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How does land use policy modify urban growth? A case study of the Italo-Slovenian border

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This study examines the impact of land use policy variations on urban growth in a transborder region. A primary analysis is conducted using multitemporal maps and satellite imagery for the adjacent cities of Gorizia, Italy, and Nova Gorica, Slovenia, twin towns historically trapped on a political border, a line that has changed in its degree of separation from extreme during the Cold War to minimal today. The SLEUTH land use change model is calibrated and used for forecasting land use change from 2005 to 2040. The model is run under three different scenarios, once for the whole area and twice independently for the two sides of the border, allowing a comparison of the resulting differences. The validation of the results shows that both the cities are growing independently and that territorial cohesion has no impact on change in land use pattern of the region. To plan for a sustainable future, it is invaluable to be able to successfully demonstrate policy impacts via computer modeling, simulation, and visualization and to use the forecasts within decision and planning support systems.

Keywords: land use change; policy; SLEUTH; Italo-Slovenian borderland

1. Introduction

Over the past decade, land change science has contributed significantly to the understanding of land use dynamics, yet human use of the land continues to be at the center of the most complicated and pressing problems faced by policy makers around the world today (Reid *et al*. 2006). Lambin and Geist (2006) noted two fundamental steps in any study of land use change: detecting change in the landscape and then linking that change to a set of causal factors. Thus, it is critical that appropriate information about the causes and consequences of land use change reach policy makers so that they can create more effective policies and understand policy impacts (Goetz *et al*. 2004; Reid *et al*. 2006). This research focuses on analyzing the impact of such policies on urban growth by directly comparing two European cities, one belonging to a developed country with a capitalist economy and the other to a developing country with an economy transitioning from socialist to capitalist.

The ability to map and understand land use and land cover (Alonso 1964; Anderson, Hardy, Roach, and Witmer 1976) and land use changes, especially by remote sensing, has allowed higher resolution mapping, better precision and accuracy, more subtly delineated land use class divisions, and the opportunity to use multitemporal sequences to study dynamics beyond the ‘difference between two dates’ approach (Fung 1990;

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Collins and Woodcock 1996; Barnsley and Barr 2000; Yang and Lo 2003; Treitz and Rogan 2004; Lambin and Geist 2006). The LUCC project of the International Geosphere-Biosphere Program (IBGP) and the International Human Dimensions Program on Global Environmental Change (IHDP; Lambin, Rousenvell, and Geist 2000; Turner II *et al*. 2005) triggered numerous studies in land change science, enriching the pool of knowledge on land use dynamics, the causes and consequences of land use and land cover changes, and methodologies to forecast them effectively.

Explicit consideration of land use planning and policy and how they impact land use change has been less common (Kaiser, Godschalk, and Chapin 1995; Walsh, Messina, Crews-Meyer, Bilsborrow, and Pan 2002; Gaunt and Jackson 2003; Zhao, Nakagoshi, Chen, and Kong 2003). Although an increase in the availability of regional policy information, geospatial data, and the use of GIS has improved matters (Landis and Zhang 2000), research efforts have been more concentrated on examining the dynamics of urban form than in its process (Herold, Liu, and Clarke 2003; Seto and Fragkias 2005). Perhaps the bulk of new understanding about land use change has come from the genre of computer simulation modeling, and this study continues the precedent. While the types of models in use have ranged from economic equilibrium models to agent-based ones (Parker, Manson, Janssen, Hoffmann, and Deadman 2003), the impact of cellular automaton-based models has probably been the highest (Batty 1997; Batty, Couclelis, and Eichen 1997).

Modeling involves the use of artificial representations of the interactions within the land use system to explore its spatiotemporal dynamics and developments (Verburg, Rounsevell, and Veldkamp 2006). For many years now, cellular automata (CA) models of spatial complexity have been used to understand the general complex adaptive system of the environment (Torrens and O'Sullivan 2001). Arguably, the advantage of CA lies in its simplicity and ease of adaptation. With CA's ability to simulate a macroscale urban structure within a given lattice and set of transition rules, a CA model can connect a form with its function and a pattern with its process (Torrens and O'Sullivan 2001). This study used one such popular CA model called SLEUTH land use change model to study the urban growth pattern of the twin cities of Gorizia and Nova Gorica on the Italian and Slovenian border (Figure 1).

SLEUTH has been applied extensively in the geographic simulation of future planning scenarios (Clarke and Gaydos 1998; Clarke, Gazulis, Dietzel, and Goldstein 2007). It has been comparatively examined with many alternative CA and other models of land use change (e.g., Agarwal, Green, Grove, Evans, and Schweik 2002; Gaunt and Jackson 2003; Pontius *et al*. 2008). SLEUTH has been shown to produce both convincing and statistically valid results and has been integrated into methods for scenario planning (e.g., Jantz, Goetz, and Shelley 2003). Recent work has experimented with SLEUTH to test theories of complex future urban forms (Silva 2004; Gazulis and Clarke 2006; Goldstein 2007), and the impact of policy via SLEUTH has been studied with respect to the coastal zone protection and Williamson Land Conservation Act in California (Onsted 2007; Onsted and Clarke 2011). The present research extended these applications to a highly relevant study area (Figure 1) in a transborder region of Italy and Slovenia and with a well-documented land use history.

Border regions pose different characteristics compared with the parent nation. They represent a transitional zone, which is a region of flow and connection between two socioeconomic systems (Bufon 2008). According to Van Houtum and Scott (2005), presently, there is no single prevailing theory, concept, or discourse on political boundaries or borders for European integration and enlargement. One of the political geographers Minghi (1963) has defined boundaries as the *most palpable geographic phenomena*. The socioeconomic

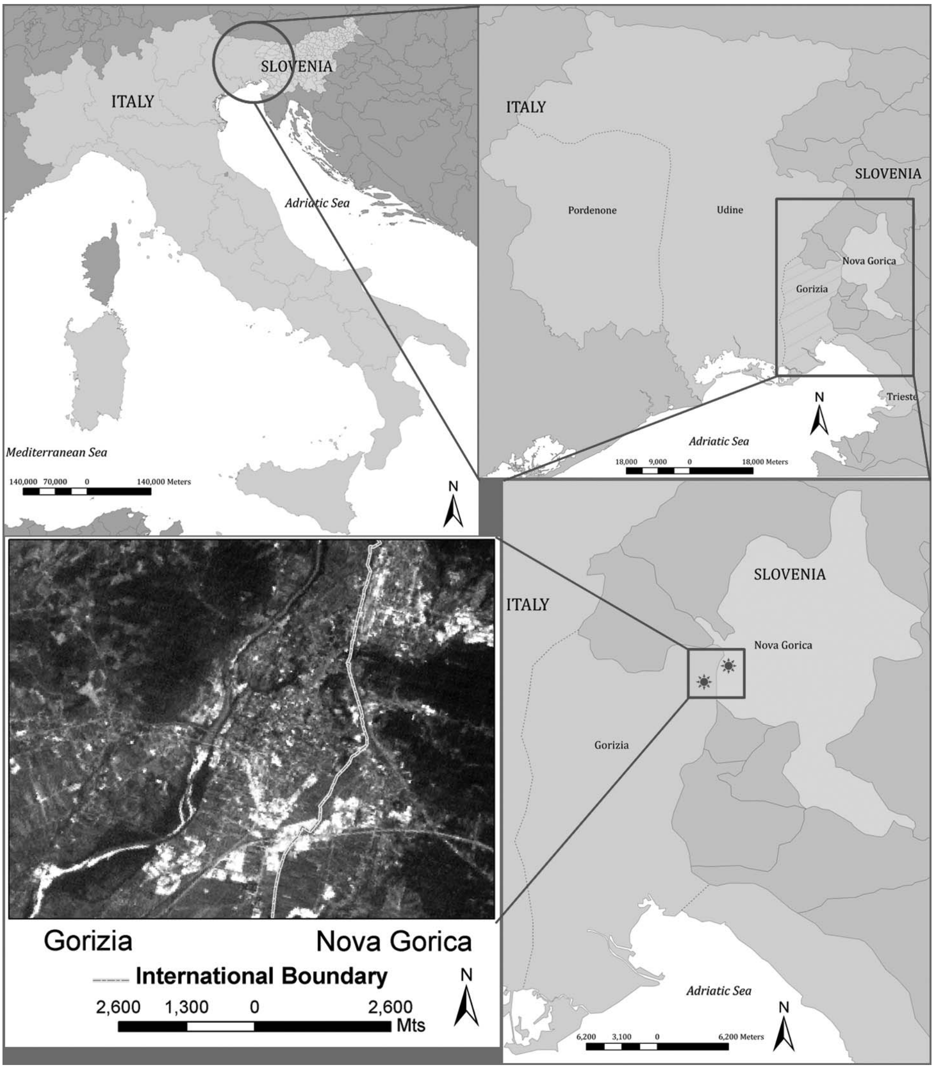


Figure 1. Location map of Gorizia, Italy, and Nova Gorica, Slovenia.

impacts of border issues have been the domain of political geography for years. In the beginning of the twentieth century, a distinction existed between *natural or good boundaries* and *man-made or bad boundaries*, but over the years of horrific consequences and extreme politicization of the naturalistic borders on humanity, border scholars have become skeptical in describing borders as natural (van Houtum and Scott 2005). In a study on the socioeconomic impact of the integration on the EU NUTS III (The Nomenclature of Territorial Units for Statistics) border regions, Topaloglou, Kallioras, Manetos, and Petrakos (2005) found that the process of integration in Europe is still marked by significant differentiation in the border zones. The development potentials of border areas depend on a number of factors (Bufon 2002, 2008), which include different geopolitical situations and historical experiences of each border section; the nature of political and economic relationships between bordering states; the extent of border permeability, regional conditions, the dynamics of socioeconomic development in the border area; and the attitude of the population toward the maintenance and development of cross-border links (Bufon 2008). The international political boundary between Italy and Slovenia (erstwhile Yugoslavia) is undoubtedly one of those in Europe that has undergone the greatest changes over the past century in terms of demarcation, morphology, and function. The present Italo-Slovenian boundary runs through a region that underwent extensive transformation in the political–geographical delimitation of the border and profoundly affected the contemporary development, the socioeconomic transformation, and the function of the region (Klemencic and Bufon 1991). The region's physiognomy and function now straddle the political boundary and join both sides into an interdependent spatial unit. Thus, the border has ceased to be a geographic and strategic dividing line but has become a factor for regional connectivity (Bufon 1995, 2008).

Modeling cities of a transborder region necessarily involves solving problems of data fusion to create long-term land use and transportation maps and change trajectories. Such data fusion requires confronting issues associated with the consistent mapping and modeling of land use and transportation change through highly heterogeneous data at irregular time intervals, from different sources, and with different resolutions, scales, and accuracies (e.g., historical maps, several generations of remote-sensing data, and national mapping programs with seams at international borders; Hall and Llinas 1997). The fact that most of these differences are now disappearing makes the region an ideal case study for testing the impact of policy on urban growth. In this study, policy has been defined as a combination of those political decisions and situations that have directly affected land use and land-based activities and policy makers broadly as those land managers and political leaders whose decisions affect land use at the local level (Reid *et al*. 2006). Furthermore, the study asks, can the differences in impact of policy on land use dynamics be captured into a land use model, sufficiently that past effects may be replicated within tolerable measure of accuracy?

2. Study area

Gorizia is a small town on the Isonzo River at the foot of the Italian Alps, astride Italy's northeastern border with Slovenia. It is the capital of the province of the same name and is a local center of tourism, industry, transportation, and commerce. The town's history dates back to settlement by ancient Rome and has been the site of a medieval castle since 1001. Gorizia was occupied by Italy in WWI from the Austro-Hungarian empire. For two years, the front line ran directly through the town, resulting in its almost complete destruction. The Germans retook the city in 1917 only to have it returned to Italy in the treaty of 1918. In 1927, Gorizia became a provincial capital within Italy's Friuli–Venezia Giulia. During 1943–1945, the city was again under German administration and suffered heavy damage during the war. Finally, it was returned to Italy in 1947. At the end of the war between Germans and Yugoslavian partisans, the front line again ran directly through the city, and only the train station remained on the eastern side.

Under an agreement negotiated by the Allies, the peripheral communes of Salcano and San Pietro, together with much of the Province of Gorizia's territory, were handed over to Yugoslavia. The new centrally planned city of Nova Gorica was built on the Yugoslavian side overnight and included these regions to compensate for the void created by the loss of the old town. During the Cold War, the border was fortified and traffic across the border stopped. With the new border dividing this area, 8% of the previous provincial territory, 74% of the population, 38% of industrial and handicraft units, and 52% of commercial activities passed to Italy (Meinhof and Galasinski 2000). Yet a big part of the Slovene population (about 20,000) remained in Italy, along with the entire city of Gorizia and the main roads and railway connections to Udine and Trieste (Meinhof and Galasinski 2000). From the second half of the 1960s, cross-border relations remarkably improved due to the Udine Agreements (Government of the Federal People's Republic of Yugoslavia 1956), which regulated cross-border movements of people and goods in a 20-km border area. This improved the cross-border socioeconomic and cultural relations, both at private (individuals, organizations, enterprises, etc.) and at public (policy makers, bodies, and institutions) levels (Meinhof and Galasinski 2000). According to Bufon (1995), due to the abolition of entry visas and stable political relations between Italy and Yugoslavia toward the end of the 1960s, this border became *one of the most open boundaries in Central Europe*. This situation remained until the breakup of Yugoslavia, when the new nation of Slovenia inherited both the Nova Gorica and the international border with Italy in 1992. Slovenia entered the European Union in May 2004 and became part of the Eurozone (common with Italy) in January 2007.

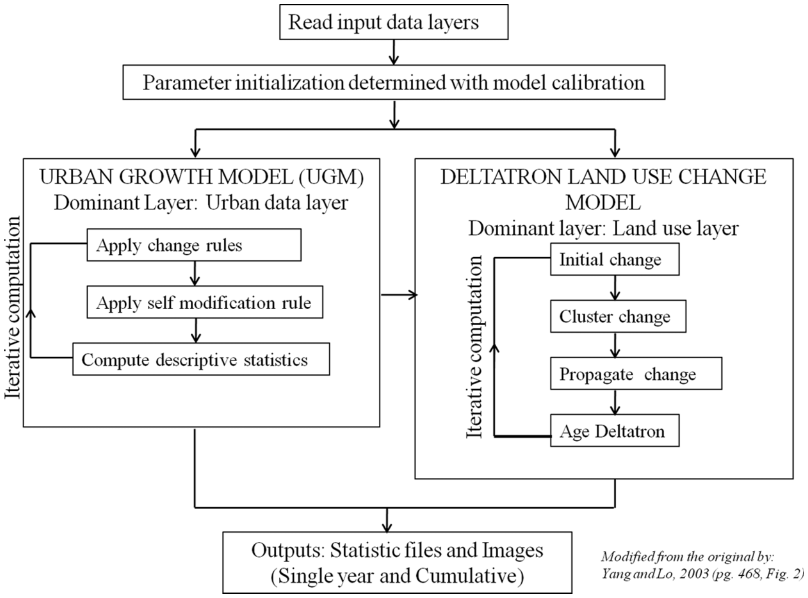
Before territorial cohesion, agriculture and trade influenced development of cross-border and regional relations. Farmers who owned land on both the sides of the border made a major contribution to the development of this region (Bufon 1995). The intensity of local cross-border traffic shaped both the cities of Gorizia and Nova Gorica. Currently, the democratic Republic of Slovenia is one of the aspirant nations of the EU. Cross-border cooperation further improved due to EU policies, particularly with INTERREG (http://www.interreg3c.net/sixcms/detail.php?id=310), which increased cooperation between the Autonomous Region of Friuli–Venezia Giulia and the Republic of Slovenia. Other initiatives undertaken by governmental organizations, such as the Spatial Development Strategy of Slovenia in 2004 (planned to promote agglomerated urban growth), the 'Cross-border Territorial Agreement' (undertaken by the municipalities of Gorizia and Nova Gorica and the surrounding area, to reach a stronger level of cooperation for economic activities, transport, natural and cultural wealth, valorization and protection, tourism, etc.), and the 'Pilot Project for the Reconciliation between Gorizia and Nova Gorica' (aimed to influence various spheres such as urbanism, environment, health, transport, education, university, sports), intended to maximize the integration of the two communities living across the border (Meinhof and Galasinski 2000).

Before 2004, the two sides of the border had radically different land use controls and growth strategies in their respective countries. However, now with European integration, unhindered traffic flow, and changed land use policy, these impacts are expected to fade and their consequences become more uniform. Thus, the objective of this study is to evaluate the ability of computer modeling to closely capture these political changes in land use patterns.

3. Methodology

3.1. SLEUTH model

SLEUTH is a CA model for computational simulation of urban growth and land use changes that are caused by urbanization and has been applied to different cities and regions of the world (Clarke, Hoppen, and Gaydos 1997; Clarke and Gaydos 1998; Clarke *et al*. 2007; Clarke 2008). The land cover deltatron model is tightly coupled with the Urban Growth Model to form SLEUTH (Figure 2). SLEUTH is an acronym for the gridded map input data layers required by the model, slope, land use, exclusion, urban extent, transportation, and hillshade, and simulates land use dynamics as a physical process (Gazulis



Modified from the original by: Yang and Lo, 2003 (pg. 468, Fig. 2)

Figure 2. Structure of the SLEUTH model. Modified from the original by Yang and Lo, 2003 (p. 468; Fig. 2).

and Clarke 2006). The two CA run in sequence and the output of the newly urbanized cells determines the number of times the deltatron code will be executed. Thus, when urban growth is stagnant, land change pressure is reduced and alternatively when other land use classes are being consumed by rapid urban growth, more interclass transitions are created (Clarke 2008).

The urban areas inside this CA model behave as a living organism, which is trained by a finite set of transition rules that influence the state of changes within CA as a set of nested loops (Clarke and Gaydos 1998; Sietchiping 2004; Gazulis and Clarke 2006; Dietzel and Clarke 2007). To model the physical differences that exist in a study area, SLEUTH calibrates the historical data input to derive a set of control parameter coefficients (dispersion coefficient, breed coefficient, spread coefficient, and slope resistance factor) that control the behavior of the system and encapsulate the past urbanization trends of that region (Clarke *et al*. 1997; Gazulis and Clarke 2006). The sum of these coefficient values calculates the growth rate that determines the degree to which each of the four growth rules (spontaneous, diffusive, organic, and road influenced growth) influences urban growth in the system (Clarke *et al*. 1997; Gazulis and Clarke 2006). Apart from the initial growth rules, there is a set of second-level rules that control the behavior of the macro-system called the 'self-modification' rules, which respond to the aggregate growth rate and increase or decrease the growth control parameters in each of the growth cycles accordingly (Sietchiping 2004). Self-modification is important to avoid linear or exponential growth of the area in the model (Silva and Clarke 2002).

This model uses a brute force calibration process during which the set of control parameters are refined by three sequential calibration phases: coarse, fine, and final calibrations (Silva and Clarke 2002; Dietzel and Clarke 2007). The Optimal SLEUTH Metric (OSM) (Dietzel and Clarke 2007) helps to choose the combination of parameters that provide the most robust results for SLEUTH calibration (Clarke 2008). The optimal set of parameters produces an image that most closely resembles the control data images (Clarke 2008), which is then used in the next step of calibration. The combination of parameters with highest OSM value in the final calibration phase is then used for forecasting.

3.2. Data

SLEUTH requires a consistent set of spatiotemporal input information. The location of the region of study made it difficult to find high-resolution and temporally consistent geospatial data. For this reason, this study used datasets from different sources and time periods and integrated them accordingly, to build a coherent dataset suitable for the model application. The area (Figure 1; 23 km^2) under focus included the city of Gorizia in northeastern part of Italy and the city of Nova Gorica (including the settlements of Solkan and Nova Gorica in the north to Sempeter in the south) in the western part of Slovenia. As per the requirement of the model, Shuttle Radar Topography Mission (SRTM) data were used to create the slope and the hillshade layers; land use maps of years 1985 and 2004 and four urban maps of years 1985, 1991, 1999, and 2004 were created from landsat images and two weighted road maps of years 1969 and1999 were used. Landsat TM 1985, Landsat5 TM 1991, Landsat 7 ETM+ 1999, and Aster 2004 were classified (according to Anderson classification level 1 (Anderson, Hardy, Roach, and Witmer 1976)) into land use maps with four classes namely urban (red-roofed houses and concrete buildings), agriculture, forest, and water by using supervised maximum likelihood classification. Accuracy analysis with the ground truth points (Beekhuizen and Clarke 2010) showed that the kappa statistics (a measure of overall accuracy) for the input images varied from 0.74 to 0.80. The two land use layers were also used to create transition matrices which show class-to-class transitions among the land use classes (Clarke 2008).Urban layers for the years 1985, 1991, 1999, and 2004 were created by reclassifying the land use map into a binary format of urban and nonurban (urban pixel = 1, nonurban pixel = 0). For validation of the output images, additionally Landsat 7 ETM+ (2005) and Landsat 5 TM+ (2010) were processed and classified in the same way as the input images to create the observed maps of those years.

Because of the unique location of the study area, high-resolution multitemporal road network maps with similar attributes were not available, so they were created by integrating data from multiple sources. The first network map was extracted from the Italian topographic map of 1969, which included both the Gorizia and the Nova Gorica. The second road network map was developed by merging a 1998 parcel map of Gorizia and a 1999 topographic map of western Slovenia, covering Nova Gorica. To overcome the disparities (due to varied sources of the data) in location and structure of the transportation network of the overlapping areas in both the maps, a logical decision was taken with reference to the satellite imagery and present transportation network structure of the area. In SLEUTH model, exclusion layer is used to regulate urban growth in areas where it is not possible to urbanize (e.g., in water bodies). In this study, three exclusion layers were used to build scenarios for comparative analysis of the impact of policies on urban growth and land use change. Details about the modification in the exclusion layer are provided in the next section.

3.3. Scenario development with the exclusion layer

In this study, the model was calibrated under three different scenarios to emulate and to compare the impact of human decision making (Agarwal *et al.* 2006; Shearer 2005) in the form of policies. Each of the scenarios intends to simulate the phases of sociopolitical

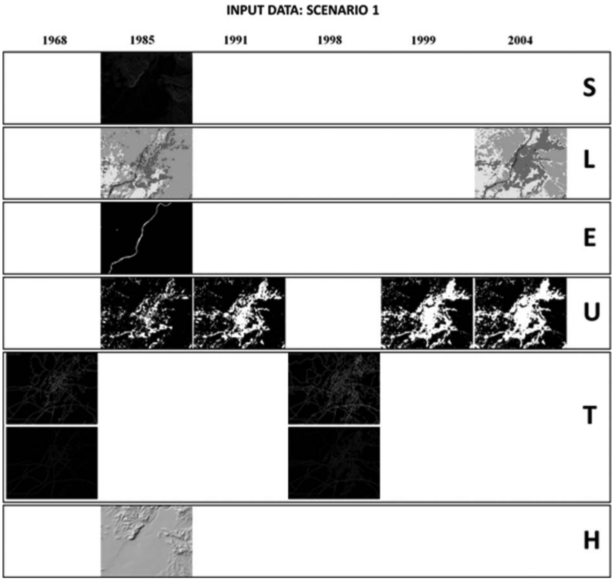


Figure 3. Input data for scenario 1.

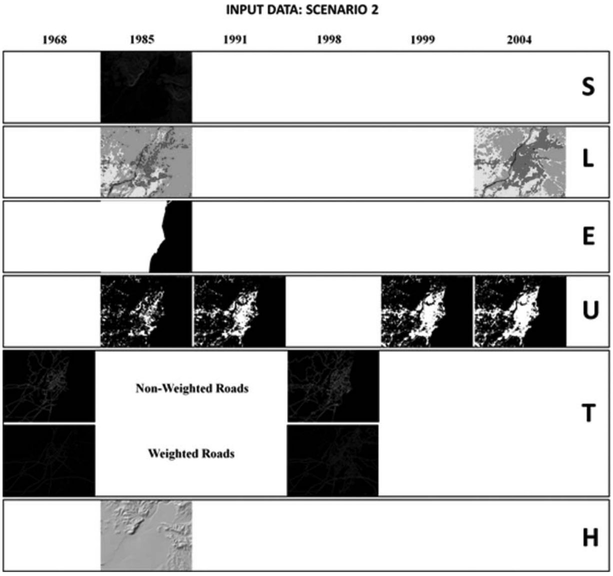


Figure 4. Input data for scenario 2.

history of the region that directly changed the structure and function of the twin city and the international border. In the first scenario (Figure 3), all water bodies were excluded, and the whole area was made available for urbanization, representing the situation after the European integration of Slovenia in 2004. In the second scenario (Figure 4), Nova Gorica (the Slovenian part of the study area) along with the water bodies were excluded leaving only the Gorizia area available for urban growth. In the third scenario (Figure 5), Gorizia

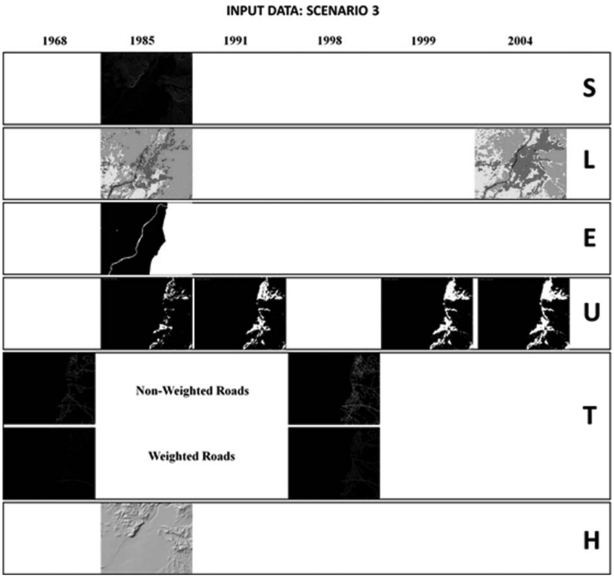


Figure 5. Input data for scenario 3.

(the Italian part of the study area) along with the water bodies were excluded leaving only the Nova Gorica area available for urban growth. The last two scenarios represented the situation before 2004 when the international border was rigid, with strict enforcement.

There were two sets of road data used for modeling to assess the influence of road development on urban growth of the region. In the first road dataset, the roads were assigned equal weights to represent equal accessibility. In the second road dataset, the roads were weighted according to the classification scheme provided in the topographic map of 1969 (the major roads are given a pixel value of 100, the secondary roads 25, and the tertiary roads 10 [http://www.ncgia.ucsb.edu/projects/gig/About/dtInput-Transportation.htm]). Road weighting allowed us to test the importance of accessibility on urban growth for each of the scenarios. The road-influenced growth behavior in the SLEUTH model assumes that urbanization of pixels will occur at locations with increased proximity to roads. The influence of road lines on urbanization may vary from region to region, but road weighting does not influence a road pixel's likelihood of being found during a road search. Instead, the weighting affects how the new urban center can be dispersed along the road network during a random walk. All the road pixels have an equal probability to influence urban development. The highest road weight allows a maximum distance (or number of steps) for the new urban center to travel along the road, and a lower road weight will cause some proportion of this maximum distance to be traveled. In this way, tertiary roads will have a more local affect, while major roads may allow urbanization to occur further away along the network (http://www.ncgia.ucsb.edu/projects/gig/v2/About/gwRoadWeight.htm). For maintaining the spatial consistency of the input data, all the urban layers and road layers of scenarios 2 and 3 were masked according to exclusion layers. Except the different types of exclusion layers, all the scenario runs had the same set of input data. Note that the exclusion layer controls growth only in the urban layers and not in the land use layers.

The only way to incorporate the effect of policy in SLEUTH model is by manipulating the exclusion layer. In this study, scenario 1 aims to simulate the urban growth pattern of the region without the international border. It is assumed that the predictions made from 2005 onward under this scenario will closely represent the trend of urbanization after territorial cohesion, if the EU integration policies are successful, whereas scenarios 2 and 3intend to simulate the real situation till 2004 with the restricted border and is expected to predict mutually independent and localized urbanization of the region. In these two scenarios, the interdependencies present in scenario 1 are absent. The same urban footprint was used for all the scenarios, the only difference in scenarios 2 and 3 was that each of the cities was masked out. Although it is expected that this will lower the calibration coefficient values for scenario 1, nevertheless it will help to show the probability of future urban growth in the region when the segregated cities are simulated separately and then merged together. In order to evaluate the validity of such an approach, the results were further validated outside the model by using a map comparison approach. The observed map showed the present trend of urbanization of the region. The forecasted images for the years 2005 and 2010 from all the scenarios were compared with the observed maps of the years 2005 and 2010. The validation of each of the scenario results will thus reveal the ability of the model to capture it. In that case, if the results of scenario 1 are more accurate than scenarios 2 and 3, then it will indicate that the implementation of the EU policies for integrated development is successful, and if the results of scenarios 2 and 3 are more accurate that means the territorial cohesion has not yet influenced the urban development of the region.

4. Results

4.1. Calibration results

The calibration of the input images provides a set of five parameters, which produces *the best projections of the present day* (Clarke and Gaydos 1998). In essence, these parameters capture the nature of urban growth in the region (Silva 2004; Clarke *et al*. 2007). For this study, the high OSM values (Table 1) of scenarios 2 and 3 indicate that their optimal set of parameter coefficients produce a strong fit to the historic data compared with scenario 1. Each of the parameters captures the types of urban growth that took place in that region. In scenario 2, with both the non-weighted and weighted road dataset, the diffusion coefficient is the most influential factor of growth, which indicates the dominance of spontaneous and road influenced growth. Spread coefficient is highest in scenario 3 with both types of road data, and in scenario 1 with the non-weighted road data, which indicates the prevalence of edge growth in the area. In scenario 1 with the weighted road data, the road gravity coefficient is the highest, which indicates the prevalence of road influenced growth. Notice that the road weighting does not influence the behavior of urban growth of the individual cities in scenarios 2 and 3. These optimal calibration parameters were eventually used for model forecasting.

Table 1. Parameters used for prediction in each of the scenarios.

Scenarios		OSM	Diffusion	Breed	Spread	Slope	Road
Scenario 1	Non-weighted	0.076	73	3	81	1	40
No Border	Weighted	0.127	20	10	73	35	80
Scenario 2	Non-weighted	0.627	100	1	75	5	40
Italy only	Weighted	0.621	100	1	75	24	1
Scenario 3	Non-weighted	0.511	12	13	94	6	59
Slovenia only	Weighted	0.582	10	35	100	50	40

4.2. Prediction results

The model generates probability maps for the final year of prediction. Figure 6 shows some of the predicted images of simulation results from each of the scenarios. The probability histogram for the study area (Figure 7) shows that the high probability of development (95–100%) is greater in scenario 2 compared with scenario 3. Scenario 2 is almost equivalent to scenario 1, which indicates that European integration will not influence the probability of urbanization in Gorizia as significantly as it will in Nova Gorica.

The percentage of urban growth probability (Figure 8) is highest in scenario 2 and lowest in scenario 3. The numbers of clusters are highest in scenario 1 with weighted roads but much lower with non-weighted roads. In Gorizia, the number of clusters is predicted to increase over time with both the non-weighted and the weighted road data, with its peak during 2025, whereas in Nova Gorica, the numbers of clusters increase from 2005 to 2010 but then remain constant over time with both the road datasets.

Thus, it can be seen that there is an increase in the percentage of urban growth over time in all three scenarios, but the number of clusters for scenario 3 remains relatively

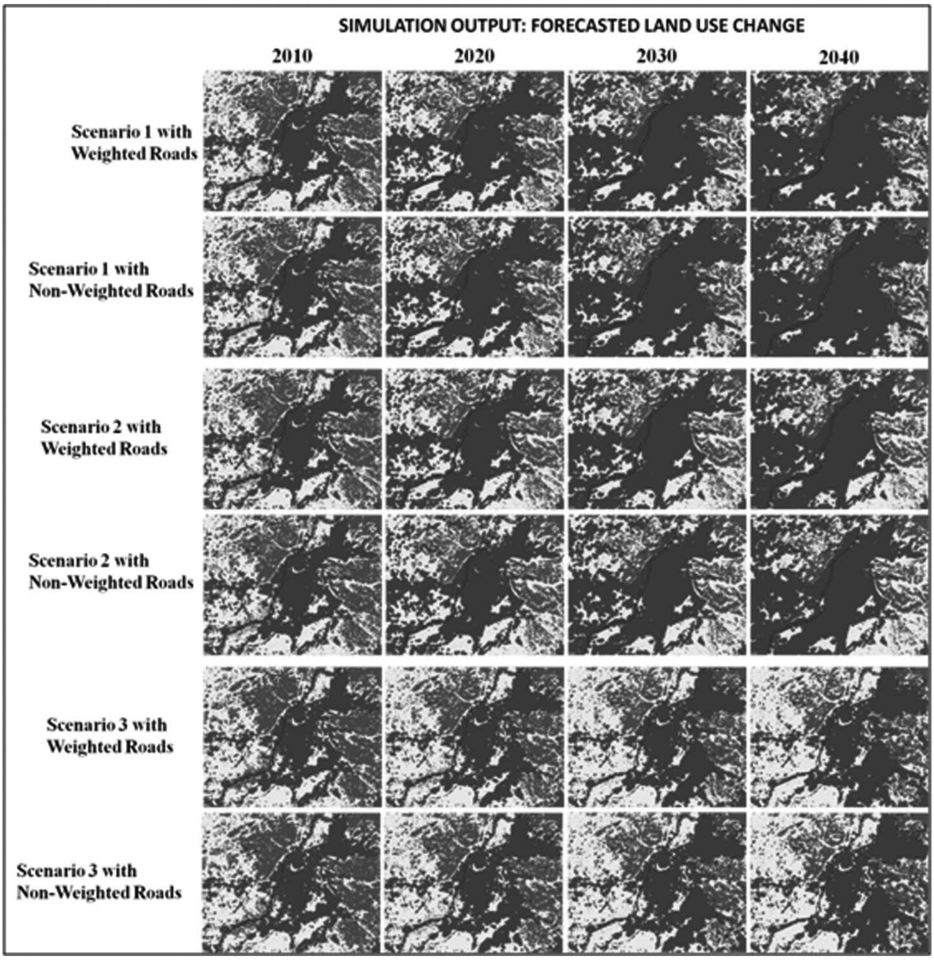


Figure 6. Predicted maps for all scenarios.

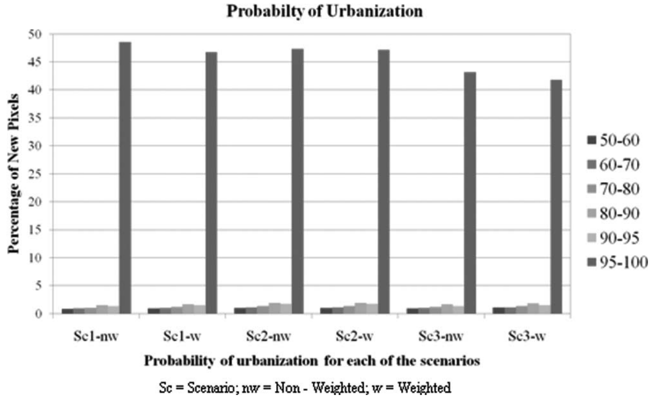


Figure 7. Probability histogram. Sc, Scenario; nw, non-weighted; W, weighted.

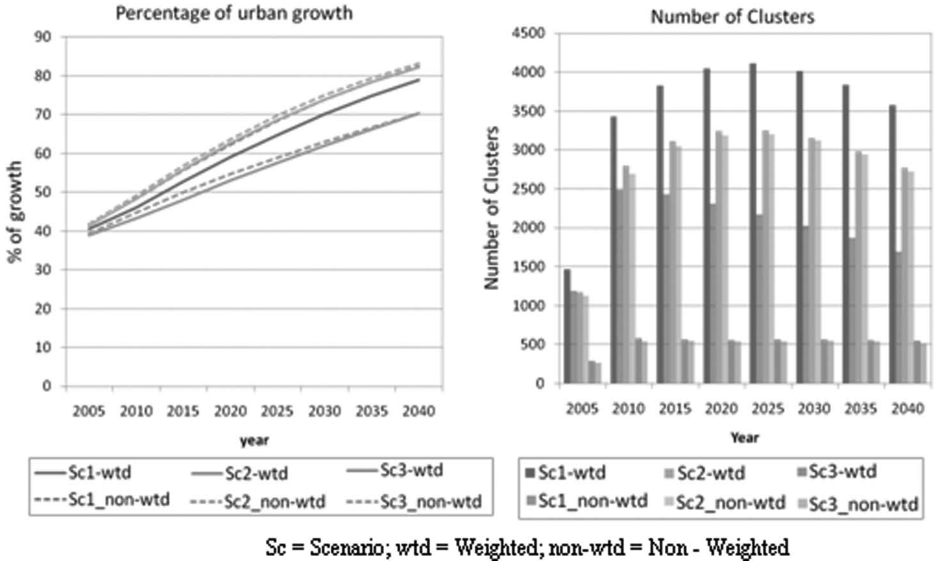


Figure 8. Graphs showing percentage of urban growth (a) and number of clusters in predicted maps for all the scenarios (b). Sc, Scenario; nw, non-weighted; W, weighted.

constant over time. This indicates that the road weighting, in this study, did not influence the development of new urban clusters but only the size of the individual clusters.

Transition probabilities (Figure 9) are calculated with land use classes at the Anderson level 1. The transitions that are forecasted during the SLEUTH calibration phase are an approximation of reality depending on the available time slices in the dataset. Thus, input data with more time slices and accurate classification will produce better approximation. The transition probability matrices are computed from raw pixel counts from each of the available classes for each of the years and normalized over time to avoid the issue of uneven time intervals between input data years (Clarke 2008).

A trend in the transitions from agriculture to urban, forest to urban, and agriculture to forest is persistent over time for all the scenarios, whereas on the other hand, it can be seen that the transition probability from agriculture to forest increases to some extent in the later years.

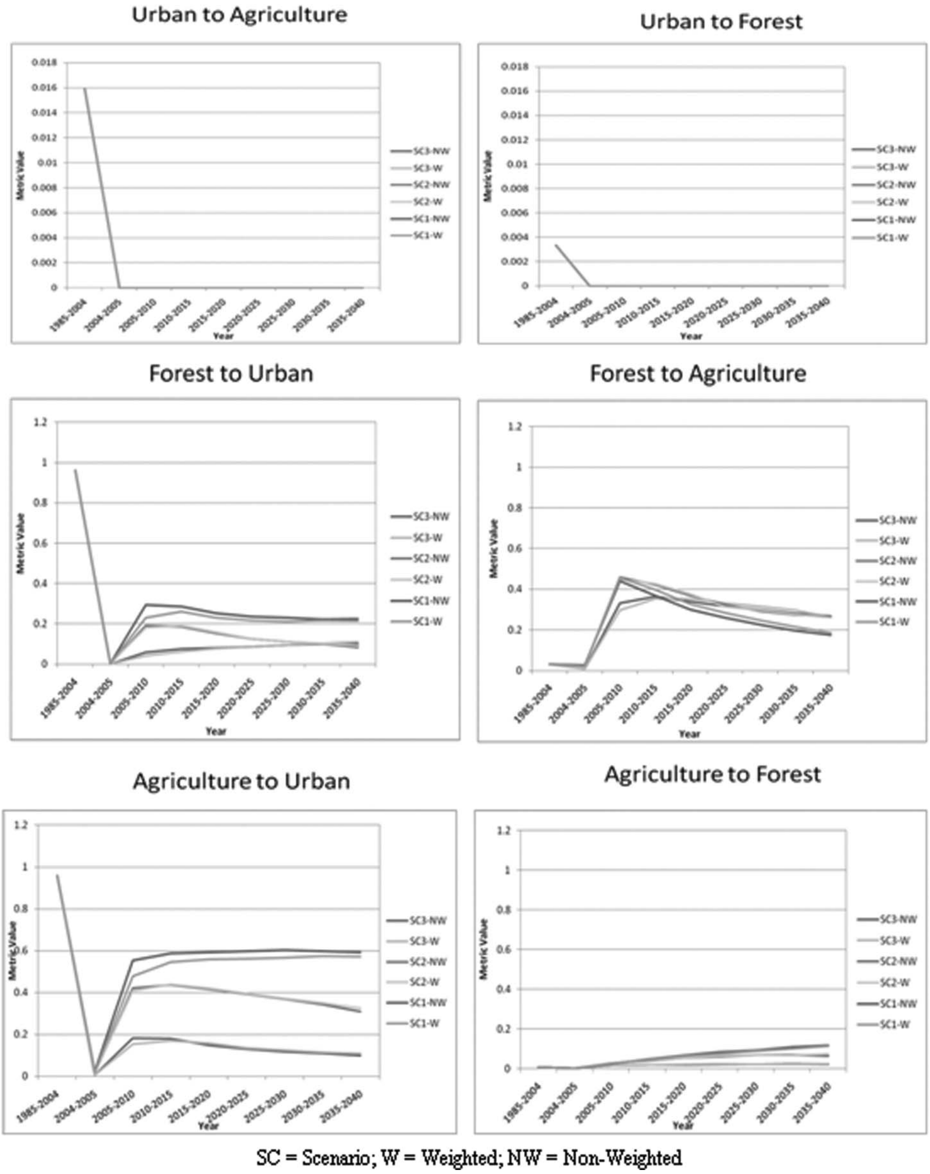


Figure 9. Graphs showing transition metrics among different classes. (a) Urban to agriculture, (b) urban to forest, (c) forest to urban, (d) forest to agriculture, (e) agriculture to urban, and (f) agriculture to forest. Sc, Scenario; nw, non-weighted; W, weighted.

4.3. Spatial metrics

Spatial metrics are measurements derived from the digital analysis of thematic–categorical maps exhibiting spatial heterogeneity at a specific scale and resolution (Herold, Couclelis, and Clarke 2005). In this study, spatial metrics were used to analyze the structure and pattern of predicted urban areas over time (Figure 10). Further, the spatial metrics of the predicted images were compared with the spatial metrics of the observed images to understand the ability of the model and to simulate the pattern of urban growth (Figure 12).

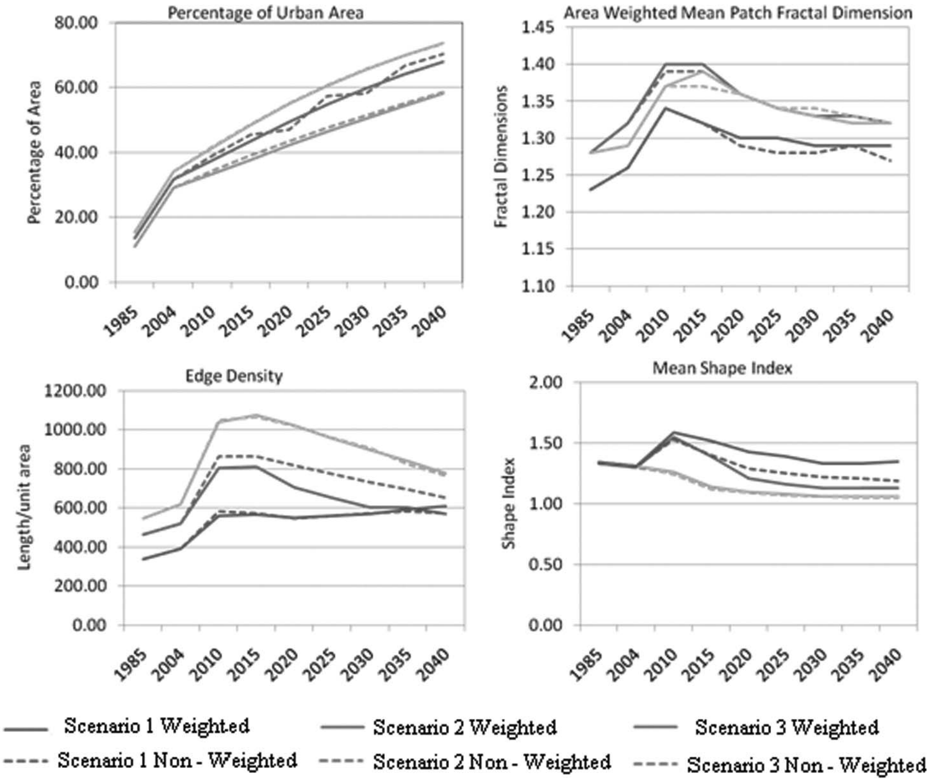


Figure 10. Comparison of spatial metrics for all scenarios. (a) Percentage of urban area, (b) area-weighted mean patch fractal dimension, (c) edge density, and (d) mean shape index.

In a multitemporal dataset, spatial metrics can be used to analyze and describe change in the degree of spatial heterogeneity over time (Dunn, Sharpe, Guntenspergen, Stearns, and Yang 1991; Wu, Jelinski, Luck, and Tueller 2000; Herold *et al*. 2005). For the calculation of spatial metrics, FRAGSTATS version 3.3 (McGarigal and Marks 1994) was used. The results from all the scenarios show that the major part of the landscape is occupied by the urban class, which consistently increases over time (Figure 10). In 1985, the percentage of land covered by the urban class for scenarios 1, 2, and 3 was 13.54, 15.30 and 10.90%, respectively. In 2040, these values will rise to 70.26 and 67.89% in scenario 1, 73.48 and 73.70% in scenario 2, and 58.59 and 58.20% in scenario 3 with non-weighted and weighted roads, respectively.

The area-weighted mean patch fractal dimension (AWMPFD) describes the complexity and the fragmentation of a patch, by perimeter–area comparison (McGarigal and Marks 1994; Herold and Menz 2001). The lowest value is 1 and is found when a patch has a compact quadrangular or rectangular form with a small perimeter relative to the area (Figure 10). For all scenarios in this study, the AWMPFD value for the urban class varied from a minimum of 1.23 (scenario 3 in 1985) to a maximum of 1.40 (scenario 1 with weighted road data in 2010 and 2015). This medium range of values indicates the presence of closely spaced moderate-sized patches. Edge density (ED) standardizes edge to a per unit area that is the amount of border between patches (McGarigal and Marks 1994). The ED increases until 2010 and will remain constant till 2015 for all scenarios, but it will decrease after 2015 for scenarios 1 and 2 and will remain constant for scenario 3, indicating that Nova Gorica will retain its fragmented form until 2040 (Figure 10). Mean shape index (MSI) measures the average patch shape, or the average perimeter-to-area ratio, with values higher than 1 indicating a noncircular patch type (McGarigal and Marks 1994). The MSI values decreased toward 1 in all the scenarios over time, except for scenario 3 and scenario 1 with weighted roads, which suddenly increases in 2010 then gradually decreases over time (Figure 10). This shows that the structure and pattern of urban growth for both sides of the border have no significant difference, and the territorial cohesion is forecasted to have little effect on the spatial pattern of the urban areas in the future.

4.4. Validation

A model is an abstraction of reality, so sensitivity testing is necessary to evaluate the performance of complex models (Clarke 2004). The success of a model is defined by how well the simulated maps match with the known maps (Pontius and Schneider 2001). In this study, the predicted images of 2005 and 2010 were compared with observed images of the respective years, derived by classifying Landsat 7 ETM+ (2005) and Landsat 5 TM+ (2010) and validated for quantity, location, and structural pattern of forecasted change. The overall accuracy of the classification of the observed images was 88.40% with a kappa coefficient of 0.83 for 2005 and 91.20% with a kappa coefficient of 0.87 for 2010. Kappa coefficient analysis for the predicted images was performed using the Map Comparison Kit (MCK) software. The program was written in the Geonamica language and the latest version was developed in 2004 by the Research Institute for Knowledge Systems (RIKS) and the Netherlands Environmental Assessment Agency (MNP – RIVM) in the Netherlands (Visser and de Nijs 2006).

The kappa statistic is computed from a confusion matrix derived from cell-by-cell comparison of the observed map and the predicted map (Hagen-Zanker and Martens 2008). It is based on the percentage of agreement between the observed map and predicted map and is corrected for the fraction of agreement that can be expected by pure chance. It is calculated in the following way (Foody 2004):

$$\text{Kappa} = \frac{P_{\text{o}} - P_{\text{c}}}{1 - P_{\text{c}}},$$

where P_{o} is the observed proportion correct and P_c is the expected proportion correct due to chance. Kappa has been divided into 'kappa location' (K_{loc}) (Pontius 2000) and 'kappa histo' (Hagen 2002). 'K_{loc}' compares the actual success space to the expected success rate relative to the maximum success space, given that the total number of cells of each category does not change (Pontius 2000). K_{Loc} is expressed as

$$K_{\text{loc}} = \frac{P_{\text{o}} - P_{\text{c}}}{P_{\max} - P_{\text{c}}}.$$

According to Hagen (2002), an alternative expression for the similarity of the quantitative model results in the maximal similarity, based on the total number of cells taken in by each class, called as $P_{\max}$. $P_{\max}$ can be put in the context of kappa and K_{Loc} by scaling it to P_{c}. This results in K_{histo}, because it is a statistic that can be calculated directly from the histograms of two maps and is used as a measure of quantitative similarity (Hagen 2002). K_{histo} is expressed as

$$K_{\text{histo}} = \frac{P_{\max} - P_{\text{c}}}{1 - P_{\text{c}}}.$$

The statistic for the similarity of location (spatial allocation of a particular category of pixel) is very informative, because it gives the similarity scaled to the maximum similarity that can be reached with the given quantities (Hagen 2002). These statistics are sensitive to respective differences in location and in the histogram shape of all land use classes (Visser and de Nijs 2006). Kappa (K), K_{Loc}, and K_{histo} are connected through the multiplicative relation: $K = K_{\text{Loc}} \times K_{\text{histo}}$ (Visser and de Nijs 2006). The kappa indices can be interpreted in the following way: if classification is perfect, then $K = 1$; if the observed proportion correct is greater than the expected proportion correct due to chance, then $K > 0$; if the observed proportion is correct is equal to the expected proportion correct due to chance, then $K = 0$; and if the observed proportion correct is less than the expected proportion correct due to chance, then $K < 0$ (Aickin 1990; Landis and Koch 1977; Pontius 2000). A more discrete value range for strength of interpretation was given by Landis and Koch (1977): <0.00, poor; 0.00–0.20, slight; 0.21–0.40, fair; 0.41–0.60, moderate; 0.61–0.80, substantial; and 0.81–1.00, almost perfect. In this study, for 2005 (Figure 11), the lowest kappa coefficient value is 0.82 observed for scenario 2 with non-weighted roads, and highest is 1 observed for scenario 3 with non-weighted road data. The lowest K_{loc} value is 0.91 for scenario 1 with non-weighted road data and highest being 1 for scenario 3 with non-weighted road data; and the lowest K_{histo} value is 0.89 for scenario 2 with both the types of road data and the highest value is 1 for scenario 3 with non-weighted road data. Thus, it can be seen that the coefficient values lie within the range of 0.81–1, which indicates that the model prediction is *almost perfect* for 2005. Relative comparison among the scenarios shows that scenario 3 with the non-weighted road data performs the best in terms of percentage agreement with the observed map, spatial allocation, and amount of change.

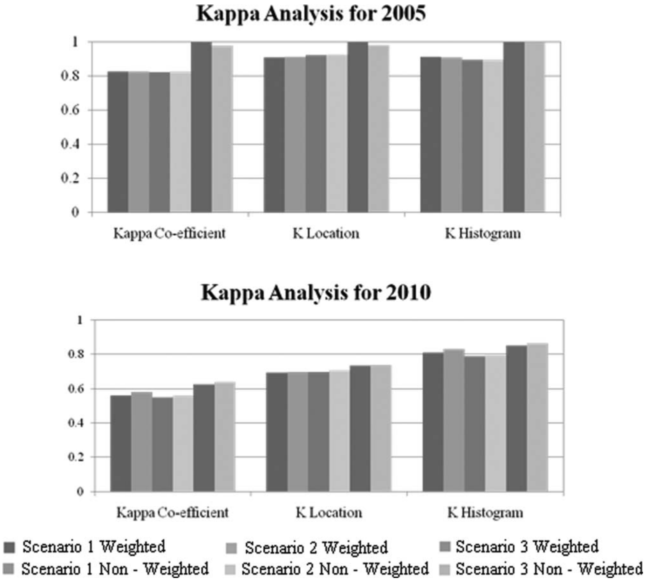


Figure 11. Kappa coefficients for 2005 and 2010 validation. (a) Kappa analysis for 2005 and (b) Kappa analysis for 2010.

In 2010 (Figure 11), the level of accuracy decreases as the uncertainty of model forecasting increases over time (Goldstein, Candau, and Clarke 2004). For 2010 validation, the lowest kappa coefficient value is 0.560, observed for scenario 1 with non-weighted roads, and highest is 0.62 observed for scenario 3 with non-weighted road data. The lowest K_{loc} value is 0.70 for scenario 1 with weighted road dataset and highest being 0.74 for scenario 3 with weighted road dataset; and the lowest $\mathrm{K}_{\text{histo}}$ value is 0.79 for scenario 2 with non-weighted road dataset and the highest value is 0.85 for scenario 3 with non-weighted road data. Thus, it can be seen that the K_{histo} values for all the scenarios lie within *almost perfect* level of accuracy, the K_{loc} has a *substantial* level of accuracy, and overall kappa coefficient values show *moderate* accuracy level. Among all the scenarios, scenario 3 with weighted roads has comparatively highest level of accuracy for 2010.

The structural pattern of the predicted land use maps was also evaluated by comparing the spatial metrics of the predicted map with the observed map of 2005 at the landscape scale (Figure 12). Landscape metrics measure the aggregate properties of the entire patch mosaic (McGarigal and Marks 1994) and are useful to gain knowledge about the structural pattern of the landscape. Patches are contiguous groups of cells (Elkie, Rempel, and Carr 1999), and the number of patches in a landscape denotes the level of fragmentation. Comparative analysis with the observed map (Figure 12) shows that SLEUTH overpredicted the number of patches for all scenarios except for scenario 3 with non-weighted roads. The perimeter–area fractal dimension (PAFRAC) describes how patch perimeter increases per unit increase in patch area. If small and large patches alike have simple geometric shapes, then PAFRAC will be relatively low. Conversely, if small and large patches have complex shapes, then PAFRAC will be much higher, indicating that patch perimeter increases more rapidly as patch area increases, which reflects a consistency of complex patch shapes across spatial scales. In this study, it can be seen that the PAFRAC index of the predicted images is very similar to that of the observed image with the exception of scenario 3 with weighted roads. This denotes that the model was able to produce the complex patchy pattern of the region. The contagion index (CONTAG; Li and Reynolds 1993) is a measure of the extent to which the landscape elements (patch type) are aggregated or clumped (i.e., dispersion); landscapes with a few large, contiguous patches have higher values, whereas lower values generally characterize landscapes with many small and dispersed patches. A high contagion index value for the study area shows that the region has

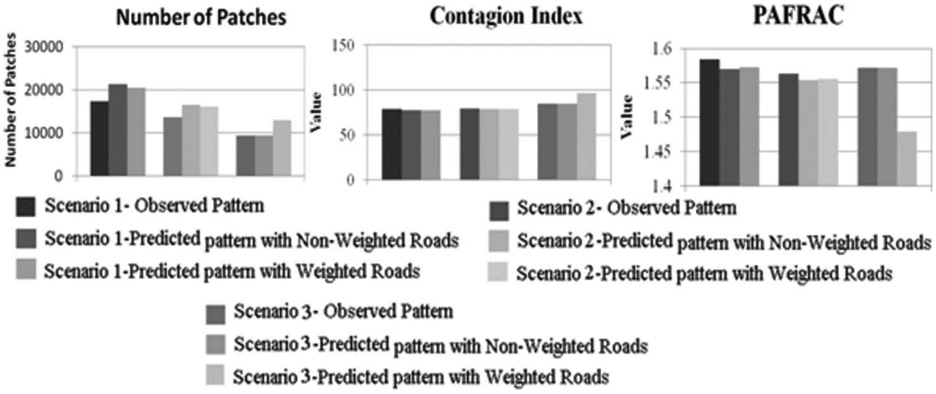


Figure 12. Comparison of spatial metrics between predicted maps and known map. (a) Number of patches, (b) contagion index, and (c) PAFRAC.

large contiguous patches throughout the landscape, and there is no significant difference between the evaluations of predicted and observed patterns. Thus, it can be concluded that the model performed successfully in capturing the spatial pattern of change in the region.

5. Discussion

SLEUTH forecasting results show that there is no significant difference between the change forecasted with weighted road data and with non-weighted road data for scenarios 1 and 2. In scenario 3, the land use change is more accurately forecasted with non-weighted road data. The change trajectory follows the usual linear trend from forest to agricultural and ultimately to urban. Among the types of urban growth, growth along the edges of the urban areas is dominant over time for all scenarios followed by the process of agglomeration in later years and least growth is reported by the development of new urban centers.

In this study, the scenarios represent the political situations before and after the territorial cohesion in 2004. The physical integration of the twin cities and successful implementation of the spatial development policy is expected to create agglomerated urban growth of the region, with less difference between the two sides of the border. This situation is represented by scenario 1, and prediction under this scenario shows the pattern of urbanization when the two historically segregated cities are allowed to grow together, whereas scenarios 2 and 3 represent the situation with a restricted border that existed until 2004, and growth is expected to create mutually independent and localized urbanization in each region. The accuracy assessment of the predicted images with observed maps of 2005 and 2010 shows higher levels of accuracy for scenarios 2 and 3 for both the years. This indicates that both Gorizia and Nova Gorica are still growing as an independent cities, and the effect of integration has not influenced the change in the land use pattern of the region. The validation of the results not only determined the actual pattern of urbanization of the region after territorial cohesion but also the ability of the model to successfully capture it.

Because of the geostrategic location and size of Slovenia, the cross-border relationship plays a very important role in the spatial and regional development of Slovenia (CEMAT Slovenian National Report 2010). For more than two decades, Slovenia has been involved in cross-border programs to eradicate sociopolitical differences and to establish a ‘gateway’ in the relationships between its neighboring countries and overall transnational European macro-regions, which may play a role in international competition, with better accessibility to the purchasing power of the neighboring EU member states and territorial cohesion together with other European ‘global integration zones’ (CEMAT Slovenian National Report 2010). This was reflected when it experienced highest economic growth during 2006–2007, which was the result of intensive export activity toward European markets and strong investment activities. However, the 2010 predicted map captures the characteristic dispersed small settlements of the Slovenian city, which, according to the CEMAT Report (2010), is caused by a serious implementation gap in the goals of the Spatial Development Strategy of Slovenia in 2004. As Hamilton *et al*. (2005) pointed out in the early 1990s, European policy makers assumed that transition of the central and eastern European cities from a socialist to a market economy would follow a uniform linear trajectory resulting in convergence through time toward the spatial–structural and functional characteristics of cities in advanced market economies and will thus eradicate the age-old border effect (Niebuhr and Stiller 2002). Thus, the policies adopted fail to address the ‘power of the past’ and path dependency on their pre-socialist as well as their socialist-period legacies (Hamilton *et al*. 2005).

This research is significant in two aspects. First is the use of spatiotemporal data fusion from various sources to create a homogeneous and coherent dataset for a land use change model and to produce reasonably accurate results. Second, it incorporates policy impacts into SLEUTH modeling and thus attempts to capture human decision making into CA modeling. CA models are used to understand the complexity of emergent urban system and evaluate alternative futures. In case of SLEUTH, it does not explicitly model the socioeconomic drivers of change but rather models their impacts by measuring the physical pattern of the land use and land cover changes across the landscape. The definition of policy in this study is an aggregate of the different political history and policies adopted over time, which have changed the pattern of urbanization in this region multiple times. SLEUTH successfully modeled such scenarios to give an overall evaluation of policy's impact on urban growth. However, the model is only able to capture the impact of such aggregate policy on form and pattern of urban changes. To have a better understanding of the effectiveness of the individual policies on the whole urban system, a more robust policy analysis should be performed outside the model framework. In future, we hope to explore the possibility of measuring and modeling policy effectiveness exogenously and couple the results with SLEUTH forecasts using more disaggregate land use classes to answer such questions. It is better to use submodels to address complex issues rather than making SLEUTH *data hungry* (Lee 1973) by incorporating more factors.

Land use models are expected to produce *good enough* results, which can enforce a discipline of analysis of the causal effect and advise the policy makers *what not to do* (King and Kraemer 1993; Agrawal *et al*. 2006). Simulating policy in the land use change model thus gives an estimate of the transformative power of a policy and validates the forecasts of both the implementation gap and the success or failure of the spatial policies. In this study, the SLEUTH model captures the effect of policy decisions related to the political situation of the region within tolerable measures of accuracy. This supports the conclusion that eradication of the physical boundary will only be successful if there is implementation of equally influential socioeconomic policies, which positively affect the system dynamics to reap the benefits of integration.

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