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Conceptual agent-based model of RUR land-use dynamics

Koper case study

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Abstract
Land-use change and land-management decisions can significantly affect human and natural systems. Using an agent-based modelling approach, we estimate a number of natural and human impacts resulting from land-use dynamics. In the first section of this deliverable we evaluate the impacts of different actors and their spatial location decisions and mechanisms on high quality soil loss, noise pollution levels, and human well-being. The first section provides a detailed description of our approach and model, the study site and the data used. The second section of this document describes the impacts of land-use dynamics guided by four scenarios. The scenarios are downscaled from the IPCC SRES (2000) as part of a broader project (www.plurel.net) that seeks to evaluate the effects of the four scenarios (A1, A2, B1, B2) on land use dynamics, among the other factors specified above, across seven case study sites (i.e. Koper, Slovenia; Haaglanden, Netherland; Liepzig, Germany; Manchester, United Kingdom; Montpellier, France; Warsaw, Poland; and Hang Zhou, China). We calibrate the model and present results exclusively for the Koper, Slovenia, case study, but the model and analyses presented within may be used as a template for other case study locations both within the PLUREL project and beyond.

Objectives
The current deliverable report has been prepared in the framework of PLUREL Work Package 4.2 by the Centre for the study of Environmental Change and Sustainability at the University of Edinburgh.

The objective of this WP is to produce a conceptual and implemented agent-based model for a generic Rural-Urban Region to analyse the influence of PLUREL defined driver scenarios (based on IPCC-SRES narratives) on urban land use change - output is in form of a conceptual description and Java-based implementation of the model.

Methodology
We use an agent-based modelling approach to integrate a variety of data and mathematical and statistical models to estimate the impact of land-use dynamics on soil quality, noise pollution, and human well-being in Koper, Slovenia. The agent-based model (ABM) is described in detail in the first section of this paper. Details include empirically informing agents using social survey data derived from a conjoint analysis, using spatial data and analyses (i.e. logistic regression equations) to guide land-use transition or development behaviours, and the incorporation of a simple and dynamic noise pollution model. The ABM and its corresponding components were developed in JAVA utilising the RepastSimphony agent-based simulation libraries.

Keywords
Agent-based modelling, land-use and land-cover change, scenarios,

Classification of results/outputs:
For the purpose of integrating the results of this deliverable into the PLUREL Explorer dissemination platform as fact sheets and associated documentation please classify the results in relation to spatial scale; DPSIR framework; land use issues; output indicators and knowledge type.

Spatial scale for results: Regional, national, European	Regional
DPSIR framework: Driver, Pressure, State, Impact, Response	Driver/Pressure/State/Impact/Response
Land use issues covered: Housing, Traffic, Agriculture, Natural area, Water, Tourism/recreation	Urban Growth
Scenario sensitivity: Are the products/outputs sensitive to Module 1 scenarios?	Yes
Output indicators: Socio-economic & environmental external constraints; Land Use structure; RUR Metabolism; ECO-system integrity; Ecosystem Services; Socio-economic assessment Criteria; Decisions	Land use structure, socio-economic (wellbeing measurements), noise pollution levels, levels of agriculturally productive soil
Knowledge type: Narrative storylines; Response functions; GIS-based maps; Tables or charts; Handbooks	Narrative storylines, GIS-based maps, tables and charts

How many fact sheets will be derived from this deliverable:	**1**

Integrating survey data, logistic regression, and agents to model land-use dynamics

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1. Introduction

The study of land systems within the field of land-change science has naturally gravitated from efforts to monitor and model changes in land-use and land-cover patterns toward estimating the impacts of those changes and patterns on ecosystem function(s) and services. The impetus for current efforts to estimate ecosystem impacts of land-use and land-cover change (LUCC) may be attributed to its role in both direct and indirect climate forcings. Direct forcings through terrestrial surface alterations by humans include among others: albedo (Pielke et al. 2002), sensible and latent heat flux (Bonan 2008), and evaporation (Betts et al. 1996). Indirect forcings via LUCC occur due to changes in market prices, institutional initiatives, demographic changes, cultural perspectives, among many others. Climate forcings associated with LUCC as well as its collective contribution to anthropogenic CO^2 emissions (~30% historically, Vitousek et al. 1997) have given further credence to land-change science research and the study of coupled natural-human land-use systems.

Paralleling initiatives to better integrate our knowledge and representation of the links between LUCC and ecosystem outcomes are efforts to map the impact-response cycle associated with the human system. Changes to quantity and location of land for agriculture, residence, recreation, and other land uses have been shown to impact settlement patterns and property values (Irwin 2002). The location and management of different land uses can create a range of socio-economic and environmental outcomes that subsequently affect human well-being. For example, the creation and propagation or dampening of noise, the emission on air pollutants, the accessibility of green space, local transport, and commercial opportunities can each create favourable or unfavourable conditions affecting human well-being and subsequently the biophysical characteristics of the landscape. Favourable conditions may attract new residential settlement, commercial development, or tourism to an area, whereas unfavourable conditions may repel or push different land uses (users) out of an area.

Conducting fieldwork, modelling, experimenting, and interrogating impact-response cycles to identify the conditions that lead to LUCC in coupled natural-human land systems is difficult. Traditional approaches (e.g. statistical models) are limited in their ability to represent 1) interaction among system components or actors within the system; 2) heterogeneity across space (i.e. via the landscape), time (i.e. via changing preferences), and amongst actors (i.e. hierarchies, types, variation in characteristics); and amongst other factors; and 3) feedbacks and thresholds that alter actor behaviours (Parunak et al. 1998). In response to the limitations of traditional approaches, agent-based modelling has become the contemporary modelling approach for those addressing complex land-change science research questions. Agent-based modelling (ABM) complements traditional modelling and analyses by representing the mechanistic components of the actors and decision makers that influence LUCC at the local scale, but which may aggregate to create regional dynamics and global processes (Holland 1995).

In the past, ABM research efforts focused on representing the quantity and location of LUCC. When natural-human impacts were estimated it was often done using landscape metrics of LUCC patterns. However, statistical relationships between pattern metrics and response variables from ecological processes have a host of problems associated with scale, non-linearity, and threshold issues (Tischendorf 2001, Wang and Malanson 2007). While the use of landscape metrics provide a valuable first step toward representing the impact-response cycle between the human and environment system they do not facilitate an improved understanding of the interactions within a coupled natural-human system.

We address a number of the aforementioned challenges by providing a useful example of how to create and apply an ABM rich in land-use and land-cover types to evaluate the impacts of LUCC on a specific case study in the face of significant data limitations. With only social-survey data on agent preferences for settlement location and land-use and land-cover data for year 2000 and 2007, we use the ABM as an integrative tool to combine process representation of residential development with a traditional approach (i.e. logistic regression) to represent the location decisions of actors for which we are data limited. We termed these logistic-regression-based agents 'statistical agents', to acknowledge that they do not include all the characteristics worthy of agency, e.g. heterogeneity and interaction. The inclusion of statistical agents provided a richer model that was representative of the case study area and satisfied desires and requirements from our Slovenian partners and the larger PLUREL project.

The presented work is part of the larger PLUREL project that has the overarching goal of improving our understanding of LUCC dynamics, human location preferences, and land system structure in peri-urban areas at seven case study sites: Koper, Slovenia; Haaglanden, Netherlands; Liepzig, Germany; Manchester, United Kingdom; Montpellier, France; Warsaw, Poland; and Hang Zhou, China (www.plurel.net). In this paper we focus specifically on the Municipality of Koper, Slovenia, but the work herein provides a template to which the other sites will be modelled and compared.

2.0 Materials and Methods

2.1. Study Area

Our study area is defined by the boundary of the Municipality of Koper, Slovenia (N 45° 32′ 05′′ and E 13° 45′ 05′′). Located in southwest Slovenia with 17.6 km of coastline along the Adriatic Sea (Istrian peninsula), the 311.2 km^2 study area borders Italy to the west and Croatia to the east (Figure 1). The municipality is characterised by a Mediterranean climate, with long hot summers, mild winters and occasional strong winds. The territory of the Municipality of Koper includes 105 settlements with a total population of 52,212 according to the latest population data (Statistical office of the Republic of Slovenia, 2010). However, the region has experienced significant population and urban growth, which have threatened the cultural quality of the region and consequently new policy actions are desired to preserve high quality agricultural lands, nature protected areas, and expand nature preserves in the area.

The population of the Municipality of Koper increased from 29,932 in 1961 to 49,827 in 2006 (~66%; Statistical office of the Republic of Slovenia, 2010). Most of the population growth was due to urban expansion around the town of Koper, where administrative, economic and cultural activities are concentrated. Due to its strategic position, the coastal location of the town and more broadly the Municipality provide an attractive location for economic development activities. The town controls the largest commercial sea port in Slovenia and is the 6th largest city in the country. Local and national economic interests lie in the expansion of the Port of Koper as well as in increasing tourism within the region. However, local government recognizes these developments threaten the cultural heritage of the area and face difficult planning choices associated with multiple and conflicting land-use demands.

The territory of the municipality can in general be divided into urban, peri-urban and rural areas. The old city centre of Koper and the remaining densely populated area surrounding it can be defined as urban. The surrounding peri-urban area has a variety of land uses: built-up area for settlement, green and recreational areas, favourable conditions for agriculture, as well as spreading infrastructure and industrial zones. The majority of the spatial area of the municipality forms the rural hinterland, which is sparsely settled and offers a unique cultural heritage. Picturesque hamlets, small churches, sites of ancient forts and valuable architectural monuments are numerous. The Municipality is also very rich and diversified from the environmental perspective, with a well preserved cultural landscape and biodiversity. In 2010, 50.3% of the Municipality of Koper was covered by forests, 39.7% was in agriculture, and 8% was in built-up areas. In addition to the economic opportunities provided by the town of Koper, the livelihoods of local inhabitants in the surrounding areas include farming (e.g. vineyards, vegetable and olive oil production and small cattle breeding in the Karst part of the municipality), supplementary farm activities (e.g. farm tourism), and production of traditional materials (e.g. crafts) and services.

Figure 1: Location of the Republic of Slovenia in the Europe and location of the Koper study area.

2.2. Model

The presented ABM was designed to represent processes of peri-urban land-use change from 2000 to 2030 using annual time-steps. Composed of three types of agents (i.e. residents, residential developers, and non-residential developers) the model explicitly includes processes associated with the interaction between residential location and peri-urban development in a heterogeneous landscape composed of seven different land-use types. The model is initialised with year 2000 land-use and land-cover (LULC) data and a transition matrix that describes the rate of land-use and land-cover transitions. The transition matrix was created by calculating the number of transitions among LULC types from year 2000 to 2007 (Section 3.1).

Each model time step begins with residential developer agents selecting *n* residential household agents, who then evaluate undeveloped lands for potential settlement. Evaluations by *n* agents, for all available cells, are aggregated to create a desire surface for residential settlement. Residential-developer agents then use the desire surface to select locations for development that maximize their utility functions. Residential development continues in the order of town centre, low density, and then high density developments until the specified quantity of development for each type, imposed by the transition matrix or some other defined rate, is reached.

After residential developments are created, residential households evaluate a subset of new and existing residential land-use cells, with available capacity for settlement, and settle at the location that maximizes their utility. Once residential development and settlement has taken place commercial, industrial, and forest transitions occur based on the actions of their respective agents. Each of these three agent types uses the same methodology (Section 2.5.2) to evaluate cell characteristics and determine their preferred locations for transition.

2.3. Landscape

The landscape within which the agents act and interact is composed of three landscape components: land-use and land-cover types, features (e.g. public transport points or roads), and impacts.

2.3.1. Land-Use and Land-Cover Types

The landscape is composed of a grid of cells, where each cell has a single land-use or land-cover type. The initial distribution of land-use and land-cover types (year 2000), and calibration data (year 2007), were derived obtained from Harpha Sea Ltd., who combined existing digital land-use and land-cover data (MAFF 2007) with cadastral data (MESP 2008) from the Slovenian government. Using additional air photo imagery, we corrected misclassifications in these data and aggregated classes to a final land-use and land-cover classification of eleven types (Table 1).

Altogether seven land uses (agriculture, commercial, industrial, low density and high density residential, town centre, and mineral extraction) and four land covers (forests, open space, water, wetlands) are represented in the model (Table 1). Agricultural lands consist of those lands used for pasture as well as land in or out of cultivation that has been directly used in the cultivation of crops and has not been overgrown by natural vegetation. We distinguish between prime agricultural land (i.e. high quality soil and favourable site characteristics) and sub-prime agricultural land (i.e. low quality soil and unfavourable site characteristics). Commercial areas are classified as those areas composed of retail, office, and tertiary services, which differ from the manufacturing, production, and secondary services that distinguish industrial land uses. We classify open quarries and mineral resources extraction services as mineral extraction land uses. Open space consists of maintained and non-maintained natural areas such as recreational fields, parks, prairie, grasslands, abandoned farm fields, and other natural areas. We classify forests as all lands with closed canopy tree coverage. Water consisted of ponds, lakes, rivers and other hydrologic features and wetlands consisted of semi-permanent saturated areas that were not open water or covered by closed-canopy tree cover. Lastly, wetlands are those lands inundated for extensive periods of time but lacking open water or pelagic classification.

Table 1: Land-use and land-cover classes used by the ABM as aggregated from Harpha data. [1]
Values report area in hectares.

ABMLand	Harpha	Yr 2000	Yr 2007	Change
Agricultural	Arable			
	Permanent Crops			
	Pasture			
		13761	11007	-2754
Commercial	Commercial			
	Services			
	Touristic Objects			
		166	181	15
Forest	Forest	14711	17416	2705
Industry	Industry Production			
	Infrastructure and Public Utilities			
	Port			
	Parking			
	Parking House			
	Parking That Can Be Built Upon			
		340	435	95
Low Density Residential	Individual Houses	615	755	140
High Density Residential	Multi-dwelling Buildings			
	Special Residential Buildings			
		122	131	9
Mineral Extraction	Mineral Extraction	59	63	4
Open Space	Open Space			
	Vacant			
	Leisure Green			
	Graveyard			
	Non-built Areas			
		1118	921	-197
Town Center	Countinuous Urban Fabric	35	39	4
Water	Water	63	42	-21
Wetland	Wetland	120	120	0
	Rail*			
	Road*			
	Total Number of Cells	31110	31110	

We also classify residential areas, those lands where households reside, into low and high density levels. For the Koper case study, low density is equivalent to individual houses and high density is composed of multi-dwelling buildings and special residential buildings (e.g. dorms or assisted living). A town centre land-use category was included to incorporate high-density mixed-use development that included both commercial and residential land uses. In the absence of household census data, housing capacity for each residential land-use type was estimated by regressing the number of cells of each residential land-use type against population[2]. The analysis was performed at the Koper settlement level (i.e. administrative unit), which yielded population capacities of 28, 103, and 353, for low density, high density, and town centre land uses, respectively. Population capacities were then divided by average household size (2.6, SORS 2002) to approximate household capacity per residential land use.

[1] Classes marked * were removed from the data set during vector to raster conversion using maximum combined area of classes within the grid cell to be created and setting the priority for the conversion to classes marked * to zero. Remaining road or rail cells (7 in year 2007) were due to errors in initial data that classified open space around these networks as part of the network. We reclassified these cells to open space. Cell resolution is 100 m.

[2] The linear regression formula: $y = 28.415*x1 + 103.114*x2 +352.554*x3$, where y = population, x1 = number of low density residential cells, x2 = number of high density residential cells, x3 = number of town centre cells. $R^2 =0.9968$, Adjusted $R^2 = 0.9966$, and p-value $< 2.2e^{-16}$.

2.3.2 Features

In addition to the representation of land-use and land-cover types, we also represent a number of landscape features that may influence the pattern of urban development by affecting the decisions of developer and resident agents. For the Koper case study we include public transportation (i.e. bus) nodes, roadways, railway lines, coastline, green space, and sea ports[3] while recognizing that other features such as schools, hospitals, and municipal buildings may also play a role. The initial location of features in the landscape is set by their year 2000 locations (e.g. railway). Some features are explicitly associated with land-use and land-cover types and are created endogenously within the model. For example, local roads and bus stops are features created with land transitions to commercial. Similarly, we define green space as those land uses and covers where recreation may take place – forests, wetlands, and open space – and include water because significant recreation and aesthetic enjoyment take place along the coastline and in association with other water features in the landscape. All features exist as Boolean presence-or-absence variables in each cell within the landscape.

2.4 Agents

2.4.1 Residential-Household Agents

Residential household agents (RHAs) evaluate their expected quality of life obtained at a future location based on their preferences for available social, economic, and ecological services. Because defining the quality of life for any one individual or household is subjective (GDRC 2009) and an elusive concept (Costanza et al. 2008) we operationalise the quality of life evaluation at a location (i.e. cell) using utility theory and a series of normalized utility functions, henceforth we use the term "utility".

Residenital-household agents perform two actions within the model. In some cases *1..n* agents may be asked to evaluate the utility they would derive from each undeveloped cell within the landscape. These values are aggregated to create a desire surface, which is later used by developer agents in their selection of locations for residential development. In the second action, each new or relocating RHA evaluates *m* residential land-use cells with available capacity of settlement and settles at the location that maximizes its utility (i.e. a bounded rational approach). Once settled, RHAs have an annual relocation probability based on an average household relocation of 15 years in the Municipality of Koper. The process of agent location occurs sequentially and in random order each time step. Residential-household agents interact indirectly with each other and with other agent types by 1) occupying space that could be occupied by other agents (i.e. may force other agents to substitute less preferred for more preferred locations), 2) by contributing to environmental impacts (e.g. noise pollution and development pressure on green space), and 3) providing information to residential-developer agents regarding their preferred locations for settlement (via the desire surface).

2.4.2 Empirically Informing Agents

Residential Household agents' location preferences were empirically informed using results from an adaptive conjoint analysis conducted by the OPENspace Research Centre at the Edinburgh College of Art using Sawtooth Software (2007) (Bell et al. 2010). To accommodate different relative perceptions of location-attribute values and lack of precision in recording minor perception differences, conjoint analysis discretises responses into a form analogous to small, medium, large, or poor, good, best for each location attribute evaluated by respondents. Conjoint analysis forces

[3] There are no airports within the Koper case study region. Bus-stop location data were derived from data acquired from Survey and Mapping Authority of the Republic of Slovenia. Sea port data were derived from aerial photograph interpretation.

respondents to make preference trade-offs through a series of pair-wise and attribute-bundle comparisons among different categorical values for different location attributes. The serial and adaptive questioning elicits respondent choice preferences in a comparative and hierarchical format that more closely mimics household decision making under real-world contexts (Aspinall 2007) when compared to other survey approaches and analyses (e.g. standard single attribute Likert scale approaches where each location attribute may be valued important to location decisions). The result of the conjoint analysis is partial-utility or part-worth values for individual respondents that can be mapped to agent evaluations of potential decision outcomes (e.g. Garcia et al. 2007).

Conjoint analysis was conducted across a number of case study sites that include: Koper, Slovenia – May 2010, n = 150; and Manchester, UK 2009, n = 254[4]. We describe results from the Koper case study whereby respondents chose among three quality levels for the following location attributes (Table 2): accessibility to green space, accessibility to public transport, accessibility to shops, and the level of noise. These attributes were chosen as a representative subset of the larger set of Sustainable Communities Indicators (SCI) that was compiled in Canada with specific emphasis on measuring the associated impacts of urban sprawl (Ditor et al. 1999). Results of the conjoint analysis were partial utilities for each discretised location-attribute value for each respondent. The sum of the partial utilities for an attribute is zero and negative utility does not imply a negative influence (Orme 2010).

Table 2: Mapping model attribute values to resident-agent partial utilities.

Attribute	Attribute Values	Attribute Category	Conjoint Partial Utility	Importance Values	Normalized Partial Utility	Rescaled Partial Utility
Access to Green Space Requires	< 300 m	Short Walk	0.454		0.072	0.147
	301 - 600 m	Long Walk	0.010	0.928	0.002	0.077
	> 600 m	Transport	-0.474		-0.075	0.000
Public Transport is	< 300 m	Very Convenient	0.604		0.096	0.235
	301 - 600 m	Convenient	0.265	1.483	0.042	0.182
	> 600 m	Inconvenient	-0.879		-0.140	0.000
Access to Shops#	< 300 m	Many	0.629		0.100	0.251
	301 - 1600 m	Few	0.313	1.581	0.050	0.201
	> 1600 m	None	-0.952		-0.151	0.000
Noise Pollution is	< 65 dB*	None	0.979		0.155	0.366
	66-75 dB*	Moderate	0.338	2.305	0.054	0.264
	> 75 dB*	Intense	-1.326		-0.211	0.000

For RHAs to evaluate the utility of a given location it is necessary to first perform a mapping from generated attribute values (i.e. distance and decibels) to the ordinal conjoint analysis categories (e.g. intense, moderate, none). Using literature values we define the threshold values for respondent categories as shown in Table 2. Threshold values for access to green space are defined as a short walk being less than 300 m, a long walk being between 300 and 600 m, and beyond 600 m requiring public transportation. These values were derived from a range of studies that describe the frequency

[4] Note that partial utilities significantly (ANOVA, p<.001) differ between the Koper and the Manchester case studies (using random sampling on the Manchester data set) indicating that location preferences are region specific. The relative importance of a location attribute can be derived by comparing the range among its partial utilities against the range for the other attributes. For example, air quality has the highest relative weight followed by noise pollution (see Table 4). We also measure which attributes have the highest discriminative power amongst respondents, i.e. they are rated most diversely. The top most discriminative attributes are: accessibility to shops and air quality.

* Noise values from Berglund et al. (1999) were used but adjusted upward by 20 dB to recognize the dampening effects of building facades to those within and other surfaces.

[#] We interpret the number of shops within proximity as access to shops.

of green space usage by distance (Coles and Bussey 2000, Giles-Corti et al. 2005, Grahn and Stigsdotter 2003, Nielsen and Hansen 2007, Schipperijn 2010a).

For example, a typical distance of 300 – 400 m is mentioned as a threshold of frequent usage, after which usage of green space at further distances declines rapidly. Similarly, in the UK, Natural England recommends that everyone have access to a green space of at least 2 ha within 300 m of their home (Harrison et al. 1995). The second threshold of 600 m is defined based on the perceived distance individuals estimated frequent usage (Schipperijn et al. 2010b), which is also the distance at which green space has been shown to influences people's exercise levels (Duncan and Mummery 2005).

We similarly define access to shops as many when they were within 300 m), few when their presence was between 300 – 1600 m, and no accessibility when shops were beyond the 1600 m limit. The upper limit was defined based on the commonly used interpretations of neighbourhood walk-ability of 1 mile (1609 m, Jago et al. 2006, Pikora et al. 2002, Frank et al. 2004, Braza et al. 2004). Because a lower bounding distance limit on shop frequenting was unavailable we used the same 300 m value used for access to green space. In the absence of available threshold values for distance from public transport the same values for distance to shops was used.

We align our residential household agent behaviour to coincide with the conjoint analysis approach for making location-based decisions by rescaling partial utility values for each conjoint respondent to [0..1]. To do this we normalise each partial utility by dividing it by the total importance of all location attributes evaluated by an agent. Importance values are defined as the range of partial utility values for each of the three attribute categories (for green space in Table 2 the importance value would be 1.11). We then rescale the partial utilities by subtracting the minimum partial utility value (after normalisation). The total utility for any location can be predicted for an agent using the following utility function:

$$\mathbf{u}_{\mathbf{r}(\mathbf{x},\mathbf{y})} = \frac{\sum_{i=0}^{n} \alpha_{\mathbf{i}}}{n}$$

where agent *r* calculates utility *u* for location *(x,y)* as the additive outcome of factors *i {1…n}*, α is the utility an agent places on one of the three values (i.e. high, medium, low) for attribute *i*. The function is then divided by the total number of attributes *n* to normalize the final utility [0..1]. Other survey analysis or data reduction techniques (e.g. component or factor analysis) used to empirically inform agent preferences require the explicit representation of preference values and preference weights (e.g. Brown and Robinson 2006, Filatova et al. 2009). In these cases a multiplicative utility function should be used (Aleskerov and Masatlioğlu 2003).

2.4.3 Agent Heterogeneity

We attempted to empirically identify generalizable resident types amongst respondent utilities using clustering methods (Hierarchical clustering, k-means and Expectation Maximization clustering). While internal measures of cluster quality (high intra-cluster similarity and low inter-cluster similarity) provided some evidence of respondent types, we were unable to interpret these clusters or obtain a significant association (Chi Square test) among the clusters and 14 respondent characteristics (e.g. marital status, age, income, etc). Similar efforts to evaluate the explanatory power of respondent characteristics to predict attribute importance values included using a classification and regression tree (R^2 ~0.22-0.30 for each attribute) as well as several other supervised learning techniques (decision tree learning, regression tree learning, and rule-based classifier). Results from the supervised learning techniques were unreliable with root relative square error (RRSE) performing worse then using the mean as a simple predictor. Efforts to cluster respondents to create an agent typology only serve to corroborate similar findings by Fernandez et al. (2005) – that socio-economic characteristics are not sufficient to explain preferences for location-based attributes.

In the absence of a clear inductive delineation of agent types we opted to use the entire sample of respondent preferences. We randomly drew agents (with replacement) from the respondent sample to create an agent population with a similar distribution of agent preferences for the five location-based attributes. While an agent typology is useful for generalization, communication, and modelling purposes, the lack of a clear typology in the data provides further evidence for the use of agent-based approaches that are capable of 1) representing the variability among actors and decision-makers, 2) matching 1-to-1 the actors of the real-world system and virtual agents, and 3) allowing for the comparison of traditional approaches (e.g. mathematical and statistical models) that represent the average actor with heterogeneous data that more accurately capture preference data.

2.5 Developer and Land-Cover Transition Agents

We represent the change or transition to each land use by a specific developer agent. The delineation of a separate developer for each land-use type allows for different behaviours, preferences, and location decisions to be implemented for those developers interested in creating commercial properties versus those interested in creating residential land uses. Constraints imposed on developers include specific land-use and land-cover types that may not be developed and the quantity of cells that can be developed. It is the converse of these constraints that form the three decisions that developers must answer at each time step of the model – 1) where can I develop and 2) how much land can I develop. In the presented version of the model the residential land-use developer agents have unique development strategies that differ from all other developer-agent types.

2.5.1 Residential Land-Use Developer Agents

We implemented three different residential land-use developer agents that are each responsible for creating one of three new residential land uses: low density, high density, and town centre land uses. Residential developer agents first select a number of residents to evaluate the available locations for development. From these evaluations a residential desire surface is created that specifies locations of high preference versus low preference. While different algorithms can be used in conjunction with the desire surface map (e.g. geographic weighted mean, random selection, or nearest to urban areas) our algorithm selects the location that was most preferred by all residential agents in the previous time step. They repeat this process until a specified number of cells have been developed.

2.5.2 Other Developer and Land-Cover Transition Statistical Agents

In addition to residential household agents and residential land-use developer agents we include industrial-developer, commercial-developer, and forest-transition statistical agents. In absence of survey data, we found a logistic regression approach provided an adequate method to extract location preferences from spatial data on land-use transitions. The approach was implemented by first deriving a number of potential drivers of land change that included biophysical characteristics (e.g. soil quality, slope, elevation); distance from existing land uses, land covers, and landscape features (Table 1, Section 2.3.2); and adjacency effects by counting the number of land-use and land-cover types in the Moore Neighbourhood of a transition. We then performed a series of logistic regressions that produced location evaluation equations for industrial and commercial developer agents as well as to evaluate locations for agricultural to forest transitions (Table 3).

Table 3: Logistic regression coefficients for independent variables contributing to the development of industrial and commercial land uses as well as new forest expansion.

	Land use, cover, or feature	Industrial Developer	Commercial Developer	Forest Expansion
Neighbourhood Count	Industrial	1.164000		
	Commercial		1.864966	
	Agriculture		1.115878	
	Open Space	0.187005	0.802314	
	Forest			0.302547
	Wetland	-0.413990		
Distance From	Industrial	-0.000505		
	Commercial		-0.002976	
	Agriculture			-0.009932
	Open Space			0.000269
	Forest			-0.003415
	Local Roads	0.000754		
	Main Roads		-0.001083	
	All Roads			0.000652
	Elevation			0.000650
	Intercept	-0.957758	-2.255870	0.380816
Percent Correct	Absence	90.0	92.5	39.9
	Presence	79.8	92.1	93.6
	Overall	85.2	92.3	77.7
R^2	Nagelkerke	0.532	0.846	0.298
	Cox & Snell	0.398	0.635	0.210

The logistic regression approach provides a method to represent whether a specific type of land-use change is likely to occur or not. Using year 2000 and 2007 land use data, we perform the regression using stepwise variable selection with forward Likelihood Ratio to find the most predictive subset of independent variables. The regression coefficients are estimated through an iterative maximum likelihood method. We compute the goodness-of-fit using the coefficient of determination (i.e. R^2) as defined by Cox and Snell (1989) and Nagelkerke (1991), which are approximate methods for R^2 as used in linear regression models. The R^2 summarizes the proportion of variance in the dependent variable explained by the independent variables, whereby larger R^2 values indicate greater explanation by the model, to a maximum of 1 (less than 1 for Cox and Snell's R^2). The overall predictive accuracy of the logistic regression in representing absence or presence of transitions was high for industrial (85%), commercial (92%), and forest (78%) land uses and covers (Table 3). Overall percent correct is computed on a held-out subset of "unseen" cases (test set) using cross validation.

2.6 Impacts

2.6.1 Soil Suitability for Agricultural Production

Within the Municipality of Koper agricultural lands serve multiple purposes. Agricultural land holdings are relatively small (4.2 ha on average, SORS 2000) compared to average Slovenian (10.6 ha) and European sizes (e.g. Germany 40.5 ha, UK 70.9 ha, FAO-WCA 2000), however farming provides a valued livelihood to an ageing rural population facing urbanization pressures. Due in part to the small family farms and their associated histories in the region, agricultural lands hold cultural and aesthetic value to both residents and to the increasing number of tourists visiting the region (Perpar et al. 2009). Using soil data created to estimate the suitability of land for agricultural production in Slovenia (Vrščaj et al. 2005), we measure the area of productive agricultural soils lost to land-use change. Soil data used were derived from the Soil Information System of Slovenia at the Centre for Soil and Environmental Science (Vrščaj and Prus 1994, Vrščaj 1996, Vrščaj et al. 1998) and classified into six categories (Table 4, Figure 2)[5].

Table 4: Study area (hectares) by agricultural production capability class.

Class Description	Yr. 2000	Yr. 2007
Impervious or No Agricultural Production Capability	1608	1817
Very Low Agricultural Production Capability	5336	5335
Low Agricultural Production Capability	12866	12810
Medium Agricultural Production Capability	3566	3533
High Agricultural Production Capability	2094	2092
Very High Agricultural Production Capability	5640	5523
Total	31110	31110

In the presented version of the model we evaluate only the transition to non-productive capacity (i.e. built-up or impervious lands) from all other categories. However, we acknowledge that there is a likely progression from very high production capability to low agricultural production capability with continued cultivation.

2.6.2 Noise Pollution

Despite a paucity of research on the impacts of noise pollution, it has been recognized as having significant socio-economic effects. For example, the Department for Environment, Food and Rural Affairs (DEFRA) estimated the cost of noise pollution in England to be in excess of £7 billion per annum, with “£3 - £5 billion in annoyance costs, adverse health cost of around £2 - £3 billion and productivity losses of another £2 billion” (DEFRA 2008). We concerned our impact measurements with the role of noise as a location-based amenity because it is the most widely recognized impact of noise affecting resident’s quality of life. It is also the only noise impact that has undergone economic valuation (DEFRA 2008).

Noise pollution is defined as “any unwanted sound” and is based on people’s perceptions of the term unwanted (DEFRA 2008). The subjective interpretation of noise pollution poses problems for its measurement as perceptions are not likely to be stationary across space or time and are also likely to vary dependent on the recipient’s socio-economic characteristics. Decibel measurements may be used to objectify nuisance claims due to noise and infractions delivered for noise creation beyond acceptable thresholds. However, these measurements and infractions are rarely documented and literature on the topic is sparse. With respect to land-use systems, noise pollution applications have primarily occurred as the construction of noise maps by independent firms contracted by local governments to satisfy the EU Noise Directive 2000/14/EC. As a result, most noise measurements are proprietary and unavailable to the public, which inhibits our ability to replicate their results. For these reasons noise pollution and its subsequent social and ecosystem impacts are rarely included in land-use and land-cover change models and analyses.

We take a simplified approach to noise mapping using known levels for human induced noise sources (Table 5), existing noise maps, and equations for noise propagation and summation. While noise levels vary over time for a variety of reasons, including the hour of day, we assume that all noise sources are constant or that their maximum values are noticeable by the model agents.

[5] Soil data acted as the template to which all other raster data (e.g. land use and land cover) were matched such that a specific cell in one data layer corresponded to the same cell location in all other raster datasets. Cell resolution is 100 m, therefore the number of hectares is equal to the number of cells in each class.

Similarly, we do not incorporate a range of factors that may affect the prediction of noise values, such as weather variability; air absorption; friction and reflectance by ground, building, and other surfaces; and variation in noise source strength over time.

Table 5: Noise levels in dBA for land uses and features incorporated in the ABM. All measurements were taken or are assumed to have been acquired at a distance of 10 m.[6]

Land Use or Feature Type	Decibel Level (A)
Road Type	
Motorways	80
Main roads	75
Regional roads	70
Local roads	65
Public paths	60
Rail	97
Industry/Seaport	75
Commercial	60

Noise levels for industrial and commercial land uses, transportation networks (i.e. road and rail), and sea ports are modelled by first, locating them as noise sources in the landscape. Then we model noise propagation individually across space using the following equation:

$$L_{New} = L_{Orig} - 20Log_{10}(d_{New}/d_{Orig})$$

where $L_{(New)}$ is the decibel level at the new location, L_{Orig} is the original decibel level measured for the noise source, d_{Orig} is the distance from the original source dB_{Orig} was measured at, and d_{New} is the new distance from the source (IPPC 2002). Finally, where multiple noise sources overlap we perform a noise summation using the following equation:

$$L_T = 10\ Log_{10}\ (10^{L1/10} + 10^{L2/10} + \ldots + 10^{Ln/10})$$

where L_T is the total sound level and L_1 to L_n are the individual sound values in dB from different sources (IPPC 2002). Results from applying the above noise pollution model for year 2000 data are shown in Figure 2 as classified by the levels affecting residential location decisions.

The noise level of a location factors into the residential-household agent's utility function as outlined in Section 2.4.2 such that when L_T is < 65 dB the agent uses the partial utility associated with no noise pollution. Similarly, if L_T > 75 dB the agent uses the partial utility associated with intense noise pollution. While thresholds vary at which noise begins to present an annoyance to residents, the overarching impact is negative such that at higher levels of noise a resident experiences greater disutility or a negative impact on his or her quality of life. Future research may consider the adjustment of the threshold values used to distinguish high, medium, and low noise pollution according to the subjective perception of survey respondents or the production of noise pollution by residential agents.

To measure the impact of noise within the ABM we simplify the noise map and observe the aggregate count of landscape cells with noise pollution levels above 75 dB and then report these

[6]Values are derived from a combination of literature and extrapolation from existing noise maps for other regions (e.g. Scottish Noise Mapping Initiative conducted by AECOM and Hamilton & McGregor). Other sources included: FICN (1992), IPPC (2002), Jones (2005), FEHRL (2006a,b), www.nonoise.org, and www.chchearing.org/noise-center.

results disaggregated by land use type (e.g. the number or proportion of forest, open space, low density residential land use cells with intense noise pollution values).

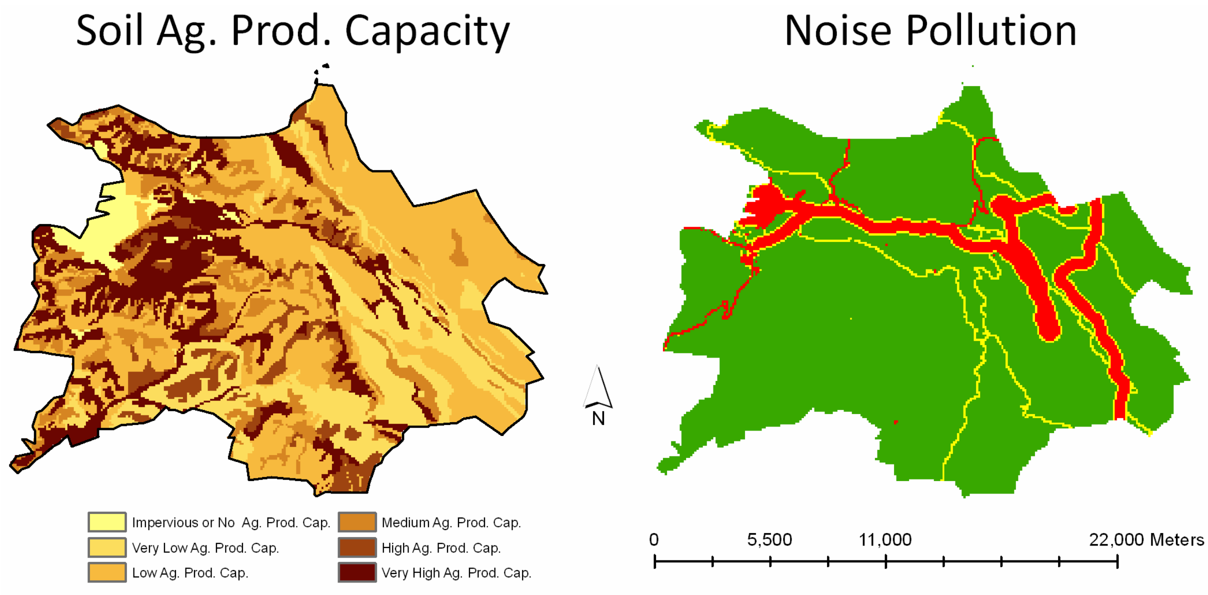

Figure 2: Map of soil agricultural productive capacity (left) and noise pollution (right) for the Municipality of Koper, Slovenia. Both datasets are based on year 2000 data. Noise pollution map is based on the methodology outlined above in Section 2.6.2.

2.6.3 Well-Being and Quality of Life

We measure the well-being of the residential population based on their derived overall and partial utility values for each computational experiment. Utility values provide a way to derive a numeric rank-ordering of preferences for location attributes that are difficult represent along a single dimension (e.g. monetary value, Marshall and Oliver 1995). While classical economic theory would restrict the comparison of utility values, our normalisation procedure has assigned equal impact weighting to each individual, which when combined with all RHAs using the same utility function provide a common base from which we can measure aggregate utility. Aggregate utility calculations are sometimes referred to as Utilitarian measurements because the interest lies in evaluating the betterment of the entire society rather than a single individual (Dolan 2001). We apply the same approach to the partial utilities that agent's acquire for each of the four location attributes (e.g. access to green space, Table 2). Looking at the partial utilities provides a method for measuring how the different location attributes affect agent utility levels under different model experiments.

For all soil quality, noise pollution, and well-being impact measurements we test for significant differences among experiments using student-T test based on the average and standard deviation of 30 model runs (for each experiment). We constrict our number of runs to thirty because it provides enough room for variable results without manipulating the significance of results by our ability to create a large number of runs, which would render all results significant.

2.7 Verification and Validation

The necessary level of verification and validation required to produce a useful land-use model continues to be a topic of discussion within the land-use modelling community and specifically among those using agent-based approaches. Differences in the terms (e.g. Oreskes 1994 versus Parker et al. 2003), approaches, and in model design and purpose (e.g. explanatory or exploratory versus descriptive or predictive, Parker et al. 2003) conflate the issue. However, an agreement rests on the fact that high accurate model prediction using mechanistic approaches is significantly difficult. Calibration of a non-linear model with heterogeneous agents interacting in a heterogeneous environment using training data and then comparing results against a second set of site specific data under the assumptions of stationarity in represented processes, stochasticity in human decision-making and natural events, and system simplification to represent a manageable collection of drivers of change stack the odds against validation success. Brown et al. (2005) illustrate this difficulty by showing that replication of a model run using the same model (and different random seed) is very difficult and incorporating additional processes to match location patterns run the risk of overfitting the model to the data. Therefore, because our goal is not prediction, and instead is to better understand the impacts of various processes driving land-use and land-cover change in the Municipality of Koper, we selected the above experiments to aid evaluation of model behaviour.

As various subsections of the materials and methods section point out, we calibrate a large number of the structural processes and agent characteristics using empirical data derived from social survey and spatial analyses. While a number of challenges to empirically inform ABMs of land-use change exist (Janssen and Ostrom 2006, Robinson et al. 2007), the degree to which an empirically informed model may be further calibrated in the traditional sense (i.e. parameter alteration to improve the goodness-of-fit of the model to data) also presents a number of problems since parameter values may correspond to structural components. In response to these issues of accreditation, we calibrate the model by specifying the overall quantity of transitions to residential, commercial, industrial, and forest land uses. We then define the experiments that follow to verify model behaviour and better understand the interaction among the incorporated processes while simultaneously estimating the impacts of development on the productive capacity of soils, noise pollution, human well-being, and land-use and land-cover patterns.

3. Computational Experiments

3.1. The Null Model

We first provide a model with randomly defined land-use and land-cover change processes – a null model. The null model provides a baseline to which we can determine if our model outcomes are statistically different from random. We first used land-use and land-cover transitions from year 2000 to 2007 to define a land-use and land-cover change transition matrix. We removed 3.7% of the land-use and land-cover transitions that were 1) highly-unlikely and due to digitizing, aerial photograph interpretation, or spatial alignment errors, or 2) involved processes not represented in our model (e.g. land expansion into the Adriatic Sea). The altered transitions, which account for 0.5% of the total study area, were assumed to remain in their original land use or land cover (Table 6). Using the resultant transition matrix, we probabilistically implemented those transitions using a Markov Chain approach (e.g. Costanza 1989).

Table 6: Transition matrix amongst land-use types from year 2000 to 2007 in the Municipality of Koper

	Industrial	Commercial	Agriculture	Open Space	Forest	Wetland	Water	Mineral Extraction	Low Density Residential	High Density Residential	Town Center	Sum Yr. 2000
Industrial	337	0	0	0	0	0	0	0	1	0	2	340
Commercial	0	158	0	0	0	0	0	0	5	2	1	166
Agriculture	40	8	10509	69	3060	0	0	0	74	1	0	13761
Open Space	34	22	55	801	73	0	0	0	120	12	1	1118
Forest	1	0	413	8	14267	0	0	0	22	0	0	14711
Wetland	0	0	0	0	0	120	0	0	0	0	0	120
Water	0	0	0	0	0	0	63	0	0	0	0	63
Mineral Extraction	0	0	0	0	0	0	0	59	0	0	0	59
Low Density Residential	0	0	0	0	0	0	0	0	614	1	0	615
High Density Residential	0	0	0	0	0	0	0	0	0	122	0	122
Town Center	0	0	0	0	0	0	0	0	0	0	35	35
Sum Yr. 2007	412	188	10977	878	17400	120	63	59	836	138	39	31110

3.2. Business As Usual

Using the rates of change to industrial, commercial, high and low density residential, town centre, and forest from the transition matrix (Table 6), we run the model forward from year 2000 to 2030 with all agents enabled. Unlike the Null Model experiment, in this business as usual (BAU) experiment all agent behaviours are activated and actions by one agent influence the actions of others. Also, because the transition rate from open space and agriculture to forest is very high (Table 6), we implement forest transitions in proportion to the amount of existing area of open space and agriculture. We run the model under BAU until 2030 and evaluate output metrics associated with soil loss, noise pollution, and human well-being. The BAU experiment offers a secondary reference point, in addition to the Null Model, to which we can compare the other computational experiments.

3.3. Residential Development Constraints

We evaluate the individual impacts of different residential development agents by constraining development to one of the three types (i.e. low density, high density, or town centre). Because residential household capacity differs among residential land-use types there will be an obvious difference in the amount of area consumed by residential land uses. However, because different land-use transitions to residential may cause other developer and transition agents to substitute sub-optimal locations, the interaction among land uses will cause variable impacts with the inclusion or exclusion of different residential development types.

3.4. Commercial and Industrial Development Constraints

Similar to the previous experiment, we evaluate the individual impacts of commercial and industrial development in this experiment. We alter their behaviours by implementing a constrained cellular-automata approach to location decisions, which force commercial and industrial developments to take place adjacent or as close as possible to existing commercial and industrial development, respectively. This experiment is indicative of enforced planning controls and it provides one approach for how the model may be extended to evaluate the outcomes of different planning scenarios.

4. Results

4.1. The Null Model

The null model provided a measure of randomness to which we could compare other model outcomes against. Of the 138 mean measurements associated with agricultural productive soils, noise levels, well-being, and land-cover proportions, only 26 or 19% of the measurements were not significantly different from the null model (Table 7). Of the 26 measurements that did not differ significantly from the Null model (p=0.01), 10 were associated with the quantity of area in industrial and commercial land use, which was fixed and therefore not expected to differ. We conclude from these results that our model is significantly different from random.

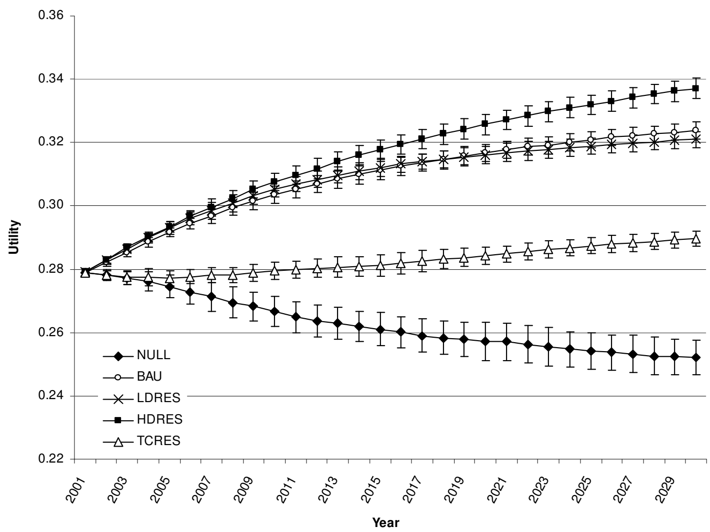

Figure 3: Average aggregate utility for the Null Model (NULL), Business As Usual (BAU), Low Density Residential only (LDRES), High Density Residential only (HDRES), and Town Centre (TCRES) computational experiments. Clustered Commercial Development (CCD) and Clustered Industrial Development (CID) experiments are not plotted, but follow the BAU utility curve closely.

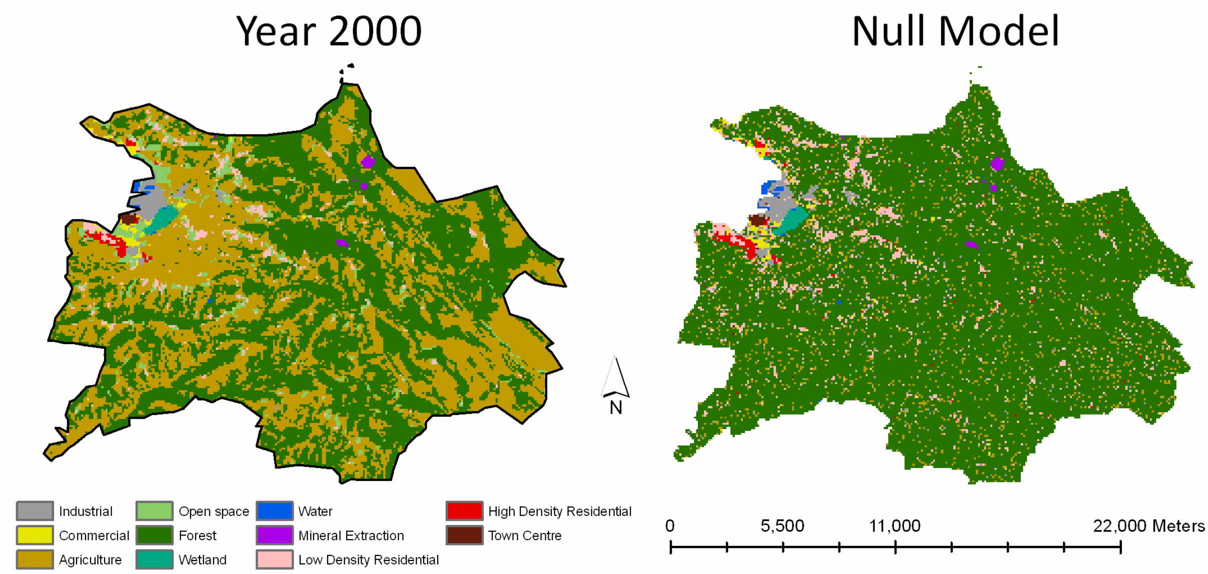

Figure 4: Map of original land use and land cover for year 2000 Municipality of Koper, Slovenia (left). Typical land-use and land-cover map for 2030 from the ABM parameterised for the Null Model experiment (right).

Based on the random allocation of land-use transitions, 14% of the very high, 5% of the high, and 9% of the medium productive capacity soils were lost. Cumulatively these soil losses account for 15% of the medium-to-very high productive soils (Table 7). Area affected by high noise increased by 278 ha, which is a 9% increase above year 2000 levels. The average total aggregate utility decreased from year 2000 levels as a result of decrease in access to shops and public transport (Figure 3). These changes can be expected due to the random allocation of land-use transitions to locations far from urban amenities like public transportation and commercial areas (Figure 4). However, because 1) the random allocation of residential land uses throughout the municipality, and 2) the high rate of transitions from agriculture and open space to forest, household green space partial-utility increased as did their partial-utility associated with noise levels. It is interesting to note that despite the random allocation of land-use transitions, which were constrained to occur from specific land-use types, the resulting metrics fell within the bounds of the other experiments.

4.2. Business As Usual (BAU)

The business as usual case involves the ABM running with all agents acting in the absence of any behavioural or landscape constraints based on the transitions shown in Table 6. In this experiment development of impervious surfaces consume a large area of high agricultural productive soil. Area in very high agricultural productive soil is disproportionately affected by urban expansion as 48% of new impervious surfaces occur on this soil designation (Table 7). The trajectory of loss of very high agricultural productive soil is linear over the duration of the BAU scenario. Expanding to those soils classified as medium, high, and very high agricultural productive capacity we find that 70% of new impervious areas consume these soil classifications.

A 7.6% increase in high noise area is due to the expansion of commercial and industrial land uses across the landscape. The corresponding creation and diffusion of noise from commercial and industrial developments increase the area classified as high noise by 227 ha (on average) over the 30 years of the model run (Table 7). Noise levels between 65 and 75 dB decreased on average (69 ha) over model runs, but the majority of high noise expansion was into areas less than 65 dB (156 ha), which suggests greater expansion of industrial and commercial areas in locations non-adjacent to existing land uses of the same type.

The areas affected by high and medium noise have a significant influence on the well-being of the agent population, since the partial utilities related to noise conditions are larger than the other three factors (i.e. access to shops, greenspace, and public transport). Due in part to the doubling of population over thirty years and their settlement in less dense and less noisy peri-urban areas, the utility of new residents increase the average utility of the population (Figure 3, Figure 5, Table 7). Settlement in peri-urban areas also increases access to green space and pulls average aggregate utility upward (Figure 3). Access to public transport and shops maintain a relatively constant average partial utility.

4.3. Low Density Residential Only (LDRO)

By constraining new residential development to low density housing we increase the total area developed in order to satisfy the same housing demand (i.e. holding population constant, Figure 4). The result is a further reduction in very high agricultural productive capacity beyond that obtained from the BAU experiment. A loss of very high agricultural productive soil of 19% occurs which composes 47% of 2373 ha of new impervious surface. The impact of low density residential development on medium, high, and very high agricultural productive capacity soils collectively is a 13% loss illustrating that the patterns of low density residential has a significant impact on agricultural productive capacity and policies reducing development density will cause a greater loss of those soils.

Noise pollution remains an issue in this experiment but the effects of development on high noise do not significantly differ to results from the BAU experiment. Also similar to the BAU scenario, partial utility derived from low noise levels provides the largest partial utility (0.1209 on average, Table 7). In this experiment residential households have the highest average aggregate utility from low noise levels compared to the other experiments. Residents also receive a positive increase in utility over the BAU experiment from their location relative to shops (0.0625) since shops are forced to move into the urban periphery due to constraints imposed by the location of available land. The result is a positive feedback as commercial developments act as attractors for some residential developments, which collectively infill or consume the greenspace sought by residential agents. Therefore, while partial utilities from greenspace increase initially they level off toward the end of the 30 year simulation run (Figure 6). Associated with the amount of sprawl are decreases in access to public transportation and the corresponding average partial-utility (0.0459). The collective result is an increase in the aggregate average utility (Figure 3), which levels off slightly below the aggregate utility attained from the BAU scenario.

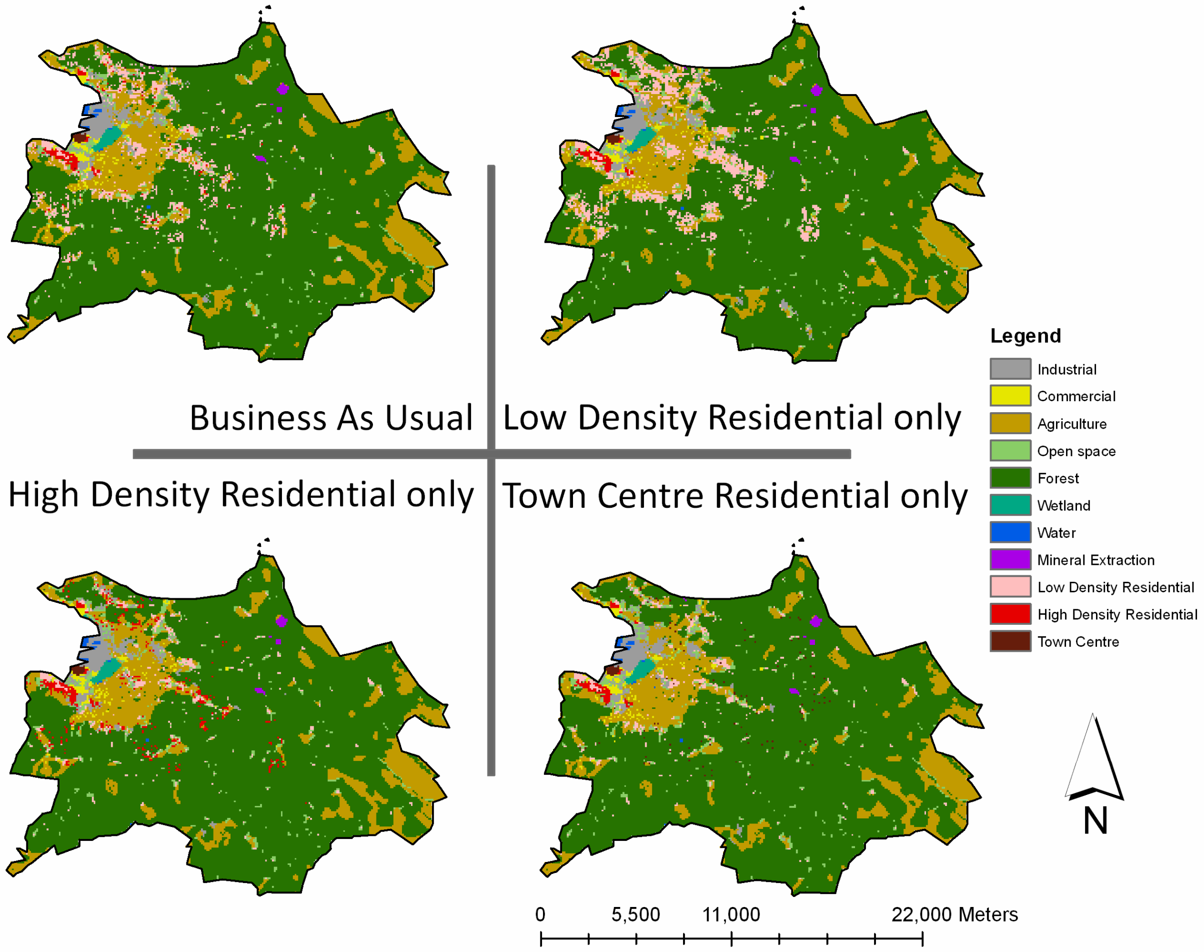

Figure 5: Maps of typical land use and land cover for the Municipality of Koper, Slovenia, in 2030 from the ABM.

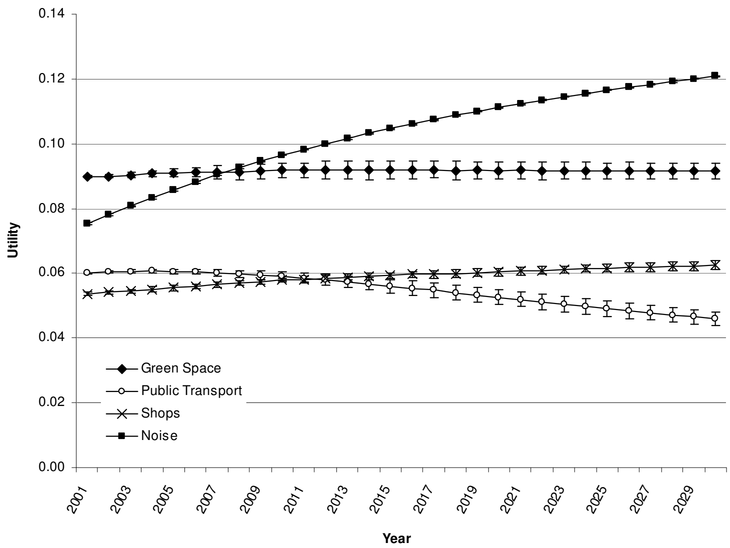

Figure 6: Partial-utilities for Low Density Residential experiment.

Table 7: Computational experiment outputs of average area and standard deviation (ha) for agricultural production capacity and noise levels at 2030. Also shown is average and standard deviation values for partial utilities and total utility for the entire population. Non-highlighted cells are significantly different from the Null experiment (p = 0.01, df = 30, t-test). All cells in regular type-face are significantly different from the Business As Usual (BAU) experiment (p = 0.01, df = 30, t-test).

		Original Values	Computational Experiments: Null		Business as Usual		Low Density Residential Only		High Density Residential Only		Town Centre Residential Only		Clustered Commercial		Clustered Industrial	
	Paper Section		4.1		4.2		4.3		4.4		4.5		4.6		4.7	
		Year 2000	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Agricultural Production Capability (ha)	Very High	5988	5127.33	20.09	5046.70	14.29	4866.83	17.43	5286.03	14.14	5419.33	12.96	5067.86	19.90	5104.00	25.32
	High	2113	*2003.00*	10.23	1995.90	11.75	1965.50	8.16	2051.90	5.09	2070.50	6.50	*2001.69*	7.49	*1990.50*	12.17
	Medium	3681	3344.23	10.43	3374.60	12.87	3323.67	12.00	3467.23	11.69	3494.97	9.29	*3381.59*	11.34	*3368.30*	14.55
	Low	12941	12486.70	21.96	12469.60	19.99	12315.20	21.72	12691.20	10.75	12750.17	9.86	12455.72	12.84	12429.00	28.66
	Very Low	5344	5188.57	10.85	5308.30	10.89	*5302.57*	5.44	5327.80	2.94	5329.73	2.69	*5311.83*	9.77	5276.60	19.11
	None	565	243.63	6.93	252.77	8.57	*249.83*	8.18	259.57	6.16	264.53	7.36	226.07	7.59	276.73	6.43
	Impervious	713	2716.53	36.01	2662.13	9.17	3086.40	13.51	2026.27	8.78	1780.77	6.37	*2665.24*	10.23	*2664.87*	10.47
Noise (ha)	>= 75 dB	2998	3276.27	19.36	3225.10	8.42	*3224.23*	10.75	3231.33	8.08	3231.43	7.42	*3225.62*	10.33	3239.70	11.12
	>65 and <75 dB	3294	3241.10	6.17	3225.23	8.05	*3223.93*	8.22	*3228.23*	6.79	3232.90	6.08	*3228.66*	8.61	3253.07	8.26
	<65 dB	24818	*24592.63*	17.17	24659.67	11.61	24661.83	12.15	24650.43	8.80	*24645.67*	8.56	*24655.72*	10.44	24617.23	13.31
Well-being (parital utilities)	Greenspace	0.0897	*0.0933*	0.0027	0.0930	0.0023	*0.0916*	0.0024	0.0952	0.0021	0.0961	0.0017	*0.0922*	0.0019	*0.0944*	0.0023
	Public Transport	0.0597	0.0326	0.0017	0.0568	0.0018	0.0459	0.0022	0.0600	0.0026	0.0773	0.0006	*0.0566*	0.0018	*0.0578*	0.0035
	Shops	0.0536	0.0419	0.0020	0.0543	0.0023	0.0625	0.0014	0.0618	0.0013	-0.0037	0.0016	*0.0556*	0.0024	*0.0526*	0.0034
	Noise	0.0750	0.0843	0.0036	0.1198	0.0005	0.1209	0.0002	0.1201	0.0002	*0.1201*	0.0007	*0.1199*	0.0007	*0.1200*	0.0007
	Total	0.2780	0.2521	0.0053	0.3238	0.0026	0.3209	0.0025	0.3371	0.0031	0.2898	0.0024	*0.3243*	0.0026	*0.3248*	0.0029
Land Use and Land Cover	Industrial	340	*643.87*	19.02	647.27	2.95	*647.13*	2.91	*647.90*	2.98	*648.27*	2.48	*647.86*	2.77	*648.43*	2.16
	Commercial	166	*260.33*	12.35	257.40	9.03	*251.27*	13.59	*258.07*	5.54	*259.57*	1.91	*258.79*	5.05	*258.03*	8.53
	Agriculture	13761	1820.83	142.08	4873.33	15.02	4756.40	13.40	5015.17	12.52	5080.90	8.78	4907.45	11.80	4847.70	14.67
	Open space	1118	78.73	34.95	830.37	13.10	785.00	14.32	895.47	11.16	937.70	9.75	799.76	12.34	920.47	12.07
	Forest	14711	26251.90	135.45	22502.17	19.48	22240.20	20.48	22931.10	11.69	23068.63	7.98	*22495.55*	15.07	22434.97	23.01
	Low Density Residential	615	1571.67	26.10	1516.93	4.69	2031.00	1.72	578.07	4.01	607.23	2.43	*1518.31*	5.75	*1517.00*	4.22
	High Density Residential	122	*188.07*	7.84	189.50	2.46	122.00	0.00	507.23	1.77	118.63	1.75	*188.76*	3.03	*189.17*	2.94
	Town Centre	35	*52.60*	3.68	51.03	2.57	35.00	0.00	35.00	0.00	147.07	2.61	*51.52*	2.59	*52.23*	3.29

4.4. High Density Residential Only (HDRO)

In this experiment we constrained residential development to include only high-density residential development land uses. The high level of housing density (11 households) relative to that in low density residential (40, town centre density = 136) reduced the amount of area in residential development relative to the Low Density Residential Only and BAU experiments (Figure 5). The effect of increased development density on area in very high agricultural productive capability was positive relative to the BAU and Low Density Residential scenarios. Overall average loss of very-high, high, and medium agricultural productive soils was 701, 61, and 213 ha, respectively. These results represent a loss of 12% of the area in very high agricultural productive soils and an aggregate loss of 8% of the area classified as medium, high, and very high. Collectively, developed land on these three soil classifications account for 74% of the 1313 ha of new impervious surface in this experiment.

The spread of noise pollution was higher in the HDRO experiment when compared to the BAU and LDRO experiments. Area classified as low (<65 dB) and medium (i.e. >65 dB and < 75 dB) noise pollution decreased by 172 ha and 66 ha, respectively. Area classified as high noise increased by 233 ha or 8%. The degree of variance was also slightly higher indicating that high density residential land uses were offsetting locations preferred by industrial and commercial developers.

The average aggregate utility achieved through this experiment was the highest of all experiments, which was due in part to a large increase in access to green space (Figure 3). The lack of available locations within Koper City forced new developments to the periphery that mixed well with green space and did not experience the infilling that occurred from the LDRO experiment. Consequently, utility from noise also positively affected the aggregate as new residents moved to quieter neighbourhoods and pulled average partial-utility from noise upward. Partial-utility from access to shops also increased with time as commercial developer-agents share similar location preferences (e.g. nearness to open space, agricultural lands, and existing shops) to those of residential agents. The only partial-utility factor to experience a decrease over time was access to public transportation; however, the decrease was much less than that achieved by the BAU and Low Density Residential scenarios.

4.5. Town Centre Residential Only (TCRO)

By restricting residential development to only town centre land use, we impose strong population density constraints limiting the area of residential development and impervious surface (Figure 5). In this experiment only 11% of the very high agricultural productive capacity soils are lost and 19% of the area collectively classified as very high, high, and medium agricultural productive soils are lost (Table 7). The total amount of impervious surface is lowest in this scenario (i.e. 1928 ha) compared to all other scenarios, of which 74% of the 1216 ha of new impervious surface consumes these beneficial agricultural soils.

Despite the agricultural benefits resulting from a reduction in the loss of highly productive agricultural soils, the results from imposing very high density constraints on residential development significantly reduced household well-being compared to all experiments (except the Null Model, Figure 3, Table 7). While the overall well-being (i.e. aggregate average utility) did increase slightly over the duration of a model run, the final level after 30 years was the lowest of all experiments. Unpacking the aggregate average utility shows that the agent population experienced an increase in average partial utility for noise at a level corresponding to other experiments. Similarly, partial utility for access to green space increased steadily over the duration of runs due to the lack of infilling over time because of the high density of the developments and their creation in proximity to land use classes defined as green space. Likewise, an increase in aggregate average partial utility for access to public transportation occurred as town centre developments located near existing nodes and commercial areas, with their corresponding transportation nodes, were free to develop in adjacent or near locations.

An interesting outcome is the significant reduction in partial-utility values for access to shops over the duration of a model run. The decrease in aggregate average utility acquired from access to shops is due to a non-linear utility distribution for preferences near shops. Instead, the majority of agents (and survey respondents) have lower preferences for having access to many shops and no access to shops and have a higher preference for having access to only a few shops. Because each town centre land use development is a mixed development and agents are not able to sort themselves amongst different development types, the overall result is a significantly lower partial utility for access to shops compared to all other experiments.

4.6. Clustered Commercial Development (CCD)

In this experiment we altered commercial developer-agent behaviour to locate adjacent to existing commercial land uses (Figure 7). While the impact of forcing adjacent commercial development was slightly positive for the preservation of very high agricultural productive soils (loss of 16%) relative to the BAU (loss of 17%) and LDRO (loss of 19%) experiments, the impact was worse than that attained by the HDRO and TCRO experiments that suffered a loss of 13% and 11%, respectively. The collective outcome on productive capacity soils was then an overall decrease of 1116 ha (12%), which composed 68% of the newly created impervious surface. Despite the forced clustering of commercial location behaviour, the impact on soil productive capacity was only slightly less than that achieved from the BAU experiment.

The clustering of commercial development resulted in the smallest area affected by high noise levels; however, the difference was only minor relative to the BAU and other experiments. Similarly, household well-being results for this experiment followed closely those from the BAU experiment. Aggregate average utility is only slightly higher than BAU over the 30 years, but not significantly different (Table 7). The lack of significant difference in the aggregate and partial utilities for the different location factors between the BAU experiment and clustering commercial development has no significant influence on human well-being under our model assumptions.

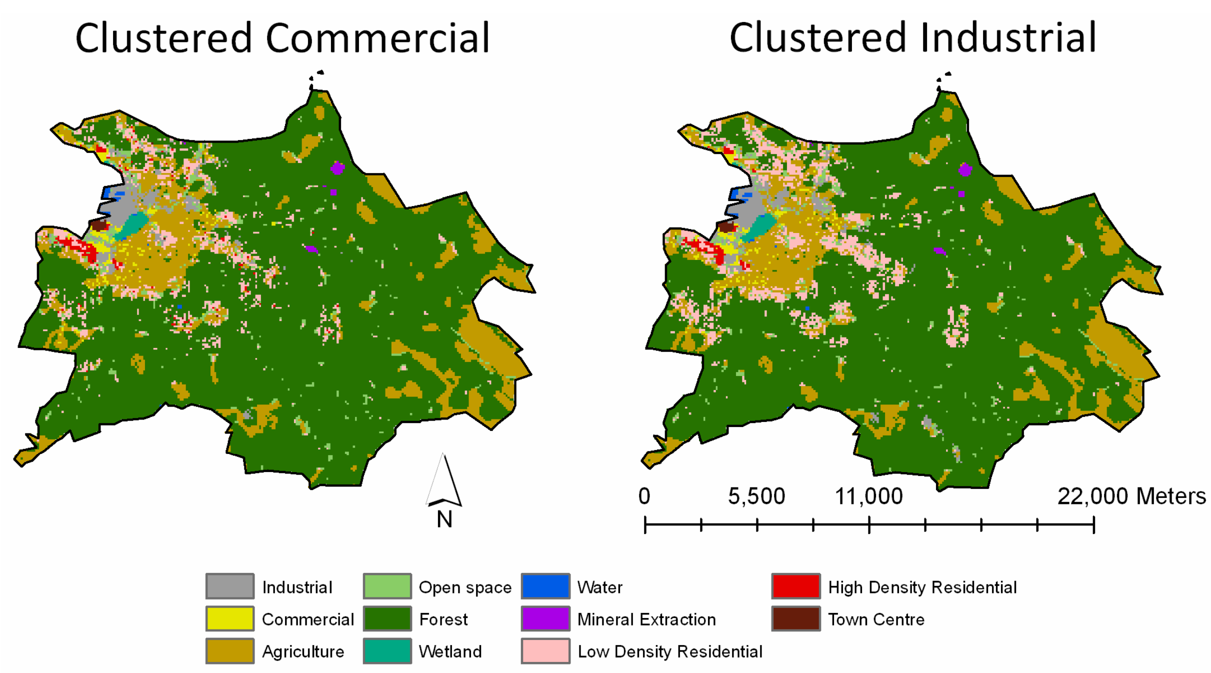

Figure 7: Maps of typical land use and land cover for the Municipality of Koper, Slovenia, in 2030 from the ABM clustered commercial and industrial experiments.

4.7. Clustered Industrial Development

When we forced industrial land uses to cluster adjacent to existing industrial land uses, similar to the previous experiment (Section 4.6) – with all else being equal to the BAU experiment, the outcome was a 2% reduction in very high productive agricultural soils (on average) compared to BAU (Table 7). The area affected by high noise (12% above year 2000 levels) was the highest (362 ha) of all experiments; however, the area affected by noise levels > 65 dB and < 75 dB was the lowest found within all experiments. The impact on human well-being remained relatively constant, with respect to noise, as the partial utility for noise was only slightly higher than that attained over the BAU experiment.

Overall, clustered industrial development improved aggregate well-being. Small increases in access to green space, public transport, and improvements in noise pollution allowed this experiment to achieve the second highest aggregate utility – HDRO produced the highest aggregate utility of all experiments.

5. Discussion

5.1. Constrained Residential Development Experiments

We evaluated the impacts of different residential development mechanisms on the provision of highly productive agricultural soils, noise pollution levels, and human well-being. While the computational experiments are designed to explore and evaluate these model mechanisms, parameterisation of the model to the Municipality of Koper provides insight into the development trends and types of policies or planning efforts that may decrease the impact of land change dynamics on both the human and natural systems.

The general outcome from increasing development density was a decrease in the loss of very agricultural productive capacity soils (Table 7). If the municipality was to implement policies or planning constraints that directly or indirectly cause a reduction in development density they are likely to increase the loss of very high, high, and medium agricultural productive capacity soils beyond current trends (i.e. BAU). Conversely, policies that increase residential development density will further preserve these soil types in the face of increasing population pressures and urban expansion.

In contrast, increasing development density caused an increase in area classified as high noise (Table 7). However, the increased area affected by high noise did not have a corresponding decrease in the partial-utility values attained by residential households. In this case, increased noise pollution was affecting natural areas more than those resided at by residential households. The contrasting effects of changing develop density on the availability of high quality soils and amount of noise pollution illustrate the trade-offs associated with mitigating impacts on both the human and natural system jointly.

Providing general conclusions and insight into the role of development density is incredibly difficult as the location attributes providing utility have different effects for different households. However, typically noise acts as a repellent, and green space and public transport act as attractors. Access to shops is none linear, such that most households provide some medium level of access rather than being in close or far proximity to many or few shops. In general, aggregate utility increases with low and high density developments, respectively, above the BAU scenario, but falls far below BAU values for the TCDO experiment.

5.2. Clustered Commercial and Industrial Development Experiments

Constraining commercial and industrial development to cluster around existing locations of the same land-use type had little effect on our impact measurements relative to the BAU experiment. There was not significant different in human well-being relative to the BAU as aggregate and partial utilities did not significantly differ between the clustered commercial and industrial experiments with the BAU experiment. The clustered commercial and industrial experiments differed from each other with respect to their impact on the amount of area affected by noise pollution. The clustered commercial experiment did not significantly differ from the BAU, but the clustered industrial experiment produced the highest amount of area affected by high noise of all the experiments (~15 ha more than the BAU). Industrial location behaviour had a much more prominent affect on noise pollution levels than commercial and residential-based experiments (Table 7).

It was also interesting to find the clustered experiments significantly reduced the loss of very-high agricultural productive capacity soils, relative to the BAU experiment. This outcome is due to the underlying spatial pattern of soil types (Figure 2). The area immediately adjacent to the year 2000 industrial areas to the northeast of the town centre is classified as low agricultural productive capacity soil. Similarly, some of the adjacent lands along the perimeter of the year 2000 urban area is classified as lower than very high agricultural productive capacity soils. Therefore the clustering behaviour has a lower impact initially as it consumes these areas, but penetrates the agricultural lowlands to the southeast of the city more with time.

5.3. Case study limitations

The development and application of an ABM to a specific-case study with little data faces tradeoffs between simplicity of design and complexity of representation. Case-study partners and constituents are interested in realism and prediction. In contrast, scientists are interested in knowledge gains by producing novel methodological, technical, and knowledge-based developments. Our presented (initial) model version strikes a balance between these objectives by providing a working model that suggests that low density residential development is the most influential driver threatening highly productive agricultural land. The model provides a useful framework leading toward an iterative modelling process within which data collection and research efforts can be focused on identifying and describing the mechanisms governing the behaviour of the statistical agents in the model. Acquisition of these process-based data and information would permit further interaction among agents and allow agents to respond to thresholds and feedbacks in the system. Drawing on the knowledge gains in the presented work, these data and computational extensions would expand the types of questions that could be asked with the presented model.

One approach to systematically extend the presented research is to develop a series of hybrid agents that are based on both statistical and process-based information. For example, it would be useful to alter the town centre developer agent location decisions to include both logistic regression information, which in the presented work focuses on neighbourhood counts and distances to land uses and land covers, and process-interaction derived information (e.g. residential desire surface, Section 2.2). The difficulty is then placed on calibration of the weighting of the logistic component against the process component to achieve appropriate location allocation of town centre land use in the study region. This example and many other extensions can be developed and compared against this first version to improve our representation of land-use dynamics in the Koper region.

While additional data and understanding of actors driving land-use and land-cover change in the Municipality of Koper can aid our ability to represent those actors in the model and understand their impact on human and natural systems, it is worth noting that data provide a fixed representation of a system that could produce an infinite number of outcomes. Extrapolating data, as was done under the assumptions of temporal and spatial stationarity, in the BAU experiment led to unlikely population and transition to forest trajectories. Because the future is uncertain and stochastic events in both natural and human systems can lead to unforeseen outcomes, the creation of coherent, plausible, and internally consistent scenarios can be used to evaluate the impacts of potential futures (MA 2005, Rounsevell et al. 2006). Future research into the development of scenarios would not only provide useful narratives for constricting the parameter space of the model, but when used amongst multiple case-study locations or research projects they may provide an approach to unify research efforts by providing a baseline for comparison.

5.4. Coupled Natural-Human Systems of Land Change

In addition to illustrating the integrative capabilities of ABM to combine statistical and process models and different types of data to represent the coupled natural-human land-use system, we also showed an approach to represent a new endogenous impact from the human system by creating a noise pollution model. We represented the dynamic nature of noise pollution through the new emission of noise by commercial and industrial developments and its interaction with existing and neighbouring noise emitting land uses, land covers, and landscape features. Although our representation of noise pollution is relatively simple, it can provide additional insight into the spatial distribution of other pollutants (e.g. air pollution is highly correlated to noise citation). Efforts to further the representation of noise should include dampening and redirecting mechanisms provided by land-use and land-cover types and other landscape features. Including these additional mechanisms would allow our noise model to be comparable to the noise maps generated for the EU Noise Directive 2000/14/EC. To the best of our knowledge, noise pollution modelling has not been incorporated into other agent-based land-use models and the methods outlined in this paper provide one approach to its representation for others.

On a request basis from our Koper constituents, we focused our analysis of ecological impacts on the loss of soils with medium, high, and very high agricultural productive capacity. Due in part to the nominal nature of the acquired soil data, we focused on the loss of soil types to impervious surface resulting from residential and business expansion. Acquisition of quantitative soil quality variables (e.g. depth, texture, soil organic matter) would permit the incorporation of degradation and enhancement processes (e.g. erosion or fertilization) that would allow soil quality to transition among soil types.

6. Conclusions

The impetus for the presented research was to evaluate the impact of future land-use changes on the provision of productive agricultural soils, the extent of noise pollution, and human well-being in the Municipality of Koper, Slovenia. In evaluating the impact of land-use change on these observables we achieved a number of conceptual and technical advances to modelling land-use change with an agent-based model. In the interest of empirically informing agent behaviours, we present one approach to link a conjoint analysis to agent decision-making. While a number of others have reviewed methods to empirically inform ABMs (Janssen and Ostrom 2006, Robinson et al. 2007), this approach has yet been adopted within land-change science research. The presented work also models settlement density gradients, which are rarely incorporated in LUCC models but have been shown to significantly influence ecosystem function (e.g. carbon storage, Hutyra et al. 2010). Lastly, a number of sub-models are used to represent the impact-response cycle within the human system by representing such processes as the creation and avoidance of noise pollution.

The presented work is part of the broader PLUREL project (www.plurel.net) that seeks to evaluate the effects of land use dynamics at the peri-urban fringe on ecosystem and human health. Although we calibrate the presented ABM and describe results exclusive to the Koper, Slovenia, case study, the model and analyses presented within this paper may be used as a template for ease of application to the other six PLUREL case study locations (i.e. Haaglanden, Netherland; Liepzig, Germany; Manchester, United Kingdom; Montpellier, France; Warsaw, Poland; and Hang Zhou, China). Additionally, we've shown that any location with social-survey data on agent preferences for settlement location and land-use and land-cover data for two dates can be used to conduct land-use change experiments. ABM provides a flexible and useful tool for integrating a range of types of data, models, and impact metrics. As the community moves forward to continue to include additional natural and human processes in the coupled natural-human land-use systems, we will improve our estimation of the impact of and feedbacks of these systems on each other.

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Modelling land-use dynamics to evaluate the impact of SRES scenarios on human and natural systems: Urban form and future impacts

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1 Introduction

Predicting long-term future impacts of land-use dynamics on human and natural systems (with certainty) remains an elusive goal. Human behaviour often cannot be modelled in a linear manner Tversky and Kahneman (1974) and social norms and group behaviour can lead to abrupt changes in human behaviour (citation). In addition, "future shocks" such as technological advances, economic collapses and shifts in weather patterns are had to predict. Therefore, extrapolating current trends to model future outcomes over medium-to-long time scales overemphasises the likelihood of a single possible future where an infinite potential exists. One approach to both expand our recognition of the role of potential futures and reduce their number to an understandable and manageable set is by developing plausible, coherent, and internally consistent scenarios (MEA, 2005).

Scenario are firsts composed of storylines, which are the qualitative descriptions that justify the quantitative components of a scenario. The purpose of a storyline may be to explore a range of possible outcomes, to define a desired outcome and a set of processes required to achieve it (i.e. a normative approach), or an extrapolation of current trends Rounsevell and Metzger (2010). The benefit of developing sound storylines is that they provide a medium for discussing and communicating relevant system drivers; they can provide a common set of data that may facilitate comparative analyses; once created, they provide a disciplined structure for evaluating other system uncertainties (i.e. creating new storylines); and they can provide an anchor point to aid cross-cutting scale, disciplinary boundaries, and methodological approaches. For example, a simple storyline consisting of increasing gross domestic product, stable population, and decreasing fuel prices could be interpreted as having a range of impacts on consumption behaviour, tourism, commute times, and urban sprawl.

In the first half of this deliverable, we described the creation of an agent based model for the case study area. In this paper we use an agent-based modelling (ABM) approach to estimate a number of natural and human impacts resulting from land-use dynamics guided by four scenarios. The scenarios are downscaled from the IPCC SRES (2000) as part of the PLUREL project (www.plurel.net), and adapted to include a series of possible and plausible shocks. The shocks represent rapid and important changes in particular sectors or themes, such as "hyper-tech" or "extreme water" (see Section 3). We seek to evaluate the effects of four scenarios (A1, A2, B1, B2) on LUCC and their subsequent impact on noise pollution, loss of highly productive agricultural lands, and human well-being, among other factors. The use of scenarios allows us to integrate other results from the PLUREL project (e.g. Boitier et al., 2008; Skirbekk et al., 2007; Rickebusch, 2010), by using the outputs of European scale models to set boundary conditions for a regional agent-based model.

In the following, we present a brief description of the model in Section 2, and how this model is set up to work within boundary conditions from European scale models. Section 3 summarises scenario storylines, and provides a set of qualitative scenarios for modelling, followed by a quantitative interpretation as model parameters. In Section 4 we report results on the relationship between scenarios, urban form, and impact indicators. In Section

5 we discuss the results with respect to the hypotheses above, and point out directions for future research.

2 Model Description

The ABM is designed to represent processes of peri-urban land-use change from 2000 to 2030 using annual time-steps. Composed of three types of agents (i.e. residents, residential developers, and non-residential developers) the model explicitly includes processes associated with the interaction between residential decision making and peri-urban development in a heterogeneous landscape composed of eleven different land-use/cover (LUC) types. In order to work coherently within a European context, we use outputs from the RUG model (Rickebusch, 2010) as boundary conditions for the ABM, which then carries out a local downscaling of the RUG results.

We model three land use/land cover change (LUCC) processes which are implemented through rates of land use creation (used by land use developer agents). The first process is residential development, including town centre (TC), high density (HD) and low density (LD) residential housing. The second LUCC process is Commercial and Industrial development. The third process is agricultural land abandonment, which leads to an increase forest and open spaces.

2.1 Summary of model implementation

The model consists of three components: an agent-based residential model, a set of developer agents, and a land use model. The discussion following is a brief overview. Further details on processes and the method of informing the model from data are found in the first half of this deliverable.

The land use model is a parameterised for use with the Harpha Sea data set, mentioned in the first half of this deliverable. We have aggregated the Harpha LUC classes into 11 land use/land cover classes appropriate to our modelling. There three different types of residential land use, commercial and industial areas, agriculture, and a range of non-managed land uses - see Table 1. Each cell within the landscape has a single LUC class, but it may additionally have an unlimited number of *features*. These represent sub-cell features of interest, which would otherwise be difficult to model accurately - see Table 2 for a list. The land use model calculates a set of *attributes*, based on the land uses and features on the landscape. These include distances (e.g. to shops or public transport) and acoustic noise. The noise model is based on noise emissions levels for features and land uses and simple noise transmission model. Finally, each land use may have a residential capacity, which allows a number of resident agents to live there. As previously described in the first part of the deliverable, these capacities were derived from existing populations and land use maps using multiple regression.

Table 1: Land use types used in the model.

Name	Residential Capacity	Urban	Can be developed	Provides	Noise value (dB)
Industrial		Y	Y		75
Commercial		Y	Y	Shops	60
Agriculture		N	Y		
OpenSpace		N	Y	Green space	
Forest		N	Y	Green space	
Wetland		N	N	Green space	
Water		N	N	Green space	
MineralExtraction		N	N		
LowDensityResidential	11	Y	Y		
HighDensityResidential	40	Y	Y		
TownCentre	136	Y	Y	Shops, Public transport	

Table 2: Features used in the model.

Name	Provides	Noise Level (dB)
Bus Stop	Public transport	
Motorway		80
Main Road		75
Regional Road		70
Railway		98
Coast		
Port		75

The residential submodel consists of a population of individual residents, and some mechanisms for managing the population at an aggregate level. When a resident enters the model, it attempts to find a cell with spare capacity which maximises its utility. Residents have several *issues* which affect their assessment of a particular place to live. The residents' assessment of any given cell is a linear sum of their scores for the different *issues*. The score for each issue is calculated by segmenting the value of an underlying *attribute* into a human perceptual value, which can then be assigned a partial utility (see Figure 1). Conjoint analysis conducted by the OPENspace Research Centre at the Edinburgh College of Art (Bell et al., 2010) was used to obtain partial utility values for a set of actual residents from the region. We use four issues from the conjoint analysis in this model: access to public transport, access to green space, shops in the neighbourhood and noise levels. Finally, a *resident desire surface* is calculated, which indicates the average utility which a sample of the population gives to each cell on the map. This is calculated for non-residential cells as well, to provide a complete surface which can be used to drive future development. Population change is carried out at an aggregate level using a population change rate, as no demographics are present in this version of the model. If the rate is positive, a number of new agents are added. If the rate is negative, a number of randomly selected agents are removed. If there is no free residential capacity for new agents, they are forced to leave the mode.

The developer model consists of several agents, one for each land use class which is to be created. Each developer has a rate of creation, and each step it attempts to allocate the given number of cells if its land use. The location of new cells is constrained as to what source land uses can be used — for example, residential areas cannot be turned into industrial or commercial. For all the available cells, an evaluation is carried out to find the most favoured development locations. In the case of industrial and commercial developers, evaluation is based on a multiple regression analysis of previous development locations. Residential developers evaluate locations based on the resident desire surface discussed previously. The process of land abandonment is modelled as a forest "developer" which converts agricultural land into forest, again using a multiple regression analysis to determine locations. The rate for this transition is proportional to the amount of existing agricultural land. Finally, development happens in a prescribed order, to reflect prioritisation of high value land uses. The order is: town centre, high density residental, low density residential, commercial, industrial and forest.

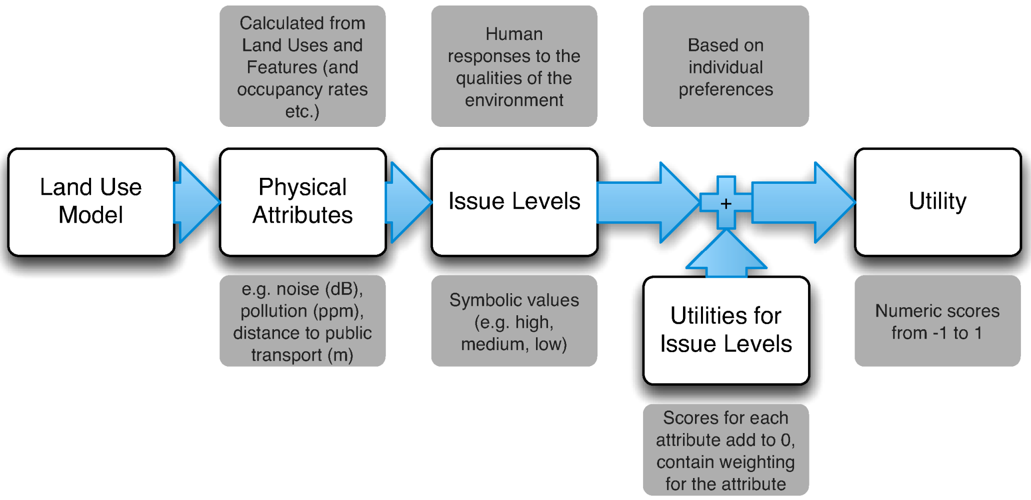

Figure 1: Block diagram of residential utility calculation

Within each timestep, the following processes are carried out (see Figure 2):

- The resident model updates the perceptual values for all of the issues that the residents work with. Next, the residential population grows or shrinks.
- for each of the LUCC processes given above, in priority order, the relevant developer attempts to convert a number of cells to the given land use. All of these changes are submitted to the Land Use model, but no change is carried out within the timestep.
- once both the submodels have finished their behaviour for the timestep, the Land Use Model applies all the requested change to the landscape, and recalculates the physical attributes based on the new landscape, and the residential desire surface.

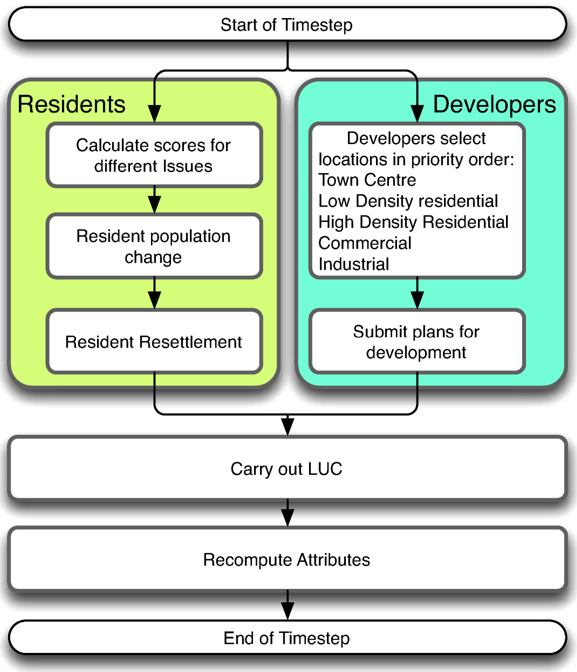

Figure 2: Operations within each timestep

2.2 Role of RUG

The RUG model (Rickebusch, 2010) is a European scale model of land use change, and will be used to provide a boundary condition for the agent based model. RUG calculates the amount of Artificial Surfaces (AS), i.e. built-up areas including residential and industrial/commercial land uses, by a linear regression model linking the proportion of artificial surfaces per NUTS2 region to the population and gross domestic product (GDP) per captita. Additional factors are codes for the country and the urban type (large city, small city or rural region). The regression model is then applied to the projected values of population (Skirbekk et al., 2007; KC et al., 2010) and GDP per capita (Boitier et al., 2008) for 2015 and 2025. Table 3 displays the total increase in Artificial Surfaces from 2000 to 2025 in km^2 as calculated by the RUG estimates for the Koper area. Note that the total proportion of Artificial Surfaces predicted by RUG can exeed 100%, which is interpreted as high pressure on the land and leads to building in the 3rd dimension. In the results reported here we neglect the 3rd dimension since we are only interested in the total area covered by AS.

Table 3: Increase in areas with Artificial Surfaces for 2025 as calculated by the RUG model.

scenario/AS	2000	2025 area	diff AS area	% increase
A1	10.323	19.70906	9.38606	0.91
A2	10.323	6.98335	6.66035	0.65
B1	10.323	14.11525	3.79225	0.37
B2	10.323	15.27109	4.94809	0.48

2.3 Local Downscaling: Coupling with RUG outputs

Local downscaling is the process of regional adaptation of scenario storylines. We carry out this downscaling by setting up boundary conditions derived from scenario modelling at the European scale, and using the ABM to spatially and thematically disaggregate these inputs. We first define a list of relevant input parameters to our model and then qualitatively interpret future trends using the PLUREL scenario settings (see Table 4). We then create quantitative model inputs using a combination of values from RUG, regional expert judgement, published literature, and deviation and/or continuation of current trends (as described in Section 3.1).

In order for the ABM to run, the following parameters must be given:

- Rates of population change. These can be positive or negative, and should represent aggregate change in population once all demographic processes have been taken into account (birth, death, immigration etc.).
- Rates of creation for the 5 artificial surface land uses, which will be used be the relevant Developers when deciding how many cells to convert each year.
- A rate of agricultural land abandonment/forest clearing, representing the transitions between agriculture and forested land.
- A set of resident utilities, representing the preferences of the agents as they are making their location decisions. This is the output from the conjoint analysis (Bell et al., 2010).

These model inputs can be divided into those which are constant across scenarios; those which are constructed using scenario analysis methods; and those which can be derived as constraints from given changes in population and artificial surface area. We make the following links to construct boundary conditions:

- Population growth is driven directly from (Skirbekk et al., 2007) instead of continuing current trends. This gives a richer representation of future changes, as it is based on European simulations with multiple variables.
- Where previously we used a transition matrix to set up LUC rates, now we use the output from the RUG model as a boundary; this gives a total amount of artificial surface, which must be thematically disaggregated for the ABM.

Two constraints follow from this: 1) A given amount of AS must be created 2) enough residential capacity must be created to house the population if it grows.

To meet the second constraint, we work from the idea that residential development is closely matched to population change, so we try to match housing supply perfectly with demand. This assumption has some issues, which are discussed in Section

5. One of the key factors in urban development (as discussed in the first half of this deliverable) is the choice of different types of housing; we model this as a ratio between our three residential land uses (low density, high density and town centre). The housing ratio is a parameter which can be manipulated to match the different development types given in the scenarios. The housing ratio can also be combined with the capacities of each land use type to calculate the amount of each land use which must be created:

$$C_{avg} = \sum_{u \in LU} c_u w_u$$

$$\Delta_{Res} = \frac{\Delta_{Pop}}{C_{avg}}$$

$$\Delta_u = \Delta_{Res} w_u$$

(where C_{avg} is the average capacity of the given land use mix, c_u is the residential capacity of a land use, w_u is the proportion of that land use and LU is the set of residential land uses; Δ_{Pop} is the population change, Δ_{Res} is the change in residential land area and Δ_u is the change of a single land use). Note that these capacities were derived using regression analysis in the first half of this deliverable.

In a similar manner, the scenarios can be used to examine the ratio of commercial to industrial development (r_c). Since the total amount of artificial surfaces is given as a constraint (Δ_{AS}), it is now possible to calculate the amounts of commercial and industrial development which should occur:

$$\Delta_{com} = r_c(\Delta_{AS} - \Delta_{Res})$$

$$\Delta_{ind} = (1 - r_c)(\Delta_{AS} - \Delta_{Res})$$

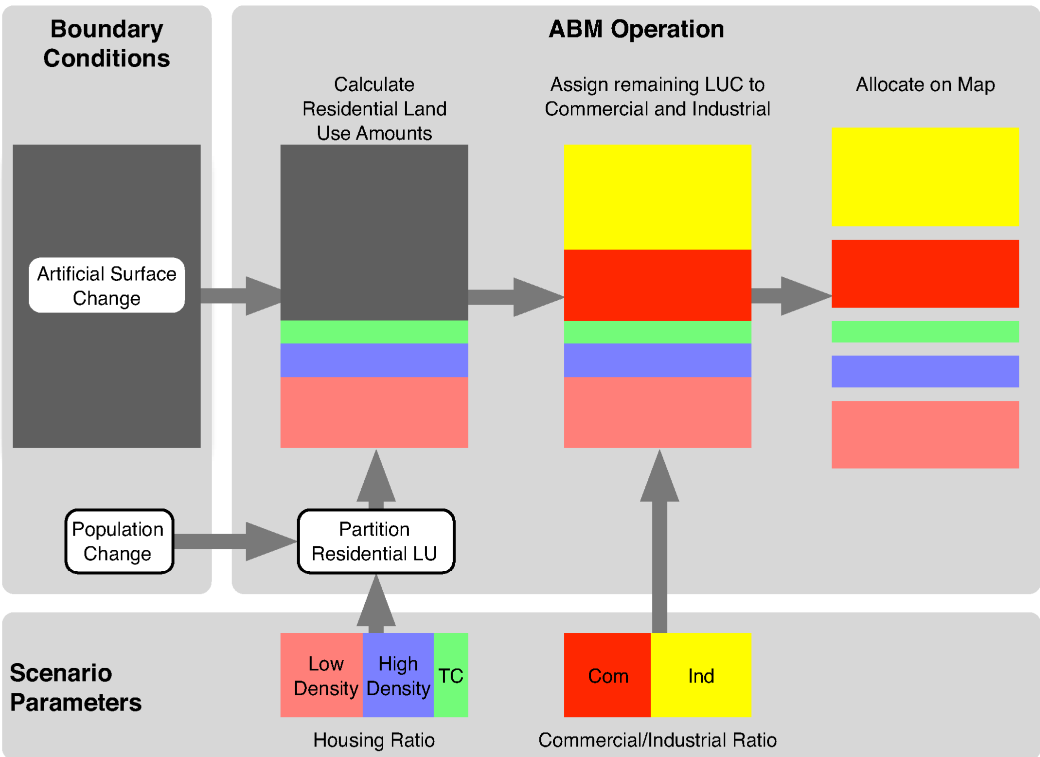

Figure 3: Use of boundary conditions and land use ratios to determine land use change rates for the ABM

The final land use change process — conversion of land between forest and agriculture — is modelled according to the assumption that change is occuring due to land abandonment, and is proportional to the remaining area of farmland.

3 Scenarios

Scenarios are commonly used to investigate different socio-economic development pathways for uncertain futures, (e.g. Allen and Lu, 2003; Fontaine et al., 2010; Grubler et al., 2006; O'Neill, 2005;

Reginster and Rounsevell, 2006; Rounsevell et al., 2006), amongst many others. Qualitative storylines can be translated into quantitative outcomes (projections) using (computational) models. This process involves the interpretation of model input parameters using expert judgement, deviation and/or continuation of current trends or the results of other scenario studies (Rounsevell and Metzger, 2010). This process often involves downscaling global storylines to a regional level.

Here, we describe current trends in the Koper region, and then derive narrative storylines which are appropriate for the case study region and the drivers and processes which are being modelled.

3.1 Current trends

The following main trends can be observed in the case study area according to a recent analysis of the Koper region (Perpar, 2009):

- Slovenia has highest GDP per capita of eight former communist nations who joined the EU in 2004.
- Population in Koper increased by 66% since 1961. This is mainly due to immigration.
- One of the main challenges in the Koper region is to balance economic growth in commercial/industrial and tourism with cultural heritage in small farming.
- Koper is Slovenia's outlet to the sea with an narrow coastal belt, where there is high competition between the port area, tourist facilities, residential housing.
- The urbanisation of the costal belt together with the increasing deployment opportunities led to migration from the rural hinterland to the coast. The direct consequences include deserted villages, poor maintenance of infrastructure, abandonment of farming and agricultural land, and decay of the cultural landscape.
- In the 1980s the migration process reversed, due mainly to more private housing possibilities and improved infrastructure.
- Furthermore, the urbanisation of the costal belt also threatens high quality agricultural land.
- Industrial activities include the petroleum industry, shipbuilding, car production, canning industry, fine mechanics, production of chemical and food industry. The share of employment in services is constantly increasing.
- More than 1/3 of the municipality is under Natura 2000.

Furthermore, we observe the following changes in land use and land cover types by comparing Harpha Sea LUC maps from 2000 and 2007. There is a considerable increase in build-up surfaces: Industrial 28%, Commercial 9%, Low Density Residential 23%, High Density Residential 7%, and Town Center 11%; whereas the following types decrease: Agriculture 21%, Open space 18%.

3.2 SRES Scenario Storylines adapted to peri-urban LUCC

The IPCC-SRES scenario framework (Nakicenovic and Swart, 2000) has become a standard for scenario studies within environmental change assessment (see, for example O'Neill, 2005; Reginster and Rounsevell, 2006; Rounsevell et al., 2006; O'Neill and Sanderson, 2008; Fontaine et al., 2010).

These scenarios were then adapted by the PLUREL project (Ravetz, 2008) to reflect urbanisation processes, spatial policy, urban-regional governance, and other important drivers that act at various spatial scales. The PLUREL scenarios also include a a series of possible and plausible "shocks", i.e. rapid and important changes in particular sectors or themes, such as 'hyper-tech' or 'extreme water'. Furthermore, PLUREL applies the global SRES scenarios to the EU space, up to the years 2025 and 2050. Please see Ravetz (2008) for further details.

The adapted scenarios are shown as a 2x2 framework (Figure 4): the vertical axis is differentiates between globalised, top-down dynamics and localised, bottom-up dynamics. The horizontal axis focuses on public and collective values versus private enterprise values.

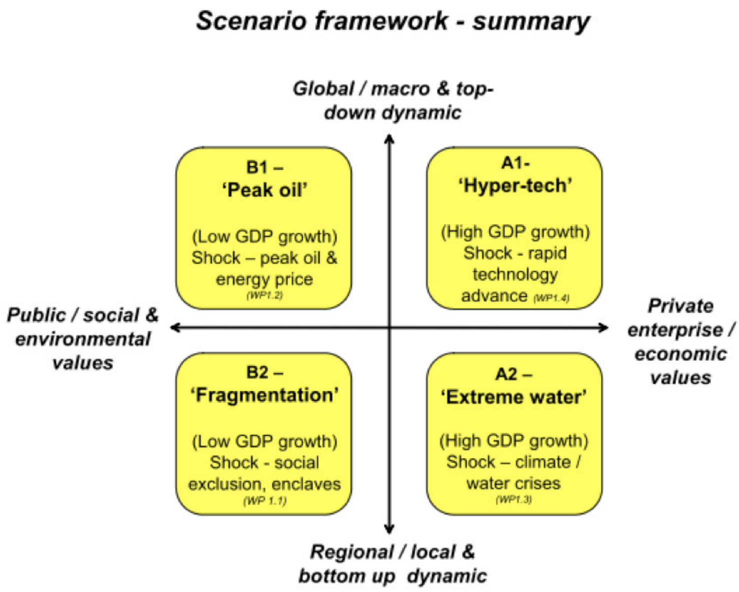

Figure 4: PLUREL scenario framework

In the following we repeat the PLUREL storylines following Ravetz (2008), and give our interpretations of these storylines for the Koper case study region. This is supplemented by some selected parameters from the summary table in Ravetz (2008) to give qualitative values for model parameters (these both shown in Table 4). The model parameters we are interested in setting are the proportions of residential land use types; the ratio of commercial to industrial development; and the rate of land abandonment and subsequent conversion to forest.

Table 4: PLUREL scenario settings and qualitative interpretations for model variables

	A1	A2	B1	B2
	Plurel scenario settings			
general urbanisation trend	counter-urbanisation	sub-urbanisation	compact city urbanisation	Peri-urbanisation
rural--urban migration	rural society	urban	urban	Peri-urban
peri-urban / rural population growth	high	low	very low	medium
Industrial production	high-medium	medium	medium	medium
Commercial production	high	medium	high	medium
Trade growth	High-medium	Medium	Medium	Low
Agricultural Land Use growth	medium	medium	low	high
Forestry Land Use growth	medium	medium	high	low
	Qualitative interpretations			
Proportion TC	- -	+	+ +	- -
Proportion HD	- -	+ +	+	- -
Proportion LD	+ +	-	- -	+ +
Commercial/Industrial Ratio	+ +	-	No change	-
Land abandonment rate	-	-	No change	- -

3.2.1 A1 - Hyper-Tech

The 'hyper-tech' scenario describes a future world of rapid economic growth, global population that peaks in mid-century, and the rapid spread of more efficient technologies. Information and communications technology (ICT), nano-technology and bio-technology, transform lifestyles and working patterns. For peri-urban areas in Europe, this scenario is likely to see small "polycentric" towns and cities become even more popular. New transport technologies lead to more rapid journeys and the expansion of

> the commuting distances around towns and cities. New ICT enables people who prefer country life to work from home or the neighbourhood centre, and this leads to peri-urbanisation and “metropolization” of rural areas on a massive scale. (Ravetz, 2008)

Koper’s status as a port combined with globalisation and the region’s strong economic position keeps imports cheap and accessible. Improved transport allows commuters to relocate outside the cities where quality of life features are higher. We interpret this to mean a move to exclusively low density residential development. We interpret this as a shift from industry towards a more commercial orientation in non-residential development. Finally, despite a continued increase in prosperity and GDP, the current high rate of land abandonment is slowed, although not stopped.

3.2.2 A2 - Extreme Water

> The ’extreme water’ scenario shows a more heterogeneous world of self reliance, local enterprise and preservation of local identities. While population growth and technology innovation are slower, the effects of climate change come on more rapidly than expected. Peri-urban areas are strongly affected; affluent yet vulnerable city-regions such as London or the Dutch Randstad spend huge sums of money on defence and adaptation strategies. Population growth due to climate-induced migration puts more pressure on urban infrastructure and services. (Ravetz, 2008)

In this scenario, a lot of urban growth, concentrated towards the suburbs of Koper can be expected. Local government resources must be spent maintaining the coastal areas in response to rising sea levels. This leads to a pressure on urban land. High denstity residential can be constructed by individual developers without much central coordination, but is economically favourable as urban land becomes scarce. We interpret this to mean an increase in the building rate of high density residential, and to some extent town centre. The reduced levels of globalisation require the region to be more self sufficient, so non-urban development swings towards industrial rather than commercial. We speculate that increasing issues with relying on the import of food leads to a reduction in the rate of land abandonment.

3.2.3 B1 - Peak Oil

> The ’peak oil’ scenario describes a future of environmental and social consciousness — a global approach to sustainable development, involving governments, businesses, media and households. To achieve this some sacrifices have to be made, such as individual liberties and local enterprise. For peri-urban areas, rising energy prices have an enormous effect on location choices as transport costs limit commuting distances. Although tele-working is encouraged, most people attempt to return to larger cities and towns, and many of the more remote rural areas decline.(Ravetz, 2008)

The trend towards a sustainable, globalised structure calls for more compact urban development. The influence of local government and increasing difficulty with communting combine to slow the current rate of migration back to the hinterlands. We interpret this as an increase in the level of town centre, and to some extent high density residential development. The ratio between commercial and industrial development is unchanged from its current value as many factors are in tension; for example, the lowered focus on local enterprise balances the lower GDP (and hence consumer spending). The continued decline of the rural areas leaves the current rate of land abandonment unabated, leading to massive reforesation.

3.2.4 B2 - Fragmentation

> Although local community cohesion is high, across Europe there is a fragmentation of society, in terms of age, ethnicity and international distrust. The ethnic division of cities is driven by the increased in-migration of the working-age population from outside and within the EU. Cities become more dispersed as younger migrants dominate city centres and older natives populate the outskirts and enclaves outside the cities, so that peri-urban areas become "peri-society" areas. New development slows down but much existing urban form redistributes its population and activities (Ravetz, 2008).

Under the Fragmentation scenario, the complex residential trends combine to give a shift towards peri-urban growth. The current rate of rural migration is increased as the urban population ages and attempts to move back towards their roots in the countryside. We interpret this as a reduced rate of development, and what development there is being in the form of low density rural residences. We assume that the current urban housing stock being sufficient to house the immigrant population. The non-urban development shifts strongly towards industry, as the emphasis is on self sufficiency without trade, and abandonment of consumer values. Finally, the need for increased agricultural production combined with the trend towards more extensive methods halts the rate of land abandonment.

3.2.5 Quantitative scenario variables

We now derive numerical values for the describe qualitative scenarios using expert knowledge:

- For the residential land use proportions, there are only two degrees of freedom in the parameters (as they are constrained to sum to 1). Also, the proportions of HD and TC are small compared to the total. We hence altered the HD and TC proportions, and assigned the rest to LD. We map the qualitative trends from the scenario table (Ravetz, 2008) as follows:
  - parameters marked "+ +" are taken as a 100% increase,
  - parameters marked "+" are a 50% increase,
  - parameters marked "No change" stay the same,
  - parameters marked "-" are decreased to 50% of their previous value,
  - parameters marked "- -" are decreased to 0.
- The commercial/industrial ratio is adjusted in a similar manner, as the proportion of commercial development is small. The remainder is left as industrial.
- Finallly, we assume that the current land abandonment trend constitutes and extreme, and will generally decline in future scenarios. As such, only negative or "no change" values were chosen, with "-" representing a halving in the rate of land abandonment, and "- -" representing cessation land abandonment.

It should be noted that these are relatively extreme values, to ensure that the scenarios cover a reasonable range of future outcomes. Furthermore, extreme scenario exercises serve to increase the understanding of how the different types of artificial surface created lead to different urban forms, especially since the amount of change is constrained by external inputs.

3.3 Scenario Parameters and Future Projections

3.3.1 Artificial Surfaces

The actual model parameters which will be used are the rates of creation of different land uses. These are a combination of:

- the amount of artificial surface growth output from RUG, and the population change which underlies this,
- the scenario variables derived above,
- and the current baseline values.

In the following, we take the quantity of urban land use change as predicted by RUG model (Rickebusch, 2010) for the four scenarios and thematically disaggregate them according to historic transition rates, scenarios and population growth.

As discussed in Section 2.3, we first calculate the amount of residential land use needed according to the mix of residential land use types and the population change. Next, we allocate the remaining artificial surface area specified by RUG to commercial and industrial development. Finally, we assume that agricultural land is abandoned at a rate dependent on the scenario.

As outlined previously (see Figure 3), we then disaggregate the predicted amount of AS into our residential housing types and industrial/commercial land use, according to historic transition rates, scenarios and population growth. We first calculate the amount of residential capacity needed according to the predicted population increase (Skirbekk et al., 2007; KC et al., 2010). We then compute the total amount of residential area needed according to the proportions of different types of residential housing (TC, HD, LD) and their respective capacities (see Section 2).

We then divide the rest of the AS between industrial and commercial land use cells according to their scenario-specific ratios, see Table 4. The area which is not covered by AS is transformed from agriculture into forest according to the agriculture abandonment rate. Since we are modelling the abandonment of farming (rather than the explicit creation of forest), this is modelled as a proportion of the existing agriculture which is removed, rather than a constant rate of transition.

Table 5: Table showing the derivation of rates of change within the model. Input values are shown in purple, scenario values in orange and derived values in green.

	A1	A2	B1	B2	Baseline
Artificial Surface Growth (cells/y)	37.5442	26.6414	15.169	19.7924	
Proportion TC	0	0.036	0.048	0	0.024
Proportion HD	0	0.066	0.0495	0	0.033
Proportion LD	1	0.898	0.9025	1	0.943
Com/Ind Ratio	0.292	0.073	0.146	0.073	0.146
Abandonment Rate	0.01415	0.01415	0.0283	0.01415	0.0283
Average Residential Capacity	11	17.414	18.4355	11	
	Population Change (Households over 5 years)				
2000-2005	537.6923	537.6923	537.6923	537.6923	
2005-2010	192.9759	192.9759	192.9759	192.9759	
2010-2015	95.1652	0	-95.1652	0	
2015-2020	0	0	-95.1652	0	
2020-2025	95.1652	-95.1652	-190.3303	-95.1652	
2025-2030	0	-95.1652	-190.3303	-95.1652	
	Land Use Rates (2000-2005)				
Residential surface growth rate	9.776223636	6.17540255	5.833227198	9.776223636	
TC Rate	0	0.222314492	0.279994905	0	
HD Rate	0	0.407576568	0.288744746	0	
LD Rate	9.776223636	5.54551149	5.264487546	9.776223636	
Com Rate	8.108249098	1.494017814	1.363022829	0.731180875	
Ind Rate	19.65972727	18.97197964	7.972749973	9.284995489	
	Land Use Rates (2005-2010)				
Residential surface growth rate	3.508652727	2.216330539	2.093524993	3.508652727	
TC Rate	0	0.079787899	0.1004892	0	
HD Rate	0	0.146277816	0.103629487	0	
LD Rate	3.508652727	1.990264824	1.889406306	3.508652727	
Com Rate	9.938379804	1.783030071	1.909019351	1.188713551	
Ind Rate	24.09716747	22.64203939	11.16645566	15.09503372	
	Land Use Rates (2010-2015)				
Residential surface growth rate	1.730276364	0	0	0	
TC Rate	0	0	0	0	
HD Rate	0	0	0	0	
LD Rate	1.730276364	0	0	0	
Com Rate	10.4576657	1.9448222	2.214674	1.4448452	
Ind Rate	25.35625793	24.6965778	12.954326	18.3475548	
	Land Use Rates (2015-2020)				
Residential surface growth rate	0	0	0	0	
TC Rate	0	0	0	0	
HD Rate	0	0	0	0	
LD Rate	0	0	0	0	
Com Rate	10.9629064	1.9448222	2.214674	1.4448452	
Ind Rate	26.5812936	24.6965778	12.954326	18.3475548	
	Land Use Rates (2020-2025)				
Residential surface growth rate	1.730276364	0	0	0	
TC Rate	0	0	0	0	
HD Rate	0	0	0	0	
LD Rate	1.730276364	0	0	0	
Com Rate	10.4576657	1.9448222	2.214674	1.4448452	
Ind Rate	25.35625793	24.6965778	12.954326	18.3475548	
	Land Use Rates (2025-2030)				
Residential surface growth rate	0	0	0	0	
TC Rate	0	0	0	0	
HD Rate	0	0	0	0	
LD Rate	0	0	0	0	
Com Rate	10.9629064	1.9448222	2.214674	1.4448452	
Ind Rate	26.5812936	24.6965778	12.954326	18.3475548	

4 Results

In this section we present the results of running the agent based model for the scenarios. Since the model is stochastic, a range of presentations are necessary to explore the range of outputs produced. We therefore present values drawn from 30 runs of each of the sceanarios.

Unless otherwise indicated, maps show the averaged behaviour over all runs, and graphs show summary statistics from all runs.

In the following, we first analyse the amounts and locations of land use change. Next, we examine the loss of good quality agricultural land, and the factors which cause it. We then use invariant and variant regions as a tool to examine the spatial uncertainty in model outputs. Finally, we explore quality of life issues in the modelled population.

4.1 Land Use Change

Figure 8 shows a side by side comparison of land use in 2030 under the four scenarios. Each map represents a single run from a stochastic model. It is therefore important not to place too much emphasis on any particular map. However, these example maps serve to give a useful visual indication of the patterns which emerge. Visually, the most striking change in the maps is in the forest area. This is backed up by Figure 5, which shows the amount of each land use for each scenario, using the same vertical scale for each graph. Mapping the land use changes into the same scale clearly shows the dominance of changes in the agricultural and forest areas.

Figure 9 reduces the map to only locations where land use change has occurred. While still being dominated by changes in the agricultural and forest areas (except in scenario B2), Figure 9 also highlights different patterns of development of industrial and commercial areas. Clustering of commercial and industrial areas can mainly be observed around the port region and sub-urban areas due to a gravity effect of the existing areas. This is supported by Figure 10 which accentuates the transitions to artificial surfaces, i.e. transitions to Commercial, Industrial and Residential areas.

Finally, Figure 6 shows changes in each of the main land uses over time, along with aggregated artificial surface area and residential area. This gives a general understanding of the temporal dynamics of land use change in the simulation. Figure 6 shows the change rate of each land use towards the total amount of artificial surface created. For Scenario A1, Commercial development constitutes most of the non-residential development due to the predicted increase in GDP. Whereas in scenarios A2, B1, B2 most of the artificial surfaces are created by Industrial development, whereas the share of Commercial development is less.

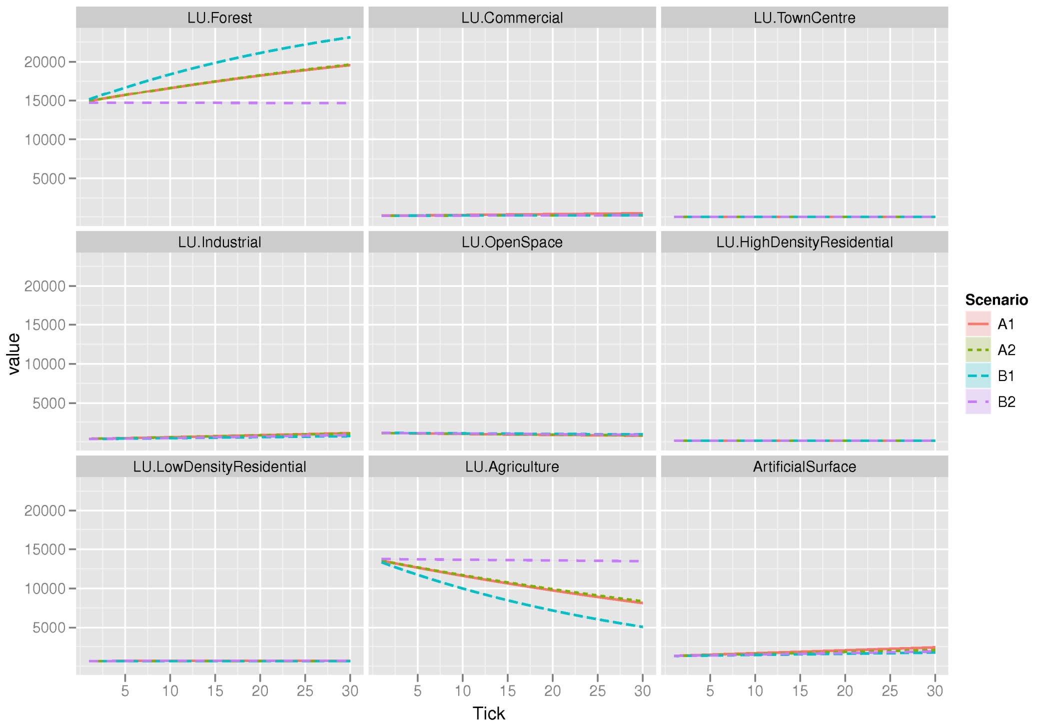

Figure 5: Areas of each land use under each scenario, with fixed y-axis for comparison

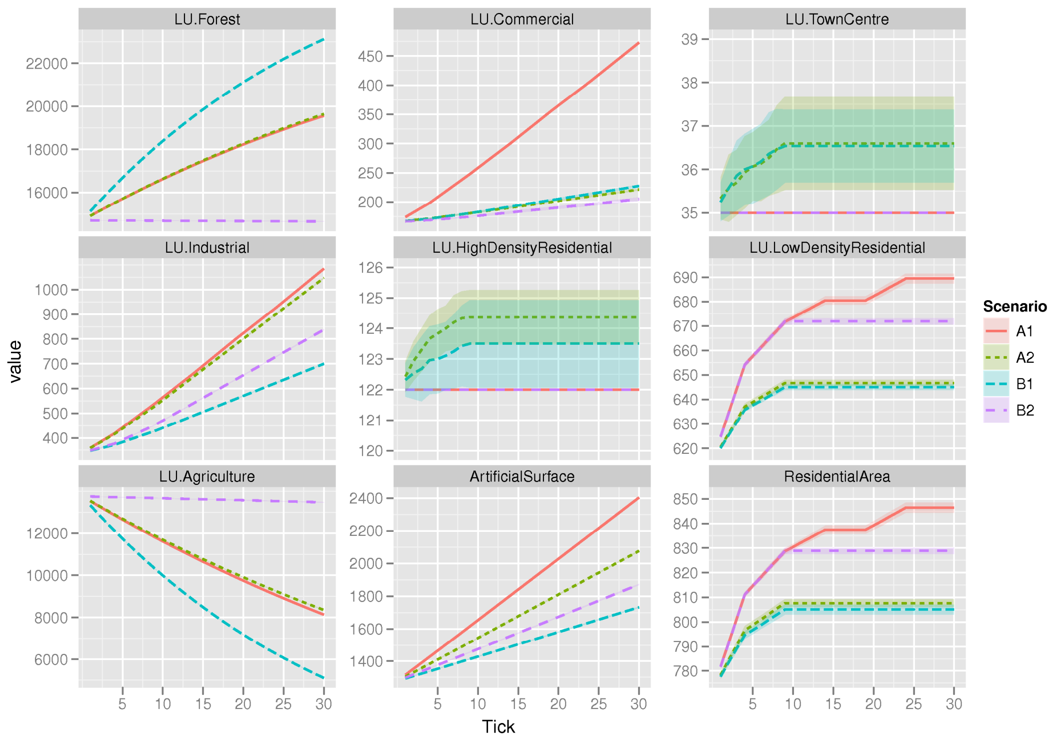

Figure 6: Area of land use classes under each scenario, averaged over 30 runs. Lines represent the mean of each scenario, and the shaded areas delimit the standard deviation

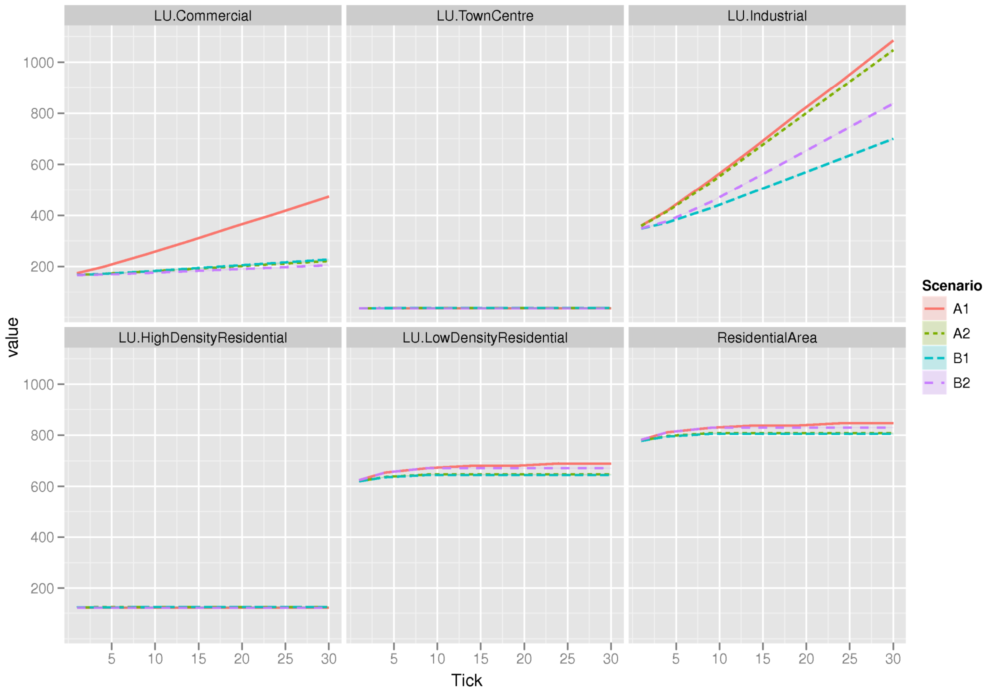

Figure 7: Areas of artificial surfaces under each scenario, broken down by category and an aggregate residential area measurement

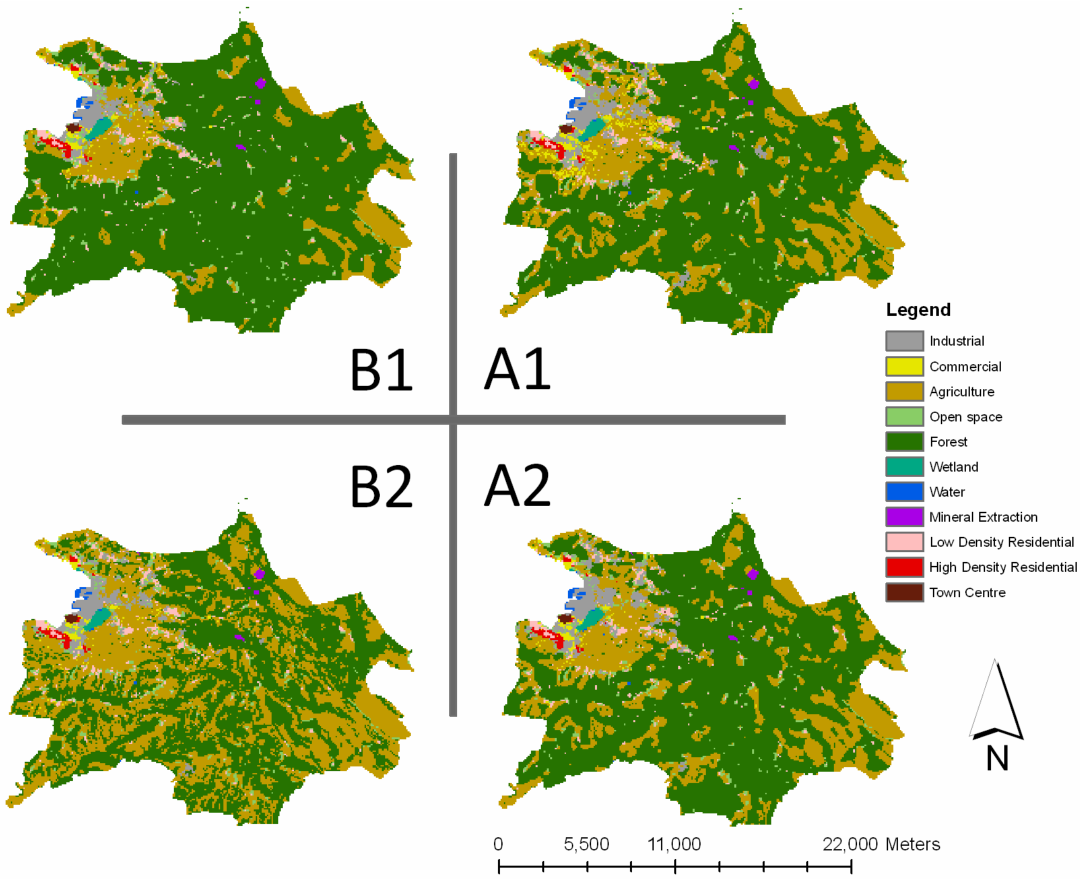

Figure 8: Final land use under different scenarios

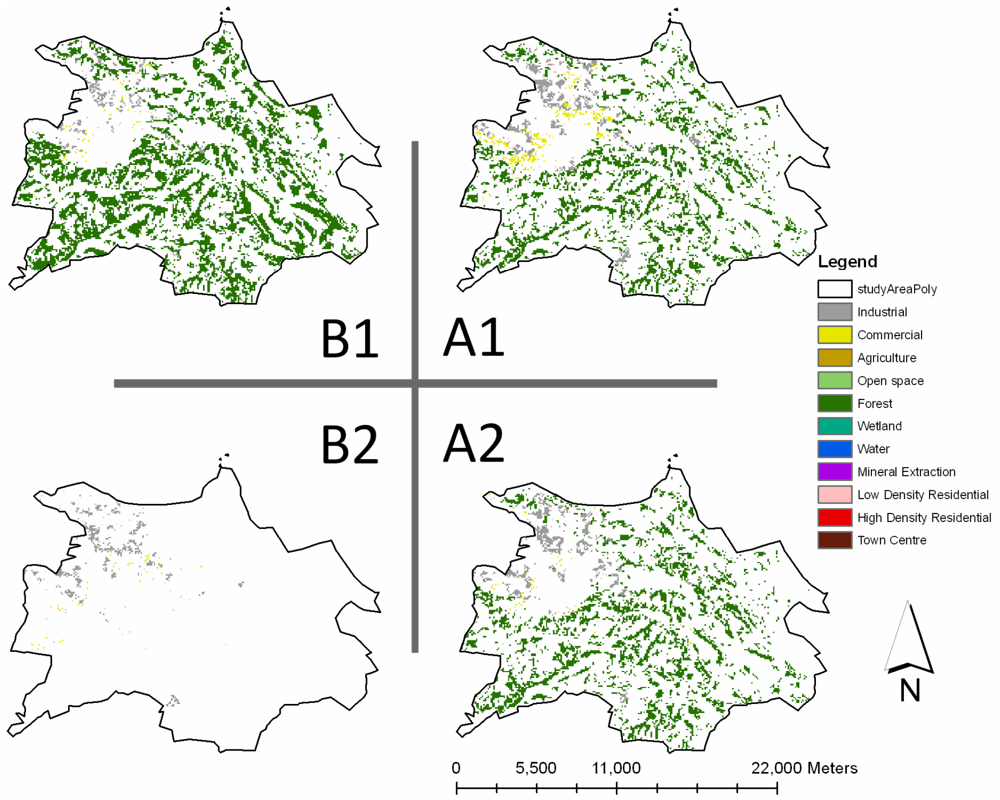

Figure 9: Locations and type of land use change under different scenarios

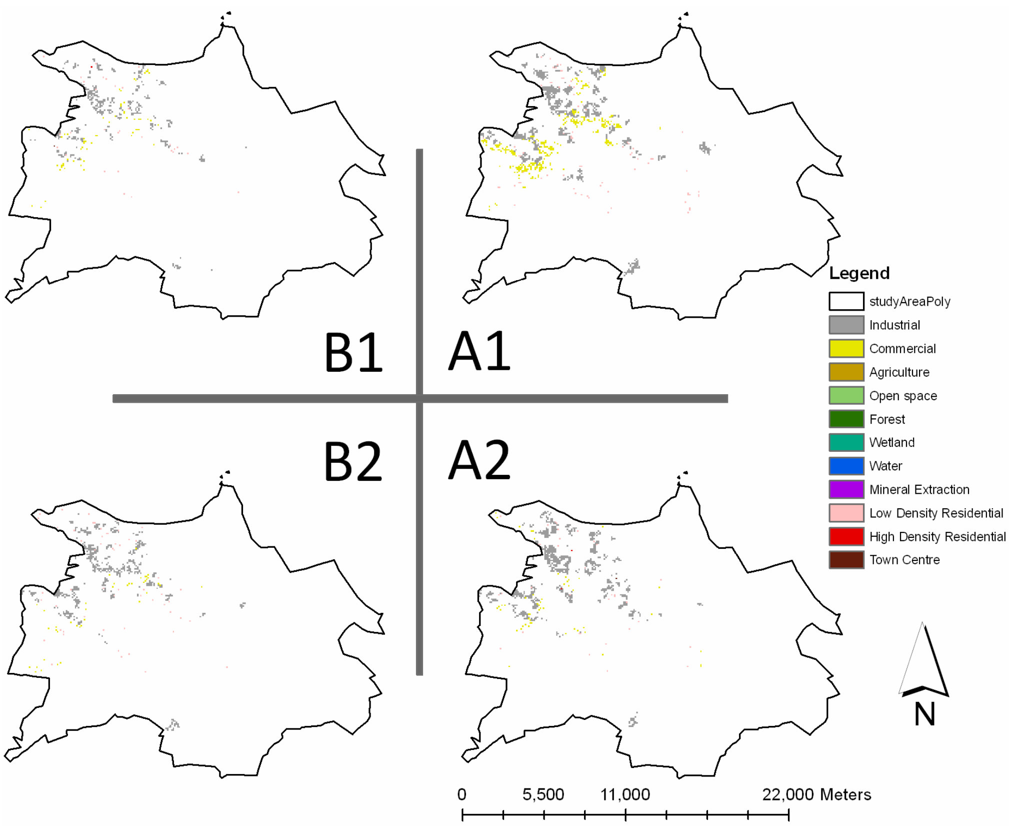

Figure 10: Locations and type of artificial surface creation under different scenarios

4.2 Loss of agricultural land

Figure 12 focusses on the changes in agricultural land availability, which is divided into seven different soil types:

- Q0 represents artificial surfaces
- Q1-Q6 represent increasingly high quality agricultural land
- "Good Agricultural Land" combines Q5 and Q6

In general, the amount of agricultural land (Q1-Q6) decreases in inverse proportion to the increase in artificial surfaces for all the scenarios, with the highest loss in A1 and the lowest loss in B1. Most of the loss occurs for the best agricultural land (Q6) with a maximum of ≈ 500 cells for A1 and a minimum of ≈ 200 cells for B1. The major proportion of new artificial surfaces originate from industrial and commercial development, as discussed in Section 4.1. Figure 11 shows the LUC classes which replace good agricultural land in each scenario. From this, we can infer that the majority of good agricultural land is lost due commercial and industrial development.

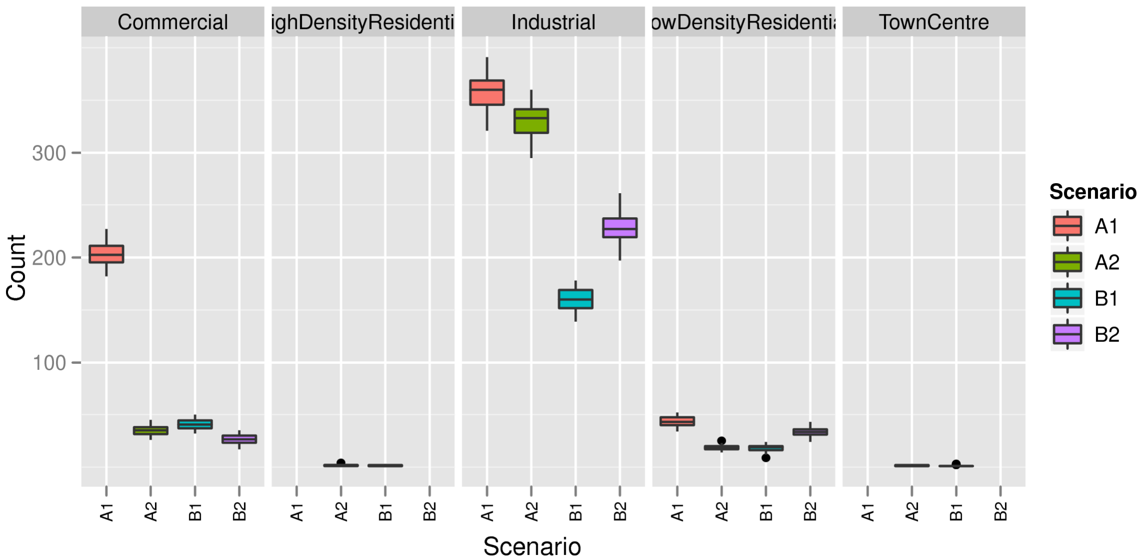

Figure 11: Counts of land use classes which occupy good quality agricultural land.

This is confirmed by Figure 13, which shows the location of the different soil types, with the good agricultural land being located around the port area and sub-urban areas, just where the new industrial and commercial areas are predicted to be developed (see Section 4.1, Figure 10).

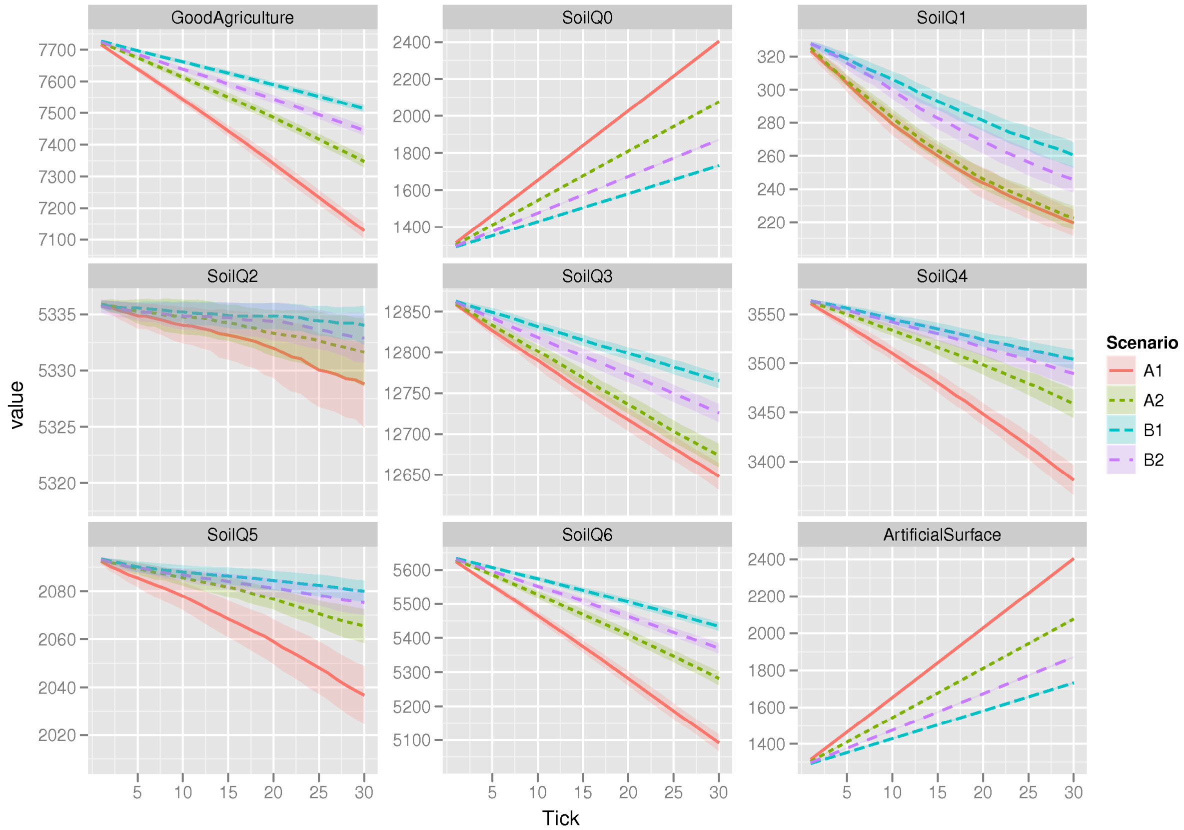

Figure 12: Quantities of agricultural land, averaged across 30 runs of each scenario. “Good Quality” is the sum of Q5 and Q6

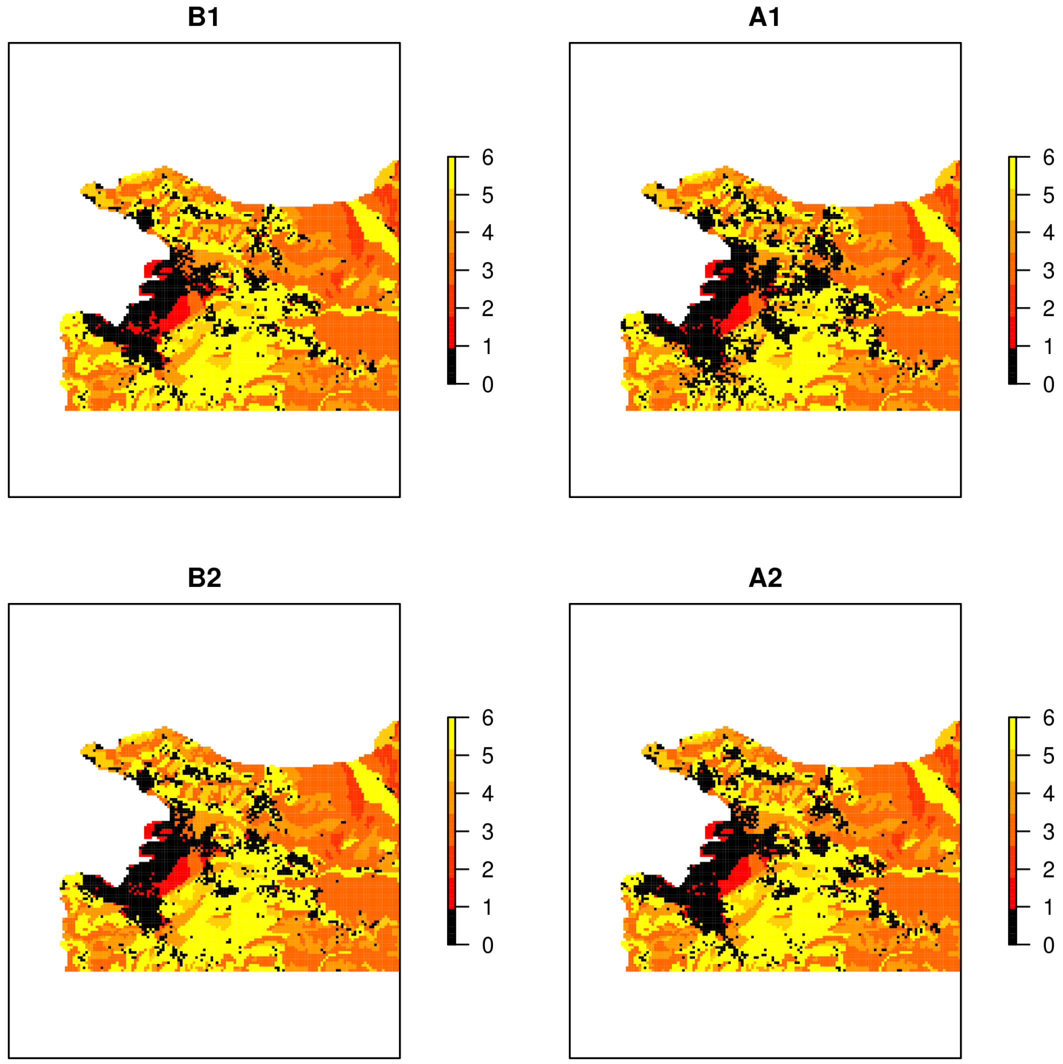

Figure 13: Locations and type of quality of soil for agricultural land under different scenarios

4.3 Development hotspots - variant and invariant regions

We now compute the probability of development for each cell. Stochastic land use models typically produce regions where the predicted land use varies to different degrees, see Brown et al. (2005)'s "variant" vs. "invariant" regions. Knowing the probability of change enables us to determine what we do and do not know know spatially, i.e. a measure of "spatial uncertainty". Figure 14 shows the probability of development on a cell by cell basis, by counting the number of scenarios in which it is developed, compared to the number in which it is not. In general, the amount of cells where the probability of change is greater than 1 is proportional to the amount of artificial surfaces generated by the RUG model. Development "hotspots" are the port region and the sub-urban areas, which is consistent with predicted land use change in Section 4.1, see Figure 10.

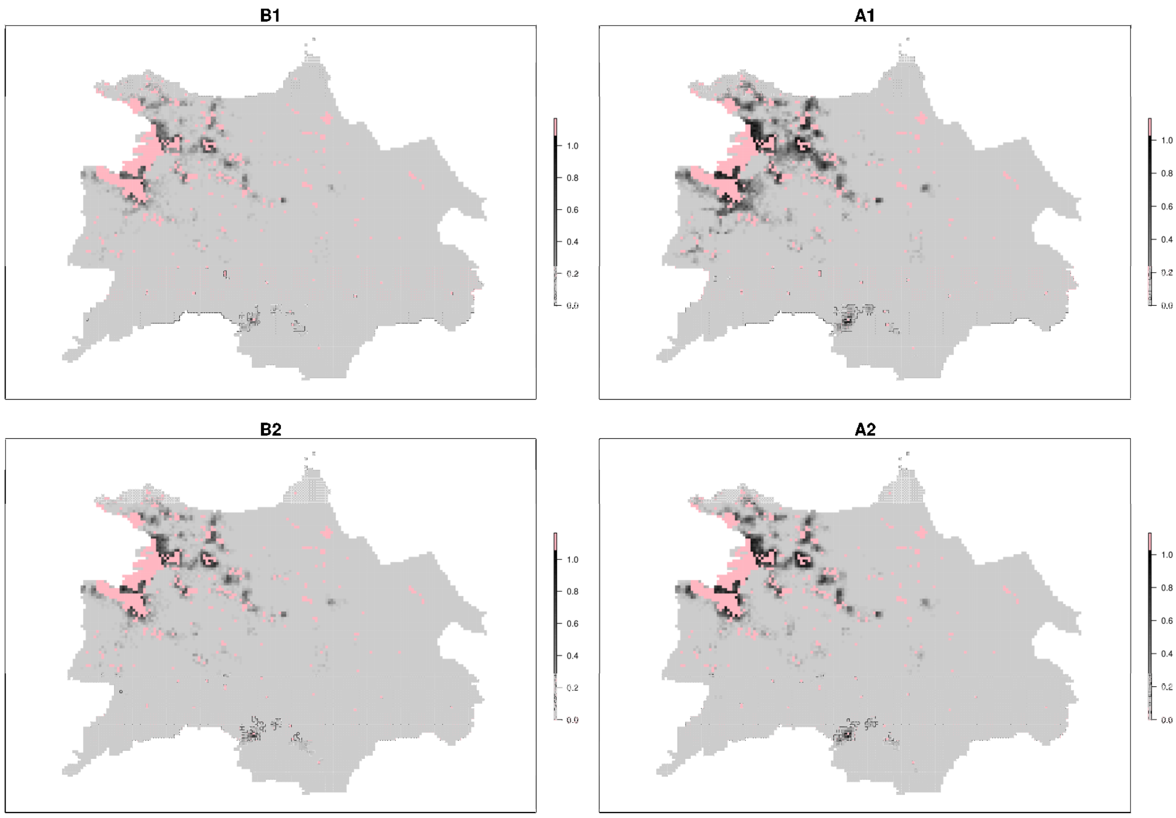

Figure 14: Comparison maps showing the probability of new artificial surface creation under different scenarios. Existing artificial surfaces are shown in pink for reference

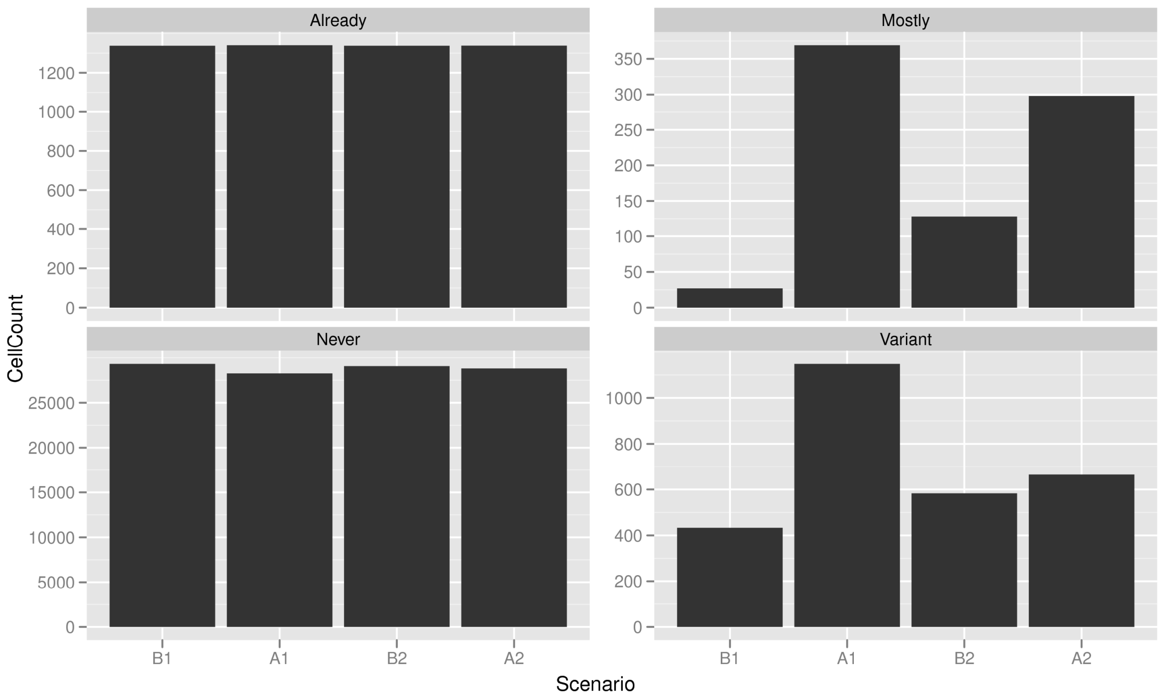

Figure 15: Distributions of probability of change on a cell-by-cell basis under different scenarios, using ?=0.3.

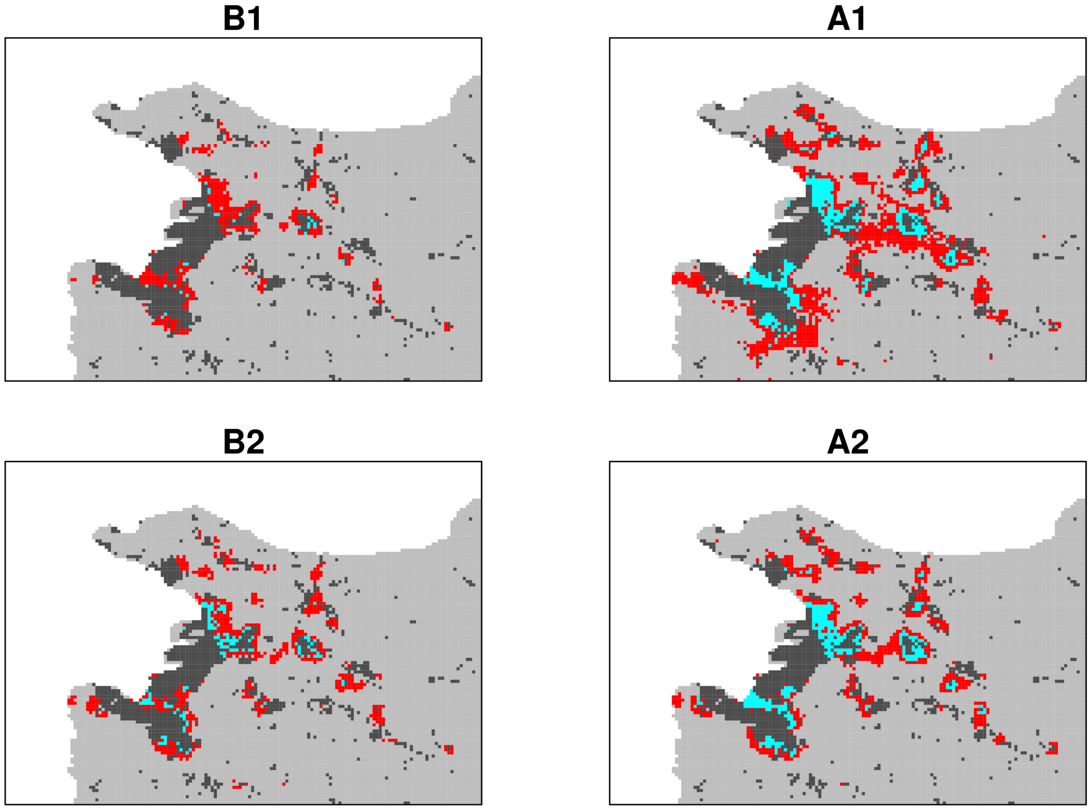

Figure 16: Variant and invariant cells around the city of Koper. Red: Variant, Blue: Mostly, Dark Grey: Already, Light Grey: Never

Figure 15 shows the different distributions of probability of change under different scenarios, i.e. "spatial uncertainty" ranges per scenario. Following Brown et al.'s invariant-variant method we can define variant cells as those with a probability of change □<*p*<1□□. Classifying cells using □=0.3 gives the following classes:

- "Never": *p*<0.3
- "Variant": 0.3<*p*<0.7
- "Mostly": 0.7<*p*
- "Already": cells which were previously developed.

B1 has the highest ratio of "Variant" cells to "Mostly" developed, i.e. the highest level of spatial uncertainty per unit development. Figure 16 shows these cells spatially for the region around Koper city. It can be seen that there is a large amount of variant area under A1, which extends into the prime agricultural areas east of the city. Under the other scenarios, variability is more strongly concentrated around regions which are mostly developed. The higher variability under B1 can be clearly seen, as very few cells are "Mostly" developed.

4.4 Residential dynamics and Quality of Life

Figure 17 shows population change over time, along with several quality of life based measures: the average utility of the population, the average score for new residents and average change in utility. The average change in utility shows the difference in utility between each agent's utility when it moved into a cell and its current utility from that cell. From these we can see that the population is behaving as expected — a verification that the model is correct: The average utility of the residents tends downwards in all scenarios, with A1 showing the largest decrease and B2 the smallest. The score of agents coming into the model is in all cases higher than the existing agents score. Since the agents entering are always entering into newly developed areas, this indicates that new residential areas are being built in more desirable places. This also accounts for the increase in average score over the first 5 years under A2, B1 and B2. In constrast, the graph of average utility change shows that for each individual agent, the quality of life tends to decrease, again most strongly under A1.

The Gini coefficient Gini, 1912; calculatedfollowingOgwang, 2000 is a measure of inequality, with 0 representing perfect equality, and 1 representing a population where one individual has all of the wealth. From this we can see that under all scenarios, the inequality is increased. Under A2, B1 and B2, the Gini curve tends downwards for the first few years, indicating a decrease in inequality. Since the new agents coming in have a higher average utility than the existing population, this implies that there are existing residents with high utility, and the new arrivals are increasing the proportion of residents with high utility. It should be noted that the Gini coefficient is sensitive to translations of the input values (i.e. *G*(*X*)⍰*G*(*X*+*c*) for a vector *X* and constant *c*). Since the utility values come from a conjoint analysis process, which explicitly centres values around 0, the absolute value of the Gini coefficient cannot be discussed. However, changes from a baseline value can still be considered relevant.

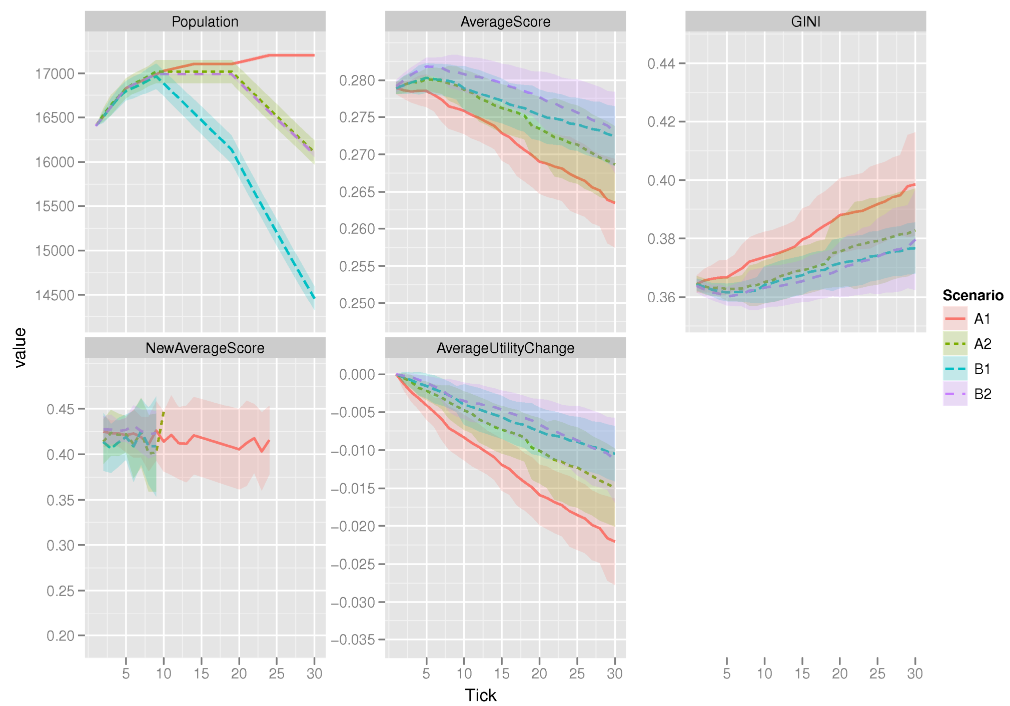

Figure 17: Population change over time, with aggregate scores for current utility, the utility which new residents can obtain and the average change in each resident's utility between entering a cell and the current date

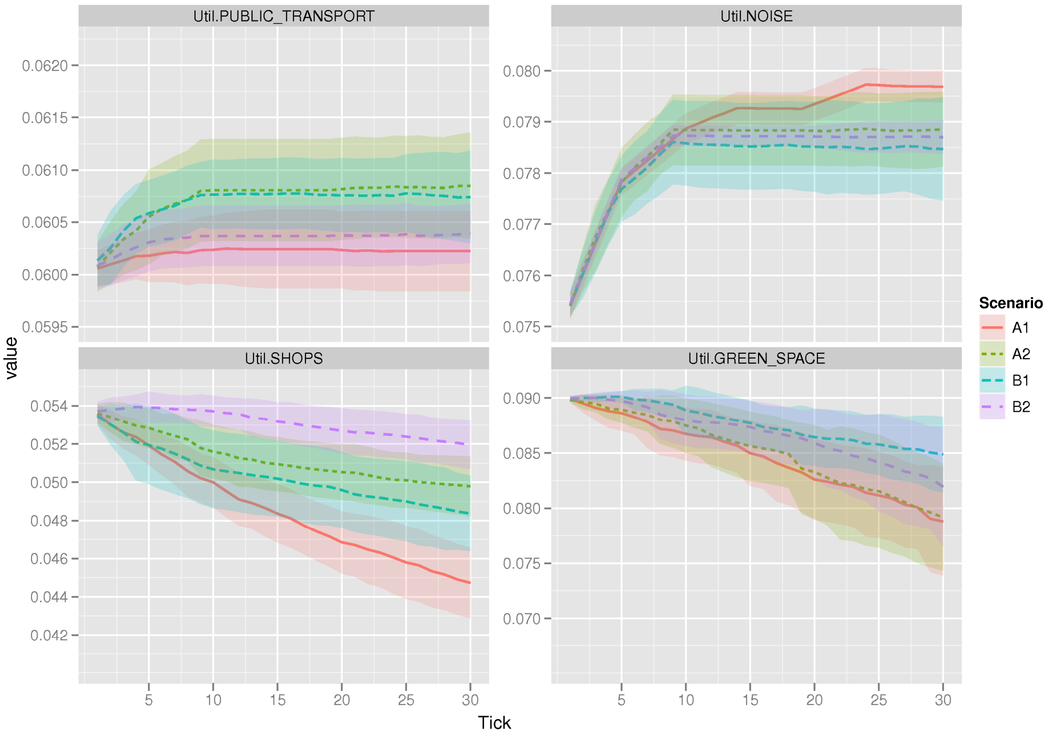

Figure 18: Average partial utilities for residents, averaged over 30 runs per scenario

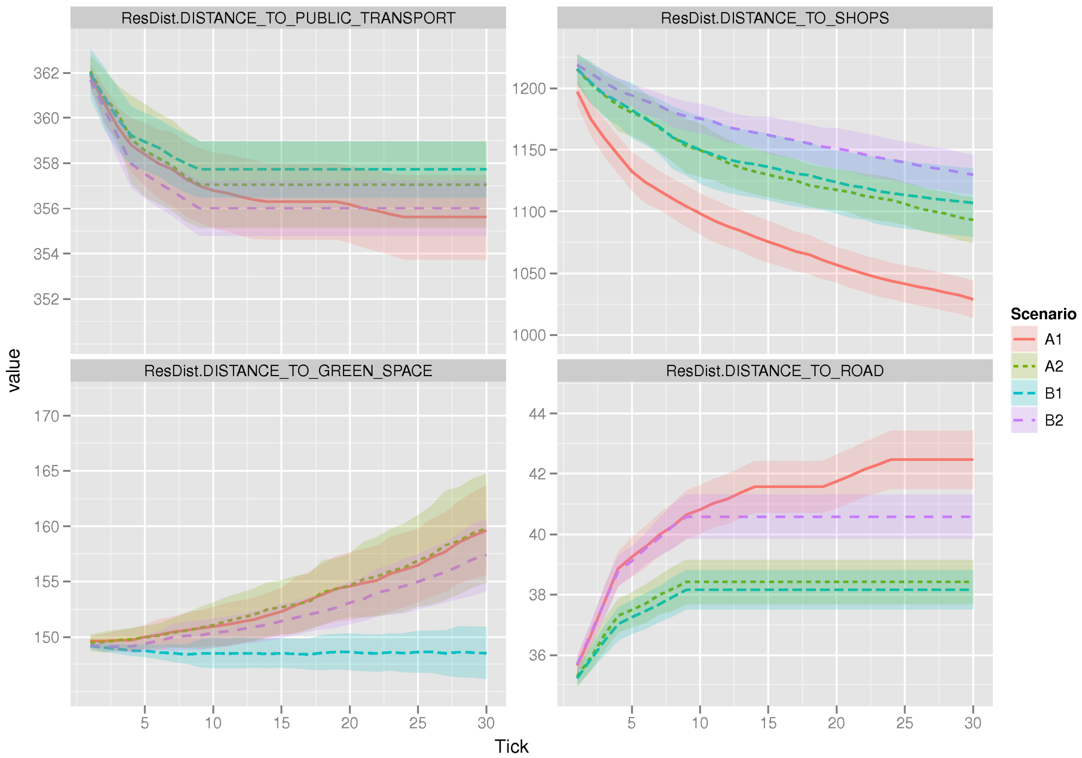

Figure 19: Average distances from residential cells to several points of interest

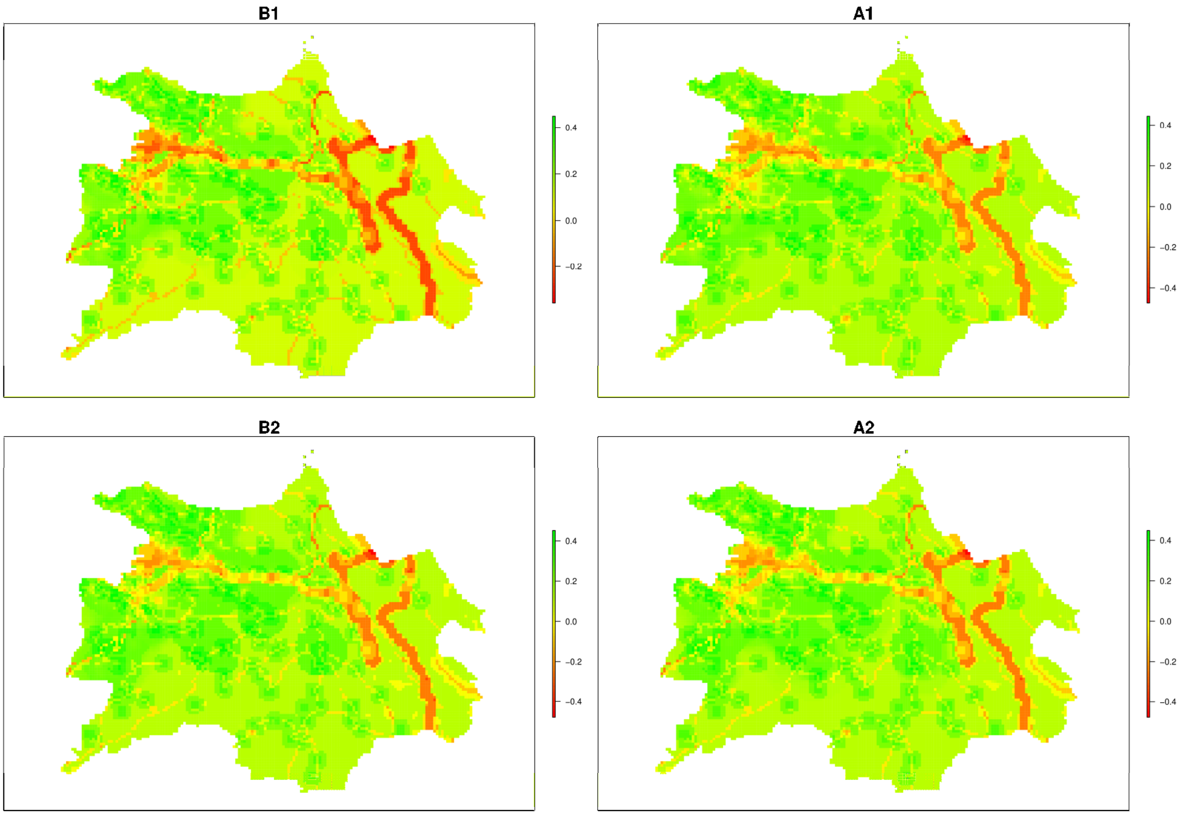

Figure 20: Agent potential utility per cell averaged over 30 runs for each scenario

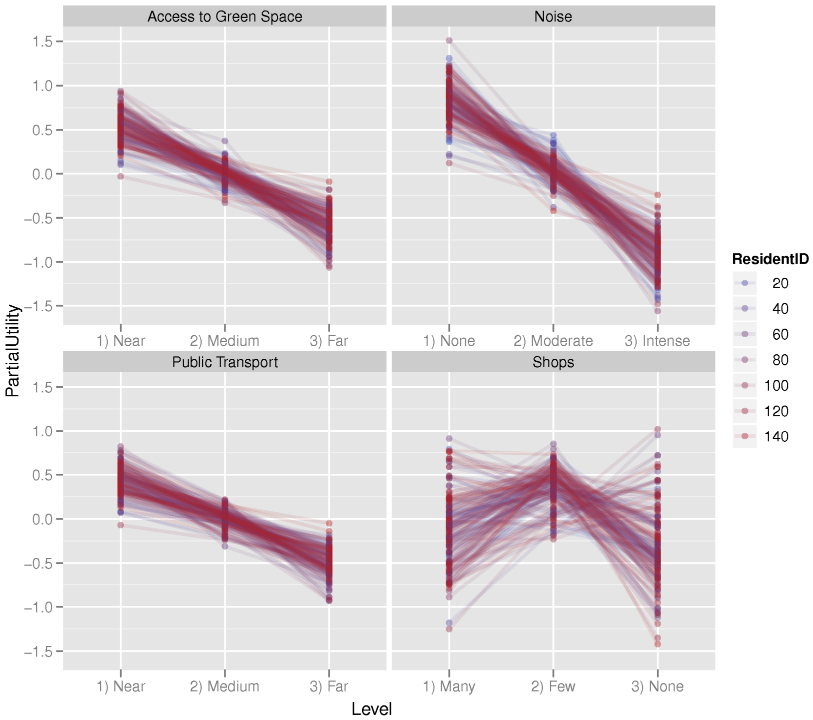

Figure 21: Parallel coordinates plot of partial utilities used in the resident's assessment. Each line represents an individual respondent in the conjoint survey.

Figure 18 shows the average partial utilities the residents get for each issue (see Section 2). We see a slight increase in the public transport utility across all scenarios. The only new points of public transport access occur when town centre is built, and there is only a small amount of town centre constructed under any scenario (typically less than two cells — see Figure 6). Therefore, the increase in utility for public transport must be attributed to new development occuring near to existing public transport access points. This is supported by Figure 19, which shows the average distance to public transport declining at times of population increase. Similarly, the utility from living in a low noise environment increases across all scenarios, while the number of low and medium noise cells overall decreases (Figure 23). This must also be attributed to new residential development occuring in low noise areas (see Figure 22). The utility for shops decreases generally (Figure 18), especially for A1, despite the average distance to shops decreasing (Figure 19). To understand this, Figure 21 shows a parallel coordinate plot of resident utilities. We can see that for most residents, the highest utility is obtained for having some shops in the neighbourhood, rather than many. The extreme commercial development in A1 results in a profusion of shops, which does not match the residents' preferences. Finally, the utility for access to green space trends downwards across all scenarios, especially A1 and A2. This can be attributed to the increase in distance to green space (Figure 19).

Figure 20 shows the "resident desire surface" under different scenarios. It is immediately apparent how much of the structure of the noise map (Figure 22) is apparent in this surface. We can also observer the "hotspots" of desirability around public transpot points, and the areas of lower utility around new industrial development.

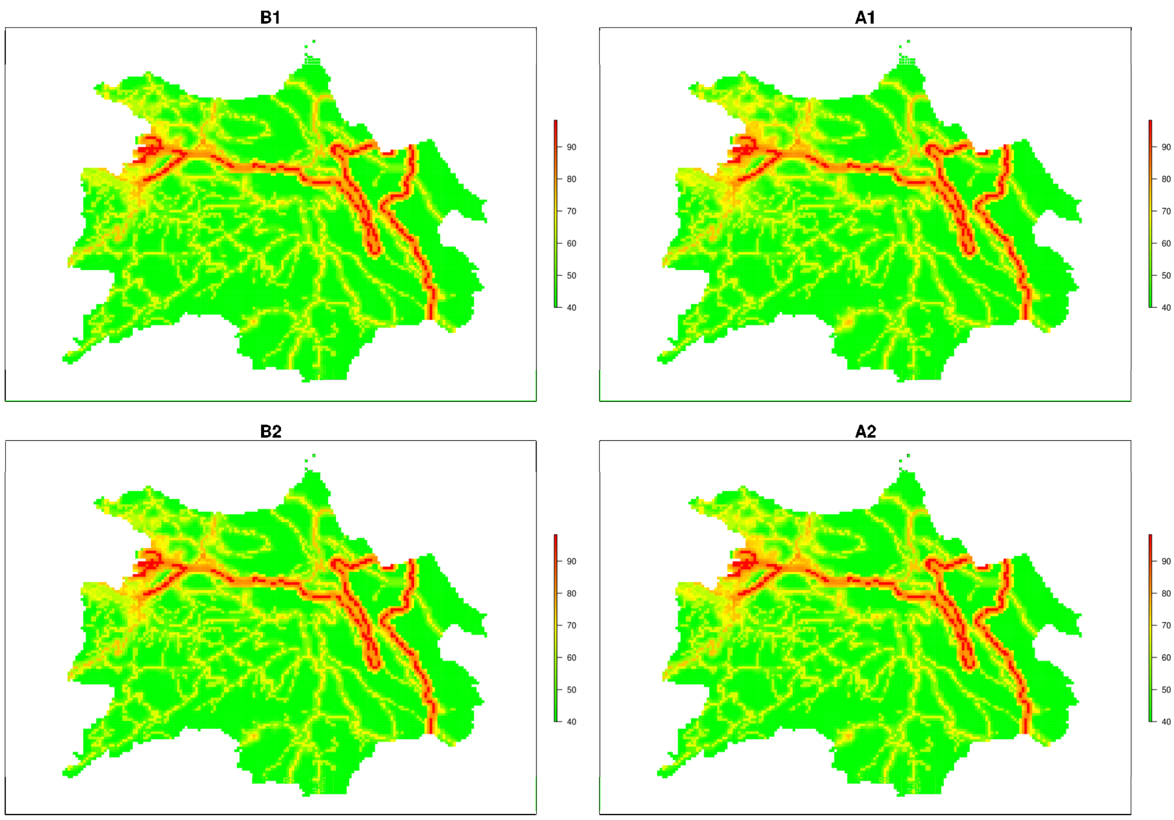

Figure 22: Average noise level (dB) as a simple mean of the noise values for 30 scenario runs

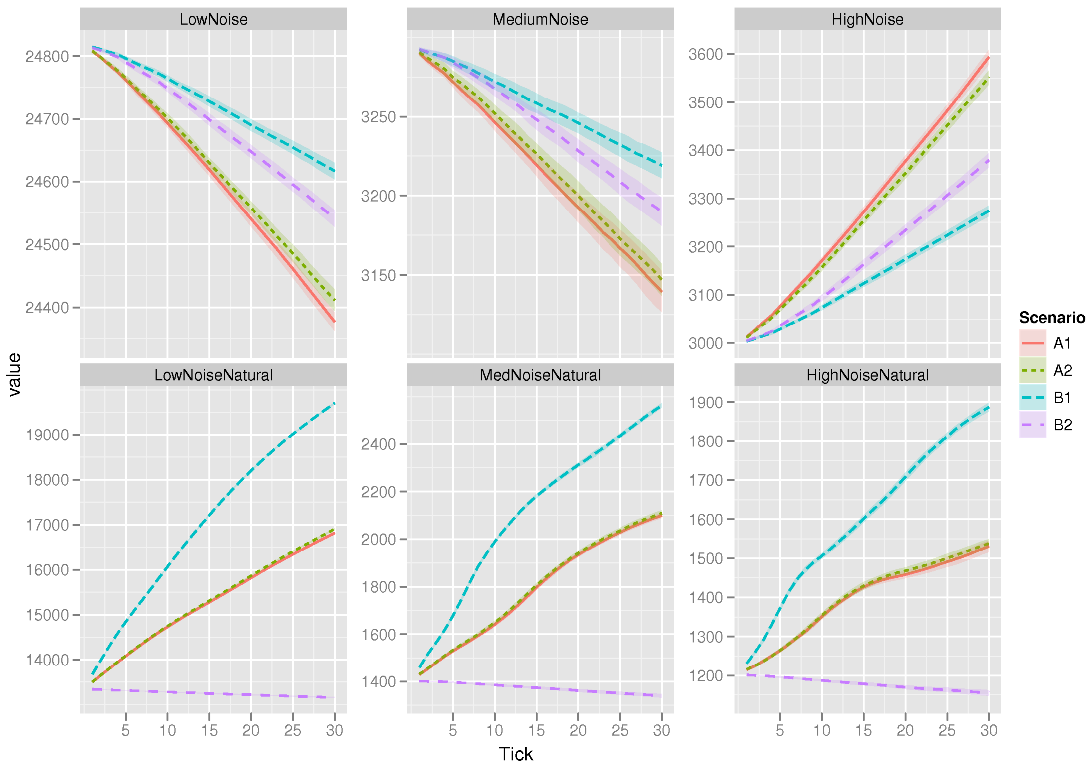

Figure 23: Numbers of cells in each noise category under the four scenarios

5 Discussion and Conclusions

5.1 Discussion of Scenarios

The use of scenario storylines for coupled natural-humans systems research achieved prominence with the development of the Intergovernment Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES 2000). The SRES created standard datasets corresponding to a series of scenarios that have enabled the comparison of a range of ecosystem, climate, and integrative assessment models (Nakicenovic and Swart, 2000).

Despite the importance of land systems as drivers of local, regional, and global climate and economic conditions (citations), the land change science community has been relatively fragmented and lacks a unifying mechanism to which complementary research may be compared. For example, contemporary research efforts model LUCC dynamics and impacts across a range of study sites - Munroe County, Indiana (Evans and Kelley, 2008); Southeast Michigan (Robinson and Brown, 2009); East Anglia, UK (Fontaine et al., 2010) - but there has been little to no cross site comparisons that could facilitate generalising results to improve the broader impacts and findings from the community. We believe one approach to unify research efforts is through the use of common scenarios, such as those provided by the SRES, which could provide an anchor point for land change scientists to connect and a baseline for comparison of results across study sites.

Similarly, when attempting to model LUCC synamics at a regional scale, it must be acknowledged that the region does not operate in isolation, and is subject to influences from the surrounding regions. Scenarios provide a methodology for using these external influences as drivers for a regional model in a principled manner.

We have presented one approach to use scenarios as an integration tool that relates large scale drivers to local LUC changes. By taking a scenario based approach, we produced a highly constrained model of land use change where the amount of land use change is given, as is the change in the agent population. Ideally, the quantity of change and population growth rate would be emergent properties from our agent based model. However, we sought to create a simple and tractable model, which still showed marked differences among the scenarios. The differences among scenarios include location of development hotspots; the agents' satisfaction with their environment and their inequality; and the loss of good agricultural land, which is affected by more than simply amount of artificial surface expansion. Similarly, we have shown that thematically disaggregating artificial surfaces plays an important part in its location, and the resulting impacst.

5.2 Role of Planning

The presented model has no explicit representation of planning decisions. However, the partitioning of different types of residential development could be interpreted as the net effect of interactions between planning constraints and the actions of developers. When considering the loss of good quality land, the major driver of its loss is non-residential development. These results suggest that planning controls affecting the location of commercial and industrial development may reduce the loss of good agricultural soil. For example, the existing Natura 2000 areas could be expanded, or specific agricultural protection measure could be introduced.

5.3 Population dynamics and residential development

The heterogeneous distribution of residential preferences has different impacts at different scales. We observed that incoming residents were consistently able to find higher quality of life in new developments, even though the average quality of life of the population was declining. This indicates that existing housing stock is not arranged according to the quality of life indicators which we have been using. This mismatch may indicate that while important, quality of life is not the only determinant of existing urban form; alternatively, the mismatch could be a result of changing preferences over time. An increase in inequality of well being under all scenarios was observed, which could be interpreted as better situation of new development according to the residents' preferences. The strongest increase in inequality occured in A1, which can be attributed to the larger expansion of urban area into desirable areas, coupled with an increase in commercial activities around existing residential locations.

We designed and constructed a parsimonious LUC model to allow for a transparent integration with a series of scenarios. As part of this transparency, the residential dynamics is purposefully simple, to allow for a very direct interfacing with external drivers. One of the strengths of agent based modelling is the emergence of these large scale properties from local interactions. The presented model and its framework provide a strong basis for expanding the current design to include a more dynamically rich residential model. This more dynamic model could then be calibrated to reproduce large scale trends, rather than having those trends imposed. The addition of more agent types and dynamics among them would allow for an enhanced interpretation of narrative storylines — for example, immigrants could be represented as a separate population with different preferences, and the ageing of the existing residents could be modelled.

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