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Mots-clés : aménités agricoles, politique d'aménagement foncier, étalement urbain, mitage, espace ouvert, rente foncière, modèle monocentrique.
Keywords: agricultural amenities, land development, land use policy, urban sprawl, leapfrog, open space, land rent, farming, monocentric model.

Résumé : Dans ce papier, un modèle spatial est développé pour examiner le rôle des aménités agricoles dans la structuration des espacex urbain et périurbain. En introduisant de manière endogène les aménités agricoles dans un modèle monocentrique, nous donnons une explication intuitive au mitage de l'espace. Nous montrons comment les formes du développement urbains dépendent de l'intensité agricole et de la fourniture de services environnementaux par l'agriculture. Nous montrons également que même en l'absence d'attribut paysager particulier, ou d'aménité exogène, le mitage est une forme possible de développement dès lors que la ville est entourée par un environnement agricole qui varie dans l'espace. Enfin, nous montrons comment les taxes foncières permettent de contrer l'étalement urbain sous certaines conditions de préférences des ménages et des caractéristiques agricoles de l'espace périurbain.

Abstract: This paper presents a spatially explicit model to examine the importance of agricultural amenities as a determinant of the urban and suburban spatial structure. By introducing endogenous agricultural amenities into the classical monocentric model, we provide an intuitive explanation of leapfrog development. We show how urban development patterns highly depend on the intensity of surrounding farms and their ability to produce amenities. We also show that, even in absence of a particular landscape feature or any exogenous source of amenities, fragmented urban sprawl is a natural development pattern for a city surrounded by a spatially varying agricultural environment. Finally, we show how land tax policies could curb urban sprawl under certain conditions on households' preferences and farming.

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Abstract

This paper presents a spatially explicit model to examine the importance of agricultural amenities as a determinant of the urban and suburban spatial structure. By introducing endogenous agricultural amenities into the classical monocentric model, we provide an intuitive explanation of leapfrog development. We show how urban development patterns highly depend on the intensity of surrounding farms and their ability to produce amenities. We also show that, even in absence of a particular landscape feature or any exogenous source of amenities, fragmented urban sprawl is a natural development pattern for a city surrounded by a spatially varying agricultural environment. Finally, we show how land tax policies could curb urban sprawl under certain conditions on households' preferences and farming.

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Keywords : Agricultural amenities, Land development, Land use policy, Urban sprawl, Leapfrog, Open space, Land rent, Farming, Monocentric model.

1 Introduction

Although its importance first became apparent in the second half of the 20th century, urban sprawl is still considered to be a major problem today. It refers to the spreading outwards of a city to its outskirts that is excessive relative to what is socially desirable. Most observers seem to agree that fragmentation of housing with low-density is the most significant feature of urban sprawl. Fragmented areas can take two forms: first, they are connected to the city taking the form of an contiguous urban extension. Second, they can be relatively far from urban areas, reflected by a discontinuous urban area, so-called leapfrog development (EEA, 2006; Irwin & Bockstael, 2007).

Numerous studies have revealed the nature of urban sprawl and the reasons for its occurrence in different contexts (Anas *et al.*, 1998; Brueckner, 2000; Brueckner *et al.*, 2001; Glaeser *et al.*, 2004; Nechyba & Walsh, 2004; Burchfield *et al.*, 2006; Patacchini *et al.*, 2009) The role of physical geography, the rise in household incomes, population growth and the decline in the cost of commuting are often identified as the fundamental forces that have led to sprawl. However, other factors play a major role in shaping the

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urban structure. For instance, farming in vicinity of cities is one of these factors. Indeed, in recent years, most sprawl in the United States or Europe has occurred on agricultural land. While planning and zoning policies play an important role in controlling the conversion of agricultural land, the general trend is for the large majority of urbanised land to have been converted from agricultural uses (Greene & Stager, 2001; Walker, 2001; EEA, 2006; Livanis *et al.*, 2006). It is also recognized that agricultural amenities in suburban areas have a strong pull effect on household location decisions and may encourage the development of areas occupied by both farmers and commuting households (Roe *et al.*, 2004; Cavailhès *et al.*, 2004; Ready & Abdalla, 2005). Despite these observations, few studies have been undertaken on the role of farming in the ongoing decentralization of urban areas.

The purpose of this paper is to investigate the interaction between agriculture and urban sprawl. We present a spatially explicit model which highlights the role of agriculture in determining suburban spatial structure.

Many prior studies examine the influence of amenities on urban development, but a few explicitly consider the spatial effects of agricultural amenities. The most widely used theoretical structure in the related literature is the monocentric city model, derived from the pioneering contributions of Alonso (1964), Muth (1969), Mills (1972) and Wheaton (1974)[1]. In this model, areas close to the central business district (CBD) have higher land prices and greater housing density. These areas are more desirable because of lower commuting costs. One important assumption of this model is to consider that urban development occurs on a featureless plain. Under this assumption, only the expectation behaviour of owners could explain the existence of scattered urban areas. This mechanism has been the subject of several papers on sprawl (Mills, 1981; Wheaton, 1982; Titman, 1985; Capozza & Helsley, 1989).

Polinsky & Shavell (1976) gave up the hypothesis of uniform landscape and introduced an environmental amenity characterized by its distance to the CBD. They show how the amenity changes the spatial pattern of the city. In the same vein, to explain the fact that in some cities poorer people live near the city center, while the rich live on the periphery, Brueckner *et al.* (1999) expand the monocentric city model to include amenities, characterised by distance to the CBD. In these two studies, amenities do not occupy space. In contrast, Mills (1981), Nelson (1985) and Lee & Fujita (1997) analyse the effects of "greenbelts" that form a ring of open space around a city. In all these studies, amenities are spatially homogenous.

Otherwise, the spatially heterogeneous amenities have been also used as a possible reason for the fragmentation of urban space. This is due to the fact that the household bid-function is not necessarily monotonous with regards to the distance from the CBD (Ogawa & Fujita, 1980; Yang & Fujita, 1983; Fujita & Kashiwadani, 1989). Several recent papers develop two-dimensional urban models including environmental amenities that show the effect of the location, size and shape of open space on spatial equilibrium in a monocentric city model (Wu & Plantinga, 2003; Wu, 2006; Kovacs & Larson, 2007; Tajibaeva *et al.*, 2008; Newburn & Berck, 2011). These studies provide a more intuitive explanation for leapfrog development than previous studies, but still treat agricultural rent and amenities as exogenous.

Overall, monocentric city models exploring the possibilities of leapfrog development, assume an exogenous agricultural rent to define the city boundary. By doing so, these

[1] A good synthesis is provided by Fujita (1989).

studies are not able to explain entirely the interactions between agriculture and cities. Thus, farm structures have no effect on agricultural land conversion. However, there are some studies that explicitly consider the movement of city limits in relation to an agricultural hinterland lying beyond the city (Muth, 1961; Walker, 2001; Cavailhès *et al.*, 2004). These studies borrow ideas from the monocentric-city model and the spatial agricultural model developed by von Thünen. They were not specifically concerned with urban sprawl, but offer an interesting analytical framework for better understanding the interactions between the city and agriculture.

Our model builds on Wu & Plantinga (2003), Wu (2006) and Cavailhès *et al.* (2004). Contrary to Wu & Plantinga (2003) and Wu (2006), we model the behaviour of farmers *à la* von Thünen. Small and intensive farms are located close to the city boundary while larger, more extensive farms are further away. This can be explained by the urban pressure on agricultural land prices. Far away from the city boundary, land becomes less expensive and may be substituted to capital. This may occur within a few miles for small cities, and up to ten miles away for larger settlements (Cavailhès & Wavresky, 2007). We emphasize the role of agricultural amenities, as a joint-product of farming, in household welfare. In Cavailhès *et al.* (2004) amenities are proportional to the agricultural land. Thus, intensive farms produce the same level of amenities as extensive ones. This assumption is simply at odds with reality. We observe most often a certain spatial heterogeneity of agricultural amenities which depends on the intensity of agriculture. Thus, contrary to Cavailhès *et al.* (2004), we assume that the level of amenity is defined at each point in space according to the level of agricultural intensity. So, within the farming area under the influence of the city, intensive farms produce fewer amenities than extensive ones. This expansion allows us to consider a richer set of situations on urban sprawl and the spatial configurations of agriculture.

The remainder of the paper is organised as follows. In section 2, we present the model and discuss the conditions for spatial equilibrium and more particularly for leapfrog development. Section 3 gives a numerical illustration of the main results of the model, while in section 4 we expand our model to include the case of the introduction of a land tax policy. Section 5 concludes the paper.

2 The model

2.1 Structure of the city

In order to study urban development patterns in the presence of spatially varying agriculture, we develop a static model of a monocentric open-city. Space is represented by the real line $X = (-\infty, +\infty)$ with a CBD at its origin. It is assumed that all non-agricultural employment is concentrated in the CBD. There are two types of agents competing in the land market: N identical households working in the CBD and N_a identical farmers. We assume that all land is owned by absentee landlords.

The farmers' bid function To produce Y, farmers use two kinds of input: land (L) and non-land inputs (K)[2]. The production function is given by $Y = F(K, L)$. This function is increasing and concave in each of its arguments and has constant returns to

[2] The non-land inputs represents the agricultural inputs such as gears, seeds, fertilizers and all other equipments used in different agricultural activities.

scale, which implies $y = Y/L = f(k)$, where y is the output per hectare and k is non-land input per hectare[3]. We assume $f(0) = 0,\ \ f'(k) > 0$ and $f''(k) < 0$. Each farm sells its products at the local market within the CBD, as in a Von Thünen approach. We assume that transportation costs are proportional to the distance to the CBD x and that t is the cost per unit of distance. Crops, land and non-land inputs are available without restriction at competitive prices, respectively p, r_a and p_k. The farmers' profit function is:

$$\pi(k, x) = (p - tx) f(k) - p_k k - r_a \tag{1}$$

Profit maximisation with respect to k implies that $(p - tx) f'(k) = p_k$. If $f(k)$ is a Cobb-Douglas then $f(k) = Ak^{\alpha}$ with $0 < \alpha < 1$, we obtain:

$$k^* = \left[\alpha \frac{A(p - tx)}{p_k}\right]^{\frac{1}{1-\alpha}} \tag{2}$$

and

$$y^* = A\left[\alpha \frac{A(p - tx)}{p_k}\right]^{\frac{\alpha}{1-\alpha}} \tag{3}$$

Eq (2) shows that k is continuous and falls with increasing distance away from the city. Agricultural activities are influenced by the distance that separates them from the city. Near to cities, farms tend to be intensive. The more intensive farms are, the higher the ratio k. Far away from cities, farms become progressively more extensive as the ratio k falls. We note that k reaches zero at p/t. This entails that output (Eq (3)) is a decreasing function of the distance to the CBD and equals zero at the critical distance p/t.

Since $f(.)$ has constant returns to scale, in equilibrium, all farmers make zero profit per unit of area at each x, that is:

$$r_a^*(x) = A(1 - \alpha)\left(\frac{\alpha A}{p_k}\right)^{\frac{\alpha}{1-\alpha}} (p - tx)^{\frac{1}{1-\alpha}} \tag{4}$$

We note that $r_a(x)$ is a continuous and decreasing function of distance and equals zero beyond p/t. In his model, Beckmann (1972) shows that in the presence of different types of agriculture, a continuous decreasing bid-rent gradient is also observed. Our decreasing gradient of farming intensity and agricultural bid-rent, consistent with empirical observations (Katzman, 1974; Heimlich & Barnard, 1992; Cavailhès & Wavresky, 2007), is based on the assumption of a Von Thünian behaviour in the model. In current cities, this observation is also partly explained as a result of the pressure that the adjacent urban area exerts on agricultural land prices (Capozza & Helsley, 1989), making farmers substitute land for non-land inputs (e.g. compound feeds, chemical fertilisers, pesticides and increased mechanisation). Empirical research in the US and in Europe shows that both Von Thünian behaviour and urban pressure significantly explain the decreasing gradient of farm intensity and agricultural land value with distance from the city (Plantinga *et al.*, 2002; Cavailhès & Wavresky, 2003; Livanis *et al.*, 2006).

Suburban agriculture stops at $\underline{x}$, beyond which agriculture becomes independant from any urban influence and can be considered as exporting farming with an exogenous

[3]This specification is inspired by Beckmann (1972)

constant rent $\widetilde{r_a}$. This agriculture will only be studied here as the marker of the suburban agriculture boundary. $\underline{x}$ is reached when $r_a(x) = \widetilde{r_a}$:

$$\underline{x} = \frac{p - \widetilde{r_a}^{1-\alpha} A \left(1-\alpha\right)^{\alpha-1} \left(\frac{\alpha}{p_k}\right)^{-\alpha}}{t} \tag{5}$$

Beyond $\underline{x}$, agriculture is homogenous, with a constant intensity $\widetilde{k}$.

Household's location decision The household's location decision consists of a trade-off between accessibility to the CBD, land consumption and level of amenities. Each household chooses a combination of residential space q_h, location x, and a numeraire of non-housing goods s to maximise their utility $U\left(s, q_h, a(x)\right)$ subject to the budget constraint:

$$\max_{q_h,s,x} U\left[s, q_h, a(x)\right] \qquad \text{s.t. } w = r\left(x\right) q_h + s + \tau x \tag{6}$$

where w is the gross household income and τ is the round-trip commuting cost per kilometre. $r\left(x\right)$ is the housing rental price at x. We use a Cobb-Douglas specification of the utility function : $U\left[s, q_h\right] = q_h^{\beta} s^{1-\beta} a(x)^{\gamma}$ (with $\beta \in [0, 1]$ and $\gamma > 0$). The level of amenities provided at location x is denoted by $a(x) = a_u(x) + a_p\left(x\right)$, where $a_u\left(x\right)$ represents urban amenities distributed uniformly in the city and equal to one for simplicity; and $a_p\left(x\right)$ is the agricultural amenities distribution function endogenously distributed outside of the city. Agricultural amenities are considered as a joint-product with agricultural products and are detailed in the next section. We suppose that there are no spillover effects, meaning that amenities are consumed by households at their residence location x only. The first-order conditions for the utility maximisation problem define the optimal choice of housing space and non-housing goods at each location:

$$s^* = \left(1-\beta\right)\left(w - \tau x\right) \tag{7}$$

$$q_h^* = \frac{\beta\left(w - \tau x\right)}{r\left(x\right)} \tag{8}$$

Eq (7) shows that expenditures on composite goods fall with increasing distance x. For each unit of distance from the CBD, total expenditures on the composite good fall by $\left(1-\beta\right)\tau$. We can then derive the households' bid-rent functions:

$$r^*\left(x\right) = \left[\frac{\beta^{\beta}\left(1-\beta\right)^{1-\beta}\left(w - \tau x\right)}{\overline{V}}\right]^{\frac{1}{\beta}} a(x)^{\frac{\gamma}{\beta}} \tag{9}$$

The bid-rent function (9) corresponds to the household's maximum willingness to pay for housing at location x. At equilibrium, households are indifferent to where they locate because their exogenous equilibrium utility level $\overline{V}$ is the same at each location. Recalling that, within the city, we have $a(x) = a_u(x) = 1$ and that outside of the city, we have $a(x) = a_p(x)$, we can distinguish urban households from periurban households. Urban households live in the city, they benefit from the accessibility to the CBD and consume urban amenities only. Periurban households live outside the city where they have higher commuting costs but enjoy agricultural amenities. Bid-rent functions can be written as follows.

$$r_u^*(x) = \left[\frac{\beta^{\beta}(1-\beta)^{1-\beta}(w - \tau x)}{\overline{V}}\right]^{\frac{1}{\beta}} \tag{10}$$

$$r_p^*(x) = \left[\frac{\beta^\beta (1-\beta)^{1-\beta} (w - \tau x)}{\overline{V}}\right]^{\frac{1}{\beta}} a_p(x)^{\frac{\gamma}{\beta}} \tag{11}$$

where $r_u^*(x)$ and $r_p^*(x)$ respectively denote the urban and periurban bid-rent functions. Eqs (10) and (11) reveal the difference between urban and periurban households. Urban bid-rent always falls with the distance away from the CBD to compensate residents for the costs of commuting. With spatial variation in amenities distribution, the pattern of housing prices is more complicated. Clearly, periurban households decide to live in rural areas if $a(x) > 1$ and they must be compensated for the loss of urban amenities and higher level of commuting costs. In this case, agriculture must therefore produce a sufficient level of amenities to attract households.

We define $\rho(x)$ as the density of households at each location (i.e. number of households per hectare). Let:

$$\rho(x) = \frac{1}{q_h^*(x)} \tag{12}$$

In a case where the housing density distribution within the urban area is analysed, it is common to introduce the building height at each location. However, the introduction of this new variable would require the presence of land developers as a third economic agent. As we choose not to focus on urban density, we leave our model without any developers, without loss of generality.

Agricultural amenities To improve the land resource, farms carry out stewardship practices such as the maintenance of hedges and tracks, drainage, erosion control, and crop rotation. These practices also have the advantage of providing a range of environmental goods and services. These positive externalities of production can be considered as agricultural amenities, which may be highly valued by periurban residents (Huylenbroeck, 1999). Insofar as agriculture has an undeniable spatial dimension, we can deduce that the spatial distribution of agricultural amenities is not an exogenous phenomenon.

Without loss of generality, we consider agricultural amenities as a net balance of positive agricultural externalities (e.g. landscape quality, biodiversity) and negative ones (e.g. pollution, nuisances). More extensive farms provide a higher level of agricultural amenities in the sense that their crop management favours the joint-production of positive externalities and that fewer non-land inputs lowers negative externalities. Indeed, Hodge (2008) explains that households preferences "tend to be towards the landscapes generated by longstanding and less intensive agricultural systems rather than by modern, more intensive ones". Conversely, intensive agricultural systems were empirically shown to significantly produce negative externalities (Abler, 2001, 2004). Therefore, in our spatialised economy, we assume that farms located near the city provide a lower net flow of amenities because they use more non-land inputs per hectare. As we get further away from the urban area, farming gets more extensive and the joint-production of agricultural amenities increases (see Fig. 1).

As a by-product of agricultural activities, the amenity level depends on the ratio k. Note that farmers don't take amenities into account in their behaviour as they are externalities and they are not paid for their production. However, these amenities are valued by periurban households who make their trade-off between accessibility to the CBD and residential space consumption. The level of agricultural amenities impacts this trade-off in the sense that periurban households may wish to bid more in areas where

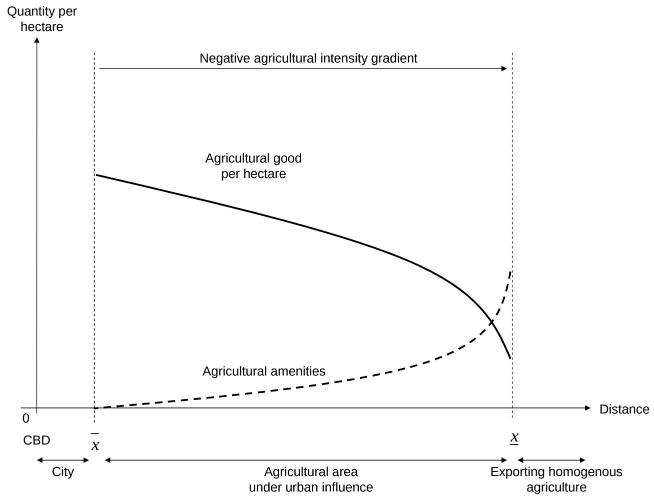

Figure 1: Jointness between agricultural production and amenities distribution in the urban influenced space

amenities are high enough. However, by converting agricultural land to residential use, periurban households also destroy agricultural amenities. Urban sprawl therefore reaches its limits in the destruction of valued landscapes and agricultural environment, justifying the introduction of a negative externality between periurban households themselves (Irwin & Bockstael, 2002; Roe *et al.*, 2004). This is introduced in the model making use of the fact that at any location, available land is unity. Noting that the periurban space is shared between periurban households and farmers, we have:

$$\rho_p(x)q_h(x) + \rho_a(x)L(x) = 1 \tag{13}$$

where $\rho_p(x)$ and $\rho_a(x)$ are respectively the density of periurban households and of farmers at x, and $q_h(x)$ and $L(x)$, their land consumption. We define $\Theta(x)$ as the fraction of land dedicated to agricultural use:

$$\Theta(x) = \rho_a(x)L(x) = 1 - \rho_p(x)q_h(x) \tag{14}$$

We consider the following specification of the amenity distribution outside of the city:

$$a_p(x) = \delta\frac{\Theta(x)}{k(x)} \tag{15}$$

where δ is a positive constant which can be interpretated as the capacity of a given type of agriculture to provide amenities, or in other words, the degree of jointness between amenity production and agricultural activity. For example, we can imagine that some agricultral activities, such as single-crop farming or soilless livestock farming, could be considered to have a low capacity to provide amenities valued by households, regardless of their intensity level (Palmquist *et al.*, 1997). On the other hand, viticulture, extensive livestock farming or fruit horticulture can produce more valued amenities and would therefore have a higher δ (Le Goffe, 2000; Irwin, 2002).

As we move away from the CBD, the amenity level gets higher as farms become more extensive (i.e. with lower k). Without any regulation, households could outbid farmers and agriculture amenities would be destroyed when new households would come and locate, as in Hardin's tragedy of the commons. Introducing $\Theta(x)$ in $a_p(x)$ allows us to take into account a negative externality between periurban households. When $\Theta(x)$ increases, meaning a larger share of agriculture, the level of amenities increases. On the contrary, if the share of residential use gets more important, $\Theta(x)$ decreases and the level of amenities gets lower.

Note that beyond $\underline{x}$, from which agriculture becomes independant from urban influence, farming intensity remains constant and provides the same corresponding level of amenities at any location. This area corresponds to an agricultural core zone, not much prone to competition with urban development and profitable enough to keep the land in agriculture (OECD, 2009).

2.2 Spatial equilibrium conditions

After deriving the behavioural functions for farmers and households, we present the conditions for the existence of the city and leapfrog development. Land use is defined by the competition between households and farmers for land.

Existence conditions of the city The city is the area where urban households live. Let $\overline{x}$ be the boundary of the city. Land being rented to the highest bidder, the city can be represented by the set C:

$$C = \{x < \overline{x} \mid r_u^*(x) > r_a^*(x)\} \tag{16}$$

The location of the urban fringe $\overline{x}$ is given by:

$$r_u^*(\overline{x}) = r_a^*(\overline{x}) \tag{17}$$

Proposition 1 *$\overline{x}$ exists if the households and farmers' bid-rent functions intersect at least once within the interval $[0, \underline{x}]$. To reach this situation, parameters of the model must obey the following conditions:*

$$w > \Omega p^{\frac{\beta}{(1-\alpha)}} \text{ and } \frac{w}{\tau} < \frac{p}{t} \tag{18}$$

where Ω is a positive constant (see A for details). These conditions mean that households income must be large enough, relative to the prices of agricultural products, and that the trade-off between urban and agricultural land use can only be made within the interval $[0, \underline{x}]$.

Existence conditions of the periurban area We determine the conditions for the occurence of a periurban area, where the space is shared between farmers and households, meaning that they have the same bid-rent. Let P be such an area. It is defined by:

$$P = \left\{x \in [\overline{x}, \underline{x}] \mid r_p^*(x) = r_a^*(x)\right\} \tag{19}$$

Proposition 2 *A periurban or mixed-land use area P exists if the capacity of farming to provide amenities, all other parameters being equal, is higher than a minimum threshold $\delta_{\min}$, given by:*

$$\delta_{\min} = \arg\min_{x} \ k(x) \left(\frac{r_a(x)}{r_u(x)} \right)^{\gamma/\beta} \tag{20}$$

This ensures that farming generates enough amenities to compensate households from higher commuting costs (see proof in B).

Urban extension or leapfrog development conditions Depending on the location of the periurban area, we can observe different development patterns. Leapfrog development occurs if and only if P is not simply connected to C. Intuitively, leapfrogs occurs in areas disjoint from the existing developed area. On the contrary, urban extension is observed if P is connected to C, the periurban area is located right next to the urban area.

Proposition 3 *The capacity of farming to provide amenities determines the location of the periurban area, all other parameters being equal:*

- *If $\delta \geq \delta_{\max}$ the periurban area is located right next to the urban area (P is connected to C), we define this development pattern as urban extension.*
- *If $\delta < \delta_{\max}$ there is an agricultural area seperating the city from the periurban area (P is disconnected from C), we define this development pattern as leapfrog development.*

where $\delta_{\max}$ is given by:

$$\delta_{\max} = \left[\alpha \frac{A\,(p - t\overline{x})}{p_k} \right]^{\frac{1}{1-\alpha}} \tag{21}$$

The proof is available in C. Clearly, when leapfrog development occurs, there exists $x_1 < x_2 < \underline{x}$, so that:

- for all $x \in [\overline{x}, x_1] \cup [x_2, \underline{x}]$, we have $r_a^*(x) > r_p^*(x)$, meaning agricultural use only.
- for all $x \in [x_1, x_2]$, we have $r_p^*(x) = r_a^*(x)$, meaning a mixed land use with both farmers and periurban households.

(x_1, x_2) are endogenously determined by the model, using $r_a^*(x)$ and $r_p^*(x)$ as specified in Eqs (4) and (11) respectively and the amenity level valued by periurban households being given by $a_p(x) = \frac{\delta}{k(x)}$ (from Eq (15) with $\Theta(x) = 1$, as all space is originally occupied by farmers only).

In the case of urban extension, the first border of the periurban area is located at the city boundary ($x_1 = \overline{x}$). The characteristics of the periurban area in terms of fragmentation and fraction of agricultural land, discussed next section, are similar both in the cases of urban extension and leapfrog development. The only difference between the two configurations is the location of the area itself.

Characteristics of the periurban area Once x_1 and x_2 are determined, we define the density characteristics within the periurban area. Note that the density of periurban households will not change x_1 and x_2. As soon as a single periurban household moves in the periurban area, we have $\Theta(x) < 1$ and the amenity level is lowered (Eq (15)). If the periurban area was completely built, we would then have $\rho_p(x)q_h(x) = 1$ and $\Theta(x) = 0$, meaning no amenities and $r_p^*(x) = 0$ (Eq (11)). This illustrates that if the level of amenities is too low, notably because too many periurban households move in, their reservation utility would not be reached and they would migrate to other cities. The complete urbanisation of the periurban area is therefore not possible in our model. Consequently, a mixed land use in the periurban area implies $\Theta(x) \in]0,1[$, reflecting the fragmented configuration of the area, which holds for both urban extension and leapfrog development.

Recalling that $r_p^*(x) = r_u^*(x)a_p(x)^{\frac{\gamma}{\beta}}$ and using (19), we can define the optimal amenity distribution inside the leapfrog area:

$$a_p^*(x) = \left(\frac{r_a^*(x)}{r_u^*(x)}\right)^{\frac{\beta}{\gamma}} \tag{22}$$

We derive the optimal periurban household density within the leapfrog area, from Eqs (14), (15) and (22):

$$\rho_p^*(x) = \frac{1}{q_h^*(x)}\left[1 - \frac{k^*(x)}{\delta}\left(\frac{r_a^*(x)}{r_u^*(x)}\right)^{\frac{\beta}{\gamma}}\right] \tag{23}$$

Definition of spatial equilibrium We sum up spatial equilibrium for land developement. Land is rented to the highest bidder, thus spatial equilibrium is reached if the following conditions are satisfied:

1. The spatial equilibrium is given by the prevailing land rent at x:

$$r^*(x) = \max\left\{r_u^*(x), r_p^*(x), r_a^*(x)\right\} \tag{24}$$

where $r_u^*(x)$ is given by Eq (10), $r_p^*(x)$ is given by Eq (11) and $r_a^*(x)$ is given by Eq (4).

2. At equilibrium, the delimitations of the different areas are characterised by the city boundary $\overline{x}$ given by Eq (17), the limits of the leapfrog area (x_1, x_2) determined by the relative position of $r_a^*(x)$ and $r_p^*(x)$, and the limits of the agricultural area $\underline{x}$, given by Eq (5).

3. The urban area (resp. periurban area) must be sufficient to provide housing for all urban (resp. periurban) households who have chosen to settle in (resp. outside of) the city. The number of urban and periurban households is endogenously determined by the model and given by:

$$\int_0^{\overline{x}} \rho_u^*(x)2\pi x dx = N_u \quad ; \quad \int_{x_1}^{x_2} \rho_p^*(x)2\pi x dx = N_p \tag{25}$$

where $\rho_u^*(x)$ is given using Eq (12) and $\rho_p^*(x)$ is given by Eq (23). The fraction of agricultural land within the periurban area is given by[4]:

$$\Theta^*(x) = 1 - \rho_p^*(x) q_h^*(x) = \frac{k^*(x)}{\delta} \left(\frac{r_a^*(x)}{r_u^*(x)} \right)^{\frac{\beta}{\gamma}} \tag{26}$$

4. At equilibrium, the level of total amenities $a^*(x)$ is given by:

$$a^*(x) = \begin{cases} 1 & \text{if } x \in [0, \overline{x}] \\ \left(\frac{r_a^*(x)}{r_u^*(x)} \right)^{\frac{\beta}{\gamma}} & \text{if } x \in [x_1, x_2] \\ \frac{\delta}{k^*(x)} & \text{otherwise} \end{cases} \tag{27}$$

3 Spatial pattern of land development

3.1 Comparative static analysis

	$r_u^*(x)$	$r_p^*(x)$	$r_a^*(x)$	$k^*(x)$	$\overline{x}$	x_1	x_2	$a_p^*(x)$	$\Theta^*(x)$	N_u^*	N_p^*
w	+	+	0	0	+	−	+	0	−	+	+
τ	−	−	0	0	−	+	−	0	+	−	−
$\overline{V}$	−	−	0	0	−	+	−	0	+	−	−
γ	0	+	0	0	0	−	+	0	−	0	+
p	0	−	+	+	−	+	−	−	+	−	−
p_k	0	+	−	−	+	−	+	+	−	+	+
t	0	+	−	−	+	−	+	+	−	+	+
δ	0	+	0	0	0	−	+	+	−	0	+

Table 1: Comparative static analysis

The mechanics of the model can be demonstrated analytically with comparative statics. Typically, our analysis is consistent with the main interactions of the monocentric city model without amenities (Wheaton, 1974; Brueckner, 1987). The introduction of agricultural amenities enriches the model by linking households behaviour and spatial organisation of agriculture. Table 1 summarizes the main interactions variables and parameters[5].

Rising incomes and falling transportation costs increase households bid-rents in both urban and periurban areas, leading the city to expand but also producing a larger periurban area and therefore a larger total number of households. The fraction of agricultural land within the periurban area (Θ^*) falls with a positive variation of income.

The equilibrium utility level has a negative impact on households' bid-rents, which leads to a negative impact on the urban boundary and on the size of the periurban area. Thus, the effect of a rise in the utility level is to contract the city. If the equilibrium utility level is too high, households leave the city, migration being costless, and the total population tends to decrease. Finally, the weight of amenities in the preferences (γ) intuitively has a positive impact on the periurban bid-rent, on the size of the periurban

[4]Constant returns to scale do not allow us to determine the land demand function for farmers. We therefore can't calculate $\rho_a^*(x)$ and $L^*(x)$ separately. However, we have the fraction of agricultural land $\Theta^*(x) = \rho_a^*(x) L^*(x)$.

[5]Detailed calculations are available in a separate Appendix document, available from the authors.

area $(x_2 - x_1)$ and on the number of periurban households, but has a negative impact on the fraction of agricultural land within the leapfrog area Θ^*.

The impact of the changing price of agricultural goods on the farmers' bid-rent is similar to the impact of changing incomes for households. As p increases, the farmers' bid-rent will increase. A higher p leads to further intensification of farms and thus a lower level of agricultural amenity. Therefore, lower amenities reduce the periurban bid-rent. The change in farmers and periurban households' bid-rents affects both the size of the leapfrog area and the city boundary. Thus raising agricultural prices leads to a smaller city and a lower leapfrog development, meaning a decrease in the total population. Conversely, the price of non-land inputs has a negative impact on the farmer's bid-rent, but a positive effect on the periurban bid-rent. If their price increases, a farmer will tend to substitute his non-land inputs with land, and therefore extensify his farm, providing a higher level of amenities. The urban bid-rent remains unchanged. Thus, an increase in p_k will lead to a larger city and a larger leapfrog area.

An increase in the capacity of farming to provide amenities (δ) does not affect the agricultural intensity or the farmer and urban bid-rents, but impacts positively on the amount of agricultural amenities provided (a_p). Thus a higher δ increases the periurban bid-rent, the size of the periurban area and the number of households located within this area. Therefore, the development pattern is strongly dependent on the jointness degree between farming and amenities.

3.2 Simulation of the model

To visualise the relative positions of the bid-rent functions, we run several simulations of our city model, using observed data. Most of our data come from the INSEE (French National Institute of Statistics and Economic Studies) database[6] and from the Farm Accountancy Data Network[7]. According to the INSEE, between 2000 and 2010, the average income for French households was $33,384$ €. Around a quarter of their total consumption is dedicated to housing (25.6% in 2010). Commuting costs for households are given by the French Internal Revenu Service, around 0.4 €$/km$. Assuming there are 1.5 workers per household travelling back and forth to the CBD all year long, we set $\tau = 400$ €$/km/year/household$.

As for the agricultural parameters, the FADN gives a share of non-land costs per hectare estimated at approximatively 90% of total costs and gives an average level of charges $p_k k^* = 1861$€$/ha$ per farm and an average gross product $pAk^{*\alpha} = 1714$€$/ha$ per farm, in 2009. Combining this with the estimated share of non-land costs per hectare, around 90% of total costs according to the FADN, we obtain a ratio between the output price and the non-land input price of 2.85. We assume this ratio is constant for any average French farm. We choose to set $\alpha = 0.8$, $p_k = 1$ and $p = 2.62$. The Agreste (French institute of agricultural statistics)[8] gives an average agricultural land price of $5,000$ €$/ha$ in France. Assuming a discount rate of 0.05, we set $\widetilde{r_a}$ to 250 €$/ha/year$.

The specification of the model's parameters is given summed up in Table 2. We perform an analysis to determine $\left\{\delta, \gamma, \overline{V}, t\right\}$.

We look at how the model behaves along with the parameters. The first parameter we analyse is δ, which can be interpretated as a technical parameter representing the

[6]http://www.insee.fr/fr/themes/ (last visit: May 22nd 2012)
[7]http://ec.europa.eu/agriculture/rica/database/database_en.cfm (last visit: January 18th 2012)
[8]http://agreste.agriculture.gouv.fr/ (last visit: August 3rd 2012)

Symbol	Interpretation	Value
w	household income	$33,000$ €$/household$
τ	household transport costs	400 €$/km/year/household$
β	share of expenses dedicated to housing	0.25
$\overline{V}$	equilibrium utility level	10 100
γ	periurban households' preferences for amenities	0.2
p	agricutural goods price	2.62 €$/outputunit$
p_k	non-land inputs price	1 €$/non-landinputunit$
t	farmers transport costs	0.02 €$/km/outputunit$
A	technical constant	1
α	elasticity of production factor k	0.8
δ	capacity for a farm to provide amenities	18 case of leapfrog development 22 case of urban extension
$\widetilde{r_a}$	exogenous exporting farming rent	250 €$/ha/year$

Table 2: Parameters value and signification

capacity of a farm to provide amenities. Simulations were first made by changing δ at a given level of $\left\{\gamma, \overline{V}, t\right\}$. We have $\partial r_p/\partial\delta > 0$, an increase in δ should increase the periurban bid-rent. The urban and agricultural bid-rent both remain unchanged. Fig. 2a shows how the size of the leapfrog area $(x_2 - x_1)$ evolves as δ changes. Three possibilities for spatial development patterns arise. The first case consists in the absence of any sprawl development. In this case, $\delta < \delta_{\min}$, meaning that farms provide a level of amenities too low to convince periurban households to locate. The second possibility is the emergence of leapfrog development ($\delta_{\min} < \delta < \delta_{\max}$). Farms provide sufficient agricultural amenities to persuade periurban households to relocate. Leapfrog development then occurs, i.e. a periurban area appears, disconnected from the city. Between $\delta_{\min}$ and $\delta_{\max}$, the leapfrog urban area gets larger as δ increases. Finally, the third case is an extension of the existing urban area. In this particular situation, farms have such a high capacity to provide amenities that the periurban area eventually links up with the city ($\delta > \delta_{\max}$). In our case, $\delta_{\max} = 23.6$ and $\delta_{\min} = 14.8$. Once the periurban area has joined the city ($\overline{x} = x_1$), its size increases more slowly until $x_2 = w/\tau$. The maximum size of the periurban area is therefore $(x_2 - x_1)_{\max} = (w/\tau) - \overline{x}$, to which $(x_2 - x_1)$ tends when δ increases.

The second parameter we consider is the preference for amenities γ. This parameter makes the difference between the urban bid-rent and the periurban bid-rent. As it represents the preferences that households have for amenities, we foresee that when it increases, households will tend to settle outside the city ($\partial r_p/\partial\gamma > 0$). Fig. 2b shows the impact of γ on the size of the leapfrog area, at a given level of $\left\{\delta, \overline{V}, t\right\}$. Once again, only the periurban bid-rent is changed. When preferences are lower than a threshold $\gamma_{\min}$, no sprawl occurs because periurban households have no incentive to move. In our case, we have $\gamma_{\min} = 0.17$. Over $\gamma_{\min}$, the households' preference are high enough for the associated amenities to be a sufficient trigger to move to a periurban area. The disconnected periurban area therefore gets larger as γ increases.

Making γ and δ vary simultaneously, we obtain the diagram in Fig. 3. For a given (γ, δ) we can observe what the expected spatial pattern will be, all other parameters being equal. As soon as δ gets higher than $\delta_{\max}$, the leapfrog development pattern will

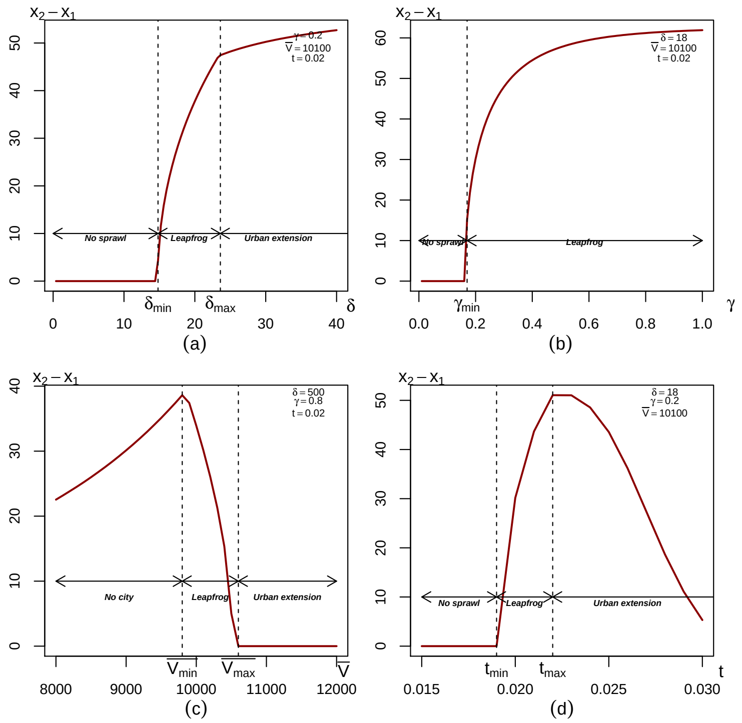

Figure 2: Impact of a change in δ, γ, $\overline{V}$ and t on spatial equilibrium patterns

disappear, to be replaced by a fusion between the city and the periurban area, at any γ. Fig. 3 allows us to refine our interpretation of δ. The parameter δ scales the ability of several agricultural types to generate a net balance of externalities. To illustrate this, take the example of grasslands or forests, where higher levels of production intensity do not prevent relatively high levels of amenity being produced. On the other hand, agriculture activities such as livestock farming, generate manure production and can require the construction of additional farm buildings all of which may be negatively valued by households. The level of intensity has therefore a greater impact on the level of amenities provided. Over $\delta_{\max}$, sprawl takes the form of urban extension only because amenities at the city fringe are sufficiently high for periurban households ($a(\overline{x}) > 1$). Leapfrog occurs under two conditions: high households' preferences for amenities and an intermediate capacity of farms to generate them. Note that the equation of the curve $\delta_{\min}(\gamma)$ and of $\delta_{\max}$ are given by the existence conditions of the periurban area, in Eqs (20) and (21) (Proof in B and C).

According to our model, cities surrounded by highly amenity generating farming (for example, grasslands) would be prone to sprawl under an urban extension scenario, whereas cities surrounded by agriculture characterised by a low capacity to produce amenities (for example, crop or livestock farming) may be subject to leapfrog development.

We now turn to the equilibrium utility level. In our open-city case, migration in and out of the city is costless, so that the equilibrium utility level is exogenous, and the population size is endougenously determined by the model. Fig. 2c presents the impact of a change in the equilibrium utility level on the size of the periurban area. From Table 1, we have $\partial\overline{x}/\partial\overline{V} < 0$ and $\partial x_1/\partial\overline{V} > 0$ and $\partial x_2/\partial\overline{V} < 0$, so that the impact of an

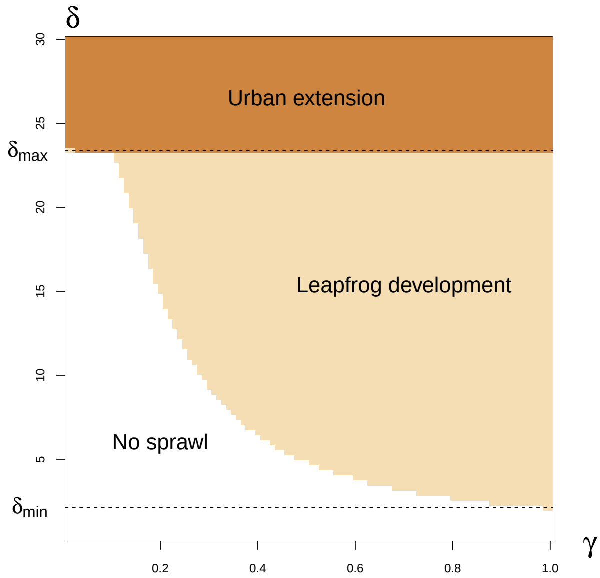

Figure 3: Urban development pattern depending on (δ, γ)

increase in $\overline{V}$ should be the reduction of the leapfrog area. However, we observe that while $\overline{V}$ is inferior to $\overline{V}_{\min} = 9800$, the size of the periurban area keeps increasing. This is due to the fact that we have $x_1 = \overline{x}$ (case of urban extension) and the city boundary $\overline{x}$ moves faster towards the CBD than x_2 does. The combined effect is that the periurban area gets larger. Beyond $\overline{V}_{\max}$, the city "disappears", meaning that the urban bid-rent is too low for the city to continue to exist: that is all households prefer to migrate away from the city. All other parameters being equal, we have $\overline{V}_{\max} \simeq 10600$. Between $\overline{V}_{\min}$ and $\overline{V}_{\max}$, we are in a leapfrog situation and the size of the periurban area decreases as $\overline{V}$ increases, as shown in Table 1.

The final parameter that must be analysed is transport costs for farmers. This parameter impacts on farmers' bid-rent functions, but also on periurban households' bid-rent via the level of k^* and thus the level of amenities provided. Fig. 2d shows that up to a minimum threshold $t_{\min} = 0.019$, no sprawl occurs. This is due to the fact that farms become more intensive when transport costs to the city are lower $(\partial k/\partial t < 0)$. The direct effect of agricultural transport costs on farms structure, has an impact on the amenity level and thus on the location decision of households. Over $t_{\min}$, leapfrog development occurs. The increase in transport costs for farmers means that they can be outbid by households. Moreover, it leads to a reduction in their use of production inputs, providing a higher level of amenities. Finally, the maximum threshold $t_{\max} = 0.022$ indicates the moment when the periurban area joins up with the city, leading to urban extension. From this threshold, the size of the periurban area declines for two reasons: the first is the fact that it is limited by w/τ over which households would exceed their incomes. The second is the fact that the urban fringe keeps moving further away from the CBD and getting closer to w/τ.

From here, we set $\gamma = 0.2$, $\delta = 22$, $\overline{V} = 10100$ and $t = 0.02$. These four values ensure that we place ourselves in a potential urban extension context (see Fig. 4a). Urban households outbid farmers from the CBD up to $\overline{x}$. The urban area is immediately followed by a periurban area expanding to distance x_2, below which land is dedicated to agricultural use only. Distance $\underline{x}$ identifies the boundary between urban influenced agriculture and exporting farming.

Note that within the periurban area, the level of amenities is lower than it would be without any periurban households (see Fig. 4b). Our model allows us to specify the fraction of land which is left to agricultural use in equilibrium (see Fig. 4c). With our given parameters, the fraction of agricultural land within the periurban area decreases down to 67% below which too many amenities would be destroyed, so that no more periurban households will be incited to settle. Within the periurban area, the fraction of agricultural land first decreases, reflecting an increasing fragmentation of uses, and then increases again so that the fragmentation is lowered. The increase in fragmentation is due to the growing production of amenities, but as distance to the CBD increases, fewer households decide to locate and fragmentation decreases.

When $\delta = 18$, we reach a leapfrog configuration for which the periurban area is disconnected from the urban area. This case is depicted in Fig. 7, in D.

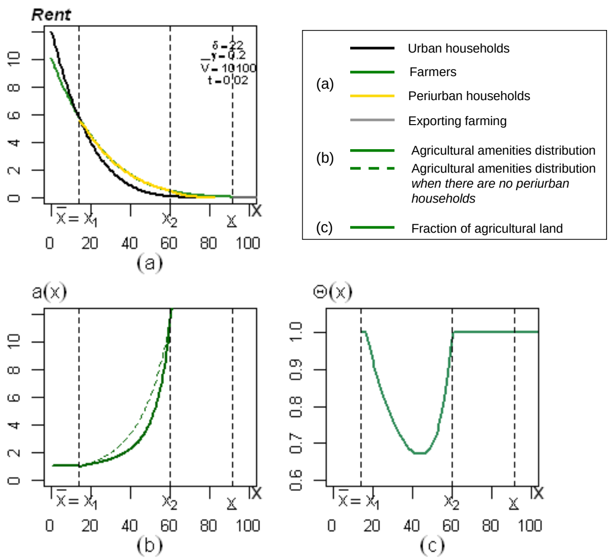

Figure 4: Spatial equilibrium pattern in the case of urban extension

4 Land tax policies and urban sprawl

In this section, we discuss the impacts of the introduction of a property tax system. We assume that public authorities set two types of property tax, one for the land used for housing and one for agricultural land. We test the effect of these taxes on spatial equilibrium.

Introduction of land taxes in our model In our model, we denote the introduction of land taxes by θ_h, the property tax rate paid by periurban households only. Thus, we obtain the following bid rent function:

$$r_p^*(x) = \left[\frac{\beta^\beta (1-\beta)^{1-\beta} (w - \tau x)}{V}\right]^{\frac{1}{\beta}} \frac{a_p(x)^{\frac{\gamma}{\beta}}}{(1+\theta_h)} \quad (28)$$

We note that the property tax rate has a negative effect on periurban households' bid-rent function. We also assume that the government applies a tax θ_a on agricultural land. The farmers' bid rent function becomes

$$r_a^*(x) = A(1-\alpha)\left(\frac{\alpha A}{p_k}\right)^{\frac{\alpha}{1-\alpha}} \frac{(p - tx)^{\frac{1}{1-\alpha}}}{(1+\theta_a)} \quad (29)$$

This tax has a negative effect on the farmer's bid-rent function. Therefore, the level of θ_a is also expected to have an impact on the location of the city's boundary $\overline{x}$. In the following we will study the effects of a land tax system on urban development.

Impact on spatial development patterns We test the sensitivity of spatial equilibrium with respect to variations in θ_h and θ_a. As expected, we see that, to curb urban sprawl, the government should tax more housing land than agricultural land. Fig. 8 (E) depicts the spatial development impacts of variations in θ_h and θ_a. We observe that θ_h and θ_a have opposite effects on spatial equilibrium patterns. While the first one leads to a smaller leapfrog area ($(x_2 - x_1)$ decreases), the second leads to a more expanded city and more developed leapfrog area.

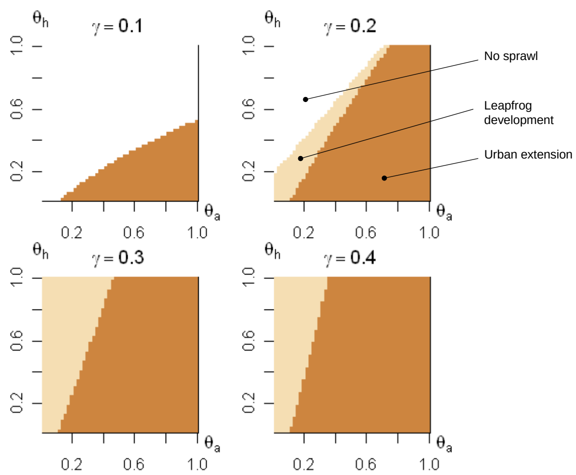

Figure 5: Impact of a change in θ_h and θ_a on the development pattern at different levels of preferences

Our model therefore shows how a land tax policy can be considered as a means of limiting leapfrog development. We observe in Fig. 5 and 6 that from a given threshold, the property tax rate on periurban households, combined with low land taxation for agriculture, can prevent them from outbidding farmers. On the contrary, a high land tax for farmers combined with a low land tax for periurban households will encourage leapfrog development or urban extension.

However, this threshold depends to a great extent on the level of household preferences (Fig. 5). For example, when $\gamma = 0.2$, the land tax rate for households must be

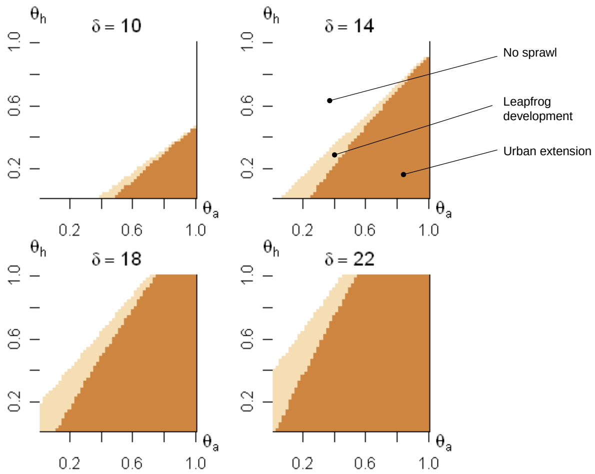

Figure 6: Impact of a change in θ_h and θ_a on the development pattern at different levels of capacity for agriculture to provide amenities

greater than 0.20 (combined with a low tax rate for farmers) in order to limit sprawl. But when $\gamma \geq 0.3$, the same combination of land taxes is not effective at preventing leapfrog development. Similary, we observe in Fig. 6 that the capacity of agriculture to provide amenities also has a strong influence on the effective combinations of land taxes. When the agricultural activity is characterised by a low capacity to provide amenities, for example $\delta = 10$, no tax is needed to limit urban sprawl. As δ increases, then the households' tax rate must also increase: θ_h must be higher than 0.2 if $\delta = 18$, and higher than 0.4 if $\delta = 22$.

More generally, if households are taxed at a level $\theta_h \leq \theta_{h\,\min}(\theta_a, \delta)$, the observed sprawl pattern is urban extension. On the contrary, if $\theta_h > \theta_{h\,\min}(\theta_a, \delta)$, the periurban area is disconnected from the city (leapfrog development). However, if the tax rate reaches sufficient threshold $\theta_{h\,\max}(\theta_a, \delta, \gamma)$, the policy can possibly curb urban sprawl. These particular values $\theta_{h\,\max}$ and $\theta_{h\,\min}$ are given by Eqs (32) and (33), in E.

From our results, we conclude that the effects of a land tax policy are highly dependent on the relative weight of households or farmers tax rate, but also on household preferences for agricultural amenities and on the capacity of agriculture to provide them.

5 Conclusion

The purpose of this paper is to formally examine the relationship between urban spatial structure and agriculture. To highlight the importance of agricultural amenities, a monocentric city model has been developed which explicitly considers the behaviour of farmers *à la* von Thünen and identical households working in a predetermined CBD. Equilibrium is reached through a competitive land market. By endogenising agricultural amenities, we offer an intuitive explanation of the role of agriculture in the explanation of urban sprawl.

The results of the model illustrate potential variations in urban structure dependent on the nature of the farms and their distance from the city. Thus, farms close to the city tend to be relatively intensive, generating a low level of agricultural amenities.

However, further away from the city, the rural landscape is characterised by a more extensive agriculture, which provides a relatively high level of amenity. Some households enjoy living close to agricultural amenities and accept the associated long commute to work. When the households' bid-rent function is higher than that of farmers, leapfrog development is more likely to occur. What makes this scenario possible is the existence of a high level of amenities in the area of extensive agriculture, far from the city. One of our main contributions is to conclude that, even in absence of a particular landscape feature or any exogenous source of amenities, urban sprawl characterised by a fragmented development pattern can be a natural configuration for a city surrounded by a spatially varying agricultural environment.

In order to simulate the bid-rent curves, we applied our model using data relating to the French context. For each of our parameters, we determined the thresholds, minimum and maximum, which allow the occurrence of leapfrog development. When households have a high preference for agricultural amenities and when agricultural activity is characterised by an intermediate capacity to provide amenities, the occurrence of isolated urban areas through leapfrog development is more likely.

Obviously this mechanism may operate in the absence of any public policy. But the introduction of a land tax system, may limit leapfrog development. Thus, to curb urban sprawl, the government should tax housing land at a greater rate than agricultural land. However, the effect of a land tax on spatial urban structure depends on household preferences with respect to amenities and the ability of agriculture to provide them. In certain cases, low taxes on land are shown not to suppress the basic mechanisms that cause leapfrog development.

In the same way as with taxation, this approach can be used to test other public policies that aim to control urban sprawl. But, needless to say, any public policy that ignores the spatial dimension of agriculture may exhibit the same limitations. However, zoning policies may produce different results since they alter the distribution of agricultural activities and amenities. These questions are left for future research.

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A Existence of an urban boundary

We show that at the equilibrium, the households' and farmers' bid-rent curves intersect at least once within the interval $[0, \underline{x}]$, where $\underline{x} = \frac{p}{t}$ is the location from which agricultural activity stops. Let's first analyze both bid-rent functions:

$$\frac{\partial r_u^*}{\partial x} = -\frac{1}{\beta}\tau \left[\frac{\beta^\beta (1-\beta)^{1-\beta}}{V}\right]^{\frac{1}{\beta}} (w - \tau x)^{\frac{1}{\beta}-1} < 0 \text{ at any } x < \frac{w}{\tau}$$
$$\frac{\partial^2 r_u^*}{\partial x^2} = \frac{1}{\beta}\tau^2 \left[\frac{\beta^\beta (1-\beta)^{1-\beta}}{V}\right]^{\frac{1}{\beta}} (w - \tau x)^{\frac{1}{\beta}-2} > 0 \text{ at any } x < \frac{w}{\tau}$$

$$\frac{\partial r_a^*}{\partial x} = -\frac{1}{(1-\alpha)} tA(1-\alpha) \left(\frac{\alpha A}{p_k}\right)^{\frac{\alpha}{1-\alpha}} (p - tx)^{\frac{1}{1-\alpha}-1} < 0 \text{ at any } x < \frac{p}{t}$$
$$\frac{\partial^2 r_a^*}{\partial x^2} = \frac{1}{(1-\alpha)} t^2 A(1-\alpha) \left(\frac{\alpha A}{p_k}\right)^{\frac{\alpha}{1-\alpha}} (p - tx)^{\frac{1}{1-\alpha}-2} > 0 \text{ at any } x < \frac{p}{t}$$

Both bid functions are continuous, decreasing and convex within the intervals $\left[0, \frac{w}{\tau}\right]$ and $\left[0, \frac{p}{t}\right]$ respectively.

At equilibrium, we have:

$$r_u^*(0) = \left[\frac{\beta^\beta (1-\beta)^{1-\beta} w}{V}\right]^{\frac{1}{\beta}} \text{ and } r_a^*(0) = A(1-\alpha) \left(\frac{\alpha A}{p_k}\right)^{\frac{\alpha}{1-\alpha}} p^{\frac{1}{1-\alpha}}$$

$$r_u^*(0) > r_a^*(0) \Leftrightarrow w > \Omega p^{\frac{\beta}{(1-\alpha)}}$$

where $\Omega = \frac{A^\beta (1-\alpha)^\beta \left(\frac{\alpha A}{p_k}\right)^{\frac{\alpha\beta}{1-\alpha}}}{\left[\frac{\beta^\beta (1-\beta)^{1-\beta}}{V}\right]} > 0$

We also have:

$$r_u^*(x) = 0 \Leftrightarrow x = \frac{w}{\tau}$$
$$r_a^*(x) = 0 \Leftrightarrow x = \frac{p}{t}$$

The curves will intersect if and only if the following set of conditions is reached:

$$\begin{cases} r_u^*(0) > r_a^*(0) \\ x_{r_u^*(x)=0} < x_{r_a^*(x)=0} \end{cases} \Leftrightarrow \begin{cases} w > \Omega p^{\frac{\beta}{(1-\alpha)}} \\ \frac{w}{\tau} < \frac{p}{t} \end{cases}$$

These conditions can be interpretated as:

1. The level of households' income must be relatively high enough, compared to the price of agricultural products.
2. The trade-off between urban and agricultural use can only be made within the interval $[0, \underline{x}]$, as from $\underline{x}$, all agricultural activity under urban influence stops.

B Conditions for the emergence of a periurban area

We want to identify the conditions on our parameters which allow the emergence of a periurban area. Such a configuration occurs when $r_p(x) \geq r_a(x)$, with $x \in [\overline{x}, w/\tau]$:

$$r_p(x, \delta, \gamma) - r_a(x) \geq 0$$
$$r_u(x) \left(\frac{\delta}{k(x)}\right)^{\beta/\gamma} \geq r_a(x)$$
$$\delta \geq k(x) \left(\frac{r_a(x)}{r_u(x)}\right)^{\gamma/\beta}$$

There is a minimum level of jointness between agricultural and amenities production $\delta_{\min}$ for a periurban area to emerge. It is given by:

$$\delta_{\min} = \arg\min_x \; k(x) \left(\frac{r_a(x)}{r_u(x)}\right)^{\gamma/\beta} \tag{30}$$

Note that $\delta_{\min}$ depends on all other parameters, in particular on households preferences for amenities.

C Conditions for leapfrog development or urban extension

We define leapfrog as a fragmented pattern of urban development, meaning that the city and the periurban area are disconnected sets. In other words, there is a $x_1 < x_2 < \underline{x}$, so that for all $x \in [\overline{x}, x_1] \cup [x_2, \underline{x}]$, we have $r_a^*(x) > r_p^*(x)$, and for all $x \in [x_1, x_2]$, we have $r_p^*(x) = r_a^*(x)$.

According to our definition of leapfrog, at $\overline{x}$, we have:

$$r_p^*(\overline{x}) < r_a^*(\overline{x})$$
$$\Leftrightarrow r_u^*(\overline{x}) a_p(\overline{x})^{\frac{\gamma}{\beta}} < r_a^*(\overline{x})$$
$$\Leftrightarrow a_p(\overline{x}) < 1$$

For the farmers to bid periurban households up at the city border, the amenity level must be inferior to 1.

$$a_p(\overline{x}) < 1$$
$$\Leftrightarrow \delta \left[\alpha \frac{A(p - t\overline{x})}{p_k}\right]^{-\frac{1}{1-\alpha}} < 1$$
$$\Leftrightarrow \delta < \delta_{\max}$$

where:

$$\delta_{\max} = \left[\alpha \frac{A(p - t\overline{x})}{p_k}\right]^{\frac{1}{1-\alpha}} \tag{31}$$

As soon as δ gets larger than $\delta_{\max}$, households outbid farmers immediately after the urban fringe. Leapfrog development as we define it can't occur. However, in the case where $\delta > \delta_{\max}$, the city sprawls under another development pattern which we call urban extension: the periurban area is connected to the urban area.

D Leapfrog configuration

Fig. (7) depicts the relative position of bid-rent curves, the distribution of amenities and of the fraction of agricultural land, in a leapfrog configuration.

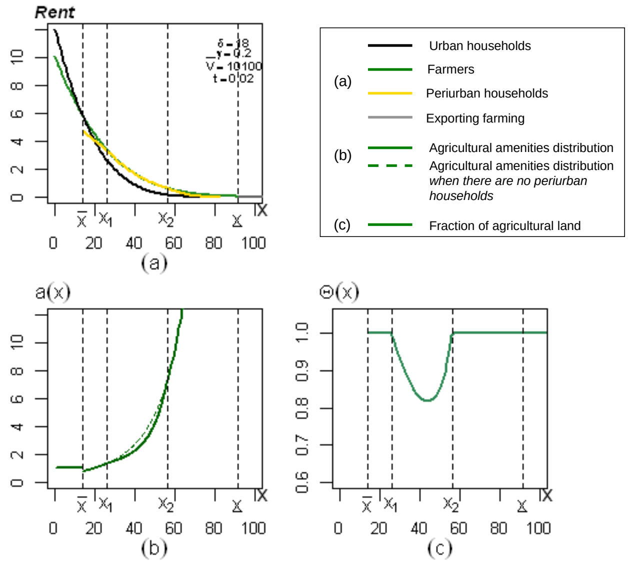

Figure 7: Spatial equilibrium pattern in the case of leapfrog development

E Land tax policy

Fig. (8) presents the impact of the introduction of land taxes on the relative position of bid-rent functions.

Using the same method as in B and C, we give the conditions for the emergence of a periurban area and for urban extension or leapfrog configuration.

A periurban area exists when we have:

$$
\begin{aligned}
r_p(x, \theta_h, \delta, \gamma) - r_a(x, \theta_a) &\geq 0 \\
r_u(x) \left(\frac{\delta}{k(x)}\right)^{\beta/\gamma} \frac{1}{(1+\theta_h)} &\geq r_a(x, \theta_a) \\
\frac{1}{(1+\theta_h)} &\geq \left(\frac{\delta}{k(x)}\right)^{-\beta/\gamma} \left(\frac{r_a(x, \theta_a)}{r_u(x)}\right) \\
\theta_h &\leq \left(\frac{\delta}{k(x)}\right)^{\beta/\gamma} \left(\frac{r_u(x)}{r_a(x, \theta_a)}\right) - 1
\end{aligned}
$$

As long as the households land tax level θ_h remains under a threshold (depending on θ_a, γ and δ among other parameters), we observe the emergence of a periurban area. It is given by:

$$
\theta_{h\,\max}(\theta_a, \delta, \gamma) = \arg\max_x \left[\left(\frac{\delta}{k(x)}\right)^{\beta/\gamma} \left(\frac{r_u(x)}{r_a(x, \theta_a)}\right) - 1 \right] \tag{32}
$$

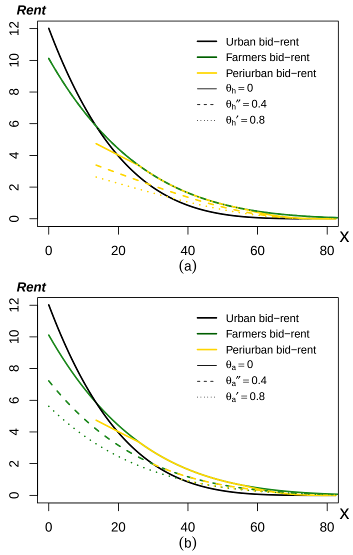

Figure 8: Impact of the introduction of land taxes on the relative position of bid-rent functions

The periurban area is disconnected from the city when:

$$r_p(\overline{x}) < r_a(\overline{x}) \Leftrightarrow r_u(\overline{x})\frac{a_p(\overline{x})}{(1+\theta_h)} < r_a(\overline{x})$$

Noting that at the urban fringe, $r_u(\overline{x}) = r_a(\overline{x})$ and that $\overline{x}(\theta_a)$, we have:

$$\begin{aligned} \theta_h &> \delta\left[\alpha\frac{A\left(p - t\overline{x}(\theta_a)\right)}{p_k}\right]^{-\frac{1}{1-\alpha}} - 1 \\ \Leftrightarrow \theta_h &> \theta_{h\,\min}(\theta_a, \delta) \end{aligned} \tag{33}$$

If $\theta_h > \theta_{h\,\min}(\theta_a, \delta)$, we observe a leapfrog configuration. On the contrary, as soon as $\theta_h \leq \theta_{h\,\min}(\theta_a, \delta)$, we observe a case of urban extension.

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