Abstract

This paper presents a model treating agricultural and urban land uses simultaneously. In particular, it takes the urban model stemming from Alonso and weds it to the seminal agricultural model developed by von Thünen. In so doing, it extends the Muth framework, which explains the encroachment of agricultural lands by linking two industries with two different forms of land use. The present formulation considers both the encroachment of natural areas and the loss of agricultural land, or urban sprawl. It also adds realism to the two-sector model of Muth by (1) reflecting appropriate sectoral behaviors for residential land consumers and farmers, and by (2) explicitly addressing structural linkages between sectors. Using the model, the paper demonstrates sufficient conditions for switching in the regimes that govern loss of natural areas. The empirical case of South Florida is considered through an application of geographic information systems to digital map archives of the region based on remotely sensed data. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Land use and land cover change; Urban sprawl; von Thünen; Florida Everglades; Economic development

1. Introduction

Human encroachment of natural areas stems from the demand for both residential space and agricultural production. These demands have been placed in spatial context by bid-rent models, originating with von Thünen, that provide a conceptual framework for econometric treatments of land use and land cover change (e.g. Chomitz and Gray, 1996; Walker and Solecki, 1999). The bid-rent formulation in both agricultural and urban
modes hypothesizes a boundary to human land use called the urban or agricultural fringe distance, for cities and agricultural hinterlands, respectively. This distance can be parameterized in important system variables, such as transportation costs and population, to produce functional descriptions (see Wheaton, 1974; Fujita, 1989; Nerlove and Sadka, 1991; Jones and O'Neill 1993a,b). If natural land lies beyond the fringe, then theoretical results linking fringe to system attributes provide models of natural areas encroachment by agriculture or urban uses (Walker et al., 1997).

Bid-rent formulations are limited in describing encroachment processes such as deforestation, desertification, and wetlands conversion for a number of reasons. Generally, they focus on long-run equilibria and make strong homogeneity assumptions about institutions and resource quality (Bockstael, 1996). In addition, they mainly focus on either urban or agricultural land use, and do not consider their interactions. In urban models (e.g. Fujita, 1989) agricultural rent is constant and provides solution values for the extent of the city, in which case the city is bounded but the hinterland is not. Agricultural models set limits to the extent of farming, but collapse the city into a dimensionless point (e.g. Nerlove and Sadka, 1991; Fujita et al., 1999). Such models are limited as regional descriptors of land use since cities and neighboring farmlands both possess finite areal extent. Moreover, relationships between the urban and agricultural sector often underlie processes of land use and land cover change, and both cities and farming encroach directly on natural areas (Walker et al., 1997; Walker and Solecki, 1999).

The goal of the present paper is to overcome the focus of bid-rent models on a single form of land use. To this end, I combine a von Thünen model (Isard, 1956; Fujita et al., 1999) with the urban model of Alonso (1964), as adapted by Fujita (1989), in order to address the case of changing regimes of natural areas encroachment. The model resulting from this effort is conceptually related to that of Muth (1961), which allows for land allocation between two profit-maximizing industries generating industry-specific bid-rent functions. Muth’s formulation focuses on agricultural conversion (i.e. urban sprawl), however, while the model presented in this paper provides a more general description of land cover change, including both urban sprawl and natural areas encroachment, it also considers functional linkages between city and hinterland, which undergo structural changes in the process of development. In so doing, the model provides a description of land cover change processes arising in the wake of economic development.

The paper is organized as follows. First I consider land use change from the perspective of Muth, who offered an explicit discussion of urban and agricultural dynamics. I then provide a discussion and empirical description of natural areas encroachment for the case of South Florida, which has been subject to dramatic land cover dynamics over the past century. The empirical account is based on an application of geographic information systems to digital cartographic data spanning the entire period. I follow this with the model description, and a statement of theoretical conditions consistent with the observed processes of change in the South Florida region, both in the local economy and land cover. I conclude the paper with a discussion of model limitations and extensions, and a perspective on policy implications.

2. Land use change

2.1. Theoretical considerations

Theoretical models for both the residential and agricultural cases have derived explicit functional relationships between the extent of land use, or fringe distance, and model attributes such as population size and commuting costs. Generally, they consider only agricultural or residential land use, with the exception of Muth (1961), who describes the movement of so-called city limits, or the urban fringe, in relation to an agricultural hinterland lying beyond the city. In the Muth model, residential and agricultural industries generate rent, and land is dedicated to the industry providing the higher value at any given location. Under an appropriate set of assumptions, residential land
use is found close to the market center, and gives way to farming beyond the urban fringe. Of relevance to the present application, the urban fringe distance is endogenous to changes in the system’s exogenous variables. For example, urban land use expands at the expense of agriculture as demand for housing grows. Muth analyzes relationships between urban fringe distance and attributes of the economic system in place, including wage rates and relative demand characteristics for housing and agricultural produce.

The Muth approach possesses two shortcomings from the perspective of the present application. First, the extent of agriculture is unbounded (Muth, 1961, p. 13), and we cannot observe the advance of either urban or agricultural land use into unutilized lands. This compromises the framework’s applicability to the case of natural areas conversion. The present model allows for two fringe distances associated with urban land use and farming, and therefore accounts for the empirical observation that both farms and urban space encroach on natural areas. Such encroachments have been reported for large metropolitan areas in the US, both in New Jersey (Walker and Solecki, 1999) and South Florida (Walker et al., 1997).

A second shortcoming stems from the conceptualization of linkages between city and hinterland. The urban sector is modeled as a residential industry maximizing profits, and individuals who may or may not demand locally-grown produce populate the city. In the present formulation, I attempt to make the nature of the structural relationship between hinterland and city more consistent with historical observation. To this end, I address both the changing nature of the relationship and the manner in which agricultural supply functions as an input to regional production. From a developmental perspective, demand-side linkages internal to a region are likely to be insignificant in relation to the supply-side interactions arising, for example, from city-based processing of agricultural staples for export to national and even international markets.\(^1\)

2.2. The South Florida case

Before presenting the model in formal terms, I consider an empirical case that demonstrates elements of the theoretical context just outlined. Natural areas in South Florida, and in particular the Florida Everglades, have attracted international attention for their ecological uniqueness and fragility. They have also endured rapid encroachments by both residential and agricultural land uses, and are under continuing threat due to population growth in the region. At the present time, both the Federal Government and State of Florida are attempting to undo environmental damages wrought by one hundred years of land cover change that has reduced the Everglades ecosystem to about 50% of its original extent, and virtually eliminated the pine forest that originally covered the so-called Gold Coast (Broward, Dade, and Palm Beach counties). A restoration effort is underway to recover the lost hydrologic function of the surface waters of the Everglades by reconverting agricultural lands into natural areas.

The initial private-sector stimulus to economic development in South Florida was provided by tourism with the arrival of Flagler’s railroad at the turn of the century. Prior to this, few people lived in the region, and the economy was based largely on animal products exploitation.\(^2\) By 1900, two hotels had been built in Palm Beach, with a capacity near 1600 rooms, and Miami possessed a sizeable operation with 450 rooms.\(^3\) In 1909, Miami alone enjoyed 125 000 tourist visits, ten times

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\(^{1}\) In adaptations of von Thünen, both Nerlove and Sadka (1991) and Fujita et al. (1999) consider the autarchic case, with a trade equilibrium between the city and its hinterland.

\(^{2}\) Key West, of course, was the third largest city in Florida at the time with nearly 20 000 inhabitants.

\(^{3}\) The hotel service workforce may be estimated at about 1700, and over $1 000 000 per year was generated in revenue. In addition, 4000 construction workers were involved in Flagler’s railroad venture through the Florida Keys after Miami had been reached in 1896. See Derr (1989) for workforce estimates. Revenue estimate assumes visitors purchased one of Flagler’s 5-week packages for $350, including round-trip coach from a northern origin. About 100 private rail cars made the round trip from Jacksonville to Palm Beach each season at a charge of $342 (Derr, 1989).
the resident population of about 12,500 (Derr, 1989).

State involvement ultimately proved crucial to the region’s development, and began in earnest at this time with Governor Broward’s efforts to convert the Everglades into a farming region. Agricultural expansion followed the successful completion of drainage infrastructure, and by 1913 over 360 km of canals had penetrated the Everglades (Derr, 1989), taking tomatoes, beans, and other crops by steamboat to Fort Lauderdale and Fort Myers for local consumption and shipment north (Blake, 1980). By 1920, 23,000 farmers cultivated 138 km², numbers growing to 92,000 inhabitants and 186 km² by 1927 (Blake, 1980). Between 1907 and the early 1930s, the main features of the current drainage system had been imprinted on the sawgrass everglades (Light and Dineen, 1994). 708 kilometers of canals were in place, connecting the inhabited parts of the peninsula to the southwest and southeast.

Anecdotal evidence suggests the agricultural and urban economies of South Florida initially possessed a certain degree of functional dependency. Urban residents added value to the export of pineapples and oranges to northern markets (through food processing and transportation), a supply-side linkage between farming and the urban sector. In addition, much of the region’s produce probably served the seasonal tourist trade. Flagler’s initial vision for developing the region involved shipping tourists south and farm products north by rail (Derr, 1989). By way of contrast, South Florida presently possesses a service economy with over 99% of its gross product (about $82 billion in 1990) accounted for by non-agricultural activities (Walker et al., 1998). Although farming is a basic sector (Snyder and Davidson, 1994; Mulkey and Clouser, 1988) delivering products to national and even international markets, the most important crop, sugarcane, had sales approaching $5 billion in 1990, a very small percentage of the region’s gross product (Alvarez et al., 1994).

The ascension of sugarcane as the key regional crop is emblematic of a process of decoupling between the agricultural and urban economies though the course of the century. Grown in the region since 1925 (Coale, 1994), the Jones–Costigan Act of 1934 and subsequent legislation restricted production, so that by 1950 only 153 km² were committed to cane (Snyder and Davidson, 1994). This changed dramatically in the wake of the Cuban revolution, with the elimination of the Cuban sugar quota in 1960 (Alvarez and Polopulos, 1988). South Florida now produces a large share of the nation’s sugar, and by 1990 occupied 1782 km² of Everglades land (Coale, 1994), over ten times its expanse in 1950. Prices are set in national markets and by federal policy.

The timing of changes in linkages between agriculture and the urban economy is difficult to track over the past century given data limitations in the US Census, which begins regular reporting in the region in 1930. Vegetable crops were grown in the 1930s for the northern winter market (Snyder and Davidson, 1994), when 2.7 percent of the Dade county workforce labored in food processing and steam railroads (US Bureau of the Census, 1930). Price instability for vegetables at this time has been attributed to a highly competitive national industry (Snyder and Davidson, 1994), but may also have reflected yearly variation in tourist visits. Indeed, one of the noted attractions to hotels in Florida in the early years was ‘good food’ grown on local farms (Derr, 1989). Nor can it be forgotten that transportation remained difficult and inefficient until well into the twentieth century. The railroad did not arrive in the everglades agricultural areas until 1925, where steamboats transported produce until 1921 (Blake, 1980). By 1990, the percentage of Dade county workers engaged in food processing and trucking was negligible, at 0.8% (US Bureau of the Census, 1990).

Table 1 presents region-scale dynamics of land cover change occurring in South Florida over this past century. These data were generated through a GIS application involving remotely sensed data and maps of the region for the years 1900, 1953, 1973, 1988, and 1995, covering the Gold Coast region of Broward, Dade, and Palm Beach Counties. These five time points allow for the definition of four conversion episodes, 1900–53, 1953–73, and 1973–88, and 1988–95, which may be used to track the dynamics of land cover change.
The table shows that in the first and second episodes, agricultural conversion of natural areas dominates urban encroachments, in excess of 70% for both periods. Subsequently, the urban component increases appreciably. Between 1973 and 1988, about 57% of natural areas conversion is accounted for by urban expansion; this dips to 50% in the following period. The table also shows other land cover dynamics, including agricultural conversions and restoration of natural areas. Loss of agriculture to urban land use (i.e. urban sprawl) is initially minimal relative to natural areas loss, but grows important in subsequent periods. The abandonment of settled areas, both agricultural and urban, becomes relatively significant by the final conversion episode, reflecting, perhaps, current efforts to improve hydrologic function by restoring land to natural conditions.

The change in the relative magnitudes of agricultural as compared to urban encroachments of natural land is consistent with the development process I seek to model. In particular, in early phases with functional coupling, natural areas loss should be primarily agricultural in nature. But as farming becomes less important to the regional economy, the stage is set for direct losses of natural areas with expansion of the city.

Table 1

<table>
<thead>
<tr>
<th>Land cover changes by period (Broward, Dade, and Palm Beach Counties), total area = 13737 km²</th>
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<td>Natural to agriculture</td>
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<td>Urban to natural</td>
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4 Regional data may be obtained for 1900, 1938, 1953, 1973, 1975, 1986, and 1995, the years in our archive. For 1938, it appears that agricultural lands include those zoned for agricultural use but not yet developed, which inflates the amount of already converted land in that year. Our data for 1975 (USGS) is from a different source than the series, 1900, 1953, and 1973, all produced by the Center for Wetlands at the University of Florida. The Center data are constructed from aerial photography except for 1900, which is an ecological ‘reconstruction.’ The Center data were put in digital form in a 1 km² grid. Comparison of 1973 and 1975 suggests some differences in the classification system used by the US Geological Survey (1990) and the Center for Wetlands, University of Florida. Calculated land cover changes between 1973 and 1975 would therefore probably reflect artifacts of classification differences; in any event, a two-year time period is too short to have much analytical value. Consequently, our analysis is based on 1900, 1953, 1973, 1988, and 1995. The 1988 and 1995 data are from the South Florida Water Management District and are based on both aerial photography and Landsat TM images. Conversion magnitudes were developed with the overlay function of ARC-INFO, based on GIS-generated aggregations of landcover to agricultural, urban, and natural land.

4 Of course, an initial conversion to farming and then to urban land use may have occurred rapidly within the period covered by the conversion episode. Unfortunately, the data do not allow a year by year account.

3. Model statement

Consider a region embedded in a national economy where individuals enjoy utility level, $u$, and earn income, $Y$, from an unspecified production process. The utility level, $u$, is fixed, presumably by a national economy, in which case the city is open to population movements (Fujita, 1989). The region is a one-dimensional, linear space (Asami et al., 1990) consisting of a port city and an agricultural hinterland; distances are measured from the port, which functions as the city center. Fig. 1 gives a stylized representation of the spatial system, consistent with the overall distribution of land use in South Florida.

The region is assumed to undergo a development process as follows. Initially, it provides an export, $q$, to the national economy, produced by urban workers who add value to an agricultural product. The export may be taken as a good stemming from conventional food processing activities in which workers add value to a locally
grown staple. Alternatively, it may be interpreted as a tourism service, produced by urban workers in conjunction with produce from the region. The export economy is initially under the control of a regional monopsonist, who sets price for local production but is a price taker in both labor and export markets. I call this initial developmental stage a coupled economy (Walker et al., 1997). In stage two of the development process, the linkage between urban workers and farming is decoupled as the regional monopsony breaks down and agricultural goods are sold directly to national markets. Muth (1961) distinguishes between coupled and decoupled regional economies, the latter of which he refers to as the national food case. For Muth, linkages between city and hinterland arise from the consumption demand for food, and decoupling takes place when the elasticity of the demand for food is low given export to a national economy.

To facilitate the exposition, I also assume technological change in agriculture. In stage one, the production factors are land and labor, which is made available to agriculture on the basis of a residential equilibrium between urban and hinterland locations. In stage two, inputs (including capital) substitute for labor, and are used in fixed proportion with land. Thus, the stage two economy is modernized, and workers live only in the city. The two-factor assumption on agricultural production is consistent with Nerlove and Sadka (1991) and Fujita et al. (1999), who assume a technology based on land and labor. Production in Fujita et al. (1999) occurs with fixed proportions between the factors.

Following the constructive approach advanced by Muth (1961), I assume the stylized fact that urban land use generally gives way to agriculture by Muth (1961), I assume the stylized fact that urban land use generally gives way to agriculture in Fujita et al. (1999) occurs with fixed proportions. Muth (1961) distinguishes between coupled and decoupled regional economies, the latter of which he refers to as the national food case. For Muth, linkages between city and hinterland arise from the consumption demand for food, and decoupling takes place when the elasticity of the demand for food is low given export to a national economy.

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Following the constructive approach advanced by Muth (1961), I assume the stylized fact that urban land use generally gives way to agriculture moving out from a city center when both land uses are present. As in Muth (1961), this is accomplished through assumptions on appropriate system parameters. The region has a market center and land that can be used for either housing or agriculture. In turn, workers can work at the center of the city or in the agricultural hinterland. City workers pay a commuting cost, \( T(r) \), for expenses associated with transport to and from their residence located at distance, \( r \), from the city center. They also pay rent. Farm workers live and work on the same parcel of land and do not pay commuting costs. In addition, their wage rate is reduced by the amount of rent paid by city dwellers at the urban fringe. This ‘implicit’ rent accrues to landowners in the agricultural hinterland, who also receive rent associated with locational advantages in agricultural production. Land use is determined by which form of the parcel bid pays higher rent.

The model is now set out in two steps. First, I consider the bid-rents associated with residential use of land and agriculture. Then, I consider the developmental framework and implications for model structure. Although the specification for agriculture changes with the development process, the form of the residential function remains the same. I follow the presentation with several numerical applications to illustrate the main points of the conceptual development.

### 3.1. Bid rents in the city and agriculture

Following Fujita (1989), residential rent paid by urban dwellers, \( \Psi \), is the maximum bid for residential use of a land parcel, and may be described as a function of the national utility level, \( u \), and distance from the market center, \( r \), or \( \Psi(u, r) \). This bid-rent, in turn, may be defined by optimizing a utility function expressing preferences for a composite good (\( z \)) and lot size (\( s \)). If the utility function is Cobb-Douglas, as shall be assumed in the sequel, or \( U = z^\alpha s^\beta \) where \( \alpha + \beta = 1 \), and if commuting costs are \( t_u r \), where \( t_u \) reflects expense per unit distance, bid-rent may be derived as (Fujita, 1989, p. 322):

\[
\Psi(u, r) = z^\alpha \beta (Y - t_u r)^{1/\beta} e^{-u/\beta}
\]

The bid-lot size, \( s \), may also be derived as:

\[
s(u, r) = z^{-\alpha/\beta} (Y - t_u r)^{-\alpha/\beta} e^{u/\beta}
\]

Define \( r_{\text{max}} \) as the maximum extent of the city in the absence of agriculture. This is given by setting \( \Psi(u, r) = 0 \) and solving for \( r \), or \( r_{\text{max}} = Y/t_u \).
For agriculture, I consider two functions reflecting the changes in agricultural technology associated with the development stages. Rent is generated, of course, by the differential in revenues and costs per unit area (Fujita et al., 1999), and for stage one of the development process we have:

\[ R_i(r) = (1/s^*)[c p^i_A(r) - Y^A] \]

where \( R_i(r) \) is agricultural rent at distance \( r \), \( c \) is output per worker, \( p^i_A(r) \) is price of the agricultural good at distance \( r \), \( Y^A \) is the agricultural wage rate, and \( 1/s^* \) is agricultural workforce density, given by the reciprocal of the bid-lot size observed at the urban fringe, \( r^* \). The functional form of price in both development stages is taken to reflect a so-called iceberg technology in the transportation sector for agriculture (Nerlove and Sadka, 1991; Fujita et al., 1999), or:

\[ p^A_i(r) = p^A_i e^{-ar} \quad i = 1,2 \]

where \( p^A_i \) is price of the good at the city center (in stage one or two) and \( a \) accounts for its transportation costs from the farm (located at \( r \)) to the market. Such price functions eliminate the need to represent a transportation sector.

The stage one framework presents theoretical complications owing to urban–agricultural linkages and the dependency of farm production on labor, which is spatially determined. The present formulation differs from Fujita et al. (1999) with respect to both land productivity and the functional relationships between agriculture and the city.\(^6\) Fujita et al. (1999) consider a trade relationship between city and hinterland, based on a closed economy (see also Nerlove and Sadka, 1991). Wages and prices are determined endogenously, and there is no export to national markets. The productivity of land is fixed, and agricultural labor is used in constant proportion to land under any set of equilibrium conditions. In the present model land productivity is a function of the amount of labor available on a given parcel (\( c/s^* \)).\(^7\) Although constant for a given equilibrium, changes in the extent of the city also change the agricultural labor per unit area, in which case output also varies. If the urban fringe advances at the expense of farming, the availability of farm labor declines, as does the productivity of the land.

To maintain labor force equilibrium between the two sectors, workers must everywhere enjoy the same utility level. This is accomplished by setting the agricultural wage equal to the disposable income of city residents at the urban fringe, \( r^* \).\(^8\) Here, commuting costs are \( t_{hr}^* \) and the amount of rent paid by individual workers is \( s^* \psi(u, r^*) \). What remains of the wage rate, \( Y \), after incurring these expenses is spent on composite good, \( z \). Thus, the agricultural wage rate is written as \( Y^A = Y - t_{hr}^* - s^* \psi(u, r^*) \), which allows workers to consume the same amount of \( z \) as their counterparts on the urban fringe. Since they live on the land they work, and workforce density is set at \( 1/s^* \), the amount of land individual farm workers consume through residential occupation is also the same as their urban counterparts on the fringe, \( s^* \). Assuming identical utility functions across sectors, the level of utility achieved by workers in farming is therefore \( u \).\(^9\)

For stage two agricultural rent, we have:

\[ R_A = dp^A_i(r) - p_I \]

where \( d \) is the fixed output per unit land (given fixed intensity of input application), \( p_I \) is the input price, and \( I \) is the amount of input application per unit land. In this construction, the non-land input is fixed and invariant to distance from the city center.

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\(^6\) Fujita et al. (1999) and Nerlove and Sadka (1991) do not consider urban land use, and the city is collapsed into a dimensionless point.

\(^7\) Strictly speaking, land is not an input to production in such a formulation, in that \( c \) is a constant. One interpretation is that agriculture functions as a cottage industry, whereby a landlord hires workers to produce an agricultural commodity, and provides the material, land, necessary to do so.

\(^8\) I follow Fujita et al. (1999) in my tenurial assumption on agricultural land. A land owner employs agricultural workers and recovers a rent.

\(^9\) An implicit assumption is that there are no negative externalities associated with residential occupation of agricultural land, a possibly strong assumption.
3.2. Constructing the sectoral linkages

To this point, I have considered the bid rents in isolation, but they must be linked in order to describe the stylized development processes of interest in the present context. I proceed initially with stage one, since this presents a number of theoretical issues. In particular, agricultural price is endogenous to the production decision of the regional monopsonist. Once selected, this price then sets up the land use regimes by establishing city limits and the extent of agriculture. In stage two, demand for the commodity is taken to be exogenous and perfectly elastic, which fixes price and essentially collapses the model into two independent bid rent functions.

Following Fujita (1989), z is numeraire and there are prices for land, labor, and agricultural produce. Also, given the open city assumption (Fujita, 1989), urban bid-rents at given values of r are fixed. I begin by assuming that commuting costs are large relative to those for transport of the agricultural commodity, or \( t_h/Y > a \). This assumption structures the city and its hinterland in a manner consistent with the stylized facts of their spatial organization.\(^{10}\) The model statement is advanced in two steps. I initially construct the sectoral linkages for residential and farming industries (Muth, 1961; p. 11).

Thus, for any given urban fringe, \( r = r^* \), \( p^*_c(r^*) \) is the city center price that would guarantee identical urban and agricultural rents at \( r^* \). Eq. (2) may be differentiated as \( dp^*_c(r)/dr = a(Y - t_h r)e^{aw} - t_h e^{aw}/c \); this is negative if and only if:

\[
a(Y - t_h r) < t_h, \]

which is true by the assumption \( a < t_h/Y \). Thus, agriculture moves closer to the market with increasing price for the farm good at the city center. This price may be bounded from above so that urban land use vanishes at higher prices (see Muth, 1961; p. 11). In particular, at the city center the solution to Eq. (2) yields \( p^*_c = Y/c \equiv p^{max} \).

Now, fix some arbitrary value of \( r \), or \( r^* \), and consider the derivatives in \( r \) of \( \Psi \) and \( R \) at distance \( r^* \). These are given as \( d\Psi/dr = -t_h/s^* \) and \( dR/dr = -acp^*_c e^{-aw}/s^* \). Under the assumption \( a < t_h/Y \), we have \( acp^*_c e^{-aw} < t_h \) for all \( r \), and therefore \( d\Psi/dr > |dR/dr| \). Thus, the agricultural rent function intersects the urban bid-rent function from below at \( r^* \); moreover, for \( r < r^* \), it is also the case that \( |d\Psi/dr| > |dR/dr| \). This does not guarantee the dominance of agricultural land use beyond the urban fringe, which is constructed as follows. The extent of agricultural land, \( r_a \), may be solved by setting \( R_i(r) = 0 \) for some \( r^* \) as \( r_a = \ln[cp^*_c(r^*)/x(Y - t_h r^*)]/a \), given that \( Y^\Lambda = Y - t_h r^* - s^*\Psi, s^*\Psi = \beta(Y - t_h r^*), \) and \( x + \beta = 1 \). By Eq. (2), we can substitute for \( p^*_c(r^*) \), obtaining:

\[
r_a = r^* + \ln(1/x)/a \tag{3} \]

Note that the extent of agricultural land use, \( r_a = r^* + \ln(1/x)/a \), does not vary in price for the farm good. Hence, the dominance of agriculture beyond \( r^* \) is guaranteed by the condition, \( \ln(1/x)/a > r^{max} = Y/t_h \). When \( r^* = 0 \), \( p^*_c \) is at its maximum, and agricultural rents are everywhere greater than urban rents, which go to zero at \( r^{max} = Y/t_h \). Although spatial extent remains the same, agricultural supply changes with \( r^* \), since land productivity is a function of workforce density. In particular, supply increases with price of

\(^{11}\) The value of \( r^{max} \) at 15 is consistent with the numerically derived curves in Fig. 3, with \( Y = 12 \) and \( t_h = 8 \), yielding a maximum possible extent of the city as \( 12/0.8 = 15 \). If we assume, as is also the case in Fig. 3, that \( x = 0.4 \) and \( a = 0.05 \), then \( \ln(1/0.4)/0.05 = 18.3 > 15 = 12/0.8 \), and the condition for agricultural dominance is upheld.
the commodity, as production moves closer to the city center and more labor is devoted to farming.

These various results and observations are illustrated in Fig. 2, showing one bid-rent curve for residential housing, and two for agriculture under different price regimes. Potential city rents go to zero at $r^{\text{max}}$, although both agricultural rents are positive at this value.\textsuperscript{11} Note that the agricultural fringe distance for high prices is less than for low ones. This is accounted for by the result in Eq. (3), which fixes the extent of agriculture beyond the urban fringe. This result, in turn, is an artifact of the iceberg technology assumption that steepens the rent curve in price, and of the specification of the agricultural wage. In particular, the agricultural wage is high when farming is close to the city center and the price of the farm good is high.

3.3. The regional economy

The structure of the regional economy is given by the production relations between the city and agriculture. In this regard, stage two is straightforward, with agricultural demand taken to be perfectly elastic and fixed land productivity. Stage one, however, involves the decisions of a monopsonist using farm goods and urban labor to produce a regional export. Let the production function for the export good be $Q(L,A)$, where $L$ is the urban labor force and $A$ is the supply function for agriculture.\textsuperscript{12} These may be ascertained in explicit form by integration:

$$L = \int_{0}^{r^{\ast}(p^{c}_{*})} \frac{\Psi}{s} \, dr \quad \text{and} \quad A = \int_{0}^{r^{\ast}(p^{c}_{*})} \left(\frac{c}{s^{*}}\right) \, dr$$

yielding $L(p^{c}_{*}) = \theta \beta \left\{ Y^{1/\beta} - \left[ Y - t_{\ast}r_{*}(p^{c}_{*})\right]^{1/\beta} \right\}$ and $A = c/s^{*}(r_{*} - r^{*})$, where $\theta = \alpha^{(x/\beta)\theta - (1/\beta)} / t_{b}$. As is evident, both are functions of the city center price for the agricultural good, whose supply is given directly as $c/s^{*}[\ln(1/x)]/a$, given that $r_{*} = r^{*} + \left[\ln(1/x)\right]/a$. The $L$ and $A$ functions may be differentiated in $p^{c}_{*}$ as

$$\frac{dL}{dp^{c}_{*}} = \theta \beta \left[ Y - t_{\ast}r_{*}(p^{c}_{*})\right]^{1 - \beta}/\beta$$

and

$$\frac{dA}{dp^{c}_{*}} = -c/(s^{*})^{2}[\ln(1/x)]/a(\frac{ds^{*}}{dp^{c}_{*}}) > 0,$$

since bid-lot size increases with distance from the market center.\textsuperscript{13} Hence, $A$ is monotone increasing in $p^{c}_{*}$ as is expected for supply functions. Moreover, since the city contracts with increases in city center farm price, $L$ is monotone decreasing in the price, given the fixed nature of the residential density curve under an

\textsuperscript{12} All agricultural produce in the present formulation is used for the export good, and may be regarded as the export base. It is not food grown for subsistence purposes. By way of contrast, Fujita et al. (1999) present a food model with endogenous consumption of the entire produce of the hinterland.

\textsuperscript{13} Since $p^{c}_{*}$ increases as distance from the market center decreases, the derivative, $ds^{*}/dp^{c}_{*}$, is negative given the relationship between $s$ and distance.
open city system (Fujita, 1989). The regional monopsonist chooses $p^c$ to maximize:

$$p^E Q(L,A) - YL - p^c A$$

(4)

where $p^E$ is the price of the export and $Y$ is wage rate, as before. Note that tourism may function as an export sector, with $Q$ serving as the provision of the tourism service.

Rather than develop a set of theoretical results, I pursue a numerical strategy to demonstrate solutions to the monopsonist’s problem, and implications for land use and land cover change. This may be accomplished by identifying the $r^*$ that optimizes Eq. (4) using the relationship between $p^c$ and $r^*$ to calculate a profit function in $r^*$. Fig. 3 shows results for two settings on the technology of regional production. Technology that is intensive in the agricultural commodity yields a profit function maximized with an urban fringe at $r_{ci}$ and, by implication, an agricultural fringe at $r_{ci} + \frac{\ln(1/\beta)}{\alpha}$. With growing emphasis on value added in the urban sector, the optimizing city moves to $r_{ui}$ extending the agricultural hinterland through urban sprawl by $r_{ui} - r_{ci}$. The shift in importance of the value-added process in effect creates employment in the city, requiring additional residential space. Similar treatments can be accomplished by varying other system parameters such as commuting costs. Fig. 4, for example, shows the effect of a reduction in $\alpha$ on the urban (and agricultural) fringe for the same price of the farm good at the city center.14

To this point, my focus has been on phase one of the development process due to the theoretical issues involved in linking the urban and agricultural sectors. In fact, as alluded to, the phase two economy presents a trivial problem when price of the agricultural good is perfectly elastic, as assumed here, and when workers are only urban based.15 In such a situation, it is unnecessary to

14 The partial equilibrium effect of commuting cost reductions on fringe distances may be established by totally differentiating (2) assuming fixed price, and observing for some arbitrary urban fringe, $r$, that $dr/dr_o = r/\alpha(Y - t_h r) - t_h < 0$, given the condition that $\alpha(Y - t_h r) < t_h$, which is true by assumption.

15 Clearly, modern agriculture uses labor inputs. Nevertheless, theoretical statements often rely on a two-factor production function. Stage two agriculture in the present formulation reflects the technological changes that have occurred in agriculture since the early part of the 19th century.
establish residential equilibrium between the city and hinterland, and rents remain fixed even as agricultural supply diminishes with advance of the city. The implication is that with urban growth the agricultural fringe remains stationary, and once \( r^* = r_a \), any expansion of the city will lead to direct urban encroachments of natural areas and the disappearance of agriculture. Fig. 5 illustrates this case. As residential rents grow, the maximum potential extent of the city exceeds \( r_a \), and passes directly into undeveloped land. City expansion may result from changes in the wage rate (as in Fig. 5), in the costs of commuting, in preferences for lot size, and in population (due to external shifts in relative utility levels).

4. Discussion

Although the model is formal in nature, I have attempted to reflect links between regional economic development and processes of land cover change occurring in a particular region, the Gold Coast of South Florida. This is inherently problematic given limitations in the available data, and I have only suggested that the model I present is consistent with historical observation, scanty as it is. I hypothesize, however, that the model structure possesses a degree of generality given (1) the importance of agricultural staples in early stages of regional development; and (2) the historic de-emphasis of agriculture in the aggregate economy, and the emergence of agricultural regions at national level with the passage of time.

Several shortcomings are apparent in the present formulation as regards South Florida. Important among these is the existence of yet another form of rent arising from the amenities and services provided by the region’s natural areas. These are typically non-market values expressed as public goods, and in which both Federal and State government have invested considerable resources through the creation of parks and other conservation areas. Such areas would
5. Conclusions

Despite limitations, the model provides a formal description of three land cover change processes, namely, the conversion of natural areas to either urban or agricultural land use, the loss of agriculture to suburbanization (i.e. urban sprawl), and the restoration of natural areas from prior human use, either urban or agriculture. Thus, the model advances the seminal contribution by Muth, and begins to bring to the surface the implicit promise of the von Thünen/Alonso framework in modeling land cover change. Although highly stylized, it captures a potentially important aspect of land cover change dynamics resulting from economic development and the interplay of urban and agricultural processes.

Extensions and adaptations of the present model could prove useful since theoretical efforts on the subject have been few and far between. This is a serious shortcoming in the policy arena, given that policy formulation requires a firm basis on behavioral understanding. With the growing recognition of the importance of land use and land cover dynamics to the environment, the need for theoretical insight and predictive modeling is likely to grow as well. Fortunately, a well-developed theory of land use already exists in regional and urban economics, and can be deployed as in this paper to tell at least part of the story about environmental change.

Acknowledgements

I would like to thank Tony Smith for mathematical critique and very helpful interpretative comments. I would also like to thank two anonymous reviewers for reactions to an early draft of the manuscript. The research was supported by the US Man and the Biosphere Program (MAB), US Department of State, and by the US National Academy of Sciences. I would especially like to acknowledge the support of Roger Soles, executive director of the US MAB program, and of Mark Harwell and John Long, chair and co-chair of that program’s Human Dominated Systems Directorate. I would also like to acknowledge Judy Bale

Fig. 6. Protected area boundary.

represent a zone of effectively infinite rent, and be given as a border to the expansion of human-dominated systems as shown in Fig. 6. Although limits to expansion were not really relevant to the dynamics of land cover change during the first half of the century, they are of great importance at the present time. In a related vein, the model does not address state intervention in either the drainage or current restoration phase, which has been key to land cover change processes in the region.

Another potential shortcoming is the assumption of phase two regarding the market situation for the prime agricultural export, namely sugar. South Florida supplies a sizeable fraction of the national demand for sugar, in which case encroachments of agriculture by urban expansion could raise prices. In theoretical terms, this would alter the rent function for agriculture, and city growth would continue pushing farmland into natural areas as in phase one. The data in Table 1 do show continued expansion of agriculture even in the later conversion episodes. This could reflect (1) differential requirements for land suitability by agriculture and urban land use; (2) the release of pent-up demand for land by the sugar industry in the wake of the embargo on Cuba; (3) the price situation just described; or (4) some other of yet undescribed phenomenon. Further empirical work will be required to resolve this issue.

16 Coupling between city and hinterland need not be strictly related to food consumption products. Sod production is presently an important form of agricultural land use in South Florida, serving both local markets and other parts of the state (Bottcher and Izuno, 1994).
and Michael Greene of the National Academy of Sciences. Discussions with my colleague and co-investigator, Bill Solecki, provided me with much insight into processes of environmental change in South Florida and elsewhere around the world. As always, Steve Hodge of the Florida Resources and Environmental Analysis Center (FREAC) at Florida State University gave superb technical support.

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