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

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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 outskirt. 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.

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 interrelated 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

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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 (Fig. 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 Fig. 2. The model is based on a 1 km^2 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