Spatial interaction model with land and water use: An application to Terceira Island

1. Introduction

The aim of this paper is to understand the interactions between economy and land use, encompassing the environmental, technological, economic and regulatory factors that affect land use. To achieve this aim, we formulate, test, calibrate, and simulate a spatial interaction model of land use and apply it to Terceira island in the Azores. Our approach responds to the increasing demand for tools that support the management of sustainable development at the regional and local levels, not only regarding urban areas but also including the hinterland and its agricultural and forestry uses. In fact global and local issues like climate change, food security, biodiversity conservation, energy management and water management involve the adoption of policies at local, regional, national and international level that take into consideration the economy and the interactions with the environment through land use.

There are many disciplinary approaches to explain land use. Descriptive models report changes in land use and attempt to predict the factors that are responsible for the changes. These models are usually applied to large areas where it is difficult to obtain the data needed to calibrate other models (Wood et al., 2004; Mulley & Unruh, 2005; and Jianchu et al. 2005). Stochastic models of changes in land use consist of probabilistic transition models between predefined states of the system (Thornton and Jones,1998). Statistical models attempt to identify the factors causing changes in land use through multivariate analyses that highlight the exogenous factors of the observed changes (Tomppo, et al. 2002; Serneels & Lambin, 2001; Joshi et al. 2006; Laney, 2004; Dorsey, 1999; Heistermann, 2006; and Verburg et al., 2002). Simulation models highlight the interactions between all of elements that comprise the environmental system. These approaches condense and aggregate complex ecosystems into a small set of stylized equations (Baker, 1989; Turner II et al., 1995; Lambin et al. 1999; Lambin et al., 2000; Stephenne & Lambin, 2001;Dietzel & Clarke, 2006; Soares-Filho, 2002). Economic land use models assume that land demand, as influenced by the system of preferences, motivations, markets, accessibility, and population, is the main determinant of land use. These approaches include both micro and macro models. Micro models attempt to explain land use changes at the farm level, using linear and non-linear mathematical programming models (Porteiro et al., 2004). Macro models use partial (Adams et al., 2005; Rosegrant et al., 2002) or general equilibrium mathematical models (Burniaux, 2002; Dyer et al. 2001; Glomsrod, 2001). Nevertheless, they have some difficulty in adapting to the spatially disaggregated schemes that are used to estimate land use evolution (Irwin & Geoghegan, 2001). Integrated spatial models combine the advantages of simulation spatial models with the qualities of spatial economic models (Verburg et al. 2006; Alcamo et al.,1998; Rounsevell et al.,1998; Abildtrup et al. 2006;, Busch, 2006;.Manson, 2006;.Veldkamp & Verburg, 2004). Finally, spatial interaction models integrate the geographical approach implicit in simulation models with the consistency of the methodology present in the gravity models of spatial interaction. In particular, this allows for integration of the consistent interpretations usually present in economic spatial models.

Gravity models of spatial interaction are built to describe and predict the flow of people, goods, and information across space (Sen e Smith, 1995). Applications of gravity models to analyze spatial interactions have long existed in the literature (Carey (1858), Reilly (1931), Steward (1948), Casey (1955), Carrothers (1956), Schneider (1959)). These studies have provided analytical tools that are commonly used in land planning, geographical study, and regional science [(Wilson, 1967, 1974; Isard (1975); Batty (1976); Anderson (1979); Haynes and Fotheringhan (1984); Fotheringhan e O'Kelly (1989); Mikkonen e Luoma (1999)]; demography [Plane (1984); Foot e Milne (1984)]; and commerce and marketing [Bergstrand (1985); Deardorff (1998); Huff (1964)]. A comprehensive review of operational gravity models of spatial interactions applied to urban regions is made by Michael Wegener

(1994) and a good presentation of the evolution of the theoretical bases of these models is undertaken both by Roy and Thill (2004) and with a larger scope on various economic fields by Roy (2004).

The main theoretical question regarding the use of gravity models for spatial interaction arose from the process of model creation. Theoretical questions regarding these models attempt to identify minimal behavioral hypotheses that justify a pre-defined intuitive and powerful model. Gravity models used for spatial interaction perform very well in explaining the spatial interaction behaviors of large populations. Nevertheless, they perform very poorly at explaining the behavior of individuals, an attribute due to the lack of information about individual spatial behavior, rather than a fault of the features of the model. There are various and complementary theoretical explanations for gravity models: a) statistical interpretation proves that the gravity model is derived from the more likely spatial interaction distribution, compatible with origin and destiny constraints (Cesario, 1973); b) the macroeconomic approach shows that the gravity model is the result of the maximization of the consumer surplus, subject to the restrictions of origin and destination (Dias Coelho,1983); and c) the microeconomic explanation demonstrates that the gravity model is derived from the application of the random utility theory to the location choice (Anas, 1983). It is important to note that random utility functions do not result directly from *a priori* assumptions about individual behavior, but translate the adaptation of individual preferences to the market conditions. Further, urban theoretical models suggest that the utility function implicit in gravity models should be an adjusted utility rather than a random utility because the same people in different cities do not keep the same utility distributions but instead adapt themselves to the new situation. According to Fujita (1989), this reasoning was first established by Von Tünen (1826) and it is an application of the concept of indirect utility to the urban reality, proposed by Robert Solow (1973).

2. Model formulation

A spatial interaction model uses the structure of a basic model (Hoyt, 1939; North, 1955 and Tiebout, 1956) according to which exports, or basic activities, are the propulsive factors of the economy. These factors determine the model dimension and the pattern of local production. The spatial interaction model distributes employment and residents to different zones of the region, taking into account the distances between those zones and their attractiveness (Dentinho and Meneses, 1996). In the spatial interaction model of land use, it is assumed that residents and each type of employment both generate land use patterns based on coefficients of land use for each activity.

This article is the result of a process that began with the development of a spatial interaction model for agricultural use (Gonçalves and Dentinho, 2007). In that report, the attractiveness of each zone for each particular activity was based on soil and climate conditions, and conflicts between activities for the same area were solved through an optimization process that allocated basic employment for different sectors and zones in a manner that aimed to match the known population (subject to the surface limitation of each sector aptitude for each zone). In another development, (Dentinho and Silveira, 2008) each zone was divided into fourteen soil classes, and conflicts between different activities for the same soil class were solved through the calibration of the respective bid-rents, which are closely associated with the estimated factors of attractiveness. In this second case, the attractiveness for residents of the different zones was a weighted attractiveness of the various soil classes for urban use of that zone. In this study, each soil class in each zone is considered a sub-zone, influencing the distance matrix such that the attractiveness for residential use can be calibrated jointly with the bid-rents of the various soil classes for other urban activities.

2.1. Formulation of the spatial interaction model of land use

The model is composed of the Eqs. (1)-(4). The population that lives in each zone is dependent on employment, both basic and non-basic, which is established in all the other zones:

$T_{(ikl)j} = E_{ikl} \{r.W_{jl} \exp(-\alpha d_{limj}) / \Sigma_j[W_j \exp(-\alpha d_{limj})]\}$ (1)

for all activities, k, in the soil classes l of zones i, and

$P_j = \Sigma_{ikl} T_{(ikl)j}$ (2)

Where:

$T_{(ikl)j}$ is the population that lives in j and depends on the activity, k, in the soil class l of zone i;

E_{ikl} is employment of sector k in the soil class l of zone i;

r is the inverse of the activity rate (the ratio of population over employment);

W_{jl} is the attractiveness of soil l in zone j, and varies between 0 and 1;

α is the parameter that defines the friction produced by distance for the commuters;

d_{iljm} is the distance between the centroid of soil l in zone i and the centroid of soil m in zone j;

P_j are all the residents in j.

In contrast, the activities generated by each zone serve the population that lives in all the other zones within a service range:

$S_{i(jkl)} = P_i \{s_k.V_{lj} \exp(-\beta_k d_{lijm}) / \Sigma_{lj} [W_{lj} \exp(-\beta_k d_{lijm})]\}$ (3)

for all activities k in the soil class l of zone j, and

$E_{jkl} = \Sigma_i S_{i(jkl)}$ (4)

Where:

$S_{i(jkl)}$ is the activity generated in sector k in soil class l of zone j that serves the population in zone i;

W_{lj} is the services' attractiveness of soil class l in zone j;

s_k is the ratio of employment of non-basic activity k to population;

β_k are the parameters that define the friction produced by distance for the people that look for activity services from sector k;

d_{lijm} is the distance between the centroid of soil l in zone i and the centroid of soil m in zone j;

The coefficients s_k are estimated based on three terms: land productivity per sector (θ_k), men productivity by sector (μ_k) and the per capita consumption for sector k (ρ_k). This is the technological information contained in the model.

$$S_k \frac{\text{Non basic employment}}{\text{Population}} = \rho_k \times \frac{\theta_k}{\mu_k}$$

Where:

$$\theta_k = \frac{\text{Employment}}{\text{Hectare}} \qquad \mu_k = \frac{\text{Production}}{\text{Hectare}} \qquad \rho_k = \frac{\text{Consumption}}{\text{Population}}$$

2.2. Calibration of parameters and bid-rents

Parameter α is calibrated so that the average commuting cost of the model is similar to the average commuting cost in reality. Parameters β_k are calibrated so that the average costs for the population to access service k are similar to the actual average costs.

There are spatial constraints within the model that must be fulfilled. The area occupied by the different activities (basic, non-basic, and residential) in each zone i, and for each class of soil l, should not exceed the total area of that zone A_{il} [Equation. (5)].

Σ_k□□$_k$ S_{ilk}□+ □ P_{il}+ Σ_{ik}□□$_k$ Eb_{ilk}□ ≤ A_{il} (for all classes l and zones i) (5)

Where:

□$_k$ is the area occupied by one employee of sector k;

□ is the area occupied by one resident;

A_{il} is the area available for soil class l in zone which, besides being an environmental constraint, can alsobe used as a regulatory constraint that restrict the use of soil classe l in zone i.

It is important to note that, in Equation (5), different types of uses, k, compete for each class of soil l in each zone i. To solve this competition, the attractiveness of soil class l in zone j (W_{lj}) must be calibrated so that the conditions of Equation 5 are fulfilled.
In this paper we applied an iterative calibration of (V_{lj}), according to expression (6).

$${}_{q+1}W_{lj} = 1 / [1 + \exp(- \theta \{□_q + □_{q-1}\})] \quad (6)$$

Where $□_q = \{\Sigma_k □□_k\ {}_q S_{ilk} □ + □\ {}_q P_{il} + \Sigma_{ik} □□_k\ Eb_{ilk} □ - A_{il}\}$ for each iteration q; and θ is the parameter used to control the path of the calibration process.
Calibration of W_{lj} is complete when the land use for each class of soil, l, in zone i does not exceed the amount of land available, A_{il}. The calibrated attractivenesses for each soil class, l, in each zone, i, can be interpreted as bid-rents or lagrangian multipliers of the soil restrictions (Roy &Thill, 2004), associated with each soil class, l, in each zone, i ($□_{lj}$).
If we assume

$$□_{lj} = \ln (1/ W_{lj}) \quad (7)$$

expressions (1) and (3) take the form

$$T_{(ikl)j} = E_{ikl} \{r. \exp (-□_{lj} - \alpha d_{limj}) / \Sigma_j[\exp (-□_{lj} - \alpha d_{limj})]\} \quad (8)$$

$$S_{i(jkl)} = P_i \{s_k. \exp (-□_{lj} - \beta_k d_{ij}) / \Sigma_{lj} [\exp (-□_{lj} -\beta_k d_{ij})]\} \quad (9)$$

Where the bid-rents, $□_{lj}$, are complementary to the transport costs, as it would be expected in spatial equilibrium models.

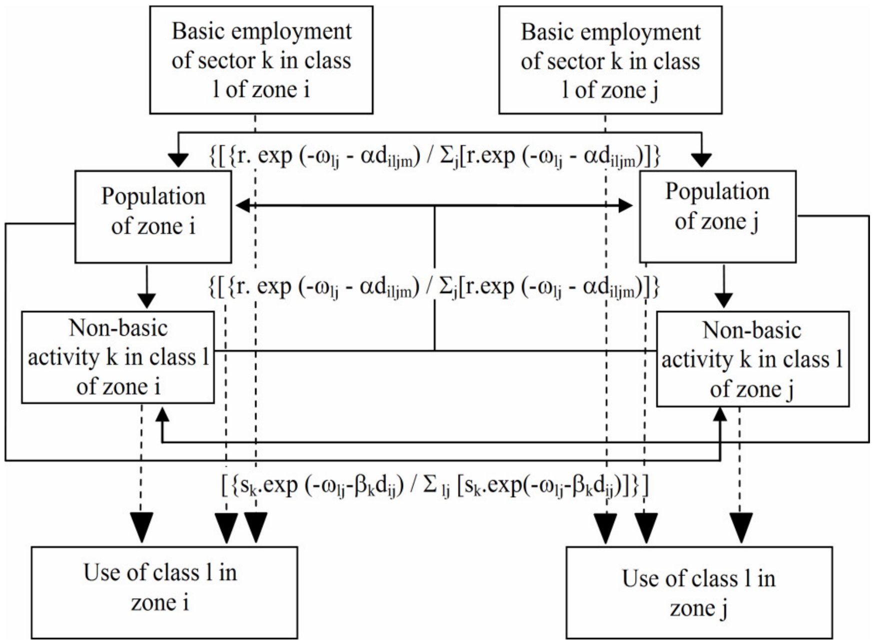

Figure 1 - Economic Spatial Interaction Model for Land Use

Figure 1 explains how the spatial interaction model works. The term basic employment refers to employment focused on or supported by external markets and/or institutions and this constitutes the main economic driver of the model. Non-basic employment refers to employment focused on the local population. In the case of basic employment, the population of different zones that are dependent on the basic activity (exports and external supports) of other zones can be estimated by multiplying the basic employment by the inverse of the activity rate and the weighted attractiveness for residence of each zone , following Eq. (1). Secondly, the population of each zone, i, induces the creation of non-basic activity (services to the population) in different zones, following Eq. (3). Third, the non-basic activity in all zones generates additional dependent population across the region, as described in Eq. (1). The second and third stages of this model are iteratively repeated until the total employment and total population calculated by the model both converge to actual levels. The endogenous variables (P_i and E_{kj}) can be obtained from the exogenous variable for basic employment (Eb_{ik}) through the use of matrices [A] and [B].

$$[E_{ik}] = \{I- [A] [B]\}^{-1} [Eb_{ikl} ; [P_i] = \{I- [A] [B]\}^{-1} [Eb_{ikl} [A] \quad (10)$$

Where:
$[A] = \{r.\ \exp(-\square_{lj} - \alpha d_{limj}) / \Sigma_j[\exp(-\square_{lj} - \alpha d_{limj})]\}$ (11)
and
$[B] = \{s_k.\ \exp(-\square_{lj} - \beta_k d_{ij}) / \Sigma_{lj} [\exp(-\square_{lj} - \beta_k d_{ij})]\}$ (12)
In summation, there are three integrated calibration processes involved in the Economic Spatial Interaction Model of Land Use. First, the attrition parameters α and β_k are estimated, such that the average transportation costs from work to residence and from residence to services used in the model are close to real transportation costs. Second, the bid-rents are calibrated such that the use of each soil in each zone does not exceed the available soil in the zone. Finally, the external relations and the distribution of basic employment are calibrated in order to guarantee that the population distributed by the model for each zone is similar to the observed population. All of these calibrations must be executed iteratively until the estimated parameters converge to stable values.

3. Data Collection and Treatment

The data requirements for the Economic Spatial Interaction Model with Land Use are related to environmental data, including the definition of soil classes and aptitudes; technological information that include the clarification of the transportation network and soil productivities; and economic statistics concerning employment, population, productivity and consumption patterns by sector:

3.1. Simulation of climatic data to Terceira Island

Allowing for the fact, that in most cases, insular territories have only climatic information from surface meteorological stations, that have a limited representativity, a methodology was developed that, starting from this basic information and using physical modulation of climatic mechanisms with local expression, allowing for a generalization of meteorological information to all the territory, and a climatic characterization at a local scale of the insular area (Azevedo, 1996).
The application of the model, using initiation and reference values, we obtained, for each month and year, average monthly values for the different climatic variables. The advective component charts (average temperature and accumulated precipitation), were obtained (Figure 2).

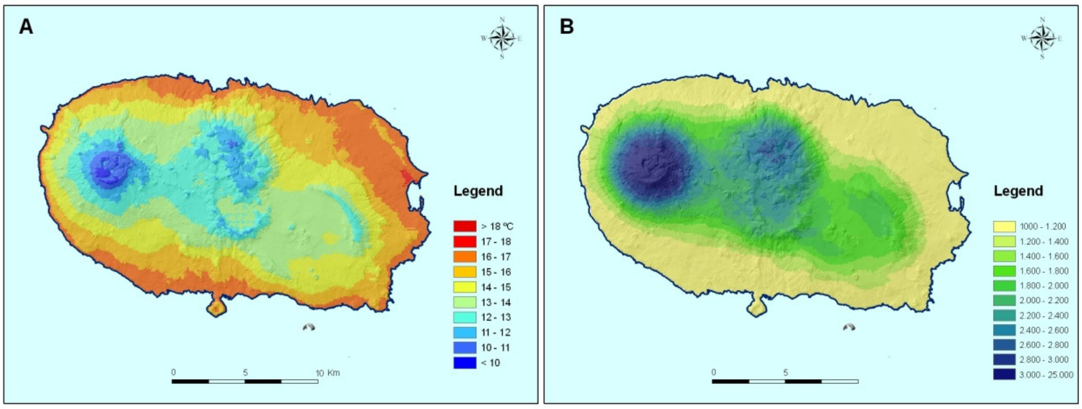

Figure 2 – Average annual temperature (A) and annual accumulated precipitation (B).

For 2070 and 2099, the same type of information was used (Santos e Miranda, 2006), for the simulation of the climatic scenarios that result from various anomalies in average annual temperature and annual accumulated precipitation.
In this work, we opted to use the scenario that presents the most significative changes in precipitation, and temperature (Figure 3).

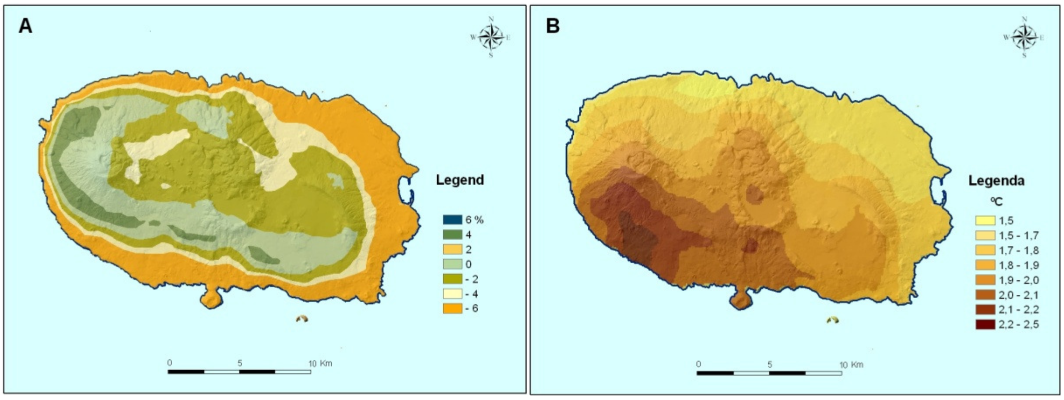

Figure 3 – Annual Precipitation Anomaly 2070 (A), and Summer Temperature Anomaly 2070 (B).

3.1. Aptitude Areas Determination

The definition of soil classes is crucial for establishing a workable model. As shown in Table 1 if we consider 4 levels of average temperature, 3 levels of annual accumulated precipitation, 4 classes of land slope and 4 types of soils, then. a total number of soil classes would have been 192, far too many to effectively integrate into the economic spatial interaction model of land use. Actually, 192 bid-rents would have to be calibrated for each zone and a matrix, $\{I- [A] [B]\}^{-1}$, of 4 zones x 192 would have to be inverted.

Table 1 - Environmental conditions for the different activities.

	Urban	Turistic	Horticulture	Arable Farming	Pasture	Forest
Average Annual Temperature	>= 16	>= 16	>= 16	>= 10	>= 12.5	> 0
Annual Accumulated			>= 1000	>= 750	>= 1300	>= 750
Slope (%)	0 - 25	0 – 25	0 – 25	0 – 15	0 – 25	0 - 50
Soil Classification	I - VII	I – VII	I-VI	I – IV	I-V	I - VI

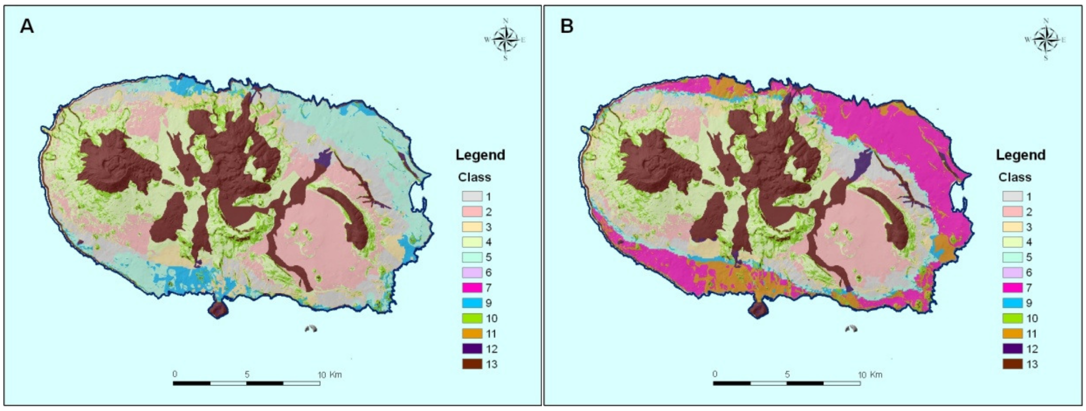

Figure 4 – Class Areas 2007 (A), and Class Areas 2070 (B).

To avoid these difficulties, the 192 potential soil classes were transformed into 14 (Figure 4) soil classes. To achieve that instead of defining the classes from the environmental conditions by themselves, new soil classes were defined considering the environmental conditions specific for the different activities. As shown in Table 2: Soil Class 1 allows all the considered land uses; Soil Class 2 is suitable only for arable farming, pasture and forest; Soil Class 3 allows all uses except arable farming; Soil Class 4 can be used for pasture and forest; Soil Class 5 allows all uses except pasture; Soil Class 6 is good for horticulture, arable farming and forest; Soil Class 7 can contain urban, tourism, arable farming and forest uses; Soil Class 8 can only sustain arable farming and forest; Soil Class 9 is suitable for urban, tourism, horticulture and forest; Soil Class 10 can only sustain forest uses; Class Soil 11 can be used only for urban, tourism and forest uses; Class Soil 12 is just for urban and tourism; Class Soil 13 does not allow any considered use; and Class 14 is for marine uses.

Table 2 - Soil class suitability for land uses.

Class	*Urban*	*Touristic*	*Horticulture*	*Arable*	*Pasture*	*Forest*
1	X	X	X	X	X	X
2	-	-	-	X	X	X
3	X	X	X	-	X	X
4	-	-	-	-	X	X
5	X	X	X	X	-	X
6	-	-	X	X	-	X
7	X	X	-	X	-	X
8	-	-	-	X	-	X
9	X	X	X	-	-	X
10	-	-	-	-	-	X
11	X	X	-	-	-	X
12	X	X	-	-	-	-
13	-	-	-	-	-	-
14	-	-	-	-	-	-

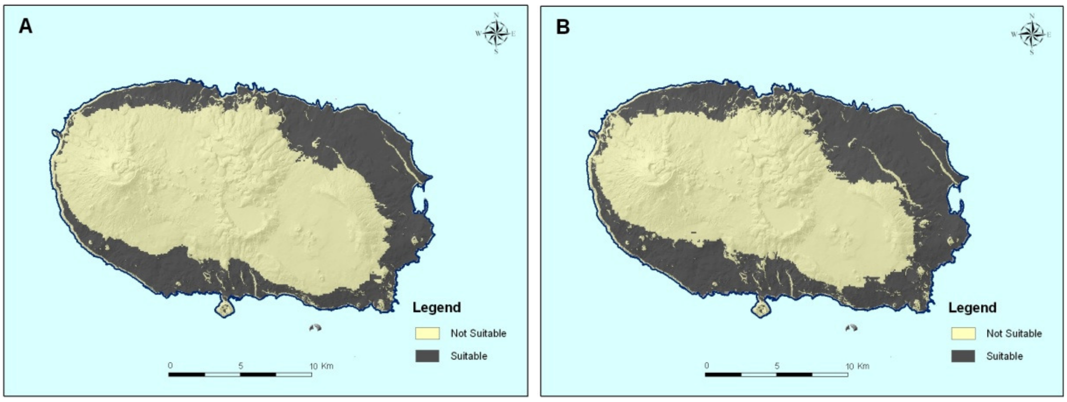

Figure 5 – Urban/touristic aptitude 2007 (A), and urban/touristic aptitude 2070 (B).

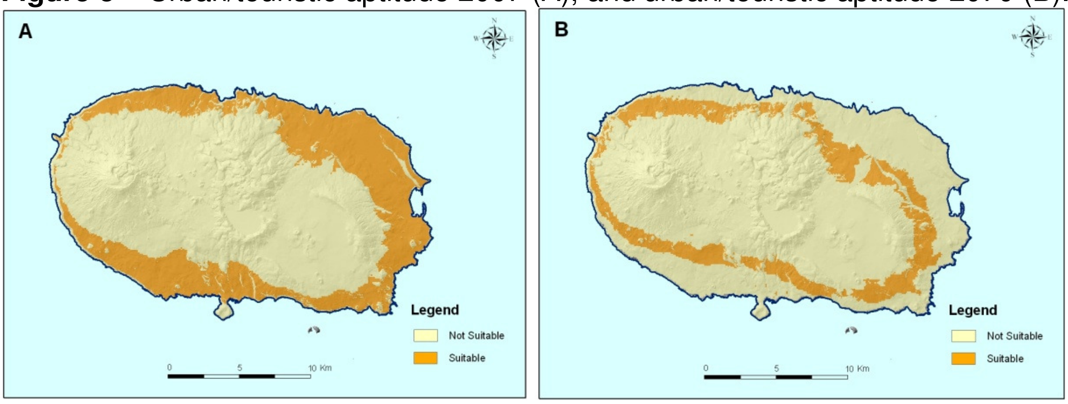

Figure 6 – Horticulture aptitude 2007 (A), and horticulture aptitude 2070 (B).

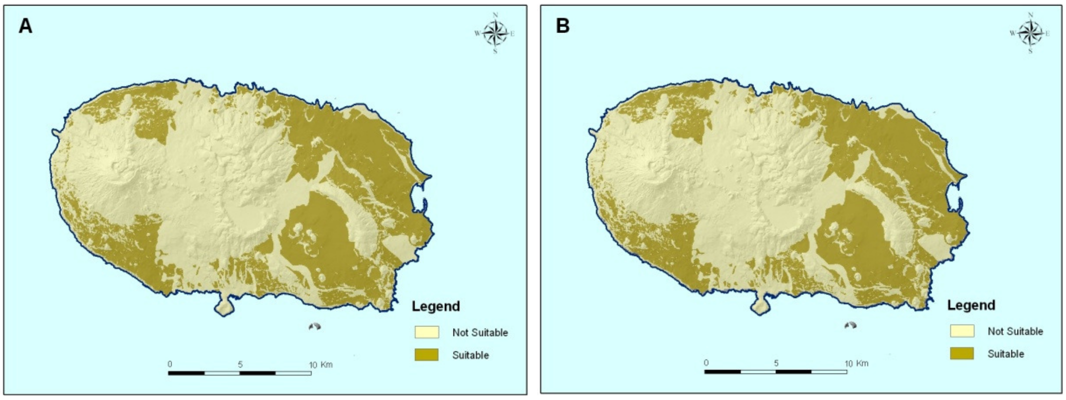

Figure 7 – Arable farming aptitude 2007 (A), and arable farming aptitude 2070 (B).

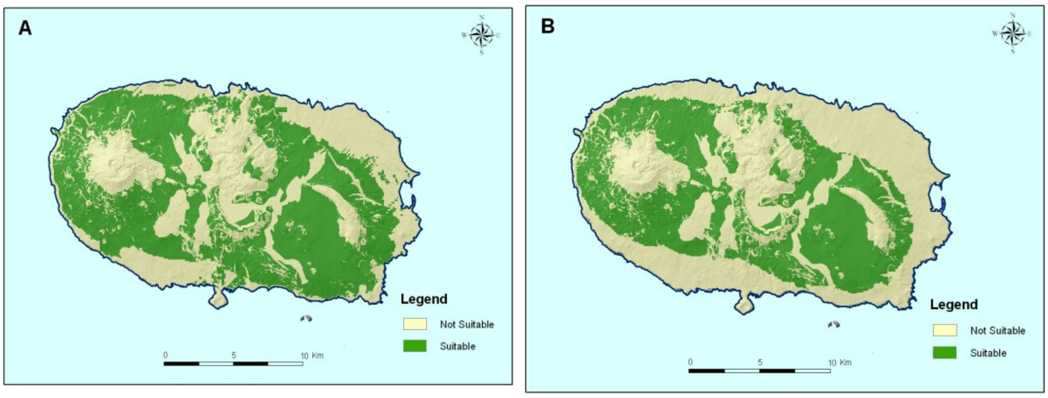

Figure 8 – Pasture aptitude 2007 (A), and pasture aptitude 2070 (B).

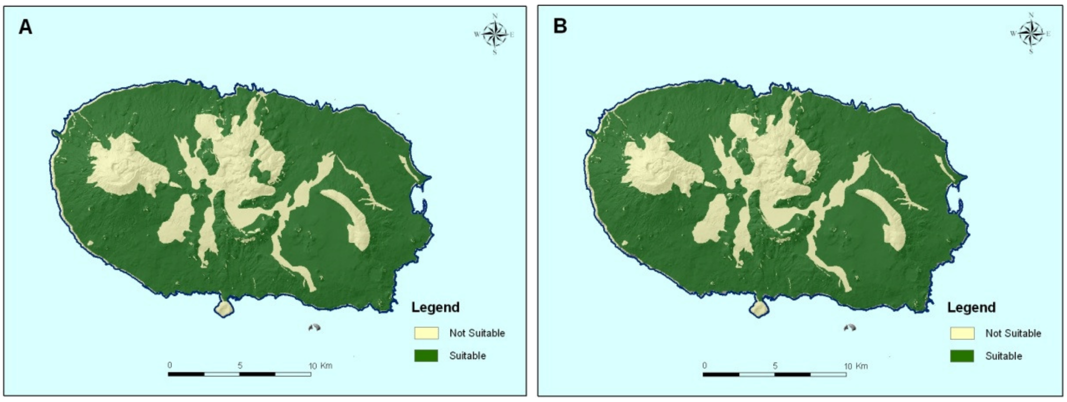

Figure 9 – Forest aptitude 2007 (A), and forest aptitude 2070 (B).

Table 3 shows the areas for each aptitude for the 2001 and 2070 scenarios. The rise of the temperature and the reduction of precipitation translates into an increase of urban/touristic aptitude area, and a significant decrease of the horticulture (without irrigation) area, the area with agricultural aptitude remains similar, a significant decrease of the area with pasture, and finally a maintenance of the forest aptitude area.

Table 3 – Aptitude total areas between 2007 and 2070.

	Urban/Touristic	Horticulture	Arable Farming	Pasture	Forest
Simulated Scenario (2007)	13122	12879	15289	21052	30785
Simulated Scenario (2070)	16147	6663	15249	16671	30755

3.2. Technological data

They were considered 4 zones, 3 inside the island and other one external. Table 3 shows the distances between the four zones. The distance inside each zone corresponds to half of the average radius, based on the surface area for each zone. The distance between each zone and the external zone, involves the terrestrial distance plus the sea and air distance, the sea and air distance considers a fix distance for embark and disembark (125 Km) plus a proportion of 12% of the real distance estimated by Dentinho (2007). The estimation of sea and air distance assumes that there is a fixed boarding cost and that the cost across air and sea is a proportion of the terrestrial cost.

Table 4 - Distances between each zone (Km).

	ZONE A	ZONE B	ZONE C	ZONE D
ZONE A	3,1	12	33	183
ZONE B	12	3,1	26	176
ZONE C	33	26	3,6	153,6
ZONE D	183	176	153,6	0

4. Results

From the analysis of the results, we verify a reduction of the population from 55,833 inhabitants in 2001 to 45,800 in 2070, assuming that the reduction of agricultural exports is not replaced by other basic activities.

The occupation of land use also has some significant changes, a decrease of the area occupied by the sectors of pasture and agriculture (for fodder), and all other activities that sustain the population and exports. It also notes changes in rents, while rents of land with pasture aptitude have a tendency to be maintained, because these soils are the limiting factors.

Table 5 - Distribution of land use occupation (ha).

	Population	Urban/Touristic	Horticulture	Arable Farming	Pasture	Forest
Simulated Scenario	55833	377,5	374,3	17106,3	22843,8	13011,2
Simulated Scenario	45800	310,9	241,6	15646,7	17541,5	8398,4

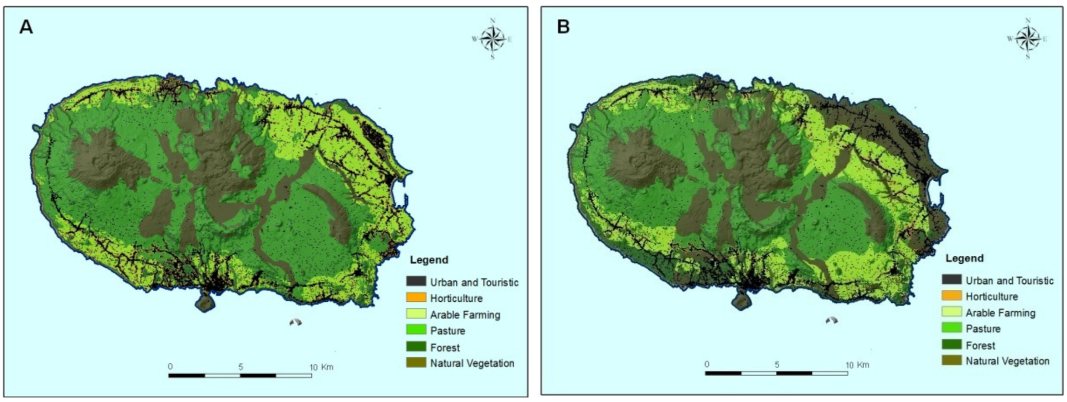

Figure 10 – Land use simulation 2007 (A) and land use simulation 2070 (B).

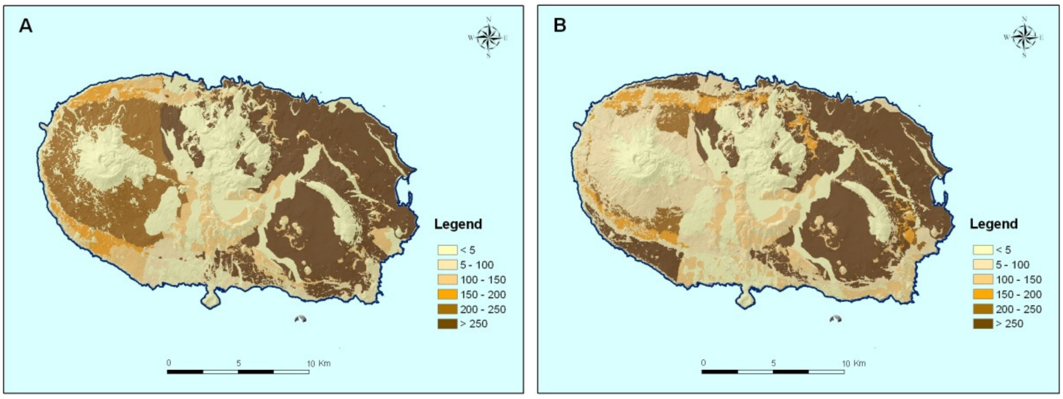

Figure 11 – Bid-rents 2007 (A) and bid-rents 2070 (B).

Using data from the Agência Portuguesa do Ambiente (2009), regarding the portuguese total CO2 emissions per land use class, and crossing this information with the total land area for the different classes (Painho & Caetano, 2005), it was possible to estimate the carbon emission/sink per unit of area (hectare).

Using the carbon emission/sink, per area unit, it was a simple step to evaluate the emissions per land use and scenario (Table 6).

Table 6 – Greenhouse emissions and sinks per área (2007 and 2070 simulated scenarios.

	Population	Urban/Touristic	Horticulture	Arable Farming	Pasture	Forest
Simulated Scenario (2007)	55833	377,5	374,3	17106,3	22843,8	13011,2
Simulated Scenario (2070)	45800	310,9	241,6	15646,7	17541,5	8398,4
	Total		CO_2 emissions per area (tonnes)			
Simulated Scenario (2007)	-29656	1760	17	770	-14946	-17256
Simulated Scenario (2070)	-20451	1449	11	704	-11477	-11138

5. Discussion and conclusion

With this work we intended to demonstrate the potential of spatial interaction models, to explain the patterns of land use, based on employment, population, productivity of land, labor productivity, coefficients between basic employment (export) and population, to different economic scenarios, environmental and technological scenarios.

The model results show that Terceira Island, although suffering strong impacts from global warming, it is still a net carbon sink in the 2007 and 2070 scenarios

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