T\nu T(\lambda_r,\theta_r)+e_D\sum_{r=1}^{m}D_r(A_r,L_r)\\ &= e_T\nu\left(\sum_r X_r+\sum_r M_r\right)+e_D\left(\frac{\tau A^2}{4\mu^2}\sum_r\lambda_r^2+\frac{(1-\tau^2)A}{8\kappa\mu^2}\sum_r\lambda_r+m\frac{\tau^2}{2\kappa}+\frac{AL}{2\mu}\tau\sum_r\lambda_r\theta_r\right)\end{aligned}$$

$$\begin{cases} Min\ E(\lambda_r,\theta_r)\\ s.t.\sum_{r=1}^{m}\lambda_r=1\end{cases}$$

$$\mathcal{L}(\lambda_r,l) = e_T\nu T(\lambda_r,\theta_r)+e_D\sum_{r=1}^{m}D_r(A_r,L_r)-l\left(\sum_{r=1}^{m}\lambda_r-1\right)$$

First Order Conditions:

$$\begin{aligned} *\ \frac{\partial\mathcal{L}(\lambda_r,l)}{\partial\lambda_r} &= 0\Leftrightarrow e_D\left(\frac{\tau A^2}{2\mu^2}\lambda_r+\frac{A(1-\tau^2)}{8\kappa\mu^2}+\frac{AL}{2\mu}\tau\theta_r\right)\pm e_T\nu\frac{AL}{A+L}-l=0\\ *\ \frac{\partial\mathcal{L}(\lambda_r,l)}{\partial l} &= 0\Leftrightarrow\sum_{r=1}^{m}\lambda_r=1\end{aligned}$$

Assuming that $\overline{m}$ regions are importing food, the sum of the first-order conditions is given by:

$$\begin{aligned} \sum_r\frac{\partial\mathcal{L}(\lambda_r,l)}{\partial\lambda_r} &= e_D\left(\frac{\tau A^2}{2\mu^2}\sum_r\lambda_r+\frac{A(1-\tau^2)}{8\kappa\mu^2}m+\frac{AL}{2\mu}\tau\sum_r\theta_r\right)+e_T\nu\frac{AL}{A+L}(m+1-\overline{m})-e_T\nu\frac{AL}{A+L}\overline{m}-ml\\ &= e_D\left(\frac{\tau A^2}{2\mu^2}+\frac{A(1-\tau^2)}{8\kappa\mu^2}m+\frac{AL}{2\mu}\tau\right)+e_T\nu\frac{AL}{A+L}(m+1-2\overline{m})-ml\end{aligned}$$

Hence,

$$l=e_D\left(\frac{1}{m}\frac{\tau A^2}{2\mu^2}+\frac{A(1-\tau^2)}{8\kappa\mu^2}+\frac{1}{m}\frac{AL}{2\mu}\tau\right)+e_T\nu\frac{AL}{A+L}\frac{1}{m}(m+1-2\overline{m})$$

Substituting the value of l in each FOC, we get:

Peripheral Regions

$$\begin{aligned} \frac{\partial\mathcal{L}(\lambda_r,l)}{\partial\lambda_r}=0 \quad&\Leftrightarrow\quad e_D\left(\frac{\tau A^2}{2\mu^2}\lambda_r+\frac{A(1-\tau^2)}{8\kappa\mu^2}+\frac{AL}{2\mu}\tau\theta_r\right)\pm e_T\nu\frac{AL}{A+L}\\ &-\quad e_D\left(\frac{1}{m}\frac{\tau A^2}{2\mu^2}+\frac{A(1-\tau^2)}{8\kappa\mu^2}+\frac{1}{m}\frac{AL}{2\mu}\tau\right)-e_T\nu\frac{AL}{A+L}\frac{1}{m}(m+1-2\overline{m})=0\\ &\Leftrightarrow\quad e_D\left(\frac{\tau A^2}{2\mu^2}\lambda_r+\frac{AL}{2\mu}\tau\theta_r-\frac{1}{m}\frac{\tau A^2}{2\mu^2}-\frac{1}{m}\frac{AL}{2\mu}\tau\right)+e_T\nu\frac{AL}{A+L}\frac{1}{m}(2\overline{m}-1-m\pm m)=0\\ &\Leftrightarrow\quad \frac{\tau A^2}{2\mu^2}\lambda_r=\frac{1}{m}\frac{\tau A^2}{2\mu^2}-\frac{AL}{2\mu}\tau\theta_r+\frac{1}{m}\frac{AL}{2\mu}\tau+\frac{e_T\nu}{e_D}\frac{AL}{A+L}\frac{1}{m}(m\pm m-2\overline{m}+1)\\ &\Leftrightarrow\quad \lambda_r^e=\frac{1}{m}+\frac{L\mu}{A}\left[\frac{1}{m}-\theta_r+\frac{2e_T\nu\mu}{e_D(A+L)\tau m}(m\pm m-2\overline{m}+1)\right]\end{aligned}$$

Core Region

$$\begin{aligned}
\frac{\partial\mathcal{L}(\lambda_r,l)}{\partial\lambda_1}=0 \quad &\Leftrightarrow \quad e_D\left(\frac{\tau A^2}{2\mu^2}\lambda_1+\frac{A(1-\tau^2)}{8\kappa\mu^2}+\frac{AL}{2\mu}\tau\theta_1\right)-e_D\left(\frac{1}{m}\frac{\tau A^2}{2\mu^2}+\frac{A(1-\tau^2)}{8\kappa\mu^2}+\frac{1}{m}\frac{AL}{2\mu}\tau\right)\\
&- \quad e_T\nu\frac{AL}{A+L}\frac{1}{m}(m+1-2\overline{m})=0\\
&\Leftrightarrow \quad e_D\left(\frac{\tau A^2}{2\mu^2}\lambda_1+\frac{AL}{2\mu}\tau\theta_1-\frac{1}{m}\frac{\tau A^2}{2\mu^2}-\frac{1}{m}\frac{AL}{2\mu}\tau\right)+e_T\nu\frac{AL}{A+L}\frac{1}{m}(2\overline{m}-1-m)=0\\
&\Leftrightarrow \quad \frac{\tau A^2}{2\mu^2}\lambda_1=\frac{1}{m}\frac{\tau A^2}{2\mu^2}-\frac{AL}{2\mu}\tau\theta_1+\frac{1}{m}\frac{AL}{2\mu}\tau+\frac{e_T\nu}{e_D}\frac{AL}{A+L}\frac{1}{m}(m-2\overline{m}+1)\\
&\Leftrightarrow \quad \lambda_1^e=\frac{1}{m}+\frac{L\mu}{A}\left[\frac{1}{m}-\theta_1+\frac{2e_T\nu\mu}{e_D(A+L)\tau m}(m-2\overline{m}+1)\right]
\end{aligned}$$