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Uncovering urban system interrelations using land-use scenario modelling

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Abstract: For the conservation as well as the improvement in life quality of human beings, today’s decision makers on the political level are challenged to tackle the complex interactions between human activities and the natural environment. In order to reach an increasing comprehension of these interactions that are particularly apparent in urban settings, model approaches turned out to be suitable tools to picture and understand the processes and dynamics within complex systems, such as cities (Haase and Schwarz, 2009). Besides using models to uncover cause-effect relationships initiating urban dynamics, they also can be applied to simulate different scenario-based decision processes leading to alternative urban futures with respective environmental impact (Alberti, 2008). Thus, urban modelling is capable to contribute to sustainable and strategic urban planning aiming at managing potential environmental benefits and burdens to the end that powerful legal frames for sustainable urban development are created, encouraging urban resilience and reducing environmental risks (Alberti, 2008; Rutledge et al., 2008).

Urban development is the results of several processes that can emerge simultaneously and can interact, expressing various effects. These might directly affect urban dwellers or their societal conditions, e.g. population aging or household compositions and decisions; others might affect the urban form (e.g. growth or shrinkage) and finally the performance of the urban ecosystem. According to major trends in European cities, the following processes can be distinguished, (1) demographic change and population aging, (2) household and preference shifts (i.e. reurbanization or regarding the modal split), (3) growth and/or shrinkage. Beyond that, urban planning itself is having a major impact.
on the development of the urban ecosystem, by the definition of land-use and zoning plans directing future urban development.

1.1 Objectives

The aim of this paper is to introduce 13 scenarios incorporating and combining these development trends and to integrate them in an already implemented and well-validated land use change model that is able to cover demographic and residential dynamics, various preference shifts and planning restrictions (Lauf et al., 2012). The model results are then analyzed regarding the future urban development trends of demographic change, land-use change, urban pattern change and ecosystem service change to cover the respective environmental effects. To meet these goals, we apply varying analytical methods.

2. METHODS

2.1 Study area

The study area consists of the city of Berlin and its closer surrounding behind the administrative border and involves parts of the federal state of Brandenburg in order to improve the understanding of the urban and peri-urban relations. It depicts the metropolitan region of Berlin covering almost 5,400 km² with a total population of over 4.5 million. The metropolitan region is characterized by a moderate density of built-up area with large, partly central-located, forested green areas, large agricultural areas in the periphery and a connected system of water bodies.

Figure 1. The metropolitan region of Berlin (2008); the area inside the inner railway defines the inner city, the area within the Berlin city border (excluding the inner city) defines the outer city and the area above the city border defines the periphery
2.2 Land-use model

The applied model consists of a combination of system dynamics and cellular automaton, integrating household and preference-driven LUC (Lauf et al., 2012). Therefore, we utilize a precise population model with all relevant demographic variables applied to eight interlinked age groups. These are transformed into seven household types based on statistical distribution patterns. As a result, current demographic processes, such as population aging or the increase of smaller households can be simulated. Based on household size and household-specific preferences, residential demand can be calculated, taking the preference-related conditions of seven residential structure types into account. Demand shift affect housing parameters, such as construction rate, vacancy rate (and eventually demolition rate) on the supply side. In consequence, the model is able to simulate growth and shrinkage and even both occurring simultaneously (in different residential structure types) and the extend of residential preference patterns, such as an increasing demand for central-located inner city living, referred to as reurbanization. The annually updated residential supply is then, together with the supply of other built-up classes (e.g. commercial, industrial areas) integrated into the cellular automaton to spatially distribute the area changes with regard to the best transition potential according to neighborhood relation of different land-use classes, transportation accessibility and planning restrictions on a 50mx50m grid. In total 22 land-use classes are considered in the model.

2.3 Scenarios

We integrated 13 scenarios to test the effects of relevant and observed processes and drivers leading to land-use and ecosystem change. Also combined scenario implications were integrated to test amplified effects. The main aspects we examined within the scenario analysis are, a baseline continuation of existing trends, the effect of planning, changed preferences on accessibility to public transportation, demographic and economic growth or decline, exceeding preference shifts towards central living and finally an exceeding increase of population aging. The scenario analysis will aim on the comparison of respective multiple effects on the demography, land use, urban patterns and ecosystem services. All scenarios were run from 2008 to 2030 covering a simulation period of 22 years. For each scenario, results were carried out on an annual basis, being either quantitative, e.g. in case of demographic variables or spatial, e.g. in case of land-use distribution (land-use maps). In this paper, we focus on the results of the initial time step of 2008 and the final simulation time step of 2030, which were comparatively analyzed according to the following methods (sect. 2.4 and 2.5).

Table 1. Overview of all scenarios applied and tested using the proposed model approach

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FB</td>
<td>Free Baseline, like BB but without planning restrictions (except for the airport transition), enabling a more &quot;free&quot; development</td>
</tr>
<tr>
<td>BB</td>
<td>Basic Baseline, development under planning restrictions and demographic and economic trend continuation</td>
</tr>
<tr>
<td>AB</td>
<td>Accessibility Baseline, like BB, but with implications of increased accessibility preference to public transportation (at a rate of 1.5)</td>
</tr>
<tr>
<td>OB</td>
<td>Overaging Baseline, like BB, but with an increase of elderly people (fertility reduction to 1 child per couple and annual immigration reduction of age groups &lt; 45y at 0.85)</td>
</tr>
<tr>
<td>RB</td>
<td>Reurbanization Baseline, like BB with a preference increase towards central living (ignoring costs preferences)</td>
</tr>
<tr>
<td>FG</td>
<td>Free Growth, like BG but without planning restrictions (except for the airport transition), enabling a more &quot;free&quot; development</td>
</tr>
<tr>
<td>BG</td>
<td>Basic Growth, development under planning restrictions (with annual GDP change at 1.096, fertility at 1.002, immigration at 1.083 and emigration at 0.997)</td>
</tr>
<tr>
<td>OG</td>
<td>Overaging Growth, like BG, but with an increase of elderly people (fertility reduction to 1 child per couple and annual immigration reduction of age groups &lt; 45y at 0.85)</td>
</tr>
<tr>
<td>RG</td>
<td>Reurbanization Growth, like BS with a preference increase towards central living (ignoring costs preferences)</td>
</tr>
<tr>
<td>FS</td>
<td>Free Shrinkage, like BS but without planning restrictions (except for the airport transition), enabling a more &quot;free&quot; development</td>
</tr>
<tr>
<td>BS</td>
<td>Basic Shrinkage, development under planning restrictions (with annual GDP change at 0.904, fertility at 0.979, immigration at 0.996 and emigration at 1.004)</td>
</tr>
<tr>
<td>OS</td>
<td>Overaging Shrinkage, like BG, but with an increase of elderly people (fertility reduction to 1 child per couple and annual immigration reduction of age groups &lt; 45y at 0.85)</td>
</tr>
<tr>
<td>RS</td>
<td>Reurbanization Shrinkage, like BS with a preference increase towards central living (ignoring costs preferences)</td>
</tr>
</tbody>
</table>
2.4 Urban patterns

For the analysis of the spatial structure all seven residential land uses classes (defined by their density and distance to the city center) are assigned to one of the following classes to condense the simulation results (cf. Figure 1):

1. Central located dense residential (inner-city block, multi-story row);
2. Intermediate residential (villa, residential park, multi-story prefab); and
3. Decentralized low-density residential uses (detached houses, suburban village).

Above that, the total built-up structure (including residential and non-residential classes) was analyzed using urban form indicators, including landscape metrics (Lauf et al., 2014a). We used commonly applied landscape metrics, such as edge density (ED; to evaluate compactness) and patch density (PD; to evaluate fragmentation). Other indicators based on land-use relations were used, such as the sprawling index (SI), the ratio of decentralized low-density residential area and the total residential area. Above that, indicators were calculated for the entire study region, the inner city, the outer city and the periphery (cf. Figure 1):

2.5 Ecosystem services (ES)

We calculated six ES indicators, namely energy provision (including solar, wind and bioenergy production), food provision (including crop, livestock and fish production), climate regulation (applying thermal emissivity), biophysical regulation (applying PMV), net carbon storage (adding up carbon sequestration and carbon production from households, traffic and industries) and finally recreation (as a potential from close-to-home urban green spaces), (Lauf et al., 2014b). The calculation of respective indicators involved diverse data ranging from remote sensing up to varying statistical data that were spatially assigned to all 22 land-use classes. Assuming that the indicators stay constant over time, annual ES changes were based on LUC. To compare the local and regional changes of ES, we used a normalization procedure, defining a common range from 0 to 10 for all ES values. This enables a summarized assessment of multiple ES change, finding expression in the applied ESA value.

3. SELECTED RESULTS AND DISCUSSION

The scenario BB revealed a slight population increase of fewer than 2%, accompanied by a considerable increase of elderly people and changes in the household configuration, with a substitution of family households with kids by smaller households without kids, resulting in higher living space demand. The increase of residential area, comprising 49% of the total built-up area increase, showed an increasing trend from dense to low-density residential area, despite a moderate demand shift from decentralized low-density to central-located dense living space, indicating a reduction of suburbanization and a continuation of reurbanization (Haase and Schwarz, 2009). This higher land consumption of low-density uses follows from the respective floor-space indexes (a measure for building density), and was mainly conveyed on former agricultural land. As a result, the sprawling index indicating the share of low-density residential area increased as well as the compactness of total built-up area, especially in the periphery. Ecosystem services showed in sum a slight negative trend which was moderated by the increase of energy production (mainly through photovoltaic on low-density houses) and the increase of recreation due to the occurrence of new residential areas in the periphery, close to recreational green spaces. The loss of food provision depicts the highest ES loss, due to the decline in arable land. The results indicate a trade-off between energy and food production which was confirmed elsewhere (Lauf et al., 2014b).
Figure 2. Percentage change of selected system indicators between 2008 and 2030 for scenario BB

Figure 3. Comparison of system indicator change between individual scenario and BB (2008-2030)
The demographic development, as confirmed to be one of the main drivers of urban (ecosystem) change (Lauf et al., 2014b), only varied in scenarios with respective scenario assumptions. We ascertained different changes for selected indicators across the scenarios; partly being very high (e.g. capita living space), as they have to be related to respective changes in BB (between 2008 and 2030). Population aging (OB) and population growth (BG) revealed higher land consumption rates which are confirmed by an increased sprawling index, resulting in reduction of the compactness, accompanied by negative effects on ecosystem services, especially for BG. Besides the expected ES decline at demographic and economic growth (BG), the results show, moreover, the negative effects on ES due to population aging (OB), one of the main challenges of future urban development. The scenarios RB and BS revealed positive effects, confirming the assumptions that urban shrinkage and reurbanization are associated with ES increase. AB showed an increase of the urban compactness leading to an improvement of ES, indicating the benefit of promoting the use public transportation in cities. FB demonstrated the relevance of urban planning in terms of sustainable urban land management; however, spatial preferences obtained under exclusion of planning might support current planning decisions by indicating suitable areas for urban development, e.g. in terms of accessibility.

These individual scenario specifics were combined to test amplifying or revers effects of certain assumptions on the urban ecosystem, which is indicated in Figure 4. The scenarios combinations revealed that the negative effects of population aging and economic and demographic growth (OG) result in the highest land consumption rates with the largest negative effects on ES; whereas the combination of increasing reurbanization trends and economic and demographic decline (RS) provided the lowest land consumption rate, associated with low effect on ES. Figure 4 shows that growth and shrinkage have similar effects in combination with other development trends. Significant effects could only be obtained under population aging (OG/OS), revealing that the amount of elderly households and the extent of intermediate residential uses depends stronger on growth or shrinkage.

Figure 4. Effectiveness of urban growth and shrinkage in different scenario combinations; the higher the bar, the higher the deviation of an indicator due to growth and shrinkage

Finally, we conducted correlations and (bivariate) linear regression models to show the dependencies and the explanatory power of pairs of indicators, using all scenario (n=13). We ascertained a high explanation of land-use change by the amount of elderly people and small households (not by the total population itself) with varying effects on compactness, indicating that small households are likely to decide to live more central, confirmed by the strong relation with intermediate (and partly with central-located dense) residential area. ES change only showed to be negatively related to the total population.
Table 2. Coefficients of determination between urban parameters (signs show the character of the correlation. Results are greyed out if R² < 0.24 or p > 0.05)

<table>
<thead>
<tr>
<th>Urban parameter</th>
<th>Land-use</th>
<th>Demography</th>
<th>Economic</th>
<th>Education</th>
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<tbody>
<tr>
<td>Population size</td>
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<tr>
<td>Urban form</td>
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<td>Land-use</td>
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Table 2 Coefficients of determination between urban parameters (signs show the character of the correlation. Results are greyed out if R² < 0.24 or p > 0.05).
4. CONCLUSION

The ascertained model quality confirms the models usage for analytical purposes (Lauf et al., 2012). With the use of our model and the number of applied scenarios in combination with the chosen methods to analyze the effects on the urban ecosystem (in terms of spatial effects and effects on ES), we investigated relevant system influences and dependencies and measured their effectiveness. The proposed method as a whole contributes to urban (eco)system understanding and is suitable to provide insights into complex interactions between human activities and the natural environment. Possible future developments under specific scenarios could support decision-making for planners or politicians, so that undesirable developments or potential risks could be recognized early, allowing for the development of early mitigation or adaptation strategies, e.g. through incentives or restrictions, or reversely, positive developments, e.g. in terms of the promotion of ES provisioning. Future research should focus on the effects of ecosystem change on human wellbeing and health as critical measure to support effective decision-making.

5. REFERENCES