USING THE SLEUTH CELLULAR AUTOMATON BASED MODEL TO EVALUATE THE IMPACTS OF MULTIPLE LAND USE POLICY SCENARIOS ON URBAN GROWTH PATTERNS IN THE PENINSULA DE SETÚBAL AREA

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1| INTRODUCTION

The population's tendency to concentrate in urban areas, often associated with a rapid urban growth, is a phenomenon that occurs at a global level. According to the World Health Organization, 34% of the global population lived in an urban area in 1960, this value raised to 54% by 2014 and the 78% threshold will be crossed by 2030 (WHO, 2015). The impacts of the conversion of natural to artificial land cover leads, in most cases, to nature destruction and the decline of natural resources due to fragmentation of ecosystems and loss of biodiversity, affecting directly and profoundly humankind in every day (Keith C. Clarke, Hoppen, & Gaydos, 1997). Thus, in the last decade the need to pursue planning policies that follow sustainable approaches has been emerging, aiming to restore the balance between natural systems and society.

Given that the increase of urban areas is a seemingly unavoidable tendency, the study of urban development can provide an opportunity to explore and evaluate strategies to help land use planning and management. Forecasting the impacts of proposed land use policies helps decision-makers assessing the consequences of certain decisions and taking more appropriate actions.

More recently, landscape planning has been taking advantage of spatial analysis methodologies that combine Geographic Information Systems with urban models based on cellular automata (CA) allowing simulations of the future urban form and dynamics (Li & Yeh, 2002). In CA models, space is represented as a grid of cells and can be understood as a simple dynamic space system. The state of each cell depends on the state of the cell itself and the previous state of the surrounding cells. The entire grid evolves in discrete time steps defined by a set of transition rules (Liu, 2009). Despite the CA models simplicity, they are capable to simulate extremely complex behavior, such as city development (Batty, 1997).

CA models have been used to study a large spectrum of urban phenomena as urban development over time (Wu & Webster, 1998), (Batty & Xie, 1997), to model land use dynamics (Maria de Almeida et al., 2003), (White & Engelen, 1993), to predict and compare the future extent of two different urban areas (Clarke & Gaydos, 1998), (Keith C. Clarke, Hoppen & Gaydos, 1997), (Silva & Clarke, 2002), (Barredo *et al.,* 2003), protection of ecological resources in urban areas (Gong & Howarth, 1990), and to simulate land use policies (Candau & Goldstein, 2002a; Jantz, Goetz & Shelley, 2004a).

According to Liu (2009), CA models, as a planning tool, have several strengths: they are interactive and dynamic, supporting "what – If" experiments; the graphical output in form of a map is particularly useful to communicate results to the non-expert public; they are compatible with GIS and raster environments. Notwithstanding the success of these models in simulating the urban growth, it is important to point out that they cannot reproduce all the processes that operate in a territory and they are just an approximation to a complex reality (Yeh & Li, 2006). The purpose of these models is to generate projective scenarios, *i.e.*, predict the future trends based on historic urban land use configuration of a certain city or territory.

The aim of this study is to apply a cellular automaton model, SLEUTH, in the Península de Setúbal area to simulate the impacts of multiple land use policies projected out to 2030. Therefore, the model was calibrated using a historic time series of 1940, 1963, 1990 and 2007 maps of built areas. Projections were made according to three different policies scenarios: (1) Current Trends, (2) Moderate Ecological Protection and (3) Extreme Ecological Protection.

The study area, located on the western coast of the Iberian Peninsula, is centered in Peninsula de Setubal and includes Sado Estuary, covering about 1432.7 km^2. Its northern and western limits are the Tagus River, next to Lisbon, and the Atlantic Ocean, respectively.

Human settlements occur largely in the marginal area of Tagus River encouraged by the proximity to Lisbon, more specifically in the cities of Almada, Alcochete, Barreiro, Benavente, Moita, Montijo, Palmela and Seixal, and around the Sado Estuary, in Setubal (Figure 1).

A large portion of Peninsula de Setúbal is under a nature conservation status, due to the richness and diversity of the existing natural heritage. In the existing protected areas, such as Arrábida Natural Park, Costa de Caparica Fossil Cliff Protected Landscape and Sado Estuary Natural Reserve, urban growth is fully constrained.

This area was selected mainly due to the severe changes caused by unplanned urban growth mainly during the decades of 1970-1980, with severe consequences to the conservation status of most biophysical systems and jeopardizing the existing natural resources, particularly, those connected to the estuary and tributary waterways.

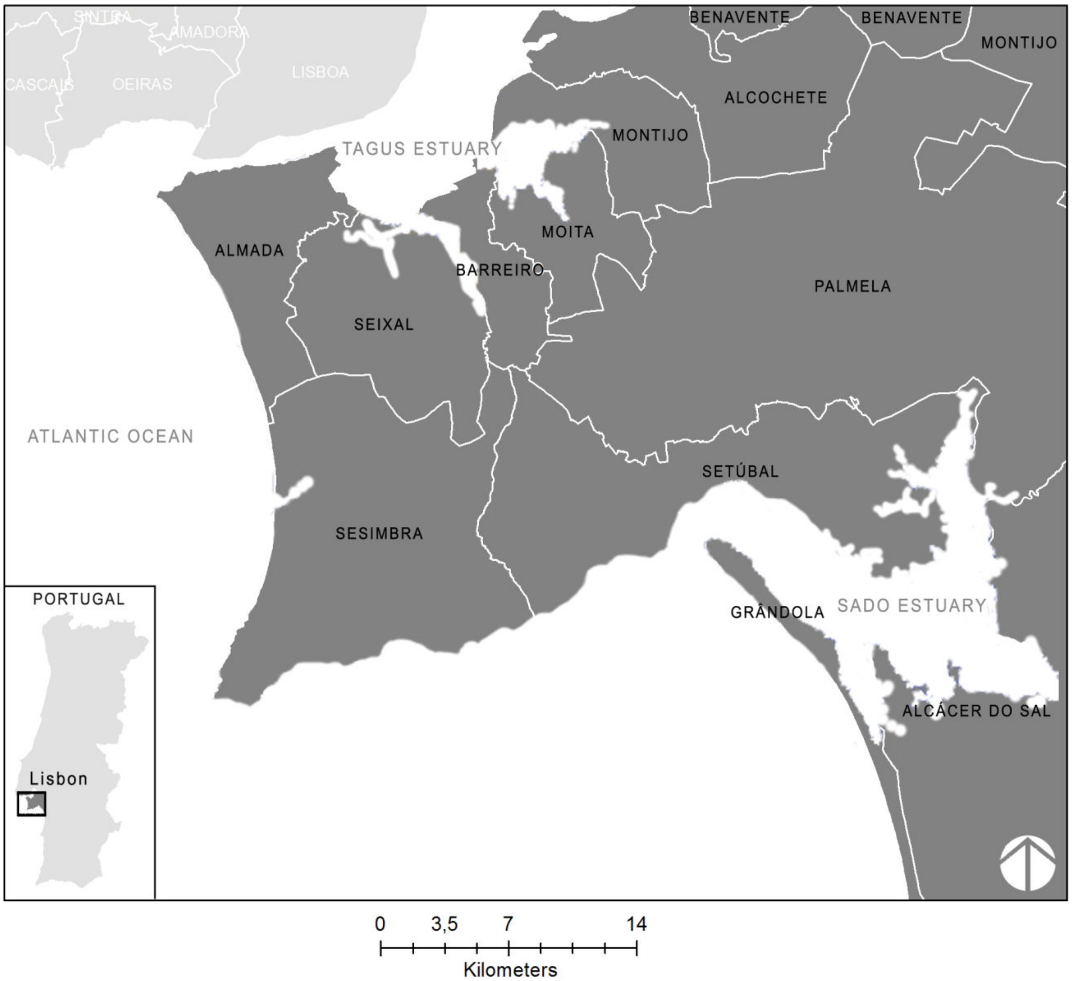


Figure 1 – Peninsula de Setúbal and Sado Estuary study area (white lines and labels refer to local municipalities)

3| METHODS

MODEL FUNCTIONING

In this study the adopted urban growth model was SLEUTH, due to its simplicity and the success of several applications in many cities and regions around the world. Developed by Clarke, SLEUTH uses a cellular automaton approach and its purpose is to simulate urban growth and land use changes induced by urbanization processes (Clarke, 2008). The prime output of the model forecast are probability maps generated through a set of Monte Carlo iterations (Candau & Goldstein, 2002).

The implementation of SLEUTH occurs in three phases: (1) Test, where the model is tested to check if it is operating properly; (2) Calibration, where the model studies the historic growth patterns and derives a set of ideal growth coefficient values of the area; (3) Prediction, where the historic growth patterns are projected into the future based on the growth coefficients determined in the previous phase (US Geological Survey, 2003; James, 2005).

For each simulation the model requires spatial data for the model inputs, which includes at least four layers of historic urban areas, two or more layers of historic transportation network, one layer with the areas that are excluded from urbanization, one layer with land use (optional), a topographic slope layer and a hillshade layer, just for the intent to ease the visualization (US Geological Survey, 2003).

The urban growth behavior is the result of four growth rules that the model can simulate and are applied sequentially during each growth cycle to the input layers: spontaneous growth, new spreading center growth, edge growth and road-influenced growth. These growth rules are controlled by four growth coefficients – dispersion, breed, spread, road-gravity and a fifth coefficient which is slope, used together to determine the probability of any given cell to become urbanized (Jantz et al., 2004).

Table 1 – Growth types simulated by SLEUTH (Jantz et al., 2004).

Growth Cycle order	Growth Type	Controlling coefficients	Summary description
1	Spontaneous	Dispersion	Randomly selects potential new growth cells.
2	New Spreading Centre	Breed	Growing urban centers from spontaneous growth.
3	Edge	Spread	Old or new urban centers spawn additional growth.
4	Road-Influenced	Road-gravity, Dispersion, Breed, Slope	Newly urbanized cell spawns growth along transportation network.
Throughout	Slope resistance	Slope	Effect of slope on reducing probability of urbanization.

At the end of each growth cycle the model allows the self-modification of growth coefficients values to ensure a more realistic growth rate that takes place in an urban system over time. If a rapid growth occurs, the dispersion, breed and spread coefficients are multiplied by a factor greater than one, expressing a boom development. If little or no growth is experienced, these three growth coefficients are multiplied by a factor less than one, simulating a bust development. These self-modification rules prevent the model of generating only exponential or linear growth (Syphard, Clarke, & Franklin, 2005; Clarke & Gaydos, 1998).

INPUT DATA PREPARATION

GIS has the potential to be a very significant engine for cellular automata (Clarke & Gaydos, 1998; Elisabete A. Silva & Clarke, 2005). The capabilities of GIS in data manipulation becomes crucial in the preparation of the input data layers, such as new map extents, projections, grid resolutions, editing and visualization of the data.

The input data layers required by the model were compiled in a geographic information system (GIS). The GIS processing was made using ESRI's Desktop ArcGIS®, assisting in creating, classificating and formatting the input layers.

The slope layer was derived from the ASTER (Advanced Spaceborn Thermal Emission and Reflection Radiometer) GDEM (Global Digital Elevation Map) with 30 meters of resolution (NASA Land Processes Distributed Active Archive Center, 2001). The GDEM was clipped to the project extent and slope values were calculated in percent.

Hillshade layer was derived from the same GDEM as the slope layer. This layer is only used for visualization purposes, providing spatial context, scale and topographic information of the study area.

The urban extent layers comprised four raster maps for the year 1942, 1963, 1990 and 2007. Data for historic urban areas came from a variety of data sources for different time periods: Portugal Military Map of 1942, Portugal Agricultural and Forestry Map of 1963, Continental Portugal Land Use and Land Cover Maps 1990 and 2007.

Transportation network maps for two time periods were created using the Portuguese Agricultural and Forestry Map of 1963 and a 2007 digital ortophotomap.

The exclusion layer represents relative constrains to urban development such as water bodies, protected areas or undevelopable land areas to remove from consideration. The values range between 0 and 100, according to the protection level required. This is the input data that allows the generation of multiple urban growth scenarios and in this case to evaluate different planning scenarios. Three different excluded areas layers were prepared based on the *National Ecological Network* proposal developed by CEAP (Centro de Estudos de Arquitectura Paisagista "Prof. Caldeira Cabral," 2013):

1) Current Trends (CT): intends to represent the urban growth if current trends were kept. The assigned values were determined by analyzing the overlay areas between each component of the ecological network and 2007 urban areas.

2) Moderate Ecological Protection (MEP): Aims to protect the biophysical systems and natural resources, while controlling the urban sprawl. This is achieved through the strict implementation of the *Ecological Network* proposal and lightly constraining the urban development to the areas that are more ecologically suitable for urbanization. The ecological network provides areas of

100% exclusion values (1st Level areas) since it is constituted by components that have a higher ecological value and must be fully protected from urban growth. Areas of lower exclusion values (2nd Level areas), ranging between 30 and 80%, where also considered.

3) Extreme Ecological Protection (EEP): Is based on MEP scenario but all areas of the ecological network proposal were given exclusion values of 100, reflecting a greater restriction of urban development and greater protection of biophysical systems. The urban areas are constrained to the areas that present no ecological impediments for urbanization.

Table 2 – Data elements and levels of protection for the three scenarios.

	Ecological Network Components	Current Trends (CT)	Moderate Ecological Protection (MEP)	Extreme Ecological Protection (EEP)
Ecological Network 1st Level	Wetlands	60%	100%	100%
	Steep Slope Areas	70%	100%	100%
	Soil of High and Very High Ecological Value	60%	100%	100%
	Coastland	80%	100%	100%
	Natural and Semi-natural Vegetation with High and Very High Conservation Value	95%	100%	100%
	Nature Conservation	85%	100%	100%
Ecological Network 2nd Level	Natural and Semi-natural Vegetation with Moderate and Low Conservation Value	0%	30/100%	100%
	Hilltops in Ancient Wet System	0%	30%	100%
	Maximum Infiltration Areas	0%	50/80%	100%
	Ecological Suitable Areas for Building	0%	30%	80%

CALIBRATION

The purpose of calibration is to "learn" the historic growth patterns and determine a set of values for the growth coefficients that best simulate the urban behavior. SLEUTH was calibrated for the Peninsula de Setubal area using historic data from the four previously mentioned years: 1942, 1953, 1990 and 2007.

PREDICTION

To predict urban growth effectively, the growth coefficients values determined in the model calibration were used. Three scenarios of land use policy were simulated for 2030: Current trends, Moderate Ecological Protection and Extreme Ecological Protection. The simulations are the result of 100 Monte Carlo iterations, which generates an annual probability map displaying the probability of where the urbanization would occur and a file of annual growth metrics.

4|RESULTS

PREVIOUS URBAN GROWTH TRENDS

In 1942, the spatial pattern of the development was characterized by widely dispersed low-density urban areas. The densest urban areas occurred mainly in the marginal zones of Tagus River, out of which the cities of Almada, Barreiro and Seixal, and further south, Setúbal are worth mentioning. From 1963 to 2007 these areas were highly consolidated, increasing their area and extension. Urban growth is characterized by an uncontrolled spread around existing urban centers and network infrastructures.

PREDICTION

Figures 2 to 4 present the outputs as a probability map of predicted urban extend for year 2030 according to the three land use policy scenarios, with the 2007 urban areas as a starting point.

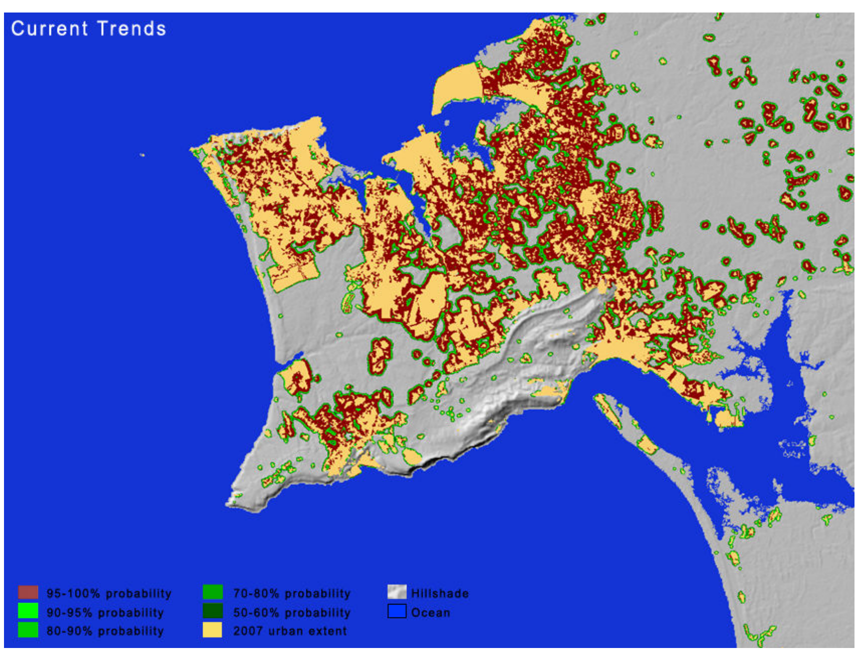


Figure 2 – 2030 prediction for the current trends scenario.

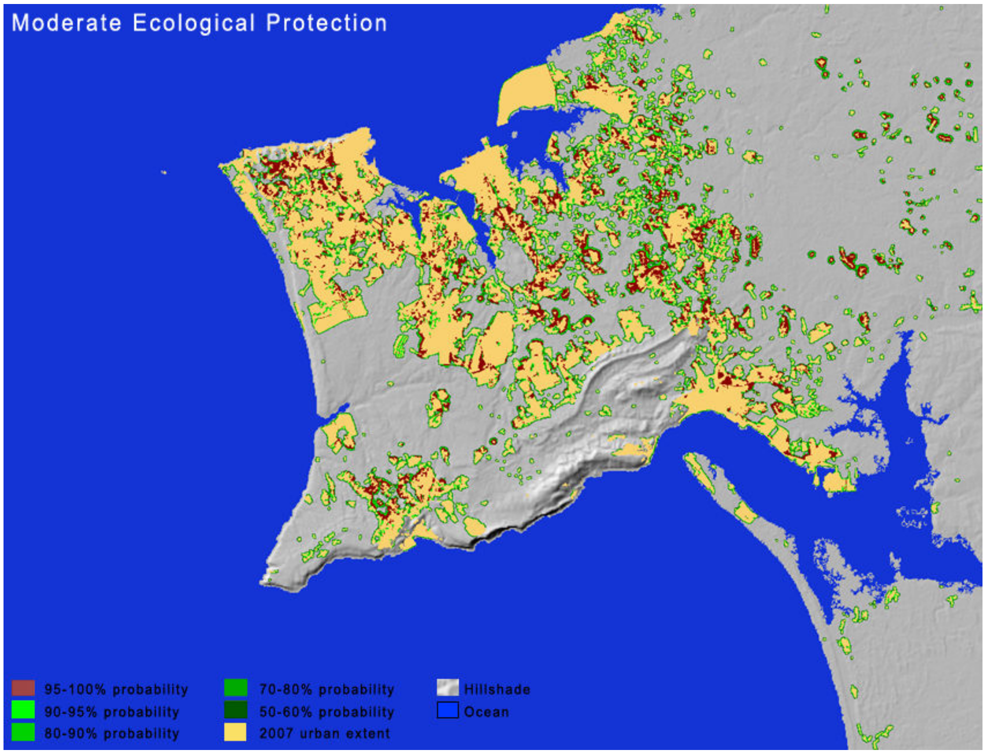


Figure 3 – 2030 prediction for the moderate ecological protection scenario

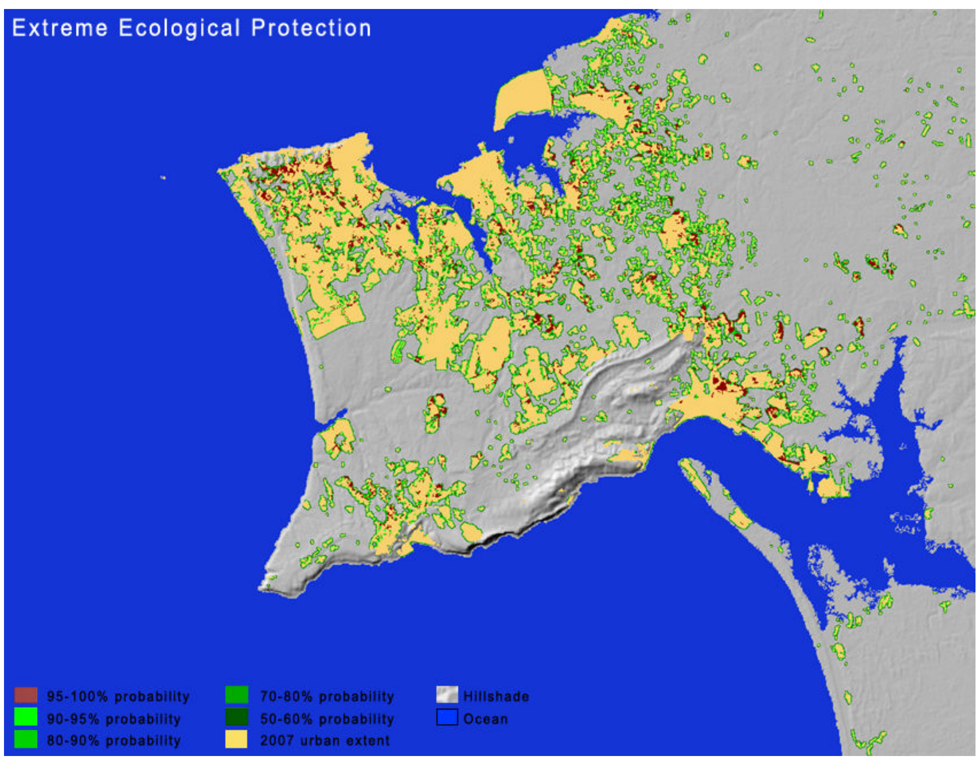


Figure 4 – 2030 prediction for the extreme ecological protection scenario

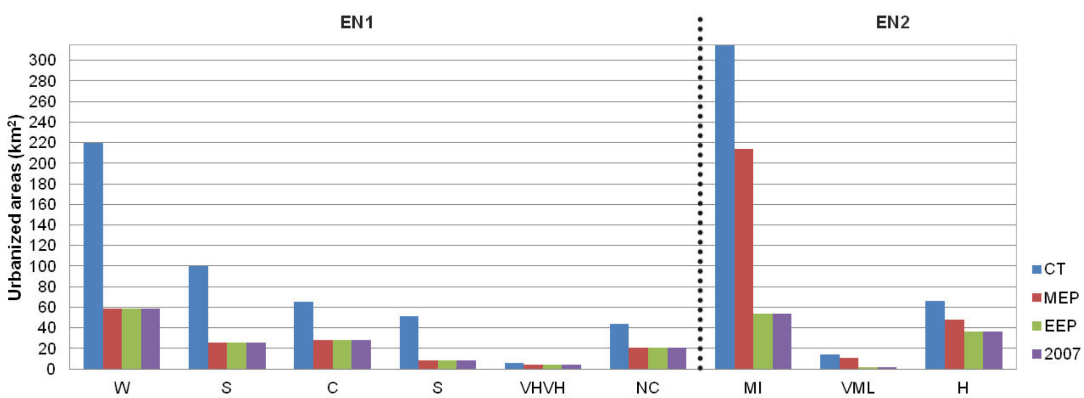
The analyses of prediction results were made according to the growth metrics file generated by SLEUTH and a set of metrics provided by Fragstats 4.2.

The CT scenario generated a forecast with an increase of urban area of approximately 603 km^2, standing out significantly from other scenarios. In 2007 the urban areas occupied 18% of the study area and according to this scenario come to occupy 45%. It features the lowest number of urban fragments and the mean area of each fragment is the highest. This is the scenario where the fragments are widespread and have a greater extent. The growth occurs around existing urban centers and transportation network. This scenario leads to substantial land use consumption throughout the study area with a simultaneous loss of natural resources due to the occupation of the area of the ecological network components with building, especially the wet system and water bodies.

The EEP scenario projected a smaller urban area of approximately 412 km^2, occupying 31% of the study area. It is the scenario that has more fragments and with a lower mean area. The urban areas are more aggregated and have a smaller extent compared to CT. Growth outside the cities is very limited so development mostly occurred as urban infill.

The MEP scenario presents an urban area of approximately 441 km^2, occupying 33% of the study area, close to the values of the EEP scenario. The number of fragments and the mean area have very similar values recorded in the EEP scenario. The urban areas are closer to each other, are less isolated and have a smaller extent than in the CT scenario but larger than the EEP. This is the scenario in which the fragments are more dispersed.

In MEP and EEP scenarios, it is possible to observe that in fact the components of the ecological structure are effectively protected, reflecting the restriction values to urbanization introduced in these land use policy.



W: Wet System; S: Soil of High and Very High Ecological Value; C: Coastlands; SL: Steep Slope Areas; VHVH: Natural and Semi-natural Vegetation with High and Very High Conservation Value; NC: Nature Conservation; MI: Maximum Infiltration Areas; VML: Natural and Semi-natural Vegetation with Moderate and Low Conservation Value; H: Hilltops in Ancient Wet System; EN1: Ecological Network 1st Level; EN2: Ecological Network 2nd Level

Figure 5 – Results of impact assessment of the urbanization on the biophysical systems for each scenario.

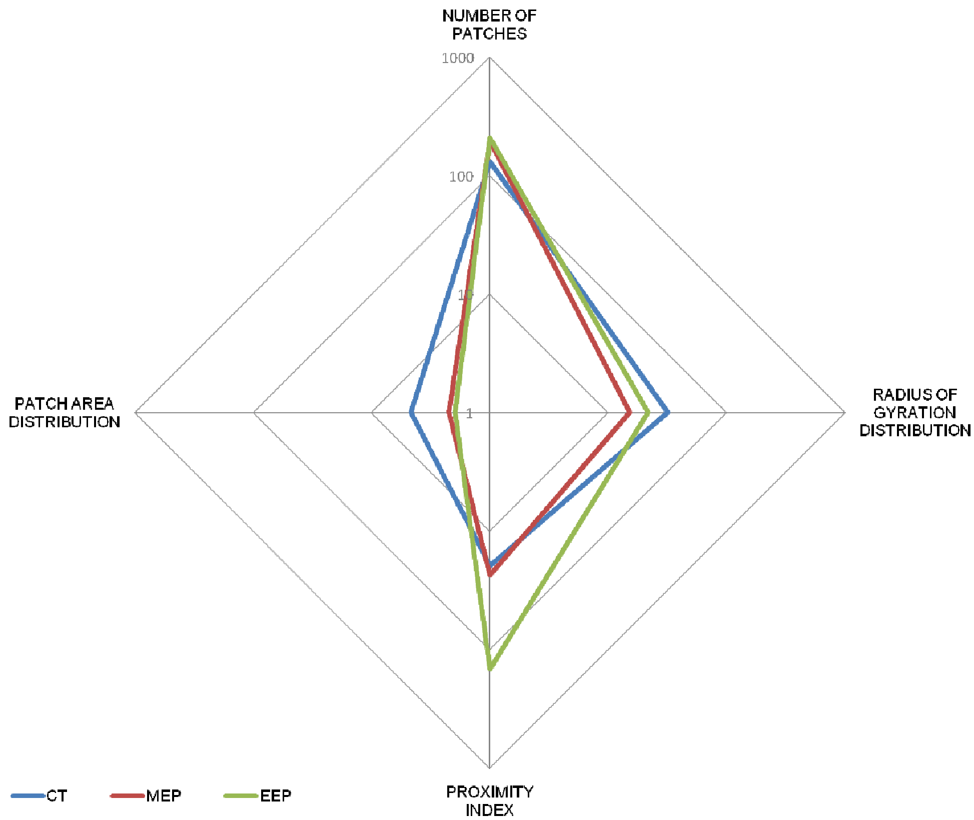


Figure 6 – Characterization of 2030 urban patterns for each scenario. Units are in logarithmic scale.

CONCLUSION

The application of SLEUTH to the Peninsula de Setúbal area showed that despite of model limitations, such as the lack of inputs related to socio-economic factors, the model can be a very useful complementary tool in regional planning. This is due to its capacity to generate alternatives for environmental and urban management, and therefore, to promote a more informed decision making among the stakeholders.Howevershould be highlighted that this is just a theoretical approach and the model should never be the determining factor in decision making because despite predictions are relatively strict, they do not reflect all the complex phenomena that occur in city growth that could be essential for planning.

This study has explored the spatial consequences of urban growth decisions, such as unconstrained development against preservation of certain areas. SLEUTH outcomes provided a graphical description of how different land use policy may affect the Peninsula de Setubal area.

Results revealed that the trend of Peninsula de Setubal growth is characterized by a sprawl pattern and the Current Trends scenario will accentuate these characteristics over time, leading to substantial soil consumption and loss of natural resources. The Ecological Network proposal, along with the areas presenting less ecological constraints for urbanization, worked as an instrument that was able to efficiently control the urban sprawl, preventing an abrupt increase in the average area of urban spaces, while ensuring the protection of natural resources. Both Moderate Ecological Protection and Extreme Ecological Protection scenarios fit the purpose of PROT-AML (Regional Plan for the Lisbon Metro Area) to adopt the compact city sustainable model in order to counteract the extensive and fragmented model that has been followed in recent decades. The EEP scenario revealed the best results because it generated a greater cohesion and aggregation of urban space allowing a better control of the urban growth, while providing simultaneously a greater protection level of natural resources.

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