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Agent-based modelling of land use dynamics and residential quality of life for future scenarios

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ABSTRACT

Current LUCC research employs scenario-based analysis to explore possible future trends and impacts by defining a coherent set of plausible future socio-economic development pathways. Typically, computational models are therein used to interpret qualitative future storylines in terms of quantitative future changes. This paper addresses these challenges and illustrates some of the advantages of a scenario-based approach using an Agent-Based Model (ABM). Storylines are shown to be useful in integrate a broad variety of knowledge sources, such as subjective expert judgement and results from other (integrative) models, which rely on a similar set of assumptions about the future. The advantages of ABMs are demonstrated for interpreting future scenarios in the context of spatial and temporal variations in socio-ecological outcomes based on heterogeneous individual behaviour. For example, ABMs are shown to enable potential hotspots of future development and LUCC to be identified. Furthermore, a procedure is presented for downscaling and interpreting storylines from general qualitative trends to local quantitative parameters within an ABM framework. This framework is applied to the Municipality of Koper, Slovenia, where the future impacts of LUCC on the loss of agricultural land and residential quality-of-life are simulated. The results are compared to a "business-as-usual" baseline and it is shown that industrial and commercial development has the greatest impact on the loss of high quality agricultural land across all scenarios. Furthermore, the model indicates an increase in inequality in the perceived quality-of-life of residential households, with new households achieving higher quality-of-life than existing residents.

1. Introduction

Exploring the future of Land Use and Land Cover Change (LUCC) is a necessary part of understanding the possible future impacts of human–environment interactions (Rounsevell et al., 2012b; Deffuant et al., 2012). In doing so, a wealth of drivers must be considered, including climate change, technological progress and socio-political attitudes and structures (Lambin et al., 2001; Abildtrup et al., 2006). However, it is not possible to extrapolate current trends to model long-term future outcomes, because this overemphasises the likelihood of a single possible future, based on the false assumption of a strictly stationary development from the past into the future ("business-as-usual", BAU). In reality, an infinite number of potential futures exists (Greeuw et al., 2000). In the absence of certainty about the future, scenario analysis has emerged as an appropriate method to explore the long-term future impacts of land-use dynamics on human and natural systems (e.g. Allen and Lu, 2003; Rounsevell et al., 2006).

Scenario-based analysis recognises the plurality of potential futures and reduces their number to an understandable and manageable set by developing plausible, coherent, and internally consistent narratives of alternative socio-economic development pathways (Rounsevell and Metzger, 2010). This follows the philosophy of Kahn et al. (1976) that: "The most likely future isn't". Scenarios are not used to predict the future, but to explore a range of possible futures by considering alternative long-term developments. Scenario analysis has been widely applied over a diverse range of disciplines that relate to the drivers of LUCC, including demographics (Grubler et al., 2006; O'Neill, 2005), climate change (Nakicenovic and Swart, 2000) and ecosystems (MEA, 2005). Using scenarios, it is possible to explore a number of

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variations for a limited, but consistent, set of model parameters. In contrast to related methods, such as (global) uncertainty and sensitivity analysis, which perform a full parameter sweep, scenario-based methods help to avoid various computational and conceptual problems, such as scalar inputs or spatial auto-correlation (Lilburne and Tarantola, 2009).

Most types of scenario analysis start with the construction of storylines (Börjeson et al., 2006): "Scenarios are plausible, proactive and relevant stories about how the future might unfold" (MEA, 2005, p. 8). However, while providing a consistent framework for exploring future trends, storylines on their own do not provide quantification of the impact of future developments. Thus, qualitative storylines are usually translated into quantitative outcomes, also know as "projections", using computational models (e.g. Nakicenovic and Swart, 2000).

In the context of modelling, the scenario method allows a range of models to be driven by the same assumptions, therefore supporting the integration and comparison of their outputs, for example the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (SRES) framework (Nakicenovic and Swart, 2000). Scenarios allow for exploration of model uncertainty using a small set of points or neighbourhoods in parameter space representing compatible values for parameters, as opposed to other methods, such as global sensitivity analysis (Saltelli, 2004) which explore the entire parameter space, and assume independence between parameters.

This paper follows recent work on increasingly empirically grounded, applications of Agent-Based Modelling (ABM) to LUCC (e.g. Parker et al., 2003; Janssen and Ostrom, 2006; Robinson et al., 2007; Fontaine and Corentin, 2010; Haase et al., 2012), in particular to model the interactions between human decision making and environmental feedbacks (e.g. Le et al., 2012; Filatova et al., 2011). The approach used an ABM combined with scenario analysis based on the SRES scenarios to assess future impacts of LUCC in the Municipality of Koper, Slovenia. An ABM approach was chosen for the modelling aspect of this work for several reasons: ABM allows for the integration of a range of data sources (including expert knowledge, current trends and existing models) as a context for agent behaviour; it supports representation of heterogeneous individual attributes, parameterised from qualitative social survey data; it allows for modelling of feedbacks between humans and their environment—in this case, the change in residential quality-of-life (QoL) in response to urban expansion.

The impacts of estimated future LUCC were assessed for four scenarios in comparison to a BAU baseline. The analysis aims to answer the question: what is the potential impact of LUCC on residential QoL and the loss of primary agricultural land. Additionally, the analysis seeks to identify hotspots of future LUCC development. Throughout the analysis, we discuss the advantages of ABMs for interpreting future scenarios by considering spatial and temporal variations in LUCC based on heterogeneous household-agent behaviour.

2. Materials and methods

The description of the modelling process starts with a description of the study area. Next, an outline of the ABM is given, followed by a description of how the SRES scenario storylines were downscaled to provide qualitative scenario descriptions at the case study level. These descriptions were interpreted as qualitative parameters, which were then translated to quantitative boundary conditions for the ABM. In addition, a BAU scenario is described. Finally, methods used to analyse the model outputs are discussed in terms of the frequency of land use transitions, QoL equality and variant/invariant regions.

2.1. Study area

Peri-urban land-use dynamics were modelled in the Municipality of Koper, Slovenia (N 45°32′ 05″ and E 13°45′ 05″). The municipality is located on the Adriatic Sea, in the southwest of the Slovenia,[1] and covers an area of 311 km^2. The area has experienced significant urban growth over the past 50 years, with the population increasing by 66% from 29,932 in 1961 to 49,827 in 2006 (SRS, 2002). Development has accelerated further over the seven year time period; the area of Industrial increased by 28%, Commercial by 9%, Residential Areas by 30% and Town Centre by 11%; whereas the agricultural surface decreased by 21% and open space by 18%. Economic growth in the municipality can be largely attributed to the expansion of the major port, which has improved local and regional access to the Adriatic sea and subsequently driven commercial and industrial development as well as facilitating growth in tourism. Local stakeholders have voiced concerns that this expansion comes at the expense of high quality agricultural land, which threatens the region's cultural heritage and traditional landscape (Perpar, 2009).

Additionally, recent years have been a time of transition for planning in Slovenia. Prior to declaring its independence in June 1991 Slovenia had a comprehensive social planning system, which combined spatial, economic and social aspects (Elliott and Udovc, 2005). When Slovenia gained independence in 1990, spatial planning was only considered at the national level, leading to issues such as developmental inequality between regions, uncontrolled building dispersal and restructuring of rural areas (Udovč, 2007). The adoption of the Spatial Planning Act in 2003 (ZUREP, 2003, 2003) was an attempt to harmonise development potentials over a range of different needs, and between national, regional and local levels.

2.2. Data collection

Two maps of land use and land cover were used, for the years 2000 and 2007, obtained from Harpha Sea Limited, based on land use (MAFF, 2007) and cadastral data (MESP, 2008), hereafter referred to as "the Harpha Sea Data Set". The 25 land use and land cover classes in this dataset were aggregated into the following 11 classes: three different types of residential land-use (Low Density Residential (LDR); High Density Residential (HDR); Town Centre (TC)), commercial and industrial areas, agriculture, and a range of non-managed land uses (Table 1). These 11 classes capture the dominant land use and land cover types that influence change within the region and correspond to available data, the project requirements from local stakeholders, and match well with the types of processes that can be represented within the ABM.

Additional data about the study area included the locations of public transportation nodes (i.e. bus stops), roadways, railway lines, coastline, and sea ports, provided by the Survey and Mapping Authority of the Republic of Slovenia and derived from satellite photo interpretation.

In the absence of census data, the residential housing capacity of the three residential land-use classes were estimated by i) regressing the population of each administrative unit in 2000 against the number of LDR, HDR and TC cells it contains ii) dividing the result by the mean household size of 2.6 (SRS, 2002).

To quantify the relative influence of indicators underpinning the quality of life of residents within the region a social survey was conducted (Bell et al., 2010, $n = 150$). In the survey, respondents carried out a conjoint analysis exercise that required them to make a series of pair-wise comparisons between possible residential locations with differing values of two or more QoL indicators. The conjoint analysis discretises survey responses into ordinal values (e.g., high, medium, low or good, neutral, bad) for each indicator and has been shown to model real-world decision-making (Aspinall, 2007). The result of the analysis is a set of partial utilities for each level of each indicator, for each respondent (see 2.3.3). Given a set of partial utilities and a set of QoL indicator levels, a utility score may be calculated for any potential location within the region to determine the preferred location.

A subset of the indicators in the analysis were selected as being amenable to inclusion in the model on the basis of data availability: i) *access to public transport*, ii) *access to green space*, iii) *proximity to shops* and iv) *noise levels*. The sum of an agent's utility from these indicators was used to represent an agent's QoL (Ülengin et al., 2001).

2.3. Model description

The ABM presented here extends a previous version (Robinson et al., 2012) implemented in Java using RepastS (North et al., 2005). This section presents new modifications to the model that enable the assessment of downscaled IPCC scenarios. In short, the model comprises: residential household agents (RHAs), residential developer agents (RDAs), and a land-use model that manages other land-use and land-cover transitions. RHAs are heterogeneous in their preferences for different QoL indicators, and developers are heterogeneous in both the type of land they create (residential, commercial, industrial), and the method used to locate new areas. Collectively these components interact and drive LUCC, leading to an alteration of the attributes which support QoL calculations, and subsequently affecting the QoL of RHAs.

2.3.1. Model processes and scheduling

The model runs on a yearly timestep. At the start of each timestep, attributes for all cells are updated. Then, RDAs calculate a "desire surface" by polling a subset of

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[1] The municipality is smaller than the enclosing NUTS3 region.

Table 1
Land-use types and their attributes as used in the model.

	Initial area (hA)	Residential capacity	Urban	Can be developed	Provides	Noise (dB)
Industrial	340		Y	Y		75
Commercial	166		Y	Y	Shops	60
Agriculture	13,761		N	Y		
Open space	1118		N	Y	Green space	
Forest	14,711		N	N	Green space	
Wetland	120		N	N	Green space	
Water	63		N	N		
Mineral extraction	59		N	N	Green space	[a]
LD residential	615	11	Y	Y		[a]
HD residential	122	40	Y	Y		[a]
Town Centre	35	136	Y	Y	Shops, PubTran	

[a] Note that although the residential land use types do not produce noise, they typically contain road-based features which do produce noise.

the RHAs for their QoL evaluation of every cell in the landscape. The RDAs then create new residential area based on this desire surface and rate of creation for each residential land use class. Commercial, Industrial and Forest agents transform land at a given rate, using cell attributes and a regression equation to locate the new areas. Finally, RHAs are created or removed, and any unhoused RHAs assess a set of available cells to find the optimum location according to their utility function.

2.3.2. Land-use model

The *land-use model* is parameterised to use the aggregated land use and land cover classes from the Harpha Sea 2000 Data Set. The landscape is represented as a grid of 100 × 100 m cells (1 hA), each having a single land use and land cover class, and a number of *features*. The *features* represent sub-cell features of interest, such as bus stops, roads, and railways and they have associated qualities, such as a bus stop providing public transport and a road generating acoustic noise. The land-use model then calculates a set of *attributes*, based on the land-uses and features on the landscape. *Attributes* include straight-line distances (e.g. to shops or public transport) and acoustic noise. Noise production levels are assigned to land use classes and features based on literature values and extrapolation from existing maps. The level of noise in a given cell is calculated based on the noise transmission model given in (IPPC, 2002)[2]—see Appendix C of Robinson et al. (2012) for full details.

2.3.3. Residential model and quality of life

The *residential model* consists of a population of RHAs, each representing an individual household. Population change occurs at an aggregate level using scenario based population change rates (see Section 2.6 and Skirbekk et al. (2007)), as there is insufficient data available to drive a demographic model. If the rate is positive, the given number of new agents is added, and if the rate is negative the given number of randomly selected agents are removed. Each new RHA surveys a randomly selected subset ($n = 20$) of residential land-use cells with available housing capacity—as a form of bounded rationality (Manson, 2006; Epstein, 1999)—and enters the cell with the highest utility according to its preference weights.

The conjoint analysis provides individual partial utilities for each respondent, so each respondent would obtain a different total utility for any given cell. The total utility u that an agent r derives from a cell c is computed as the additive outcome of factors $i = 1\ldots n$, where $\alpha_{i,r}(a_{c,i})$ is the partial utility an agent places on the level of attribute a_i in cell c.[3]

$$u_{c,r} = \frac{1}{n}\sum_{i=1}^{n}\alpha_{r,i}(a_{c,i}); \tag{1}$$

As an example, consider a cell which has high noise and good access to shops; one agent might not be affected by noise and enjoy shopping ($\alpha_{\text{NOISE}}(\text{HIGH}) = 0.0,\ \alpha_{\text{SHOPS}}(\text{GOOD}) = 0.8,\ u = 0.4$) while another agent might be bothered by noise and uninterested in shopping ($\alpha_{\text{NOISE}}(\text{HIGH}) = -0.9,\ \alpha_{\text{SHOPS}}(\text{GOOD}) = 0.0,\ u = -0.45$), so their QoL values would differ for the same cell.

Analysis of conjoint partial utilities[4] showed little to no structure among survey respondents. Therefore agent preferences are drawn at random from the entire population of 150 respondents, creating a heterogeneous population.

2.3.4. Developer model

The *developer model* consists of several agents, who are each responsible for assigning a single land use to cells. Each developer has a rate of creation, and at each step attempts to allocate the given number of cells of its land-use. The location of new cells is constrained by the source land-uses which can be used, based on the transitions observed in the two converted Harpha Sea LUCC maps. For example, residential areas cannot be turned into Industrial or Commercial. For a subset ($n = 100$) of the viable cells, an evaluation is carried out to find the most favoured development locations.

In the case of industrial and commercial developers, this evaluation is based on a multiple regression analysis of the locations at which new land uses occurred in the 2007 dataset compared to 2000. The process of land abandonment is modelled in a similar way, as the creation of forest cells, with the rate given as a proportion of existing agricultural land, and location determined by the regression analysis. Regression variables included counts of land uses in the neighbourhood, distance from land uses and roads, and elevation; cross validation showed an overall accuracy of 85% for industry, 92% for commercial and 78% for forest location (Robinson et al., 2012, Table 3).

Residential developers evaluate locations based on the residential desire surface—the average QoL for each cell, calculated from a subset of the residential population. There is a residential developer for each residential land use type, with rates of creation determined by the mix of residential classes and population growth (see Section 2.5).

2.4. Interpreting SRES scenarios for peri-urban land-use in Koper

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; Fontaine and Corentin, 2010). These scenarios were adapted by the PLUREL project[5] (Ravetz, 2008) to reflect urbanisation processes, spatial policy, urban-regional governance, and other important drivers for urban development that act at various spatial scales. The PLUREL scenarios also include a series of possible and plausible "shocks", i.e. rapid and important changes in particular sectors or themes, such as a 'hyper-tech' revolution leading to rapid and extensive technological development. PLUREL applies the SRES scenarios to the European Union, to create new narrative scenarios for the years 2025 and 2050 (Ravetz, 2008). The adapted scenarios are shown as a 2 × 2 framework in Fig. 1.

A process was followed of regional adaptation of scenario storylines, known as "local downscaling" (Murphy, 1999) to adapt the PLUREL versions of the SRES scenarios to the Municipality of Koper. For each scenario, the authors created a local storyline by: i) collecting statements about land use change, in particular peri-urban land use, from the storylines in Ravetz (2008); ii) discussing how these relate to the current land-use development in the municipality (Perpar, 2009); iii) using our judgement to create an interpretation which combines the local trends with the scenario storyline. The scenario statements used and their interpretation for the municipality are shown in Fig. 1.

2.5. Land use change rates

The narratives were combined with explicit scenario settings from (Ravetz, 2008) to derive trends for three land-use processes: proportions of residential land-use types, the ratio of commercial to industrial development, and the rate of land abandonment and subsequent conversion to forest (see Table 2, and Fig. 2). The chosen values were relatively extreme, to ensure that the scenarios covered a range of potential futures.

The demand for residential housing can be supplied using a mixture of land use types: LDR, HDR and TC. Since the proportion of LDR is much larger than the other two, the proportions of HDR and TC were first altered, and the rest of the residential demand was met with LDR.

The commercial/industrial ratio was adjusted in a similar manner: since industrial development dominates, the scenario storylines were used to set the proportion of commercial development, and the rest of the artificial surface was filled with industry. Finally, following information in Perpar (2009, p. 61) that "intensive structural changes have slowed down the decrease in the number of farms", it was assumed that the current land abandonment trend constitutes an extreme, which declines in future scenarios.

2.6. Boundary conditions and disaggregation of land uses

Boundary conditions were set for the land use change rates using predictions made by the Regional Urban Growth model (RUG, Rickebusch, 2010), which is a European scale model of land-use change. RUG calculates the amount of Artificial Surfaces (AS), i.e. built-up areas including residential and industrial/commercial

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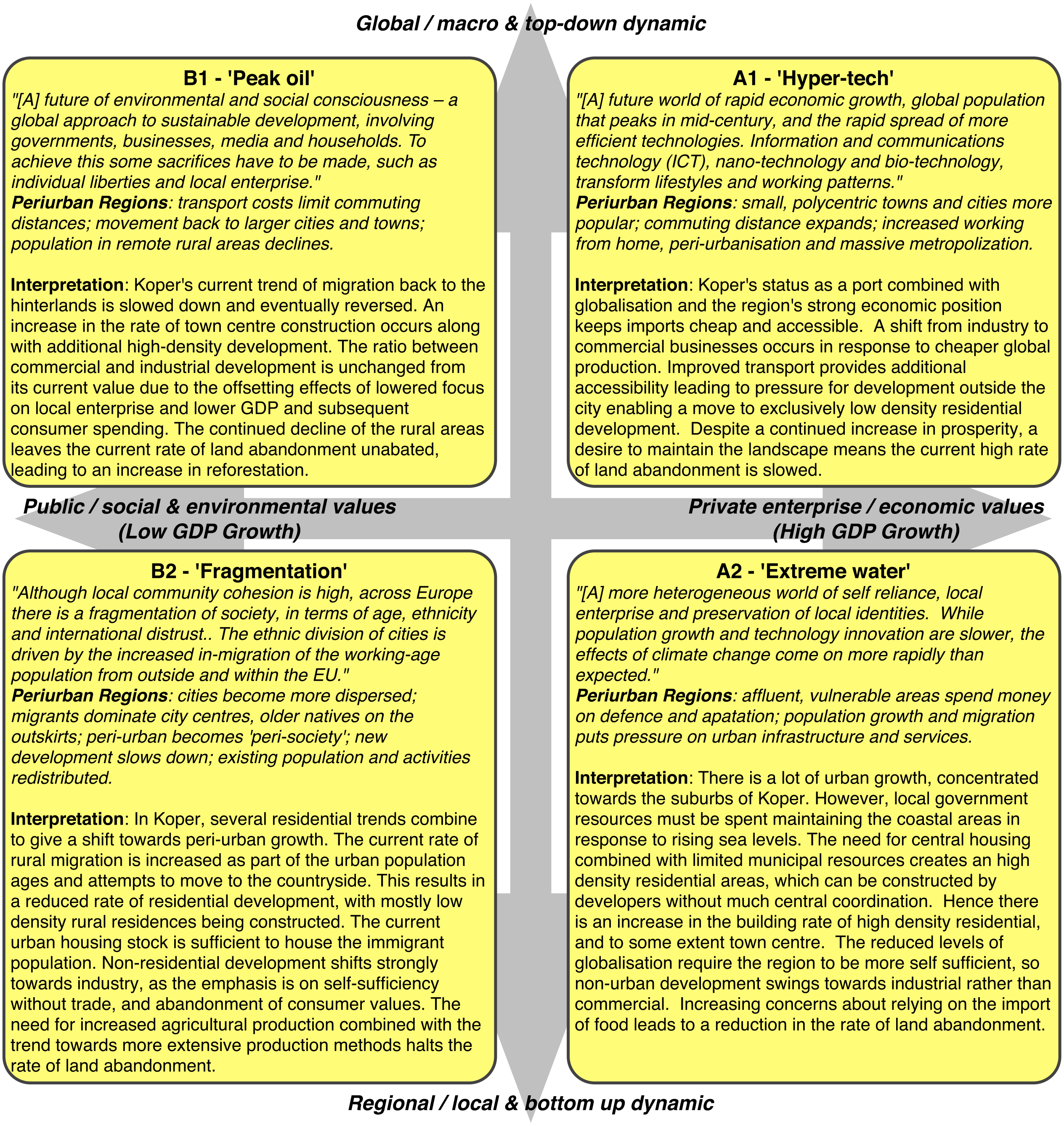
[2] The level L_{new} of a sound at distance d_{new} based on a measurement of L_{orig} at distance d_{orig} is $L_{\text{new}} = L_{\text{orig}} - 20\log_{10}(d_{\text{new}}/d_{\text{orig}})$.

[3] α values are not formally constrained; however they have been normalised using the total importance of all attributes such that they range from $-0.5\ldots0.5$. Each individual's partial utilities for all levels of a given attribute will sum to zero.

[4] Clustering, regression trees and classification were unable to show well defined types with significant association.

[5] PLUREL: Peri-urban Land Use Relationships, EU FP6-036921, http://www.plurel.net.



B1 - 'Peak oil'

"[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."
Periurban Regions*: transport costs limit commuting distances; movement back to larger cities and towns; population in remote rural areas declines.*

Interpretation: Koper's current trend of migration back to the hinterlands is slowed down and eventually reversed. An increase in the rate of town centre construction occurs along with additional high-density development. The ratio between commercial and industrial development is unchanged from its current value due to the offsetting effects of lowered focus on local enterprise and lower GDP and subsequent consumer spending. The continued decline of the rural areas leaves the current rate of land abandonment unabated, leading to an increase in reforestation.

A1 - 'Hyper-tech'

"[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."
Periurban Regions*: small, polycentric towns and cities more popular; commuting distance expands; increased working from home, peri-urbanisation and massive metropolization.*

Interpretation: Koper's status as a port combined with globalisation and the region's strong economic position keeps imports cheap and accessible. A shift from industry to commercial businesses occurs in response to cheaper global production. Improved transport provides additional accessibility leading to pressure for development outside the city enabling a move to exclusively low density residential development. Despite a continued increase in prosperity, a desire to maintain the landscape means the current high rate of land abandonment is slowed.

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."
Periurban Regions*: cities become more dispersed; migrants dominate city centres, older natives on the outskirts; peri-urban becomes 'peri-society'; new development slows down; existing population and activities redistributed.*

Interpretation: In Koper, several residential trends combine to give a shift towards peri-urban growth. The current rate of rural migration is increased as part of the urban population ages and attempts to move to the countryside. This results in a reduced rate of residential development, with mostly low density rural residences being constructed. The current urban housing stock is sufficient to house the immigrant population. Non-residential development shifts strongly towards industry, as the emphasis is on self-sufficiency without trade, and abandonment of consumer values. The need for increased agricultural production combined with the trend towards more extensive production methods halts the rate of land abandonment.

A2 - 'Extreme water'

"[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."
Periurban Regions*: affluent, vulnerable areas spend money on defence and apatation; population growth and migration puts pressure on urban infrastructure and services.*

Interpretation: There is a lot of urban growth, concentrated towards the suburbs of Koper. However, local government resources must be spent maintaining the coastal areas in response to rising sea levels. The need for central housing combined with limited municipal resources creates an high density residential areas, which can be constructed by developers without much central coordination. Hence there is 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. Increasing concerns about relying on the import of food leads to a reduction in the rate of land abandonment.

Fig. 1. PLUREL scenario framework, consolidated from Ravetz (2008). The vertical axis differentiates between globalised top–down dynamics and localised bottom-up dynamics. The horizontal axis shows how the scenarios differ with respect to society's valuation of livelihoods: on the one side (left) public/social and environmental values and on the other side private enterprise/economic values. Italicised text is taken from European trends in Ravetz (2008) while the interpretation section of each scenario is the authors' qualitative assessment of the scenario implications for periurban areas in Koper.

land-uses, using a linear regression model to estimate the proportion of AS per NUTS2 (Nomenclature of Territorial Units for Statistics) region from projected population and GDP per capita values (along with variables for the country and the type of urban area). The regression model is used to project AS into the future for the years of 2015 and 2025 using projected values for future population (Skirbekk et al., 2007; KC et al., 2010) and GDP growth (Boitier et al., 2008).

The total amount of AS (see Fig. 2[A]) is thematically disaggregated amongst the three land-use parameters in our model. The process of disaggregation is constrained by the assumption that enough residential capacity is created to house the growing population, i.e. housing supply meets demand. To calculate residential capacity amongst the three residential land-uses (LDR, HDR, TC – Fig. 2[B]), the housing ratio was combined with the capacities of each land-use type:

$$C_{\text{avg}} = \sum_{u \in \text{LU}} c_u w_u \tag{2}$$

$$\Delta_{\text{Res}} = \frac{\Delta_{\text{Pop}}}{C_{\text{avg}}} \tag{3}$$

$$\Delta_u = \Delta_{\text{Res}} w_u \tag{4}$$

Where C_{avg} is the average capacity of all residential land-use densities, 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 residential land-use. The

Table 2
Scenario settings and qualitative interpretations for model variables; "+ +" indicates a 100% increase, "+" a 50% increase, "−" a 50% decrease, and parameters marked "− −" are decreased to 0. TC = "Town Centre", HDR = "High density residential", LDR = "Low density residential".

	A1	A2	B1	B2
PLUREL scenario settings				
General urbanisation trend	Counter-urban[a]	Sub-urban	Compact city	Peri-Urban
Rural/urban migration	Rural	Urban	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 HDR	− −	+ +	+	− −
Proportion LDR	+ +	−	− −	+ +
Commercial/industrial ratio	+ +	−	No change	−
Land abandonment rate	−	−	No change	− −

[a] "Counter urbanism" here denotes a physical and psychological move away from city living, as opposed to peri-urbanism which involves living in rural areas but maintaining a focus on the city.

quantity of residential development is based on a ratio for LDR, HDR and TC, which is determined by the scenario settings (Fig. 2[C], Section 2.5).

In a similar manner, the scenarios were used to determine the ratio of commercial to industrial development (r_c) (Fig. 2[E]). Since the total amount of AS is given as a constraint (Δ_{AS}), it is now possible to prescribe the amounts of commercial (Δ_{com}) and industrial (Δ_{ind}) development as follows (also see Fig. 2 [D]):

$$\Delta_{\mathrm{com}} = r_c(\Delta_{\mathrm{AS}} - \Delta_{\mathrm{Res}}) \tag{5}$$

$$\Delta_{\mathrm{ind}} = (1 - r_c)(\Delta_{\mathrm{AS}} - \Delta_{\mathrm{Res}}) \tag{6}$$

The final land-use change process, the conversion of land between forest and agriculture, was modelled according to the assumption that change occurs due to land abandonment, and a given proportion of farmland is abandoned each year. The allocation process of the land-use quantities on the map (see Fig. 2[F]) is summarised in Section 2.3.

2.7. *Business as usual*

The BAU scenario was developed as a projection of current behaviour (Robinson et al., 2012; Section 3.1), and is included here to illustrate the difference between extrapolation of current trends and scenarios. This setting maintains the rate of creation for all artificial surface land use classes observed in the Harpha Sea dataset between 2000 and 2007. The proportion of agricultural land abandoned each year was also the same as that observed from 2000 to 2007. The same regression equations and desire surface were used to inform the location of new cells. Compared to the PLUREL scenarios, there is a greater expansion of residential area, and the rate of land abandonment is the same as the highest scenario rate (in B1).

2.8. *Analysis*

First, land-use change frequencies are reported to verify that the model responds correctly to scenario settings. Secondly, descriptions of overall land use change, maps of the likelihood of development, and the impacts as computed by the model are presented. In particular, the impact is simulated of land-use change on the sealing of agricultural land with high quality soils, which is one of several concerns of local stakeholders (Perpar, 2009). The impact is also simulated of land-use change on the levels and distribution of residential QoL. Distribution of QoL is measured using the Gini coefficient, a continuous scale where 0 represents perfect equality, and 1 represents a population where a single individual owns all of the wealth (Gini, 1912). It is used here to characterise the inequality in QoL scores for the population of agents (similar to Brown and Robinson (2006)).

The results are presented as the average of 30 model runs for each scenario—a compromise between computational cost and a good representation of stochasticity. Unless otherwise indicated, maps show the averaged behaviour over all runs, and graphs show summary statistics from all runs. Each run spans 30 years, from 2000 to 2030, with an annual time step.

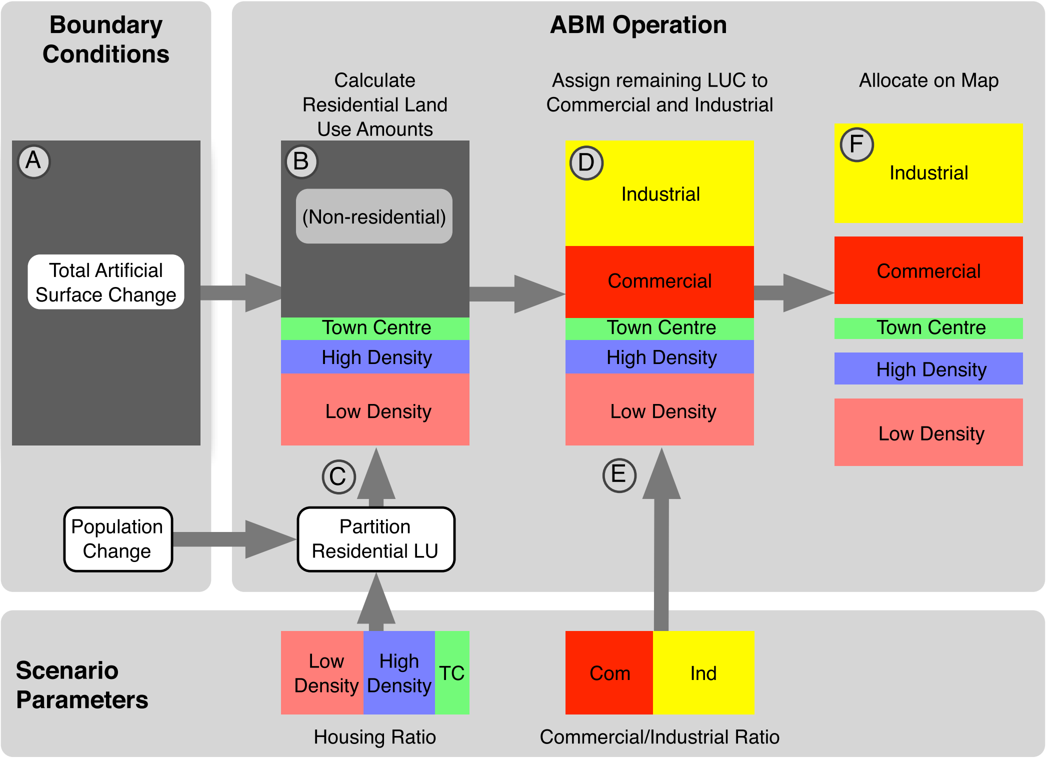


Fig. 2. Use of boundary conditions and land-use ratios to determine rates of creation of each artificial surface land-use in the ABM.

Spatial uncertainty in the results is measured by calculating the probability of development of each cell over the 30 runs of a scenario (Brown et al., 2005). A threshold of $\theta = 0.3$ was used to segment undeveloped cells into three groups based on development probability: (i) mostly undeveloped ($p < 0.3$), (ii) variant ($0.3 < p < 0.7$) and (iii) mostly developed ($p > 0.7$). This method accounts for the fact that land-use predictions vary due to path dependencies and stochastic uncertainty. Assessing the likelihood of development at a location helps a level of confidence to be assigned to the simulated change, and development "hotspots"—areas that are likely to be developed—to be identified. These are distinct from variant regions, which have considerable uncertainty about whether development will take place.

3. Results

Results from the individual scenarios are presented here followed by a comparison of specific outputs across scenarios. Amounts of land use change are given in Table 3, example maps of Land Use in Fig. 3.[6] To aid comparison, results are also given for the "Business as Usual" (BAU) experiment from Robinson et al. (2012).

3.1. Overview of scenario outcomes

BAU: The current trend of land abandonment continues, leading to a major loss of agriculture (−65%), mostly to forest. Throughout the municipality, productive agricultural land is lost. The large increase in artificial surfaces leads to a 114% increase in land that has no primary production capability. Population growth, and the housing needed to support this growth, is a major driver of this change, with a 144% increase in LDR and 48% increases in both HDR and TC.

A1: The most extreme change of LU is the expansion of Commercial space (a 185% increase), in particular around existing developed areas, with AS doubling as a whole. Scattered LDR development occurs from the north-west of the city centre towards the central region of the municipality. A decline in agriculture (−40%) results in abandonment of approximately 56 km^2 of agricultural land. There is a loss of 8% of the highest quality agricultural land, due mostly to expansion of Industrial (59%) and Commercial (34%) areas. A constant increase in population is accompanied by a decline in average QoL, and a decrease in QoL equality, driven by a) increasing commercialisation and b) reduced access to green space due to development surrounding existing housing.

A2: Development of AS is mainly characterised by expansion of the existing Industrial areas (220% increase), and a small amount of surrounding commercial development. There is some scattered LDR development, but most of the moderate population increase is accommodated in HDR development close to existing residential areas. The patterns of LUCC result in variant regions being concentrated around existing development and transport corridors. Compared to A1, less high quality agricultural land is lost (5%), mostly due to the reduced Commercial expansion. Since industrial development does not concentrate around existing residential areas (unlike commercial development), and residential development is limited, there is less development around existing housing than in the A1 scenario. This means that there is less of an impact on QoL scores of the residents.

B1: Development is reduced compared to both A1 and A2, and mostly comprises Industrial and Commercial, with very little occurring outside of the NW corner of the Municipality. The most visible change is the loss of 63% of agricultural land, primarily due to abandonment. Only a small amount of good quality agricultural land is lost to development (2.9%). A population decline, coupled with compact development, results in relatively low impact measurements, in particular the lowest increase in area noise classified as "high noise".

B2: Agricultural area is maintained, avoiding the widespread land abandonment seen in the other scenarios. Development is limited, with only small increases in AS occurring to the NW of the city centre. The increased reliance on local industry, however, means that there is a greater loss of prime agricultural land than in B1 (3.7%, Fig. 5). Residential development is mostly LDR, but limited due to the lack of population increase; this contributes to a higher QoL as access to green space is maintained, and commercialisation does not intrude on everyday life.

3.2. Land use change

As described above, the quantity and patterns of land-use change varied across the simulated scenarios with perhaps the most widespread land-use change being the abandonment of agricultural land (A1: 56 km^2, A2: 49 km^2, B1: 86 km^2, BAU: 89 km^2), with only B2 showing an approximately similar agricultural area (as loss of 0.3 km^2).

In all scenarios, the majority of the artificial surfaces were created by Industrial development, whereas Commercial development accounts for a much smaller area. Only A1 ('hyper-tech') has a large amount of Commercial development ($\approx$300 hA). The ratio between Commercial and Industrial development is determined by the level of globalisation assumed in the scenario, i.e. reliance on local production versus global imports. Hence, there is a higher ratio of Industrial to Commercial development for the "regional" scenarios A2 and B2, since for these scenarios trade relies more on local industrial production. The regression equations used showed that new commercial and industrial areas are more likely to be located near existing commercial and industrial areas and so, commercial and industrial development is prevalent in the port region and sub-urban areas (see Fig. 3).

Scenario settings for residential development were driven by the different costs of commuting (A1, B1), as well as the availability of inhabitable land due to climate change threats (A2) and social fragmentation (B2). In the A2 and B1 scenarios, The City of Koper maintains a compact form, as all new residential development is TC and HDR. In contrast, under A1 and B2 no new TC or HDR is created, with all development being LDR. This leads to a larger urban extent (Table 3), arguably with urban sprawl development in the case of A1. Overall, development of low density housing has the largest impact on the total residential area, with 100% of new residential area (ca. 65 cells) being LDR for A1 and approximately 66.7% being LDR for B2.

In the results presented so far, the observed land-use change frequencies confirm the scenario settings (while following the boundary conditions set by the European scale model outputs). In contrast, the BAU experiment shows far more residential development than any of the downscaled IPCC scenarios, with the largest expansion of artificial surfaces. However, the rates of industrial and commercial expansion are all within the bounds of the scenarios, and changes in agriculture and forest area are very close to the results for B1.

3.3. Development hotspots: variant and invariant regions

Comparing the spatial uncertainty around development for the four scenarios shows that A1 has the highest development uncertainty with 3.33% of the 31,110 cells in the model being variant,

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[6] Appendix A provides additional maps of development locations (Fig. A.7) and land use trajectories (Fig. A.8).

Table 3
Aggregate outputs of mean, standard deviation and change from starting point at 2030 for agricultural production capacity soils (ha), noise pollution (ha), partial utilities, and total aggregate population utility. Values are given for all 4 scenarios, as well as the BAU experiment from Robinson et al. (2012). Mean values with a # are *not* significantly different from the BAU experiment ($p = 0.01$, df = 29, t-test).

	Initial values	Business as usual			A1			A2			B1			B2		
		Mean	Sd	Change	Mean	Sd	Change	Mean	Sd	Change	Mean	Sd	Change	Mean	Sd	Change
Agricultural production capability (hA)																
Very high	5988	5003	17.64	−16.5%	5092	24.36	−15.0%	5282	19.67	−11.8%	5434	12.40	−9.3%	5370	14.60	−10.3%
High	2113	1998	7.76	−5.4%	2037	12.07	−3.6%	2065	6.99	−2.3%	2080	4.48	−1.6%	2075	5.07	−1.8%
Medium	3691	3358	11.63	−9.0%	3381	15.12	−8.4%	3459	14.27	−6.3%	3504	9.91	−5.1%	3489	12.76	−5.5%
Low	12,941	12,461	17.01	−3.7%	12,648	15.91	−2.3%	12,674	14.33	−2.1%	12,765	8.91	−1.4%	12,726	10.90	−1.7%
Very low	5344	5312	6.33	−0.6%	5329	3.81	−0.3%	5332	3.02	−0.2%	5334	1.71	−0.2%	5333	2.19	−0.2%
None/impervious	1278	2738	10.04	+114.3%	2404	4.40	+88.1%	2076	3.46	+62.5%	1732	3.70	+35.6%	1871	3.66	+46.4%
Areas with noise levels (hA)																
≥75 dB	2998	3225.1	8.4	7.8%	3594	15.11	+19.9%	3552	14.49	+18.5%	3274	11.07	+9.2%	3380	14.42	+12.7%
>65 and <75 dB	3294	3225	8.1	−2.1%	3139	12.92	−4.7%	3147	10.01	−4.5%	3219	8.12	−2.3%	3190	8.88	−3.2%
≤65 dB	24,828	24,660	11.6	−0.7%	24,377	14.94	−1.8%	24,411	16.94	−1.7%	24,617	13.05	−0.9%	24,541	13.07	−1.2%
Quality of life (average partial utilities, arbitrary units)																
Greenspace	0.0897	0.0915	0.00	+2.0%	0.0788	0.00	−12.2%	0.0792	0.00	−11.7%	0.0849	0.00	−5.4%	0.0819	0.01	−8.6%
Public transport	0.0597	0.0569	0.00	−4.7%	0.0602	0.00	+0.9%	0.0608	0.00	+1.9%	0.0607	0.00	+1.7%	0.0604	0.00	+1.2%
Shops	0.0536	0.0530	0.00	−1.1%	0.0447	0.00	−16.6%	0.0498	0.00	−7.1%	0.0484	0.00	−9.8%	**0.0519 #**	0.00	−3.1%
Noise	0.0750	0.1191	0.00	+58.9%	0.0797	0.00	+6.3%	0.0789	0.00	+5.1%	0.0785	0.00	+4.6%	0.0787	0.00	+4.9%
Total	0.2780	0.3206	0.00	+15.3%	0.2634	0.01	−5.2%	0.2687	0.01	−3.4%	0.2724	0.00	−2.0%	0.2730	0.01	−1.8%
Land use and land cover (hA)																
Industrial	340	788	1.07	+131.9%	1085	2.65	+219.0%	1047	2.48	+208.0%	700	1.35	+105.8%	837	2.11	+146.3%
Commercial	166	266	8.32	+60.5%	473	2.55	+184.8%	222	1.61	+33.4%	228	2.03	+37.0%	205	3.17	+23.5%
Agriculture	13,761	4847	15.66	−64.8%	8136	15.98	−40.9%	8358	12.92	−39.3%	5099	9.62	−62.9%	13,473	13.81	−2.1%
Open space	1118	779	12.70	−30.3%	**770 #**	13.23	−31.1%	797	11.89	−28.7%	924	9.68	−17.4%	868	13.51	−22.3%
Forest	14,711	22,454	15.20	+52.6%	19,558	11.39	+32.9%	19,637	12.01	+33.5%	23113	5.35	+57.1%	14,655	8.64	−0.4%
Low density residential	615	1500	3.68	+143.9%	689	2.05	+12.1%	647	1.28	+5.2%	645	1.15	+4.9%	672	1.25	+9.2%
High density residential	122	181	1.04	+48.3%	122	0.00	+0.0%	124	0.89	+1.9%	124	1.43	+1.2%	122	0.00	+0.0%
Town Centre	35	52	2.04	+48.3%	35	0.00	+0.0%	37	1.07	+4.6%	37	0.84	+4.4%	35	0.00	+0.0%

Categories of output are marked in bold.

followed by A2 (2.0%), B2 (1.67%) and B1 (1.39%). B1 has the highest ratio of "variant" cells to "mostly invariant", i.e. the highest level of spatial uncertainty per unit development. Fig. 4 shows an overview of the spatial distribution of variation for the region around Koper city. Development "hotspots" are the port region and the sub-urban areas, which is consistent with predicted land-use change in Section 3.2, Fig. 3. There is a large amount of variant area under A1, which extends into the prime agricultural areas east of the city (as further discussed in Section 3.4). Under the other scenarios, variability is more strongly concentrated around regions that are mostly developed.

3.4. *Loss of agricultural land*

The amount of good agricultural land decreases in inverse proportion to the increase in AS for all the scenarios, with the highest loss in A1 (≈600 hA) and the lowest loss in B1 (≈220 hA). Fig. 5 shows a breakdown of the cells that replace good agricultural land in each scenario. The majority of good agricultural land is lost due to commercial and industrial development (93% in A1, 95% in A2, 91% in B1 and 88% in B2), with residential development only accounting for the small remainders (7% in A1, 5% in A2, 9% in B1 and 12% in B2). In the BAU scenario, which shows the largest loss of good quality agricultural land, low density residential is by far the largest replacement (60%).

3.5. *Residential dynamics and quality-of-life*

The overall QoL (Equation (1)) increases for all scenarios (except A1) over the first five years and then steadily decreases until 2030, see Fig. 6(a). The Gini coefficient (Ogwang, 2000) shows that under all scenarios, the inequality between the highest and lowest utilities increases, see Fig. 2. Under A2, B1 and B2, the Gini curve trends downwards for the first few years, indicating a decrease in inequality.[7]

The initial increase in the residents' utility is hypothesised to arise from population growth, with residential development being driven by the agents' preferences, and hence affording higher utility. This can be seen in the scores of new agents (Fig. 6(a)), which are in all cases higher than the population average. This creation of more desirable locations gives inequality between existing and new residents, leading to the increasing Gini coefficient, since new residential agents entering the model are placed into newly developed areas.

Based on the changes in QoL scores (Fig. 6(b)), we can analyse the drivers of this change. Taken in rough order of significance, the largest absolute change is a decrease in QoL due to less access to green space, driven by the increase in distance shown in Fig. 6(c). Since new residents obtain high utility scores, this implies that while new residential developments occur with good access to green space, existing residents are slowly surrounded with industrial and commercial development. This hypothesis is supported by the observation that the largest changes occur in A1 and A2, which have the largest amounts of industrial and commercial development.

The second largest change is in access/distance to shops, which is also negative; the distance to shops steadily decreases, most

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[7] Note that the Gini coefficient is sensitive to translations of the input values. Utility values come from a conjoint analysis process, which explicitly centres values around 0, so the absolute value of the Gini coefficient cannot be discussed. However, changes from a baseline value are still relevant.

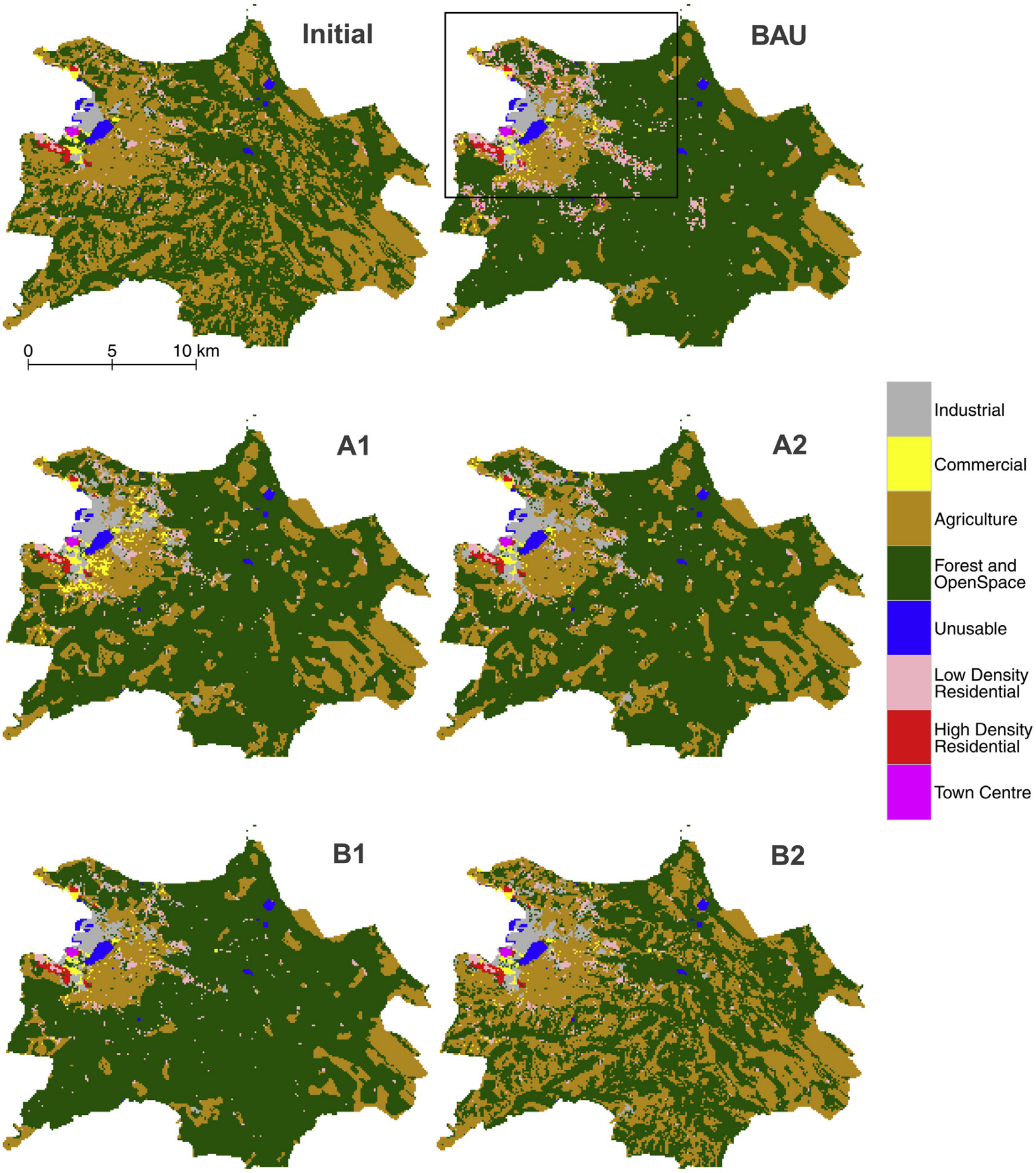

Fig. 3. Exemplar maps of modelled land-use under different scenarios for 2030. Each map is from a single model run. The black rectangle denotes the area used for Fig. 4. The "Unusable" class is an aggregation of Water, Wetland and Mineral Extraction classes to simplify the legend.

strongly in A1, due to the creation of new commercial areas.[8] Due to the heterogeneous and non-linear responses of agents to the presence of shops (Robinson et al., 2012), this causes a reduction in QoL.

The next strongest driver of utility change is noise. Although the partial utility for noise increases (Fig. 6(b)), and residents prefer quieter areas, the number of cells in the low- and medium-noise categories decreases in all scenarios, with a corresponding increase in high-noise cells. From this it can be deduced that although the landscape is becoming noisier, noise is concentrated in areas away from residential development. It should also be noted that there are no new roads and railways created in the model, which are some of the strongest noise sources. The moderately higher levels of noise in A1 indicate that the creation of a lot of LDR areas allow residents to live in areas with less noise, although this is not a strong driver.

Finally, the indicator for access to public transport shows little variation in any scenario. There is little change in the average distance to public transport (Fig. 6(c)) and the only creation of new public transport access points in the model is when TC is built, which, as previously noted, is very rare. This implies that the minor changes in distance and utility are due to building close to existing public transport access points.

By contrast, the BAU experiment shows very different dynamics from the scenarios; population growth is greater than in any of the PLUREL scenarios, almost doubling over 30 years. The average utility strongly increases, mostly driven by better scores

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[8] Although TC provides shops, the amount of TC created is very small, typically less than 2 cells, see Table 3.

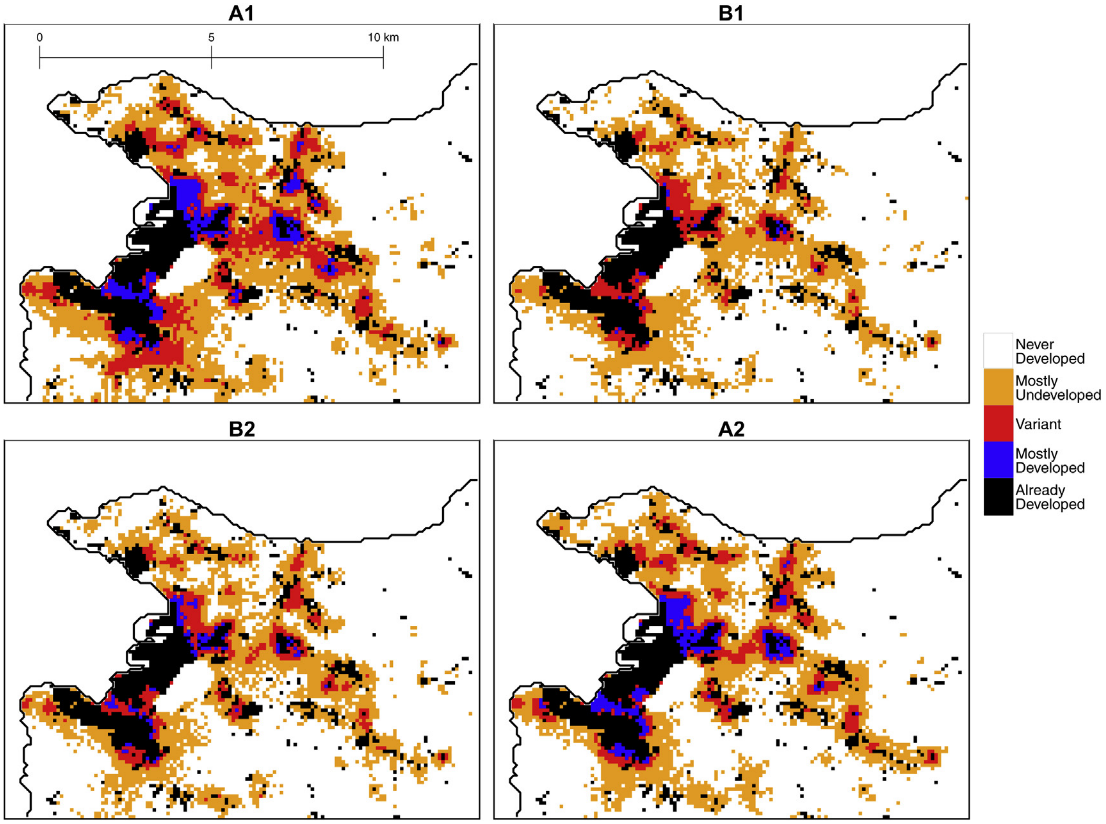
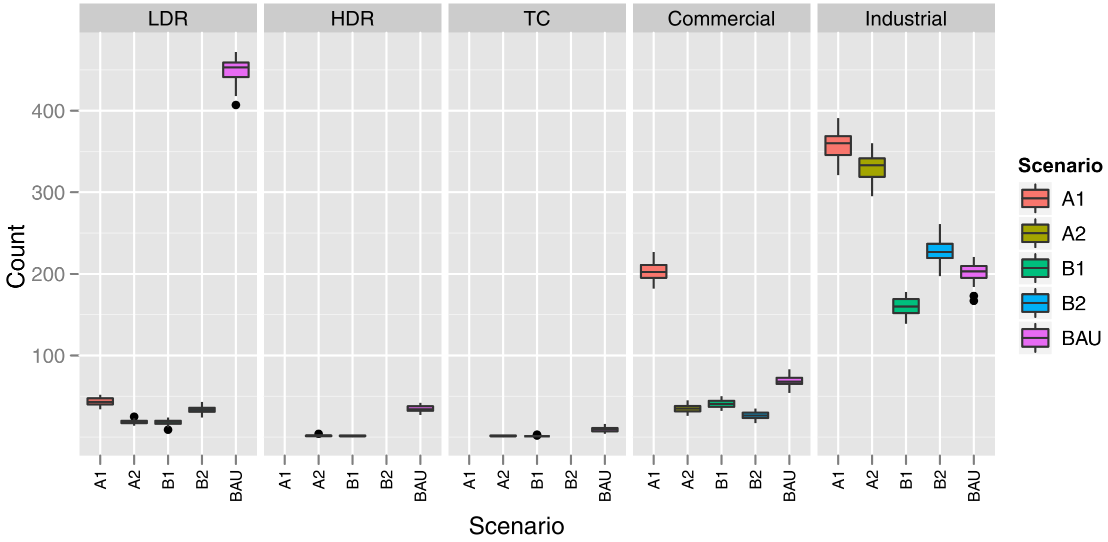
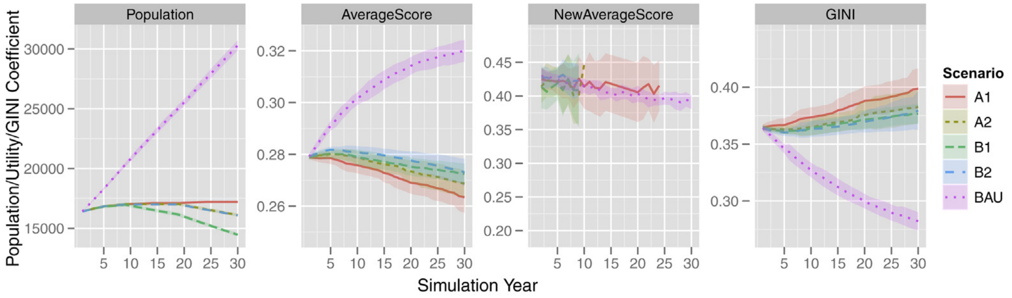


Fig. 4. Variant and invariant cells around the city of Koper with $\theta = 0.3$ based on artificial surface expansion averaged across 30 runs. Initially undeveloped cells can be: never developed ($p = 0$), mostly undeveloped ($p < 0.3$), variant ($0.3 < p < 0.7$) or mostly developed ($p > 0.7$).

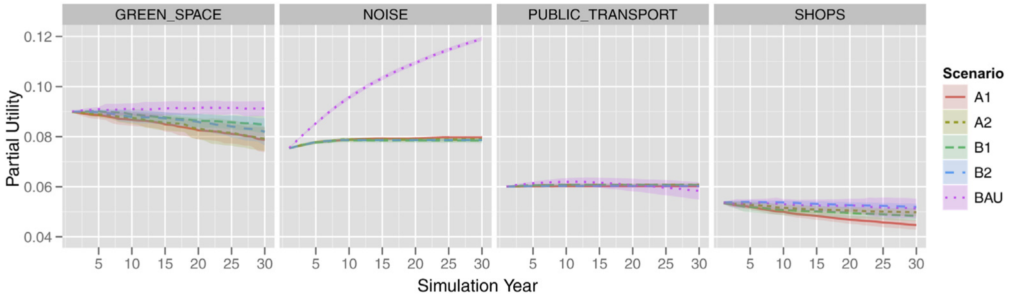


	A1		A2		B1		B2		BAU	
Industrial	358	(18.5)	331	(16.6)	161	(10.3)	229	(16.1)	192	(5.05)
Commercial	204	(11.6)	35	(4.4)	40.8	(4.5)	26.7	(4.6)	63.8	(2.9)
LDR	43.2	(5.3)	18.5	(2.6)	18	(3.2)	33.6	(4.3)	452	(5.0)
HDR	0	(0)	1.76	(0.8)	1.5	(0.7)	0	(0)	40.4	(2.3)
TC	0	(0)	1.43	(0.6)	1.29	(0.6)	0	(0)	10.8	(0.8)
Total	605.3	(23.8)	387.1	(18.5)	220.9	(10.3)	289.2	(14.7)	759.6	(3.91)

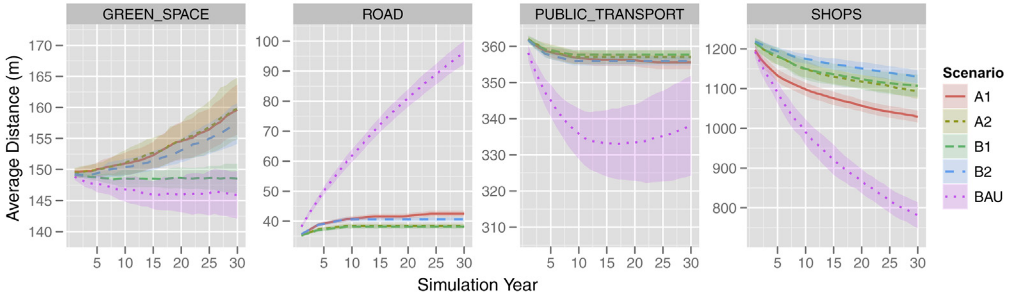
Fig. 5. Breakdown of cells that replace good quality agricultural land (standard deviation in brackets).



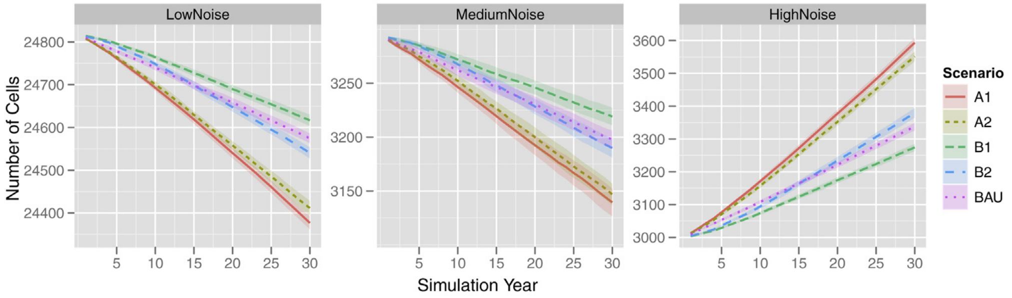
(a) Population change over time, with aggregate scores for current utility, the utility that new residents obtain, and the GINI coefficient for the population



(b) Population averages for QoL partial utility scores



(c) Average distances from residential cells to points of interest



(d) Numbers of cells in each noise category under the four scenarios

Fig. 6. Population and QoL graphs, along with the underlying distance and noise attributes. (a) Population change over time, with aggregate scores for current utility, the utility that new residents obtain, and the GINI coefficient for the population. (b) Population averages for QoL partial utility scores. (c) Average distances from residential cells to points of interest. (d) Numbers of cells in each noise category under the four scenarios.

for noise and green space, which can be ascribed to a huge amount of residential development in attractive areas. An interesting dynamic is the initial decrease in average distance to public transport, followed by a steady increase. It appears that initial development fills in some of the area close to existing public transport access points, with later development being driven away by other QoL indicators, especially noise and access to green space. The emphasis on residential development here (as opposed to industrial) means that the noise levels are in the middle of the range of outputs for the scenarios.

In summary, the overall simulated QoL decreases across all the scenarios until 2030, which can be attributed mainly to the loss of green space, and the non-linear preferences of the agents with respect to shops. However, simulated new developments take place in more desirable areas, since there is a strong connection between agents' preferences and new housing developments. Finally, even in situations where the average QoL score does not change, there is still an effect of the QoL indicators on residential household location, so this should not be taken as meaning that the indicators have no effect on the model.

4. Discussion and conclusions

4.1. Plausibility of model results

The overarching aim of the work presented in this paper was to evaluate the impacts of potential changes in LUCC on QoL and the loss of agricultural land. Thus the ABM presented here was designed as an exploratory tool to simulate a range of possible futures. Application of the model adopted one of two approaches: computational experiments (Robinson et al., 2012) and scenario analysis. The concerns of local stakeholders were used to guide the model development and to identify appropriate impact and output measurements, as well as the types of processes and constraints occurring in the study area.

The conceptual model structure (related to Schwarz et al., 2012) was developed to represent the land-use system parsimoniously, but with an appropriate level of empirically grounded realism, while also accounting for severe data limitations. The simplified design enabled parameterisation with available data as well as the adoption of regression parameters for non-residential development locations, with clear performance criteria (R^2 and predictive power under cross validation). Despite some parameters—the QoL indicators—having been defined without a clear performance evaluation (noise pollution being an exception), computational experiments were used to systematically alter parameter values and assess the impacts of different component behaviour in isolation and in combination with others (i.e., changing the types of agents present in a model run as well as their behaviour).

Having formalised the model assumptions, their implications, and approximated observed behaviours, the model was refined for scenario analysis by establishing boundary conditions based on a well established model applied at a larger spatial extent (Rickebusch, 2010; Skirbekk et al., 2007). The approach adopted here has parallels with the "Ten iterative steps in development and evaluation of environmental models" (Jakeman et al., 2006). Readers are referred to Robinson et al. (2012) for a fuller understanding of model parameters and their effect on outputs.

When working with scenarios, assessment of quality takes into account different questions. The narrative storylines used here were based on an exploratory approach (Börjeson et al., 2006), but included participatory development, following Rounsevell and Metzger (2010, Table 1). This implies high *salience* – especially since the model setup was adjusted to take account of stakeholder needs; medium *credibility*, due to the lack of formalised uncertainty analysis; and medium *legitimacy*, as a lot of weight is given to scenario experts, but stakeholders were included explicitly in the model design process.

4.2. Comparison with "business-as-usual"

The BAU scenario presented previously (Robinson et al., 2012) was a direct extrapolation of current trends, under the assumption of spatio-temporal stationarity. There are some areas where BAU produces similar outputs to some or all of the scenarios (noise impacts, changes in non-residential areas), some areas where it represents a marginally more extreme scenario (amount of artificial surface, some partial utilities), and many areas where it displays completely different results (population, QoL, Gini, distance to features etc.) compared with the scenarios. Arguably, the most fundamental differences are due to differing assumptions about population change: Koper has seen a strong influx of people in recent years (Perpar, 2009), but the population scenarios used here (Skirbekk et al., 2007) imply that this is a temporary effect, and the population will cease to expand as rapidly in the future. This disagreement is driven by different types and scales of data: the current trend is locally accurate, but has little context to make it robust when extrapolated forward in time. Other European scenarios (e.g. Westhoek et al., 2006) that include a much broader European context, as well global population analysis (Cohen, 2003), agree with this reduction in population growth, suggesting that the scenarios presented here are more plausible than an extrapolation of observed data. Another large difference is the level of land abandonment observed. Here, the 2000–2007 rate is taken as an extreme value for parameterising the scenarios, with all except B1 showing a lower rate of decline. This reduction in abandonment is in keeping with the idea that development can lead to the maintenance of peri-urban agriculture, although with increased emphasis on high value production and/or hobby farming (Simon, 2008; Houston, 2005).

4.3. Population dynamics and residential development

In Section 3.5 incoming residents were seen to be consistently able to find higher QoL in new developments, even though the average QoL of the population was declining. This indicates that the existing housing stock may not be arranged according to the subset of QoL indicators included in the social survey used to parameterise the model. This mismatch may indicate that, while important, QoL is not the only determinant of existing urban form. Other factors such as planning constraints, economics, and workplace location are likely to also play significant roles (Frank, 2004; Li and Liu, 2007; Krizek, 2003; Meen and Meen, 2003), often leading to complex functions (e.g. Joerin et al., 2001).

Alternatively, the mismatch between the BAU experiment and the scenarios could be attributed to changing preferences over time, which could only be tested through longitudinal studies of QoL indicators. Alternatively, the dichotomy between new and old residents may be attributed to generational changes in preferences or shifting preferences due to changing norms, technology, or demographics (e.g. Dahms and McComb, 1999). Longitudinal studies of QoL would enable our model to be empirically informed to account for changing preferences and the need for such data is becoming increasingly recognised. For example, QoL is increasingly being used to report on the development of countries; in particular, the OECD's "Better Life Index"[9] (OECD, 2010) seeks to replace GDP as a prime indicator of a country's progress. This increased focus on QoL issues should increase the availability of data in this area, and allow future models to deal with trends in wellbeing indicators (Helliwell, 2003).

There is also the issue of demographics: although the modelling framework is capable of simulating a demographic model, the available data do not support the parameterisation of such a model. The ageing of the European population (Cohen, 2003), in particularly in rural areas is likely to have a strong effect on rural land use (Westhoek et al., 2006).

Furthermore, the ABM approach enables the encapsulation of traditional land-use modelling approaches (e.g. CLUE (Verburg

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[9] http://www.oecdbetterlifeindex.org/.

et al., 2006a), which uses a top–down approach to land-use allocation) in addition to bottom–up representations of actors and their decision-making strategies that affect LUCC. The ABM approach illustrated here has the capacity to include changes in social preferences, but is constrained by the lack of empirical data about these changes. Because of ABMs ability to represent preferences, interaction, and human decision-making processes at the level of individual micro-level actors, it enables a bottom-up representation of land-use allocation, which gives rise to urban form.

4.4. *Role of planning*

The model presented here has no explicit representation of planning. However, the land-use change ratios for the different scenarios can be interpreted as the net effect of interactions between planning constraints and the actions of developers. When considering the loss of good agricultural land, the major driver of loss is non-residential development (see Section 3.4). This result suggests that planning controls affecting the location of commercial and industrial development would reduce the loss of good agricultural land. In addition, the loss of green space in proximity to residential areas causes a decrease in general perceived QoL, see Section 3.5. Thus, planning initiatives, such as the creation of urban green areas, may be able to reverse this trend. In general, planning can be used to alter the development of urban morphology in ways that help to maintain residential QoL.

The changing nature of Slovenian planning discussed in Section 2.1 highlights one of the advantages of scenario analysis over to projecting current trends, as scenarios allow for better representation of these types of social and policy dynamics. The scenarios presented here include some representation of the strength of central planning and organisation: for example the A1 scenario indicates a return to pre-2003 practises, especially uncontrolled construction of dispersed buildings (Table 2). The model then demonstrates that increasingly dispersed building is likely to result in decreased QoL metrics, greater QoL inequality in the population (Fig. 6(a)) and increased noise (Fig. 6(d)).

4.5. *Agent based modelling for scenario analysis*

Different types of models have been used in LUCC scenario studies (e.g. see Verburg et al., 2006b). An ABM approach was adopted in the presented analysis due to a number of advantages in system representation that are not available in statistical and equation-based modelling (e.g. Van Dyke Parunak et al., 1998) Specifically, an ABM approach is able to harness landscape and agent heterogeneity in terms of both agent attributes and decision-making structures. By working with agent heterogeneity, ABM can be used to explore how alternative distributions of agent profiles respond to scenarios and produce LUCC (e.g. Brown and Robinson, 2006) and similarly how different decision-making structures may impact land-use choices. A second strength of ABM is its ability to capture interaction and that "more is different" (Anderson et al., 1972). In the presented model, residential household agents interact through 1) substitution, i.e., a space occupied by one agent is no longer available to another agent and the second agent is forced to substitute a less preferred location in place of its optimal choice; 2) neighbourhood effects, the location of different land uses influence agent decisions and subsequent land-use change, i.e., industry attracts other industries but generates noise that repels RHAs; and 3) RHA household preferences drive developer decisions.

The incorporation of these interactions and feedbacks among agents, and heterogeneity, provide the capacity for ABM to represent non-linear dynamics (Holland, 1996), path dependence (Brown et al., 2005), and self-organisation processes that are typical of complex socio-ecological systems (Murray-Rust et al., 2011; Rounsevell et al., 2012a). These types of complex systems are not analytically tractable and cannot be represented using fixed equations. Furthermore, agents are able to adapt in response to the changing environment of a scenario. Thus, agent behaviour is not fixed at the outset of a model run and the subsequent aggregate behaviour of the system can change over the duration of a model run, which provides a more plausible representation of observed actor and system behaviour.

The model presented here is only one example of how ABM can be used to explore the consequences of scenarios, and because of data limitations, the model only reflects a small proportion of the possibilities of ABM as a scenario analysis tool. Work such as Fontaine and Corentin (2010) which uses an ABM to explore demographic scenarios directly illustrates how modelling individual demographics and preferences allows detailed scenarios of urban growth to be modelled, while (Barreteau et al., 2001) illustrates how ABM, coupled with scenarios can help stakeholders to engage in the modelling process.

4.6. *Conclusions*

Using a newly developed ABM of LUCC we were able to assess the potential impacts of future changes in population and industrial and commercial growth on the loss of agricultural land and residential QoL. Our results suggest that industrial and commercial development location decisions have the greatest impact on the loss of high-quality agricultural land across all scenarios. We also found that the QoL differed between established residents and those new to the region such that newer RHAs obtained a higher quality of life, and that the inequality in QoL scores increased. These and other outcomes are specific to the parameterisation of our model, however the model is flexible in design and available for application to other locations that may demonstrate that our results are more generalisable than can be stated at this point.

Current LUCC research employs scenario-based analysis to explore possible future trends and impacts by defining a coherent set of plausible future socio-economic development pathways. This paper contributes to the existing body of LUCC scenario literature in a number of ways. First, the use of scenario analysis is shown to produce results that are a more coherent representation of plausible futures than those based on assumptions of stationary future development ("Business As Usual"). Secondly, the method presented here outlines a structured approach for translating qualitative story lines into quantitative model inputs. Thirdly, the approach demonstrates how an ABM can be operationalised to evaluate and assess the impacts of scenarios by integrating a broad range of knowledge and data sources. Furthermore, the use of ABM and social survey data together enabled the representation of household preferences and hence the identification of hotspots of future development and LUCC. By modelling a variety of agent types and their relationships to their environment, future scenarios were simulated with detailed spatial and temporal variations in socio-ecological outcomes.

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Appendix A. Development maps and land use trajectories

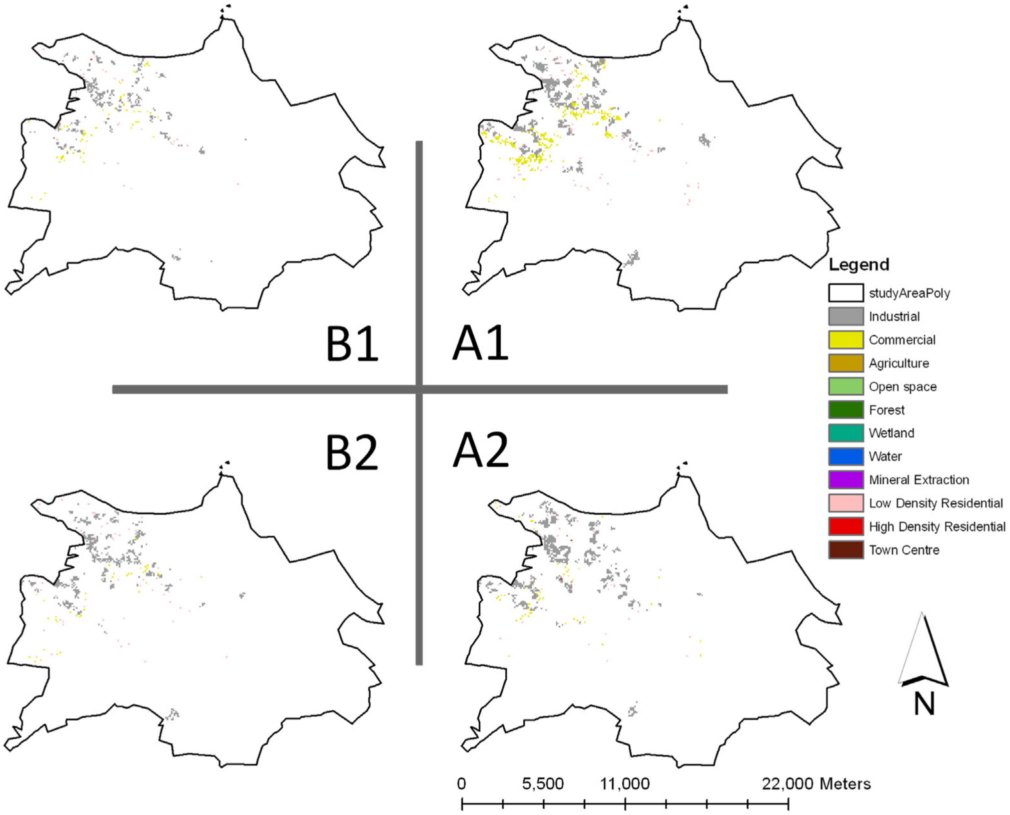

Fig. A.7. Location and type of artificial surface creation under different scenarios for 2030. Agriculture, forestry and previously developed areas are coloured white.

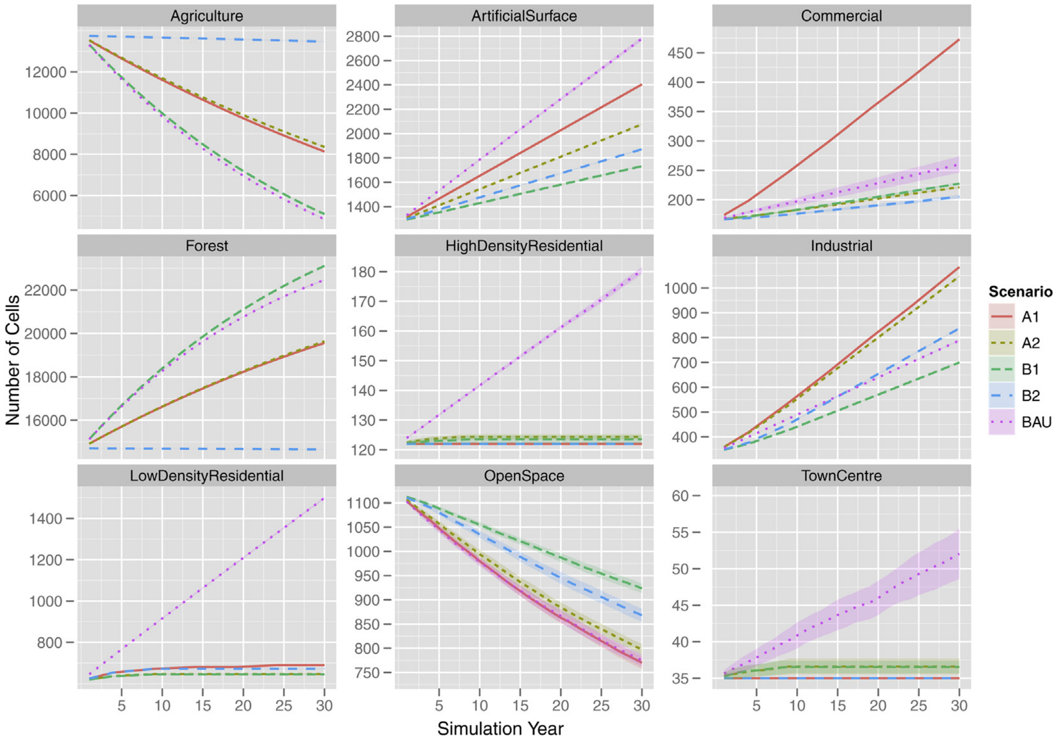

Fig. A.8. Area of land-use classes under each scenario, averaged over 30 runs. Lines represent the mean of each scenario, and the shaded areas delimit the standard deviation. The SD is small for most land uses as the model can reproduce the rates set up in the scenario; HDR and TC appear to have higher SD due to the small number of cells created.

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