

Title

Integrated modelling of urban spatial development under uncertain climate futures: A case study in Hungary

Authors

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Abstract

To provide fundamental decision support information for climate risk assessment in Hungary, an urban spatial development model of land cover change and population age structure dynamics was developed and applied to local integrated scenarios of climate change and stakeholder-derived socio-economic change. The four integrated scenarios for Hungary produced contrasting projections for urban patterns to 2100, but peri-urbanisation around Budapest was estimated to occur under all scenarios, together with a decline in working age population in the centres of the capital and major towns. This suggests that future urban planning needs to take into consideration the potential for underutilised urban infrastructure in the centre of the capital and pressures for social service provisioning in its outskirts. The integrated scenarios and model developed can be used in future studies to test the effectiveness of inter-sectoral policy responses in adapting urban planning to multiple climate and socio-economic challenges.

Keywords

Integrated modelling; Urban land cover change; Population distribution; Integrated socioeconomic and climate change scenarios; Stakeholder; Hungary;

Highlights

- An integrated model was developed of urban land cover change and population dynamics.
- The model was applied to four integrated climate and socio-economic scenarios for Hungary.
- Local stakeholders were closely involved and this ensured the plausibility and credibility of model projections.
- Contrasting projections for urban patterns were produced to aid climate risk management.
- Recommendations on good practices in collaborative environmental modelling were made.

1 Introduction

Public and scientific concern about the threat of climate change to urban areas and urban residents has become increasingly widespread: the world's urban population (over half of the total population) is expected to face more complex and often inter-related problems related to water scarcity (Schewe et al., 2014), energy demand (Christenson et al., 2006), public health (McMichael et al., 2006), amongst others. Many of these problems occur together, or are closely related to one another, in urban environments and so, it is important to understand how urban and residential development patterns might evolve in the future, and how this affects the consequences of climate change on cities.

Effective policy responses to climate change need to take account of, and coordinate, different perspectives, knowledge and interests across sectors and governance levels (Adger et al., 2005; Hurlimann and March, 2012). Knowing the role of regional and local-level actors is essential in understanding responses to policy, socio-economic and environmental drivers in cities (Antonson et al., 2016; Eikelboom and Janssen, 2013; Kumar and Geneletti, 2015). Targeted responses

may be required at regional to local levels to tackle ‘vulnerability hotspots’ where climate change impacts are particularly significant (Rannow et al., 2010). The capacity of, and interplay between, regional and local level institutions often plays a role in the functioning of multilevel governance and actions to promote such targeted policy (Hanssen et al., 2013; Vedeld et al., 2016). These considerations have resulted in a rapidly growing number of initiatives to develop lower level climate change responses, e.g., the ‘Mayors Adapt’ (<http://mayors-adapt.eu/>) and the ‘100 Resilient Cities initiative’ (<http://www.100resilientcities.org/>). However, such ambitions remain beyond the capacity of most local governments, owing to inadequate local-level information to support decisions and a lack of technical knowledge exchange across levels and sectors (c.f. Kumar and Geneletti (2015), and references therein). Assessments exploring urban development in response to climate change are urgently needed, in order to help support local governments in developing adaptation plans.

Scenario-based model projections of future land cover change are one way of supporting decision-making for adapting to climate change (Harrison et al., 2016; Prestele et al., 2016). Scenario analysis provides information about future uncertainties in a structured and consistent manner, which can support decision-makers in evaluating policy alternatives towards robust decisions (Krueger et al., 2012; Schwarz, 1991). A long-term time scale (decades or centuries) is often required in developing scenarios related to climate change and land use change, as the climate system itself responds slowly to changes in greenhouse gas concentration (Moss et al., 2010). Furthermore, urban planners often need to consider longer time horizons in establishing infrastructure projects. Engaging local stakeholders in the co-creation of scenarios provides qualitative insight into future changes that are plausible and relevant. The co-creation of scenarios has been widely adopted in other studies, e.g. Reginster and Rounsevell (2006), Volkery et al. (2008), Harrison et al. (2015) and Kok and Pedde (2016). Resources, knowledge and expertise brought by stakeholders can help to build trust and strengthen the feasibility of adaptation policies (Moss et al., 2010; Tompkins et al., 2008; Voinov and Bousquet, 2010; Voinov et al., 2016). Neglecting the engagement of stakeholders in climate change assessments may limit the effectiveness of policy responses and potentially result in policy failure (Vogel and Henstra, 2015).

Understanding how cities adapt to climate change is at least partly dependent on knowing where people will live in the future. Hence, projecting plausible long-term trends in both fine-grained urban land cover and population distribution can contribute to improving the assessment of climate risks, and support the development of effective integrated mitigation and adaptation solutions. Existing urban models have focused mostly on projecting land use/cover changes using geostatistical models (Cheng and Masser, 2003; Dendoncker et al., 2007; Jokar Arsanjani et al., 2013b; Poelmans and Van Rompaey, 2009; Verburg et al., 2004; Westervelt et al., 2011), or cellular automata (CA) and agent-based models, in which the decision-making processes of residents and/or policy-makers are embedded (Brown and Robinson, 2006; Fontaine and Rounsevell, 2009; He et al., 2008; Jokar Arsanjani et al., 2013a; Verburg et al., 2002; Vliet et al., 2009). Population is usually treated as an input and a higher level driver of land cover change, while the possible effects of land cover change on the distribution of population at lower (or cell) levels have largely been ignored. White et al. (2012) describe one of the few examples where transition rules about people’s spatial activities were embedded within a CA framework to model both land cover and population at the same resolution.

A multi-scale modelling approach is important for supporting urban decision-making across different governance levels. A fine resolution model has greater flexibility in scaling-up local-level projections of urban pattern to higher levels and downscaling the effects of existing climate policies and action plans, most of which are long-term and have been developed for national or higher scales. In this study, we focus the model development on projecting long-term urban development patterns for an entire country (Hungary) at a spatial resolution that is fine enough to represent each local administrative unit. This goes beyond most existing urban models that have been developed for smaller regions, such as a province (Verburg et al., 2002), a river delta (Weng, 2002) or a city (Cheng and Masser, 2003; He et al., 2008). Nationwide studies with fine resolution applications are rare, with studies in the Netherlands (Verburg et al., 2004) and Belgium (Dendoncker et al., 2007) being notable exceptions.

Including the impacts of climate change in modelling urban development has rarely been undertaken previously because of a lack of understanding of how climate change affects either urban land cover or population distribution (Black et al., 2011b; Vari et al., 2003). For example, some extreme weather events, such as floods and landslides, can cause direct damage to urban infrastructure. However, properties and populations may remain in hazard prone areas because people have insurance cover, rely on the government to mitigate their risks, decide to stay as the risks do not outweigh the benefits of a more favourable location, or simply cannot bear the costs of relocation. Droughts and heatwaves may have less direct impacts on urban land cover and are less likely to elicit migration/relocation, as they could possibly be managed or people could change their behaviour to adjust to these challenges (Black et al., 2011a; Fielding, 2011). In this study, given the time period considered (up to 2100), short-lived and localised extreme weather events were not modelled explicitly. However, their aggregated effects on the regional economy through time were considered. Empirical evidence has shown that frequent extreme weather events are likely to cause significant damage to the national economy (Brown et al., 2013), which may influence urban development at some level (Reginster and Rounsevell, 2006).

The main purpose of this study is to provide scenario-based future projections of urban land use and population distribution patterns at a fine spatial resolution for the whole of Hungary. At the local level, the challenges arising from climate change are already apparent, with some parts of Hungary suffering from flooding, storms, heatwaves, and water shortages (Li et al., 2017). Information about the range of plausible, but uncertain, futures facing Hungary is fundamental in supporting multi-level climate change adaptive decision-making and cooperative land use management. To this end, we developed a model that integrates advances in urban development modelling. A set of integrated scenarios of potential long-term climate and socio-economic changes (up to 2100) were co-created with local stakeholders. The stakeholders also participated in reviewing the model structure and evaluating the accuracy and usefulness of model projections. We analysed the projections obtained under different scenarios and identified those parts of Hungary that are likely to face similar challenges in urban development regardless of the scenario.

2 An integrated model for urban development

2.1 Model structure and workflow

This study is based on an integrated model that simulates the spatial dynamics of urban land use/cover change (including residential, commercial and urban green surface areas) and population dynamics for Hungary (named ALLOCATION). The ALLOCATION model consists of three sub-models operating at/across different spatial scale levels i.e., the national, regional and local levels (Figure 1, note: the NUTS3 and LAU1 levels are only for display purposes and have not been used in the current study). The general workflow is described in Figure 2. The model is based on a 1 km² cellular grid, has a baseline year of 2010 and simulates urban land cover change with decadal time steps up to 2100. The 1 km resolution was chosen so that each town, village and district of Budapest could be represented by at least 1 cell. At the beginning of each time step, the model calls the economic change sub-model (section 2.2.1) to calculate changes in the NUTS2-level social, economic and demographic factors. The urban land cover change sub-model (section 2.2.2) then executes to: (i) estimate changes in the extent of the NUTS2-level artificial land cover based on the outputs from the economic change sub-model; and, (ii) allocate these projected changes to the 1 km cells. After the cell-level land cover extents are calculated, the population distribution sub-model (section 2.2.3) simulates residential preferences for different age groups based on the distribution of artificial land covers and redistributes the NUTS2-level population.

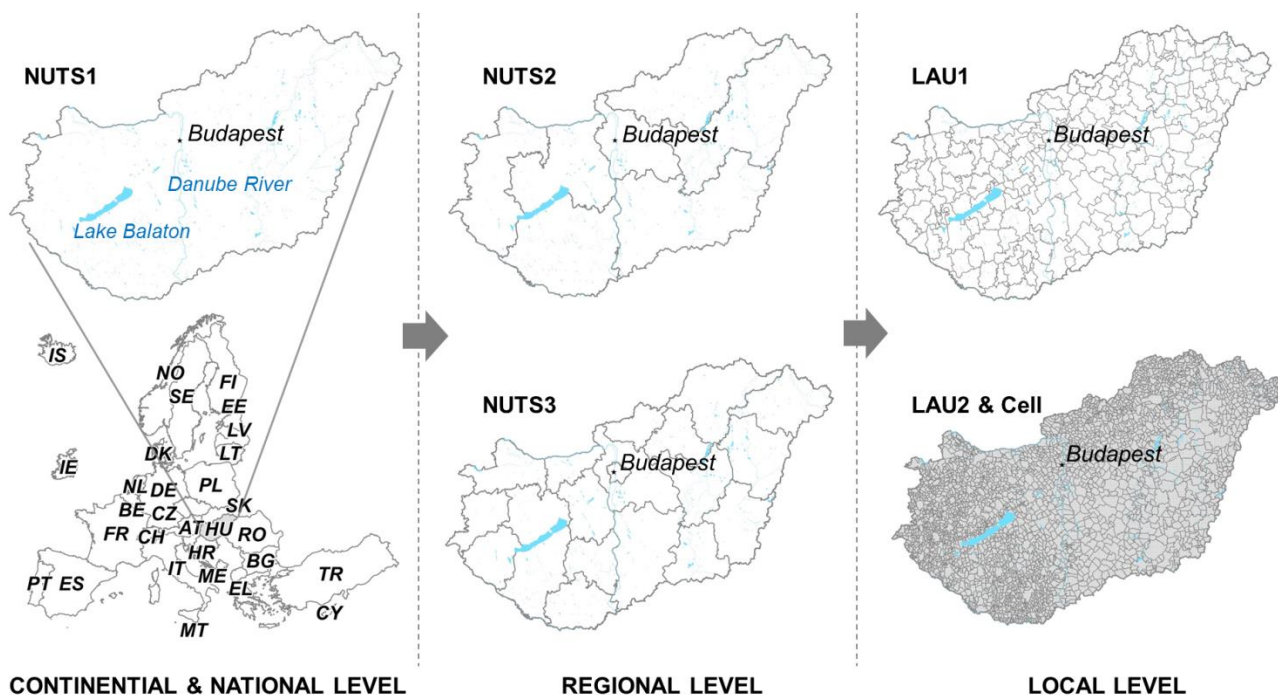


Figure 1 Study region and definition of levels

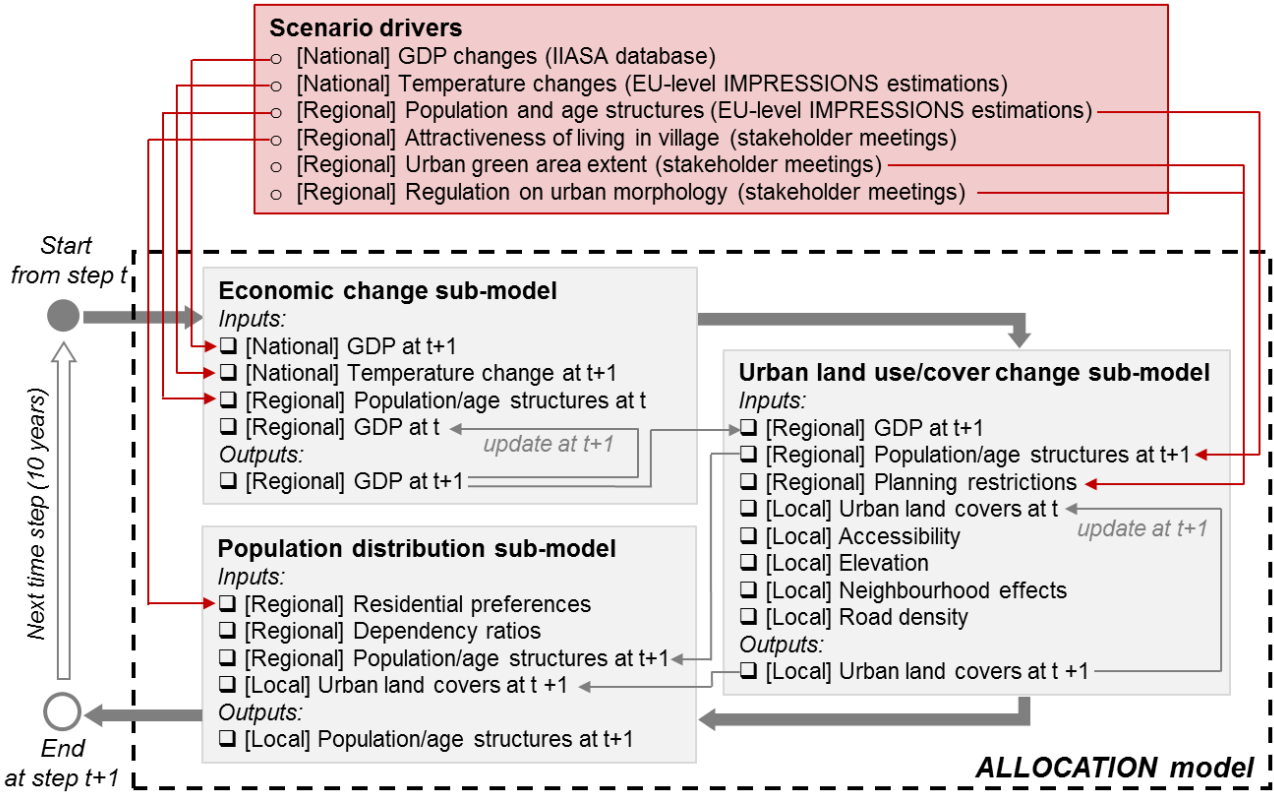


Figure 2 Model structure, parameters and linkages to scenario drivers

2.2 Model components

2.2.1 Economic change

The population distribution sub-model uses the national-level GDP data to estimate the ratio of climate change damage to GDP ($D(T(t))$) using Nordhaus's temperature damage function:

$$D(T(t)) = 1 - 1 / (1 + 0.0028388 * (T^2(t))), \quad (1)$$

where $T(t)$ is the mean temperature increase above the pre-industrial level at time step t (Golosov et al., 2014). The sub-model next disaggregates the revised GDP to the NUTS2 level using a simple empirical function derived from a linear regressive model based on the national and NUTS2-level GDP and population data from 2000 to 2010 (from the Hungarian Central Statistics Office, KSH). The GDP of a NUTS2 region in time step t is estimated as: $GDP\%(t) = 0.8899 * GDP\%(t-1) + 0.9348 * (Pop\%(t-1) * Pop\%(t))$ (adjusted R-squared = 0.99), where $GDP\%(t)$ is the ratio of the GDP of the NUTS2 region to the GDP of the whole of Hungary and $Pop\%(t)$ is the ratio of the population of the NUTS2 region to the population of Hungary at time step t .

2.2.2 Urban land cover change

This sub-model simulates cell-level urban land cover changes based on changes in NUTS2-level economic and demographic factors. It was developed using the CORINE land cover datasets (CLC) at 100m resolution for 2000, 2006 and 2012 (from the European Environment Agency, EEA, and the Hungarian Institute of Geodesy, Cartography and Remote Sensing, FÖMI). Three types of urban land cover were distinguished: (i) residential ('Urban fabric', CLC class 111-112), (ii) commercial/industrial ('Industrial or commercial units', CLC class 121) and (iii) urban green/leisure ('Green urban areas', CLC class 141 and 'Sport and leisure facilities', CLC class 142). The grid reference system was based on the European Environment Agency (EEA) 1 km² reference grid and used to extract the selected CLC land cover classes. The changes in these CLC datasets across time slices were analysed to develop the main empirical functions.

Function 1 This function estimates changes in the NUTS2 level demand for urban area based on changes in GDP and population, following the methods and assumptions used in (Reginster and Rounsevell, 2006). Three regressive functions were developed to project the changes in the three urban land cover types. Additional GDP and population data were collected from the KSH census database. In the functions for residential (adjusted R-squared = 0.99) and

industrial/commercial (adjusted R-squared = 0.96) land cover changes, per capita GDP and the extent of existing urban land cover in the region are the key positive predictors. In the function for green/leisure land cover change (adjusted R-squared = 0.99), the extent of industrial/commercial land cover, children (0-14) and working age (15-64) populations are negative predictors.

Function 2 This function estimates a cell's potential to be developed into different urban land cover types. Logistic regressive functions were calculated, which have been widely used in the development of previous urban growth models e.g., in Hu and Lo (2007), Jokar Arsanjani et al. (2013b) and Verburg et al. (2004). A wide range of explanatory variables were collected from various sources to describe (i) the accessibility (to urban centres, lakes and rivers), elevation, and neighbourhood urban composition of the cell, and (ii) the local (LAU2, municipality or equivalent unit, Figure 1) urbanisation level and densities of roads and railways. We examined the collinearity in the spatial database and subdivided it for function development and evaluation. To account for spatial autocorrelation, two additional steps were taken. First, the cell-level geographical coordinates were included as explanatory variables, as spatial autocorrelation can be alleviated to some extent by introducing location into the function (Hu and Lo, 2007). Second, following Cheng and Masser (2003) and Verburg et al. (2004), a restricted spatial sampling scheme was designed to ensure that the sub-dataset used for function development contained minimum spatial autocorrelation between the independent variables. The predictive performance of the logistic functions was evaluated using AUC (the area under the curve) values. Cut-off values to divide predicted probabilities of land cover increase into occurrence or non-occurrence were set when the sum of the logistic function's sensitivity and specificity was maximised (Liu et al., 2005). We built functions for each of the three urban land covers in each of the seven NUTS2 regions in Hungary. Different sets of predictors are included in the final models for different regions and land cover types (see the Electronic Supplementary Materials 1 for the explanatory variables and coefficients). The AUC values of the final models were mostly (26 out of 27) greater than 0.8, indicating good predictive power.

Function 3 This function was built to test the theoretical effects of planning regulations on urban morphology. In real world cases, compact development may be pursued by local authorities to increase residential urban density and prioritise developments close to the urban core, in order to reduce travel distances and save energy (e.g., the concept of "Compact City") (Reginster and Rounsevell, 2006). This type of planning regulation is introduced as $C_i = \rho_i^\delta$, where $\rho_i \in [0,1]$ is the proportion of the land cover in a cell i 's neighbourhood (3km x 3km), and $\delta \geq 0$ is the parameter describing the intensity of the effect of planning on compactness. Thus, $\delta = 0$ indicates no regulation, and; as δ increases the urban patterns' shift from sprawled to compact. The parameter can also be regarded as an abstraction of the "optimal neighbourhood density" concept explained in previous studies (Caruso et al., 2007; Caruso et al., 2005), representing a preferred level of residential density (relative to non-urban area) in the neighbourhood, which can be affected by spatial planning regulations. In Hungary, suburbanisation has been strong from the mid-1990s to around 2005, following a shift in the government's strategy towards more compact development to meet the demand for public services by a growing population (Stanilov and Sýkora, 2014). The outskirts of the Budapest region, however, remained popular for residential developments even after 2005, based on changes observed between CLC datasets. Despite the introduction of a major initiative to prevent suburban sprawl in 2005 in the 'Act LXIV on Spatial Planning in the Agglomeration of Budapest', the seven-year long negotiation to pass this law has still allowed a steady conversion of green and agricultural land into urban areas in the suburban periphery of Budapest. Based on these facts, in the model the initial value of δ for 2000-2010 was set to 0.6 (medium sprawl, unsuccessful planning regulation) for the NUTS2 region of central Hungary (including Budapest, the capital, and Pest county, which surrounds the capital, Figure 1) and to 0.8 (slight sprawl) for the other regions. The regulation of urban compactness was assumed to influence both residential and commercial/industrial areas.

Thus, this sub-model allocates the projected changes in the extents of the NUTS2-level land covers (estimated by Function 1) to the cell-level based on the cells' growth potential G , which is a multiplication of the developmental potential P (estimated by Function 1) by the strength of planning regulation on compactness C (estimated by Function 2). The spatial allocation rules allow more rapid development in cells with greater growth potential (details in the Electronic Supplementary Materials 1). Only increases are considered for residential and commercial/industrial areas. For urban green/leisure areas, both increases and decreases are allowed, as these areas are managed and can usually be converted into other land cover types. The model projects greater decreases from cells with lower growth potential for urban green/leisure areas, and with greater growth potential for residential and commercial/industrial areas.

2.2.3 Population distribution

This sub-model disaggregates the NUTS2 level, age-structured populations onto the 1km grid. It is based on a disaggregation model (Li et al., 2016b) which integrates residential preferences originating from regional economic theories and takes advantage of recent dasymetric modelling approaches. In the first step, this sub-model allocates working age populations (aged 15-29, 30-49 and 50-64) to inhabitable cells (where residential land is present) based on their age-specific weights given to the different residential preference types. The residential preference (P) is

approximated as a function of land cover density in a cell's neighbourhood, for which the projections from the urban land cover change sub-model are used. Three types of preferences are considered for the social, economic and urban greenery amenities, which are estimated by residential, commercial/industrial and urban green/leisure land cover density in a cell's neighbourhood, respectively. Another set of weights for territorial types is applied to reflect the relative attractiveness of living in the capital (a_c), a town (a_t) and a village (a_v). The second step is based on the pattern projected in the first step. Thus, the allocation of the dependent populations (aged 0-14 and 65+) is driven by their dependency rates (D) to different groups of working age population residing in areas of different territorial types.

Following the data-driven parameterisation method developed by Li et al. (2016b), the model was re-calibrated using the CORINE 2012 database and the LAU2 level population and age structure data from the KSH for each of the NUTS2 regions. The following general rules were applied to redistribute working age populations: (i) all population groups give high preferences to social amenities; (ii) senior adults (50-64) have relatively lower preferences for economic amenities, which is in line with decreased purchasing power found in the literature, and relatively high preferences for urban green amenities, and; (iii) the attractiveness of villages decreases (relative to the capital and towns) as age-class increases. For the dependent populations: (i) children (0-14) depend heavily on young adults (15-29) in the capital and towns, on middle-aged (30-49) populations in towns and villages, and on senior-aged working population (50-64) in the capital, and; (ii) the elderly (65+) depend relatively more on young adults (15-29) in the capital, and on the senior working age population (50-64) in towns and villages (see the Electronic Supplementary Materials 1 for detailed residential preference weights and dependency ratios).

2.3 Model development and evaluation

The integrated model was developed using the Repast Simphony toolkit (version 2.1) and scripted in the Java programming language (North et al., 2013). This toolkit has been widely used in developing cell-based and agent-based models. The empirical functions of the model were developed using the R statistical language (R Core Team, 2012) before integration. Based on the guidance suggested in Bennett et al. (2013), an evaluation scheme was designed for the model which combines both quantitative and qualitative measures. Quantitatively, the model was run for one time step (10 year) with the land cover and population data of 2000 and these projections, i.e., urban land cover extents and age class-specific populations, were compared with observational data around 2010. Predicted changes in land cover extents were compared with the CORINE 2012 data from three perspectives: (i) up-scaled comparisons at the LAU2 (NUTS5) level, (ii) visual comparisons at the cell level, and, (iii) summarised comparisons using distance-density plots (see details in the Electronic Supplementary Materials 2). Projected changes in population and age structure were compared with the KSH's 2011 census data at the LAU2-level only, as finer resolution observations were not available. Qualitatively, stakeholders assessed the overall model structure and the usefulness of model projections during several stakeholder workshops that took place between 2014 and 2016 (introduced in section 3.1, and Figure 3).

2.4 Sensitivity analysis

In this study, the major source of uncertainty lies within the scenarios, due to the inherent uncertainty of future political, socio-economic and technological conditions. A secondary source is related to model uncertainty, which is dependent on the performance of the different model components and the relationships among them. A sensitivity analysis of the integrated model was performed to determine the robustness of our model projections and reveal which parameters are likely to be most effective as drivers for future projections (section 3.2). A simple one-at-a-time sensitivity analysis was performed to examine to what extent the model outcomes are influenced by changes in different parameters. Thus, the projection for the baseline condition was compared with those obtained by tuning each of the selected model parameters (by +10% in this study), while leaving the others unchanged. We firstly compared the key model outputs, i.e., extents of land cover classes and populations of age groups in the capital, towns and villages. Then, following suggestions by (Barreira González et al., 2015), further comparisons were made at the cell level for (i) cell-to-cell agreements, and (ii) the shape, fragmentation and heterogeneity of projections on both urban land cover and population distributions. A detailed explanation of the settings for the analysis and selection of matrices for spatial comparisons is provided in the Electronic Supplementary Materials 3.

3 Scenario development and analysis

3.1 Developing integrated scenarios with stakeholders

Local scenarios for Hungary were based on global Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways (SSPs). The RCPs describe potential trajectories for atmospheric concentrations of key greenhouse gases over time (van Vuuren et al., 2011), which are used as input to global and regional climate models to produce climate scenarios (see Madsen et al. (2016) for further details). The SSPs describe alternative narratives of future societal

development (Kriegler et al., 2012). A set of scenario combinations (expressed as SSP x RCP) were selected (i) to cover both high-end and intermediate climate change, and (ii) to capture the extremes of socio-economic development pathways. The climate scenarios selected were RCP4.5 and RCP8.5, which cover greenhouse gas concentrations from +4.5 to +8.5 W/m² and were estimated to lead to global mean temperature increases from the pre-industrial levels by 2 – 4.3 °C and 4 – 7.8 °C by 2100, respectively. Four socio-economic scenarios were selected: SSP1, which emphasises a sustainable future, SSP3, whose central features are international fragmentation and regional rivalry, SSP4, with both across- and within-country inequality, and SSP5, which describes a future of fossil-fuelled development and accelerated globalisation (O'Neill et al., 2015). A final set of four SSP x RCP scenario combinations were selected: (1) SSP1 x RCP4.5, (2) SSP4 x RCP4.5, (3) SSP3 x RCP8.5, and (4) SSP5 x RCP8.5. The background and rationales to these selections are discussed in detail by Kok et al. (2015b).

The integrated scenarios were co-created with local stakeholders following principles developed by Gramberger et al. (2015) and Harrison et al. (2015). Figure 3 shows the general timeline of model and scenario development and how stakeholders were engaged. Two exploratory workshops focusing on the overall design of the study and to discuss and gain feedback on the model structure took place in December 2014 involving 9-12 key stakeholders from the public, civil and private sectors for each workshop. The stakeholders helped to provide sources of up-to-date data, expressed their opinion on the general acceptance of the model structure, and suggested model components to be included to address issues of local interest (i.e., population distribution and age structure). These were followed by a larger workshop on scenario development in July 2015 involving 25 participants. At this workshop, stakeholders were provided with information about the global integrated scenarios for future climate and socio-economic changes as a starting point. Then, with guidance from professional facilitators, they worked together to qualify and localise these scenarios for Hungary for the three time periods of 2010-2040, 2040-2070 and 2070-2100. Progress in the development of the model was reported for discussion leading to further model refinement to include factors of interest to the stakeholders (e.g., the attractiveness of living in villages to account for urban out-migration). The local scenarios were reviewed and extended by a subset of stakeholders at another workshop held in March 2016. The resulting local scenarios provide consistent and plausible descriptions of how events could unfold over time in major Hungarian sectors such as the economy, demographics, politics, urban development, agriculture, health, etc. These four integrated scenario were then applied to the ALLOCATION model, and the model results presented and discussed with stakeholders in a further workshop held in July 2016 involving 34 participants and later at two in-between workshops in December 2016 with 9 and 10 participants, respectively. The objectives of these workshops were to further evaluate whether the model projections were understandable and to use the projections to stimulate stakeholders' discussion on potential policy responses to climate and socio-economic change.

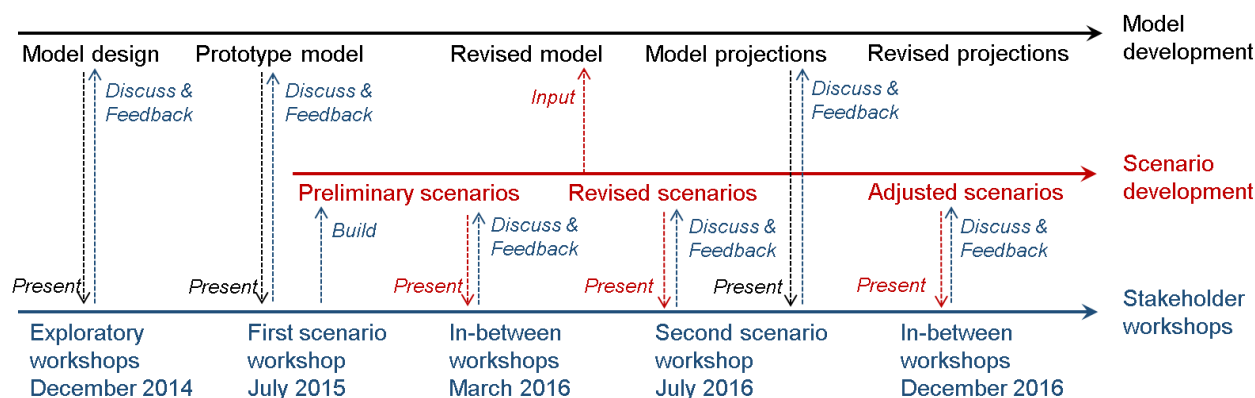


Figure 3 A timeline and interactions of model development, scenarios developments and stakeholder workshops.

3.2 Quantifying scenario drivers for urban development simulations

The localised scenario storylines were quantified for those potential drivers of future urban development which can be represented through the model parameters (Figure 2). Six scenario drivers were selected for quantification based on the availability of data on future projections, the level of interest to local stakeholders and the effort required for their quantification (Table 1). The quantification of these drivers follows the logic of the Story-and-Simulation approach (Alcamo, 2001, 2008); an iterative procedure to link narratives and quantification in scenario exercises. Two, out of the six, scenario drivers were directly quantified by stakeholders in the scenario workshops (i.e., attractiveness of living in villages and the extent of urban green areas), since these were considered to reflect the expertise of the stakeholders. The other scenario drivers were quantified from downscaling existing databases or models or through expert interpretation of the scenario narratives by the modelling team.

Economy National-level GDP data were downloaded from the SSP Database (tntcat.iiasa.ac.at/SspDb) of the International Institute for Applied Systems Analysis (IIASA). The dataset provides future trends of GDP up to 2100, projected under different SSP scenarios. In the ALLOCATION model these projections were prepared as inputs for the economic change sub-model to be downscaled and passed on to the urban land use/cover change sub-model for land demand estimation.

Climate. Projections of temperature were based on bias-adjusted and downscaled projections from global and regional climate models (Madsen et al., 2016). Temperature projections were extracted for Hungary under the RCP4.5 and RCP8.5 scenarios from the HadGEM Earth System Model downscaled with the RCA regional model. In ALLOCATION, temperature is an input to the economic change sub-model which affects GDP.

Demographics. National-level population projections from IIASA's SSP Database were statistically downscaled to the NUTS2 level for Europe (Terama et al., In press). Decadal population data up to 2100 for Hungary (Terama, 2016) were extracted for the present study as input to all three ALLOCATION sub-models: the economic change sub-model (to downscale national-level GDP to NUTS2 level); the urban land use/cover change sub-model (to estimate changes in demand for urban land), and the population distribution sub-model (to be distributed onto the 1 km grid).

Preferences. The driver, attractiveness of living in a village (versus living in more urbanised areas such as towns or the capital) is considered as a driver of urban out-migration. Possible changes in this factor under the four SSP x RCP scenarios were quantified in the stakeholder workshop using Fuzzy Set Theory (Kok et al., 2015a). In the model, attractiveness of living in villages is a factor in the population distribution sub-model which shapes the cell-level distribution of working age groups and, consequently, that of the children and the elderly.

Urban planning. Scenario drivers considered in this sector include the extent of urban green area and regulation of urban compactness. Urban green area (or infrastructure) can play an important role in the pursuit of high quality sustainable development in terms of delivering improved quality of life, promoting healthy communities and creating high quality environments for a competitive economy (Kambites and Owen, 2006). Future planning directions and rates of change in urban green area under the four SSP x RCP scenarios were discussed and analysed during the quantification exercises in the stakeholder workshops using the Fuzzy Set Theory approach. In the model, the rates of planned change in urban green area, growth or shrinkage, are applied for the urban land use/cover change sub-model to estimate the cell-level changes in the extent of green/leisure land. These changes further influence cells' residential preference and population sizes. The driver of planning regulations represents government efforts towards delivering compact urban development constrained by the specific SSP x RCP scenario. As an abstract concept, this driver was discussed during the stakeholder workshop for qualitative trends only, i.e., more compact or sprawled development trends at a low or high level compared to the baseline (sprawled). In the model, the low and high levels were converted to 30-year changes in δ by 33% and 67% (Function 3, the urban land cover change sub-model, an increasing δ indicates changes towards compactness).

The ALLOCATION model was run by assigning scenario-specific values to these scenario drivers. By using the CORINE land cover data 2012 as an approximation for a baseline land cover map, the projected changes by 2100 are compared across the different integrated climate and socio-economic scenarios. The results for the overall extent of urban land cover and population density (inhabitants per km² residential areas) are mapped at the LAU2 level (as defined in Figure 1) for a better visualisation of the general trends. Projections for different urban land cover types and population age classes are summarised using the KSH's territorial typology, by which LAU2-level administrative units are classified into five types, namely, capital (districts), town (county seat or with county rights), town, large village and village.

Table 1 Scenario settings and estimation for model variables

Class	Scenario driver	Period	Integrated climate and socio-economic scenarios ^a				Source	Estimation method
			SSP1 x RCP4.5	SSP4 x RCP4.5	SSP3 x RCP8.5	SSP5 x RCP8.5		
Economy	GDP	2010-2040	+85.10%	+63.74%	+50.63%	+116.91%	Database	IIASA SSP Database
		2040-2070	+40.61%	+15.95%	-2.18%	+94.74%		
		2070-2100	+29.64%	+4.64%	-8.43%	+81.09%		
Climate	Temperature	2010-2040	+1.3°C	+1.3°C	+1.4°C	+1.4°C	Model	IMPRESSIONS EU Integrated Assessment Platform
		2040-2070	+1.0°C	+1.0°C	+1.8°C	+1.8°C		
		2070-2100	+0.5°C	+0.5°C	+2.3°C	+2.3°C		
Demographics	Population (and age)	2010-2040	-5.24%	-10.79%	-16.47%	+1.09%	Model	IMPRESSIONS EU Integrated
		2040-2070	-6.99%	-17.72%	-27.39%	+6.10%		

	structure)	2070-2100	-12.21%	-24.82%	-32.71%	+3.54%		Assessment Platform
Preferences	Attractiveness of living in village (urban out-migration)	2010-2040	-36.33%	-18.33%	0%	-36.33%	Stakeholder workshop	Quantification using Fuzzy Set Theory
		2040-2070	0%	-36.33%	+22.17%	-57.67%		
		2070-2100	-36.33%	0%	+22.17%	-36.33%		
Urban planning	Urban green area extent	2010-2040	+11.67%	0%	-8%	-8%	Stakeholder workshop	Quantification using Fuzzy Set Theory
		2040-2070	+11.67%	-8%	-8%	-24%		
		2070-2100	+11.67%	-8%	-8%	-24%		
Urban planning	Regulation on urban morphology	2010-2040	compact	compact	sprawl	sprawl+	Stakeholder workshop	Qualitative interpretations of the integrated scenarios
		2040-2070	compact	sprawl	sprawl+ ^b	sprawl+		
		2070-2100	compact	compact	n/a ^c	sprawl+		

^a Changes between the start and end of the time period.

^b Indicating a more sprawled development trend at a high level compared to the baseline.

^c Expansion of urban area stops in 2070-2100 under SSP3 x RCP8.5, according to the qualitative scenarios.

4 Results

4.1 Model performance

The LAU2-level comparison of the modelled and observed urban land cover suggests good model performance, as the Coefficient of Determination (R-squared) was found to be greater than 0.97 for all three urban land cover types. Visual and distance-density plot comparisons also suggest satisfactory model performance in predicting urban land cover changes at the cell level. The predictive power for population distribution was also found to be good at the NUTS5 level, as the R-squared was greater than 0.83 for all five age groups. More details of the results of the quantitative model evaluation are provided in the Electronic Supplementary Materials 2.

Qualitative evaluations by stakeholders suggest general acceptance of the model structure and usefulness of model projections. In the initial stakeholder workshops (Figure 3), an in-depth discussion was conducted to clarify the model's structure and to ensure factors of stakeholders' interest (e.g., the attractiveness of living in villages to account for urban out-migration) were included. In the final workshop, the projected results under the four integrated scenarios were presented to promote discussion of climate change adaption responses that would represent progress towards the vision of a sustainable future by 2100 to the extent allowed by the logic of a given SSP and RCP. In a post-workshop survey with participants, 20 out of the 23 responses rated the question "How useful were the modelling results in discussing possible responses?" as "very positive" or "positive", with the remainder rating them "satisfactory".

4.2 Model sensitivity

The results of the sensitivity analysis suggest that the ALLOCATION model is relatively stable in projecting urban development patterns and, hence, has the potential to be useful for scenario planning (Hewitt and Díaz-Pacheco, 2017). In general, projected extents and spatial patterns of urban land cover were found to be sensitive to changes in the national-level GDP, regional-level population and planning restrictions towards compact urban development. Consequently, population distributions, which depend highly on urban land cover distribution in the model, were also sensitive to these parameters. Projected population distributions were also found to be sensitive to changes in residential preference on proximity to social amenities and on desire to live in the capital, towns or villages.

4.3 Future urban development trends in Hungary

4.3.1 Urban land use/cover change

The differences in the projected extents of urban areas are driven by GDP and population (sections 2.2.1 & 2.2.2). The spatial pattern is driven by the planning regulation parameter (section 2.2.2) and the potential of a cell to be developed further for urban land use, e.g., residential and commercial/industrial, which is calculated using the same set of rules. In general, a cell's development potential is greater with an urban land cover element, and if its neighbourhood has a higher proportion of urban area. Thus, under all scenarios, new development of urban area was projected to be mainly around the capital and regional centres (towns as county seats and towns with county rights), as shown in Figure 4. Rapid urban development was projected under the SSP5 x RCP8.5 scenario due to a large increase in both GDP and population (Table 1), despite a rise in temperature of up to 5.5°C causing an averaged decadal 2.55% damage to the GDP by 2100 (from

0.30% in 2010-2020 to 7.90% in 2090-2100). A growing GDP and a relatively stable population (albeit decreasing) were projected to contribute to a moderate increase in urban areas under the SSP1 x RCP4.5 scenario. By 2100, a temperature rise of 2.8°C is projected to cause an averaged decadal 1.05% damage to the GDP (from 0.28% in 2010-2020 to 2.18% in 2090-210). In the capital region, more rapid development was projected due to policy regulation of urban compactness to meet the targets of sustainability and reduce energy demand. Although the projected patterns under the SSP4 x RCP4.5 and SSP3 x RCP8.5 scenarios seem to be similar, two differences should be noticed: (i) the former scenario led to an overall greater increase in urban areas (hence the darker colours), as better economic conditions were assumed for SSP4 and; (ii) the latter scenario led to a more widespread pattern of urban area increase, because spatial planning regulations within a de-globalising SSP3 are assumed to focus on local security which results in sprawl. In addition, some decreases in urban areas were projected (grey areas, e.g., around the Lake Balaton region), because urban areas in these regions were mainly composed of green/leisure type, and green/leisure areas were expected to decrease under these scenarios (Table 1).

While residential land was projected to have the greatest absolute increase among the three types of land cover considered (result not shown), commercial/industrial land was projected to have the greatest growth rate (Figure 6). This result was found for all scenarios and for all territorial types, as a consequence of increasing per capita GDP. As mentioned previously, changes in green/leisure land were set to be driven by the scenario settings (Table 1) and hence, were projected to be only positive within SSP1 x RCP4.5. Comparing the projections between territorial types, it was interesting to find that large villages had the greatest increase rate in both residential and commercial/industrial land under all scenarios, except for the SSP3 x RCP8.5 and SSP5 x RCP8.5 combinations within which a greater increase rate of commercial/industrial land was found for villages, owing to a sprawl-oriented regulation policy. These large villages were mostly (i) located close to the capital, not far away from rivers, or distant from major towns, (ii) had a greater proportion of land available for future development than capital districts and the majority of towns, and (iii) had a greater extent of existing urban land covers and road density than most villages. For most NUTS2 regions, these characteristics indicated a good developmental potential for both residential and commercial/industrial uses.

Changes in artificial land cover (2010 - 2100)

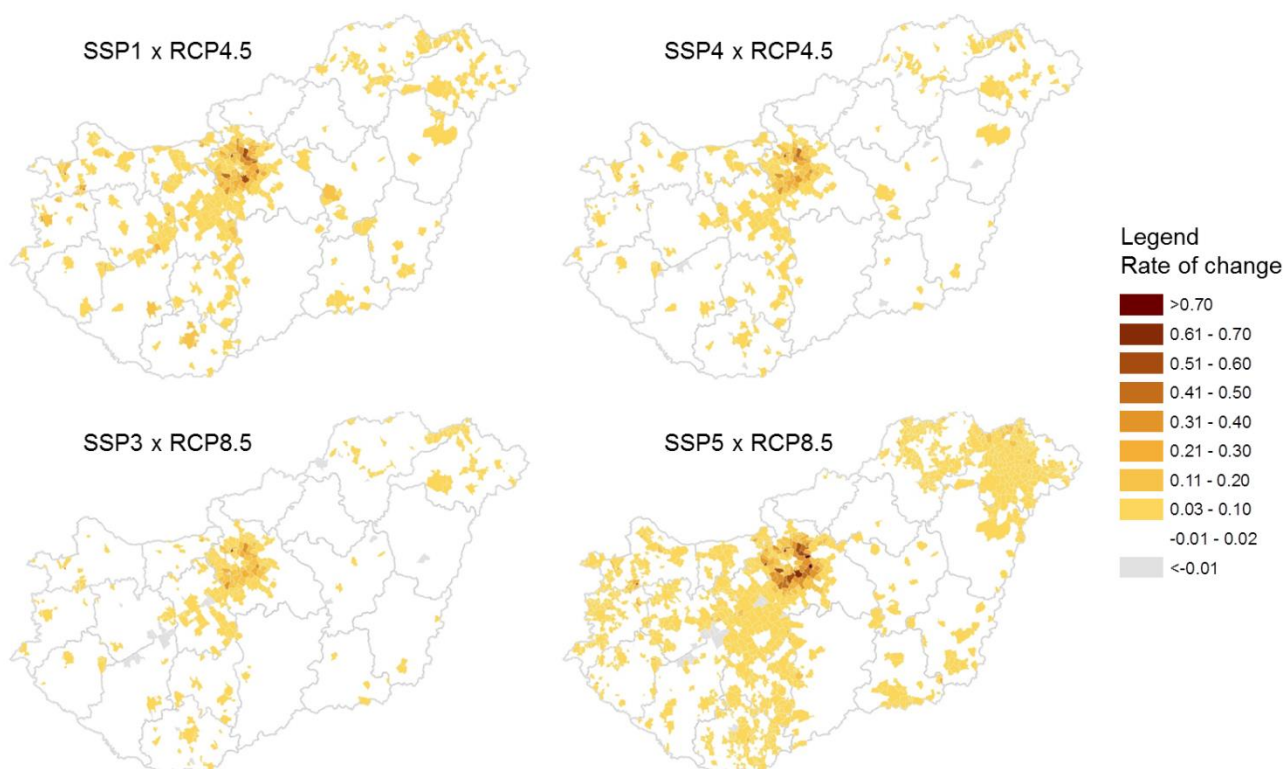


Figure 4 Simulated changes in total urban areas (2010-2100) under the four integrated scenarios.

4.3.2 Population and age structure patterns

The potential of an inhabitable cell to attract residents is a function of urban land cover densities in its neighbourhood (as residential preferences) and preference weights given to different territorial types (section 2.2.3). A major population flow in central Hungary was projected under all scenarios, caused by peri-urbanisation around Budapest: the population

was expected to move to the fringe areas of the capital. In Figure 5, it can be seen that fringe areas either increase or maintain their populations under SSP1 x RCP4.5 and SSP4 x RCP8.5 scenarios. Under the other two scenarios, in which population was expected to decline considerably (Table 1), Budapest's fringe areas were projected to have a relatively lower rate of population decrease than the Central Hungary region (results not shown). In the fringe areas of the capital, where the cells' developmental potential for residential, commercial/industrial and urban green/leisure uses were all high, the newly developed residential areas were projected to have relatively high residential preference for residents. Moreover, these new residential cells were capital cells, and in central Hungary a greater residential preference weight is given to the capital cells by the working age groups. As a result, these new residential areas in the fringe areas of Budapest attracted population from the centre of the capital and from the surrounding villages and towns in Pest County. The model further projected several areas at risk of losing population (dark red areas in Figure 5) under all four integrated scenarios, including those in Central Hungary (western Pest County), Northern Great Plain (western Jász-Nagykun-Szolnok County and northern Hajdú-Bihar County) and Southern Great Plain (northern Békés County). Under the SSP4 x RCP8.5 scenario, even though national population and GDP were expected to increase, urban land cover in these regions remained unlikely to expand (Figure 4), owing to low neighbourhood densities of baseline urban land covers and low local road densities. Hence, population was projected to migrate to other areas with greater residential preferences (i.e., better access to social and economic amenities, as new residential and commercial/industrial lands were developed).

Changes in population distribution (2010 - 2100)

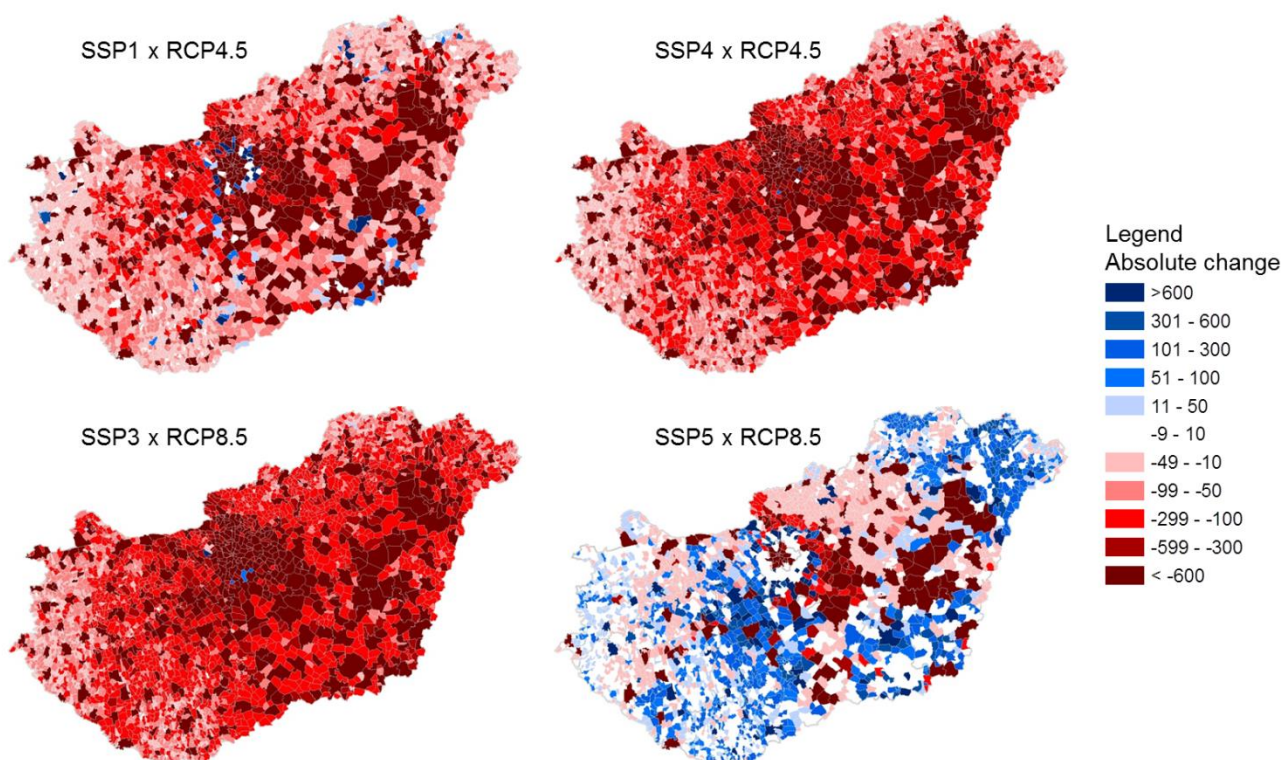


Figure 5 Simulated changes (2010-2100) in population density under the four integrated scenarios.

Some general trends for the projected changes in age structure were found under all scenarios (Figure 6): population aging and sub-replacement fertility were estimated to become a national problem, and the capital and major towns (those with county seats/with county rights) were projected to lose a significant number of the working age population. The changes in age structure further varied across territorial types, as a consequence of differences in the development potential of a cell and in the attractiveness of territorial types. Increasing urban land cover was projected to lead to better residential preferences in the cells in the capital and major towns than in the other territorial types. In theory, this could attract population from other areas, leading to a lower decrease rate of working age population in the capital and major towns under all scenarios. However, under the SSP3 x RCP8.5 scenario, differences in the rate of decrease of the working age population were projected to be similar across territorial types. This was due to the effect of residential preferences in the capital and towns being diluted by an increased attractiveness of living in villages as expected within the scenario. While under the SSP1 x RCP4.5 and SSP4 x RCP8.5 scenarios, the attractiveness of living in villages was assumed to decline, as a consequence the relative attractiveness of the capital and towns increased. This led to more population migrating from villages to more urbanised areas, and, hence, a lower decrease rate of the working age

population in the capital and towns. Finally, urban sprawl under the SSP5 x RCP8.5 scenario resulted in more cells becoming inhabitable (and having residents), in particular for large villages and villages. Although, to some extent, this helped to sustain the total size of the working age population in rural areas, the decline of population density in these areas was projected to be more dramatic than in more urbanised areas (results not shown) where residents preferred to remain, as assumed in the scenario.

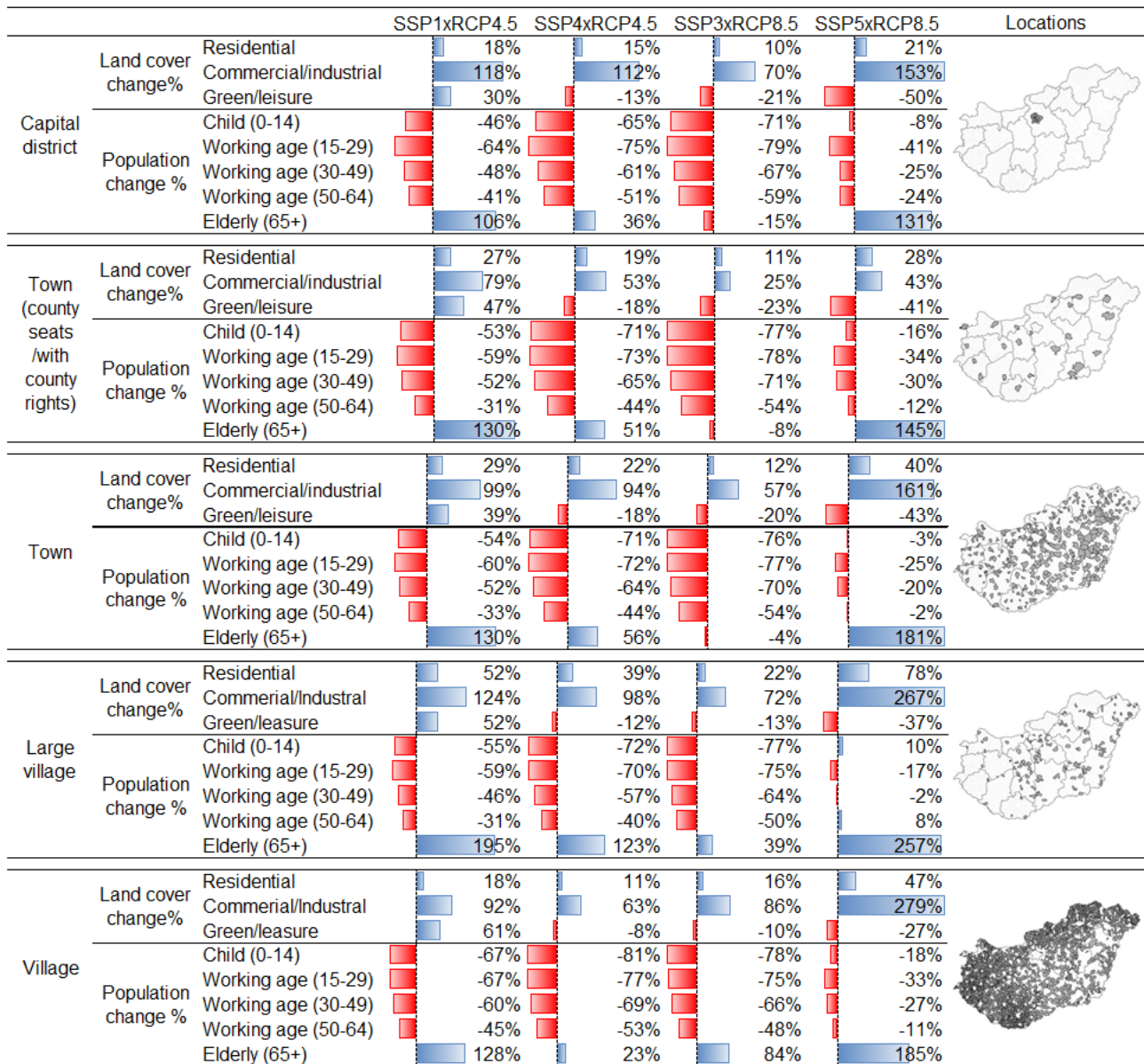


Figure 6 Projected changes (2010-2100) in urban land cover and population under different integrated scenarios, summarised by territorial types.

5 Discussion

Under the risk-based framework of climate change impact management introduced in an IPCC special report (Cardona et al., 2012), vulnerability is defined as the susceptibility of “exposed elements” being adversely affected by hazardous climate events. Urban infrastructure and population are most commonly regarded as “exposed elements” and their distribution is key to the assessment and management of climate change impacts. It is within this context that the current study was conceived. The ALLOCATION model is a product of combining existing empirical approaches to land use/cover change modelling with population mapping. Two characteristics make the model unique: (i) it is able to make fine resolution projections over a large area, and; (ii) it generates a variety of outputs including the extents of multiple urban land cover types, and age-structured populations. Since the main objective is to model a complex system for a large geographical extent and temporal frame, a top-down modelling approach was selected with careful design of the model components to balance model specificity, computational burden, data requirement, relevance and ease of

communication to stakeholders from different sectors. Integration in this modelling study is achieved from different perspectives, including integration of multiple disciplines (e.g., economics, urban/rural land use, and demographics), integration with stakeholders (in scenario and model development), and integration of scales of considerations (i.e., from national to local levels). The model developed can be classified as a coupled component model, based on the five common approaches for integrated environmental modelling summarised by Kelly et al. (2013). Even though the model was developed and calibrated for Hungary, the modelling framework has considerable flexibility and can easily be applied elsewhere. This is because the construction of the model functions only requires open access land cover data and census data at the local administrative levels both of which are increasingly available.

The plausibility of the model projections can be supported in several ways. Firstly, the conceptual model structure was developed based on a combination of three sub-components that are all based on existing empirical approaches with a certain level of realism. The selection of a top-down approach enabled parameterisation with observation data and the adoption of parameters with clear performance criteria (e.g., R-squared and AUC). Secondly, the interests and concerns of local stakeholders were used to guide development of the model and selection of impact and output measurements. This made the model appropriate and of relevance for its end-users. Thirdly, the integrated scenarios depicting the plausible futures of socio-economic and climate conditions were developed through engaging closely with stakeholders. This ensured credibility and salience of these scenarios in supporting policy decisions within the local context. Fourthly, the model performance was found satisfactory with a good accuracy of baseline projections. Finally, the local stakeholders found the projections explainable in the context of the integrated scenarios and useful in stimulating discussions on potential policy responses to climate and socio-economic change.

Rises in temperature under intermediate (RCP 4.5) and higher-end (RCP 8.5) climate change scenarios were projected to cause up to 2.18% and 7.91% damages to the GDP of Hungary by 2100. However, their influence on the urban spatial development patterns was estimated to be marginal by the model. Comparing the projections presented in this paper with those produced without considering GDP damage (not shown), the differences in residential and industrial/commercial area estimates were found to be less than 0.1% for all the NUTS2 regions under all integrated scenarios. This was because the functions to estimate changes in urban land covers (Function 1, section 2.2.2) used the per capita GDP and existing land covers in the region as key indicators, with the latter dominating (see the Electronic Supplementary Materials 2). Moreover, in both climate scenarios, the damage was estimated not to exceed 1% before 2050. Provided both GDP and population were projected to change dramatically, such a small reduction in GDP was inadequate to cause any obvious changes in per capita GDP and its consequent impact on the urban land cover change was negligible. At this scale of modelling, most of the other model factors selected for Hungary were related to socioeconomics and physical urban environments which could not be directly linked to climate change. Thus it was not surprising that the projected results suggested a negligible effect of climate change on urban development through causing damages to the national GDP. Given the current objectives and context of integrated scenarios, further modelling efforts to quantify the impacts of climate change on urban development may integrate sub-models accounting for land cover changes in other sectors, e.g. forestry and agriculture, that can directly influence urban development (through competition for land) and have a clearer link to climate impacts (White and Engelen, 1997). Finally, it should be noted that, different results may be gained when applying the modelling framework to other countries, as the factors selected, coefficients estimated and evolutions of GDP and population projected may all be different.

Applying the model to climate and socio-economic scenarios to simulate a range of plausible futures of urban development provides useful information for stimulating discussions related to climate change adaptation options. This has been frequently emphasised in the literature (van Ruijven et al., 2014) and was confirmed by local stakeholders involved in this study. In general, two types of scenario products can be distinguished: (i) qualitative narratives that contain detailed descriptions of events and complexity that cannot be easily captured in modelling approaches and are generally stakeholder-led, and; (ii) quantitative trends described in numerical forms that are needed as model input and which are often modeller-led (Pedde et al., In revision). The two types of scenario products are often combined in the Story-And-Simulation (SAS) approach (Alcamo, 2008), which refers to an iterative, stepwise process to link narratives and quantifications. The inherent difference between the two scenario types poses great challenges to their integration in the SAS approach (Houet et al., 2016). Several methods have been developed to address this issue by jointly considering research objectives, scales and desired level of participation in the scenario process (c.f. Mallampalli et al. (2016) for an overview). In this study, we applied an approach known as ‘hardwiring’ of the two scenario types (Houet et al., 2016). Thus, scenario drivers are quantified without violating the background climate and socio-economic settings of each scenario, and they consist of both quantitative model estimations (i.e., national GDP, population and temperature) and qualitative information generated through the participation of stakeholders (i.e., residential preferences and planning regulations on urban green infrastructure and urban morphology). Quantifying the drivers in strict obedience to the underlying assumptions helped to retain the internal consistency of each scenario. It further helped to reduce the overall subjectivity of the scenario driver set by limiting the entry of qualitative scenario drivers to higher levels, on which the quality of model estimations was likely to be more profound. The final four localised scenarios were used to set the

socio-economic and climatic conditions for model simulation. These scenarios were developed based on combinations of the SSPs and RCPs from the IPCC-related global scenario framework. Extending, downscaling and applying a common scenario framework is likely to increase the chance of our predictions being useful for future climate change risk management studies in the same region, as well as them being comparable with relevant studies in other regions or at a higher level.

An important lesson learnt from this study was the need for optimising the level of efforts required from stakeholders. In this study, stakeholders were closely engaged with both the scenario and model development processes (Figure 3) and provided location-specific knowledge to fill gaps in data, simplify model structure and evaluate model outputs for their acceptance and usefulness. To ease the burden, engaging stakeholders in other technical tasks, such as quantitative evaluation, was avoided. It was, thus, the responsibility of modelling experts for to perform a detailed verification and validation exercise to strengthen the technical soundness of the model (c.f. the quantitative evaluation results in the Electronic Supplementary Materials 2). Moreover, due to the diversity of stakeholders' background, the qualitative evaluation of the model structure was conducted through discussion only. It may be beneficial to include a more structured approach in such discussion, for example, by using a questionnaire to evaluate the model construction, operation and output, and by modelling experts working more closely with the stakeholders in the workshops (Bennett et al., 2013). Another lesson learnt was the need for effective communication among scenario scientists, modelling experts and stakeholders. In our post-workshop survey with stakeholders, it was found important to include a small group of resource persons who engaged with both scenario and model developments in the stakeholder meetings to ensure the transparency of the development processes. In line with Booth et al. (2016), this study highlighted the importance of having research team members capable of working comfortably across disciplines and being capable of understanding both aspects of scenario construction and modelling. Good communication also contributes to interests between the research team and stakeholder community being more balanced. For instance, several modifications of model structure took place to include factors of local interests (e.g., urban/rural out-migration). It should be further mentioned that in our workshops, a few stakeholders with scientific background or modelling skills unexpectedly volunteered in answering questions to the research team raised by the other stakeholders. This facilitated the acceptance of, and enhanced the confidence in, the modelling approach within the stakeholder community.

This study has several limitations, for which future research directions need to be suggested. Firstly, the model lacks explanatory power on the complex underpinning processes of land cover conversion and residential mobility. Future studies which aim to better explain their mechanisms, and interactions with climate conditions, may benefit from linking a bottom-up approach under an agent-based modelling framework. Such models can be developed for smaller geographical regions to better meet the demand of geospatial data, and at finer spatio-temporal scales to enable individual households, life course events and decision-making processes to be represented explicitly (Fontaine and Rounsevell, 2009). They may also be better applied to specific issues, such as international migration flows related to changes in suitability and/or preference for living next to the coast. Secondly, when focusing on smaller research areas, or on a specific set of sectors, building a wider range of localised and sectoral scenarios, may be more informative and helpful in establishing well-targeted policy responses. An example can be found for the fine level simulation of urban growth (Houet et al., 2016), in which the authors utilised a novel six-step method to generate a set of seven contrasting scenarios for climate adaption. Moreover, lower-end climate change scenarios need further attention following the ambition set in the Paris Agreement of limiting the global temperature increase to 1.5°C above pre-industrial levels. Thirdly, more scenario drivers may be included when more qualitative information is available in future studies. One interesting example is the size of neighbourhood being used to estimate a cell's residential preferences in the population distribution sub-model. This parameter is related to the distance travelled for commuting and leisure purposes, which can be influenced by climatic conditions, time use, lifestyle, transport efficiency and planning, etc. (Koetse and Rietveld, 2009; Li et al., 2015; Li et al., 2016a). Many of these factors are likely to cause contrasting patterns of change within the scenarios used in this study. Fourthly, according to qualitative feedback from stakeholders understanding local context and working in the local language are critical factors in reducing the risk of miscommunication during facilitated engagement sessions and may help avoid the need for making corrections later.

6 Conclusion

An integrated model was developed, evaluated and applied to predict fine-level urban development for the whole of Hungary. The model projected contrasting patterns of urban land cover and age-structured population under the four integrated scenarios, which revealed several societal challenges that Hungary may need to face in the future.

Under the scenarios combined with intermediate climate change (RCP 4.5), urban development paths were projected to be different between the two socio-economic conditions describing (i) a sustainable future with less inequality (SSP1), and (ii) an unequal future of increased social, economic and political disparities (SSP4). Under the former integrated scenario, the country was predicted to have moderate and compact urban growth around the capital and regional centres,

accompanied with steady rural out-migration and depopulation. Under the latter scenario, a slow urban growth rate in a compact-sprawl-mixed fashion was predicted, with strong national depopulation which is greatest in rural areas. More distinct future urban patterns were projected under the higher-end climate changes (RCP8.5) which were associated with two other socio-economic scenarios. In a de-globalising future of low-level economic growth and a seriously degraded environment (SSP3), the country was projected to have slow and sprawled urban growth across the territory. The capital region was estimated to lose a significant amount of population and newly developed residential areas around the capital were likely to be underutilised. In contrast, in an economically driven future which is highly industrialised and fossil-fuel based (SSP5), the country was projected to have a rapid and sprawled urban growth and an overall growth in population. Strong domestic migration was projected to occur in order to occupy the newly developed residential areas. This was likely to result in a more unevenly distributed population pattern. Despite the differences in shape and speed, the peri-urbanisation of the Budapest region and out-migration from the centres of the capital and major towns were projected to occur under all scenarios. This suggests that future local urban policies should take into the consideration the potential underutilisation of urban infrastructure in the capital centre, and the pressure of social service provisioning in its outskirt.

Our modelling experiments revealed the inadequacy of approximating the impacts of climate change on urban land cover change through GDP only, and suggested further integration with land cover change sub-models for other land cover types that not only affect urban developments but also respond directly to climate changes. Co-learning with stakeholders in both scenario and model developments contributed to the originality of this study. To achieve effective collaboration between scenario scientists, modelling experts and stakeholders, the study pointed out the importance of objectively deciding upon the division of work load between the stakeholders and research term, and in ensuring consistency between the two. Having participants in both groups who work comfortably across disciplines and are thoroughly familiar with the local context also supported good communication and collaboration. The projected results may provide fundamental decision support information for assessing the vulnerability of Hungarian cities to climate change. The integrated model can further be used to test the effectiveness of response options for climate change adaptation.

Software and data availability

No specific software has been developed. This paper uses R version 3.2.0 (R Foundation for Statistical Computing, Austria) for statistical analysis and empirical function construction, ArcGIS version 10.2 (ESRI Inc., USA) for spatial data management and final output visualisation, and Repast Symphony version 2.1 (Argonne National Laboratory, USA) for model development and integration. The data used for model development (section 2) and scenario configuration (section 3) are either open access or freely available upon request from the corresponding author. The final projected patterns of urban land covers and population age structures for Hungary by 2040, 2070 and 2100 are also available upon request from the corresponding author.

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