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Integrating strategic planning intentions into land-change simulations: Designing and assessing scenarios for Bucharest

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ABSTRACT

Urban regions worldwide revert to scenario-based simulations to understand and cope with uncertain land-use changes and future land-use demands. Whereas scenarios account for a variety of driving forces to simulate land change, spatial planning has received limited attention. To improve understanding of the potential contribution of planning to urban land change, we developed and simulated scenarios of development for Bucharest, addressing the local scale, and Bucharest-Ilfov Development Region, addressing the regional scale. The designed scenarios reflect (i) expected future land-use demands for living space, built-up areas, green space and agricultural areas, and (ii) statutory and strategic planning intentions extracted from four spatial plans and weighted based on expert opinion. All scenarios, alongside natural and socioeconomic driving forces, were simulated for both the local and the regional scales using the CLUMondo land-change model. Findings show that all future demands can be met under all scenarios, but that planning will make little contribution. Moreover, simulations highlight that integrating strategic planning intentions would produce a higher loss of agricultural lands than simulations with statutory planning intentions. Consequences of our findings for the role of planning in driving land change at various scales in multi-level planning systems are discussed.

1. Introduction

Urban regions are some of the most dynamic land-change systems worldwide (Hersperger et al., 2018). The demand-driven changes, mainly imposed by population growth (Verburg & Overmars, 2009) have caused urban land to gradually expand (Asgarian, Soffinian, Pourmanafi & Bagheri, 2018), posing serious issues for sustainable urban development (Li & Yeh, 2000). If the existing trend continues, the land converted into urban areas is expected to almost triple in the next 20 years (Dadashpoor, Azizi & Moghadasi, 2019), presenting additional pressures on existing urban land (Wolff, Schrammeijer, Schulp & Verburg, 2018) and increasing the competition with other land uses (Van Vliet, Eitelberg & Verburg, 2017).

Nevertheless, future land-use demands and changes are complex, uncertain and difficult to predict (Verburg et al., 2019). In this context, scenario-based simulations of plausible future land uses has become a frequently used approach to explore and map uncertainties (Pazúr & Bolliger, 2017; Price et al., 2015). Whereas information on past transitions, driving factors of change and spatial dynamics have a long tradition in simulating future land-use arrangements (Gerecke et al., 2019; Liu, Verburg, Wu & He, 2017), researchers have only recently started to pay attention to policies and plans that regulate land use (Prestele et al., 2016).

Although a widely accepted premise is that spatial planning - including land-use planning and strategic planning - influences patterns of land use and land cover, planning has, for a long time, only occasionally integrated in quantitative land-change assessments (Hersperger et al., 2018). Nevertheless, since planning is about coping with uncertainties and influencing future land uses (Onsted & Chowdhury, 2014), by directing the forces toward changes that balance the needs and enhance the best interest of communities (Anputhas, Janmaat, Nichol & Wei, 2016), planning can be considered in scenario design and further implemented in land-change simulations of future developments (Hersperger et al., 2018). Integrating planning into scenarios and

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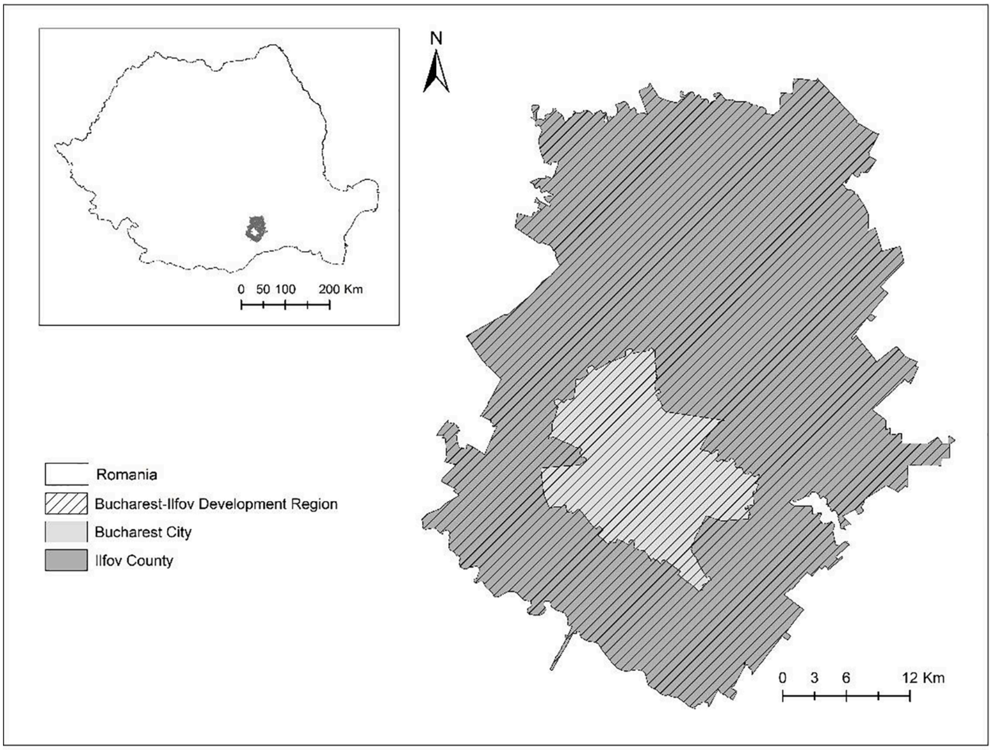

Fig. 1. Spatial extent of the study area represented by two administrative levels, the city of Bucharest and the Bucharest-Ilfov Development Region.

land-change models enables planners and managers to assess the outcomes of current planning practices and policies, as well as the outcomes of investment choices before they are put into action (Zhang et al., 2011). This information would also influence future location suitability for a specific land system or restrict land-use conversions completely (Hersperger et al., 2018; Wolff et al., 2018). Finally, since it is a better reflection of the real patterns of urban expansion (Huang, Huang & Liu, 2019), integrating planning into land-change models could also improve the accuracy of simulations (Onsted & Chowdhury, 2014).

However, despite the benefits, planning is rarely integrated into scenarios and land-change simulations due to many challenges. First, the planning intentions of development expressed by spatial plans are portrayed differently in plans, varying greatly between types of plans and even from plan to plan. For example, some plans (e.g., zoning plans) contain maps with a high geographical accuracy and clear boundaries, whereas other plans (e.g., strategic plans) are rather fuzzily represented and generally, less specific than is required for land-change simulations (Hersperger et al., 2018). Thus, most studies which include planning in scenarios and land-change models make use of zoning plans as binary variables, either allowing or hindering urban development (see Geneletti 2013, Lin and Li 2019, Zhou, Dang, Sun and Wang 2020). Research considering strategic spatial planning intentions of different intensities and weights are rare (Dadashpoor et al., 2019; Huang et al., 2019; Liang et al., 2018), even though they still provide spatial information, either in the form of geographically accurate data, diagrams or textual descriptions (Palka, Gradinaru, Jorgensen & Hersperger, 2018), which provides a solid starting point for land-change models (Hersperger, Grădinaru and Siedentop, 2020).

A second challenge emerges further from the fact that the integration of planning into scenarios and land-change models should account for the entire planning process rather than information from plans alone (Hersperger et al., 2018). For instance, as recommended by Hersperger et al. (2018), land-change models should include not only the planning intentions expressed in plans, but also the means of implementation of plans through governance processes, and the role of external conditions influencing implementation to account for the entire planning process (Hersperger et al., 2018). Nevertheless, even with the integration of the entire planning process, another pressing challenge that remains is the portraying of multi-level planning in simulations. Specifically, multi-level planning systems in place is most countries benefit from a variety of spatial plans and planning processes available at different administrative levels and mandated by a variety of sectors, all influencing land change (Acheampong, 2018; Lieu, Spyridaki, Tuerk & Vliet, 2018). Thus, the integration of the entire network of plans and processes is needed to finally understand the contribution of planning to land change (Bacău, Grădinaru & Hersperger, 2020).

Lastly, land-change models used to project scenarios are technically limited themselves and rarely allow the inclusion of input data other than the data they were designed for (Feng, Liu & Lu, 2012; Onsted & Chowdhury, 2014). Nevertheless, there are models providing support for policy implementation (Huang et al., 2019), allowing inclusion of restrictions and constraints of land system conversion at specific locations as set by spatial plans and policies (van Asselen & Verburg, 2013; Wolff et al., 2018). These plans and policies are integrated as spatially explicit and weighted layers, allowing the inclusion of planning intentions from a variety of spatial plans and with a variety of weights (Zhu, Gao, Zhang & Liu, 2020). One example of this is the CLUMondo modeling framework (see van Asselen and Verburg 2013 for an in-depth explanation of the model), which was designed to simulate land-use changes as determined by relationships between the land system and socioeconomic and biophysical factors in response to future demands for various goods and services while taking into account spatial restrictions and location suitability for each land use (Ornetsmüller, Verburg & Heinimann, 2016; Ren et al., 2019; van Asselen & Verburg, 2013).

To address these challenges and to assess the influence of planning to land change and its potential to meet future land-use demands in multi-level planning systems, we implement scenarios of future development in the CLUMondo model for two administrative levels, Bucharest (city scale) and the Bucharest-Ilfov Development Region (regional scale). The aim will be fulfilled by focusing on the following research questions:

A: How might the population trends shape the land-use demands in the city of Bucharest and the Bucharest-Ilfov Region?

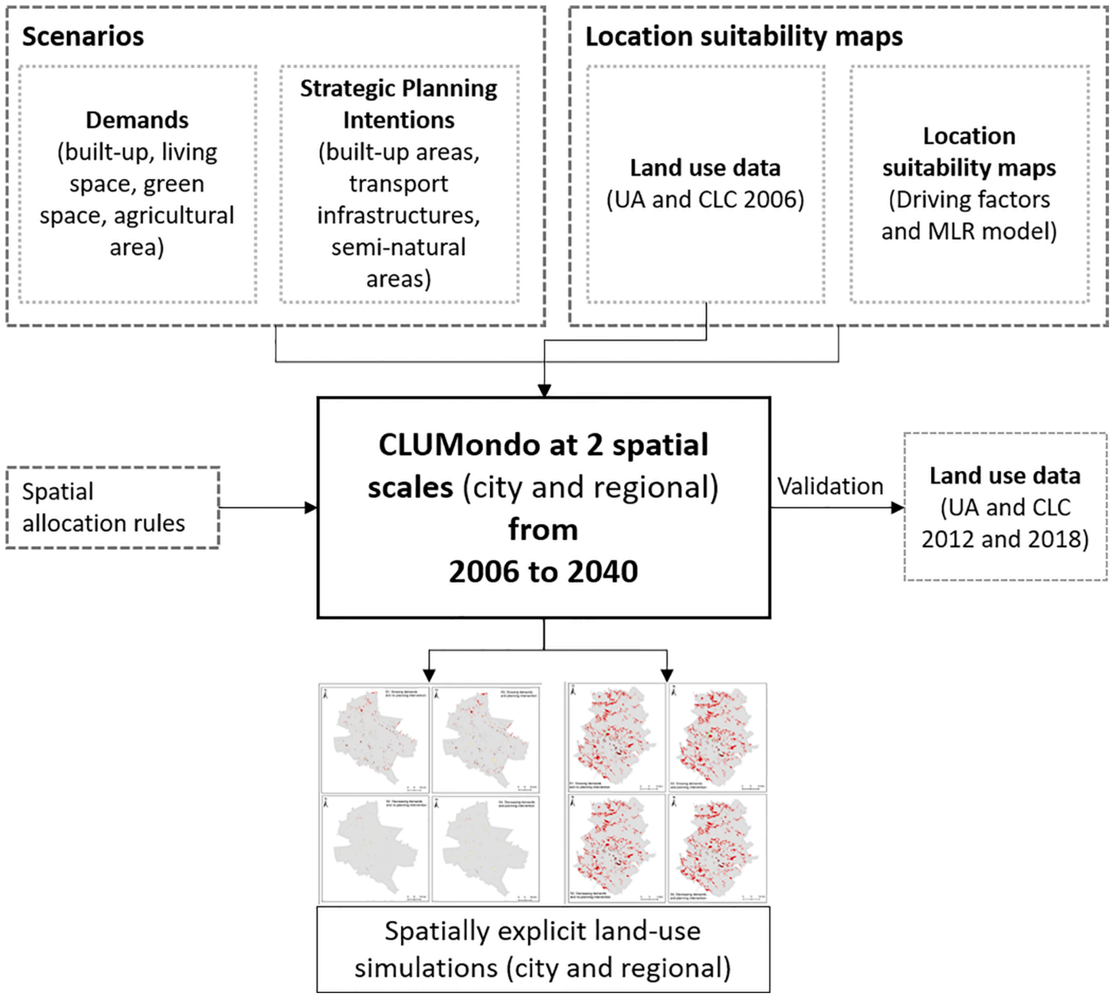

Fig. 2. An overview of the inputs included in CLUMondo model, the procedure implemented for the land-use change simulations and validation and the simulated results.

B: How will the natural and socioeconomic drivers arrange the future developments in order to meet the expected demands?

C: How does the inclusion of statutory and strategic planning intentions change the simulated outcomes?

D: What is the influence of the scale considered in the simulated outcomes?

2. Methodology

2.1. Study area

To characterize the multi-level planning systems, the study area comprises two scales of analysis, namely local (city scale) with focus on Bucharest and regional focusing on the Bucharest-Ilfov Development Region (Fig. 1).

In Romania, the current multi-level planning system only has a 20–30-year tradition. Although the fall of the communist regime happened in 1989, the new planning system only started to emerge in the early 2000s, after a 10-year legislative void. Planning instruments started to be issued only after the first law of spatial planning was adopted in 2001 (Law 350/2001). The law introduced the difference between territorial planning and urbanism, which is mainly a conceptual and scale-related differentiation. Spatial planning operates at the national, regional and county levels and sets the overall directions of development, whilst urbanism refers to the local and sub-local levels and has a statutory character.

Progress in planning was gradual in Bucharest as well. In the late 1990s, there were high hopes for a prosperous and efficient capital city, which led to the compilation of the first post-communist spatial plan, the General Urban Plan of Bucharest, issued in 2001. Despite being constantly modified under the pressure of private interests (see Nae, Dumitrache, Suditu and Matei 2019), the General Urban Plan is still currently in force. Recently, strategic spatial plans were adopted at higher administrative levels (county, region, national), adding new perspectives for spatial development in Bucharest. Among these spatial plans, those mandated by EU related to transportation, regional development, public administration and the environment were found to be the most effective even if they are mostly indicative (Grădinaru et al., 2020). Moreover, the EU accession also meant administrative restructuring in terms of creating eight NUTS II-level administrative areas existing at European level with the related institutions as a regional policy system (Dobre, 2009). Many of its objectives overlap with the spatial planning development, but since Law 350/2001 did not refer to the regional development, regional policy and spatial planning in Romania have emerged as two parallel systems, with overlapping attributes concerning spatial development, but with no coordination (Benedek, 2013).

Among the eight regions, the Bucharest-Ilfov Development Region is of particular interest. Up to 1995, Ilfov County has been managed as part of Bucharest, as its agricultural district and since 1995 Ilfov County has constituted an independent county with its own administration and institutions. Thus, reconnecting the two administrative units within a

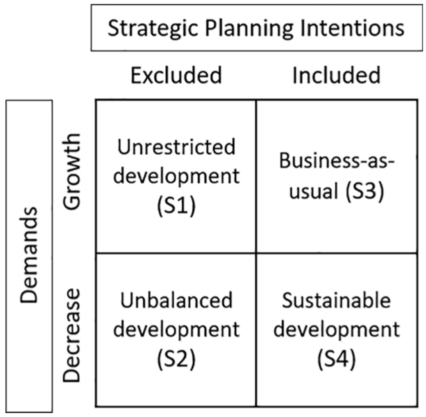

Fig. 3. The four scenarios defined for the land-use change simulations (S1, S2, S3 and S4) and how they correspond to demands for land-use and the inclusion or exclusion of strategic planning intentions.

Table 1
The sources of population data and land-use demands used in the simulations.

Population and land-use demands considered	Sources	Used for
Population size	National Censuses (2002, 2011), NIS Report (2017), Eurostat	city and regional scale
Living space/person (m^2/person)	National Censuses (2002, 2011), General Plan of Bucharest (2001)	city scale
Built-up area (m^2)	National Censuses (2002, 2011)	regional scale
Green area/person (m^2/person)	National Censuses (2002, 2011), National and European legislation	city and regional scale
Agricultural area (m^2)	National Censuses (2002, 2011)	regional scale

Development Region while still retaining separate institutions for their individual management poses challenges for spatial planning and overall land management. Although the Bucharest-Ilfov Development Region is one of the most dynamic areas of Romania in terms of land-use changes with great challenges for management (Niţă, Iojă, Rozylowicz, Onose & Tudor, 2014), spatial plans for the regional level follow a rather economic approach and are considered the weakest in the multi-level planning system (Benedek, 2013).

Therefore, even though recent studies criticize the current multi-level planning system for being incoherent (Ianoş, Sorensen & Merciu, 2017), prone to conflicting situations (Grădinaru, Iojă, Pătru-Stupariu & Hersperger, 2017) or even lacking in policies for urban development (Suditu, 2009), evaluations of processes and planning instruments in Bucharest are scarce, inconsistent and inconstant. In this sense, there is little known about the contribution of planning to land change and to meeting future land-use demands in the new multi-level planning systems.

2.2. *Scenario approach*

The simulation of future land-uses was carried out using a scenario-based approach in CLUMondo (Fig. 2). We developed four scenarios that take into account (i) the land-use demands per year (living space per person, built-up area, green space per person, agricultural area) and (ii) the strategic planning intentions for development as expressed in various spatial plans (Section 2.2.1). The allocation procedure of CLUMondo was parametrized to include: (1) the total demand per year associated with each scenario (Section 2.2.2.1), (2) location specific layers derived from the strategic planning intentions (Section 2.2.2.2), (3) an initial land-use map (Section 2.3.1), (4) location suitability maps for each land use, derived from a logistic regression analysis (Section 2.3.2), and 5) land system specific rules, defined as a conversion matrix, to promote or restrict specific transitions between land-use types (Section 2.3.3). Simulations were first performed for the time period 2006–2018 to validate their performance with available reference data for 2012 and 2018 (Section 2.4). We then explored the development trajectories under the four scenarios for the year 2040.

2.2.1. *Scenario storylines and assumptions*

We constructed four scenarios along two main axes, considering (i) possible trends of future demands and (ii) strategic planning intentions. The four scenarios take into account increases and decreases in future demands (built-up area, living space per person, green space per person and agricultural area), while either including or excluding the spatial planning intentions expressed in plans (Fig. 3).

First, the unrestricted development scenario (S1) implies growing demands over time without an expected planning intervention. In this scenario we assume the most unrestricted development to take place, as the fulfillment of demands faces no constraint. Nevertheless, satisfying all demands might lead to conflicting land uses in various areas, especially between built-up and semi-natural areas.

Second, the unbalanced development scenario (S2) takes into account decreasing future demands without an expected planning intervention. Since all future demands are low, they could be fulfilled in a balanced way. However, considering the lack of planning intervention and the fact that both demands and production are low, agricultural areas may remain unused. The results of scenario S2 might thus be able to indicate areas susceptible to future abandonment.

Third, the business-as-usual scenario (S3) follows the existing trends, i.e. increasing future demands, which benefit from planning interventions. In scenario S3 we assume that growth will be limited to the areas specified as developable in spatial plans. In this scenario plans and current planning practices are, therefore, able to balance the competing demands, diminishing the risk of land-use conflicts.

Finally, the sustainable development scenario (S4) foresees decreasing future demands and the implementation of planning intentions. Since demands are low, we expect spatial transformations to be limited to the currently developable areas or areas in their close vicinity. This will also allow spatial development with high ecological awareness, which will prevent land degradation, avoid sprawl and fragmentation and account for nature-based solutions.

2.2.2. *Scenario quantification*

Quantification of demands

The land-use demands are quantified based on the two National Censuses conducted by the National Institute of Statistics (NIS), statistics from Eurostat and data from spatial plans of Bucharest (Table 1).

The annual changes in the four demands (living space per person, built-up area, green space per person, agricultural area) included in CLUMondo, were determined using linear interpolations between known values derived from datasets for the time period 2006–2020. Trends identified for this time range were then linearly extrapolated to 2040. Since we consider the population as the major driver for future land-use demands, in order to calculate the two demands per person, i.e. living space and green areas, population size was used to determine the necessary amount demanded yearly, as a linear extrapolation of known trends. Regarding the living space per person included for the city scale simulations, data was provided by the General Urban Plan of Bucharest (2001), yielding an increase in the amount of built-up area to 15 m^2 per person by 2025. For 2025–2040 we extrapolated the trend identified from 2006 to 2025. Extrapolation of past trends indicated an increase in all demands; these trends were used for scenarios S1 and S3.

To account for decreasing demands included in scenarios S2 and S4, we reverted to the national report launched by the NIS in 2017, which predicts a decrease in the population size by 2060 (National Institute of Statistics, 2017). The predicted decrease in future population size has an impact on the demands calculated per person, i.e. living space and green space. Thus, in S2 and S4, these two demands change, whereas the demands for built-up and agricultural areas at regional scale were

Table 2
The four relevant spatial plans and the representation of their expressed planning intentions included in the simulations. Here PI = planning intention.

Plan	Issued	Type	Representation of PI	Simulation (s) including the PI
General Urban Plan of Bucharest	2001	statutory land-use plan	Text	city and regional
Ilfov County Spatial Plan	2004	strategic	Text and maps	regional
Regional Spatial Plan of the Bucharest-Ilfov Development Region	2007	indicative	Text and maps for transport development	regional
Regional Spatial Plan of the Bucharest-Ilfov Development Region	2014	indicative	Text and maps for transport development	regional

considered to remain constant (Table 4 in Appendix).

Quantification of spatial planning

Spatial planning was included in scenarios S3 and S4 through means of strategic planning intentions (PIs) extracted from spatial plans. The quantification of PIs was carried out using a three-step procedure. In the initial step, we identified and selected relevant spatial plans that contain strategic PIs for development at both the city and the regional scale. We then derived spatial layers from the PIs, using spatially explicit information found in the plans. In the final step, we conducted surveys with local experts to generate weights for the PI layers. These layers were then included in CLUMondo as location specific layers.

Step 1. Selecting relevant spatial plans: Four spatial plans covering the city and the region provided the strategic PIs required (Table 2). One plan covered Bucharest (General Urban Plan of Bucharest), two referred to the Bucharest-Ilfov Development Region (Regional Spatial Plans), and one covered the Ilfov County (County Spatial Plan) providing information on the regional level.

The General Urban Plan of Bucharest is a statutory plan that regulates the zoning of Bucharest, clearly defining areas and objectives of development (Suditu, 2012). The plan is central for the local administration despite being modified through a variety of Zonal and Detailed Urban Plans (Nae & Turnock, 2011). The County Spatial Plan is a strategic plan targeting the overall development of technical and transportation infrastructures, as well as the establishment of protected areas and management of economic activities. The two Regional Spatial Plans, adopted in line with the EU funding schemes (2007–2013 and 2014–2020), target regional economic potential, social issues, public infrastructure and natural risks. These plans, often referenced in other planning instruments in relation to their capacity to attract EU funding (see Bacău et al. 2020), were found to be the weakest in the hierarchical planning system, being often only indicative (Benedek, 2013).

Step 2. Deriving spatial layers from strategic planning intentions (PIs): The PIs were extracted through content analysis of the four plans. Since the focus was on strategic PIs, we did not focus on the zoning found in plans, but on their operational sections e.g. strategic goals, measures and actions (Schmid, Kienast & Hersperger, 2020). We extracted all PIs related to the three categories of land use namely built-up areas, transportation infrastructures and (semi-)natural areas, which would help fulfill the selected demands. We extracted the name, location and description for each PI. We then used the available spatial information from plans (i.e. maps, diagrams, text) for georeferencing, digitization and rasterization of the proposed developments, to generate spatially explicit layers containing the PIs.

Step 3. Weighting the spatial layers based on expert opinion: To assess how strong the PIs can be in leading land change, we used the analytical hierarchical schema developed by Palka, Oliveira, Pagliarin and Hersperger (2020) to express the efficacy of each PI. The analytical hierarchical schema includes key factors of the territorial governance and external forces that can influence plan-implementation (Hersperger, Gradinaru, Oliveira, Pagliarin & Palka, 2019; Oliveira & Hersperger, 2018). To be able to feed the hierarchical schema and gain insight into the overall planning efficacy in Bucharest and its region, we conducted a survey among 10 local experts, including both academics and professionals involved in the planning process. Experts were asked to complete the schema investigating the 12 components relating to governance performance (Fig. 8 in Appendix) and six components concerning the external forces (Fig. 9 in Appendix) that can affect plan implementation (Palka et al., 2020). The average strengths were then used to weight the PI layers, which were finally implemented as location specific layers in CLUMondo, either as restrictions (Huang et al., 2019) or as suitability of a particular location (pixel) to be converted to another land use (Verburg et al., 2008). All computations were performed in Python.

2.3. Data collection and modeling

2.3.1. Land use data

The European Environmental Agency (EEA) provides high-resolution and inter-comparable land-use and land-cover data commonly used in scenario-based simulations (Pazúr, Feranec, Stych, Kopecká & Holman, 2017;). EEA datasets are constantly validated, having a minimum overall accuracy of 80% (EEA, 2021(European Environment Agency, 2021)). For the simulations at city scale we thus selected the Urban Atlas (UA) dataset available for the city of Bucharest with a minimum overall accuracy of 82.1% (EEA, 2020(European Environment Agency, 2020)). Since UA has a limited spatial coverage, for the regional simulations we thus selected the CORINE land cover dataset (CLC) with an overall accuracy of 87.8% (EEA, 2012(European Environment Agency, 2012)).

The UA and CLC datasets are available for different points in time from which we selected the 2006 datasets as starting points and used data from 2012 to 2018 for validation of results. Since both datasets vary in the number of classes they contain over time, we reclassified the variation of land uses into ten and 13 land-system types for the city and region respectively to be comparable (Table 5 in Appendix). Furthermore, since the two datasets have a different spatial resolution, data was transformed to a raster format at 25 m resolution for the city scale and 30 m resolution for the regional scale, considering the central pixel value (Domingo, Palka & Hersperger, 2021), taking into account the different mapping units of the two datasets and to better capture differences in simulations at the two spatial scales.

2.3.2. Driving factors and the location suitability

For each land use, the location suitability was described by relating the initial land uses from 2006 to a set of independent variables using logistic regression models (Ornetsmüller et al., 2016). As independent variables we used a set of topographical, environmental, proximity and socioeconomic driving factors, equating to a total of 21 explanatory variables (Table 6 in Appendix), which are commonly used to explain the location of land uses (Domingo et al., 2021; Gerecke et al., 2019; Price et al., 2015). The drivers were transformed into raster format and rescaled to 25 and 30 m resolution to match the corresponding land-use data for the two scales of analysis.

Topographical, proximity and socioeconomic variables were computed for both the city and regional scales, whereas environmental variables were only considered to match the demands for agricultural areas at the regional scale. Three topographical variables were considered, i.e. elevation, slope and aspect computed based on the digital elevation model (DEM). Eleven proximity variables were computed as Euclidean distances using data from Open-Street-Map (Liang et al., 2018; Zhang et al., 2011). Of the proximity variables, four related to the transport system, two concerned the center of cities and settlements, two accounted for service areas (i.e. commercial and educational facilities)

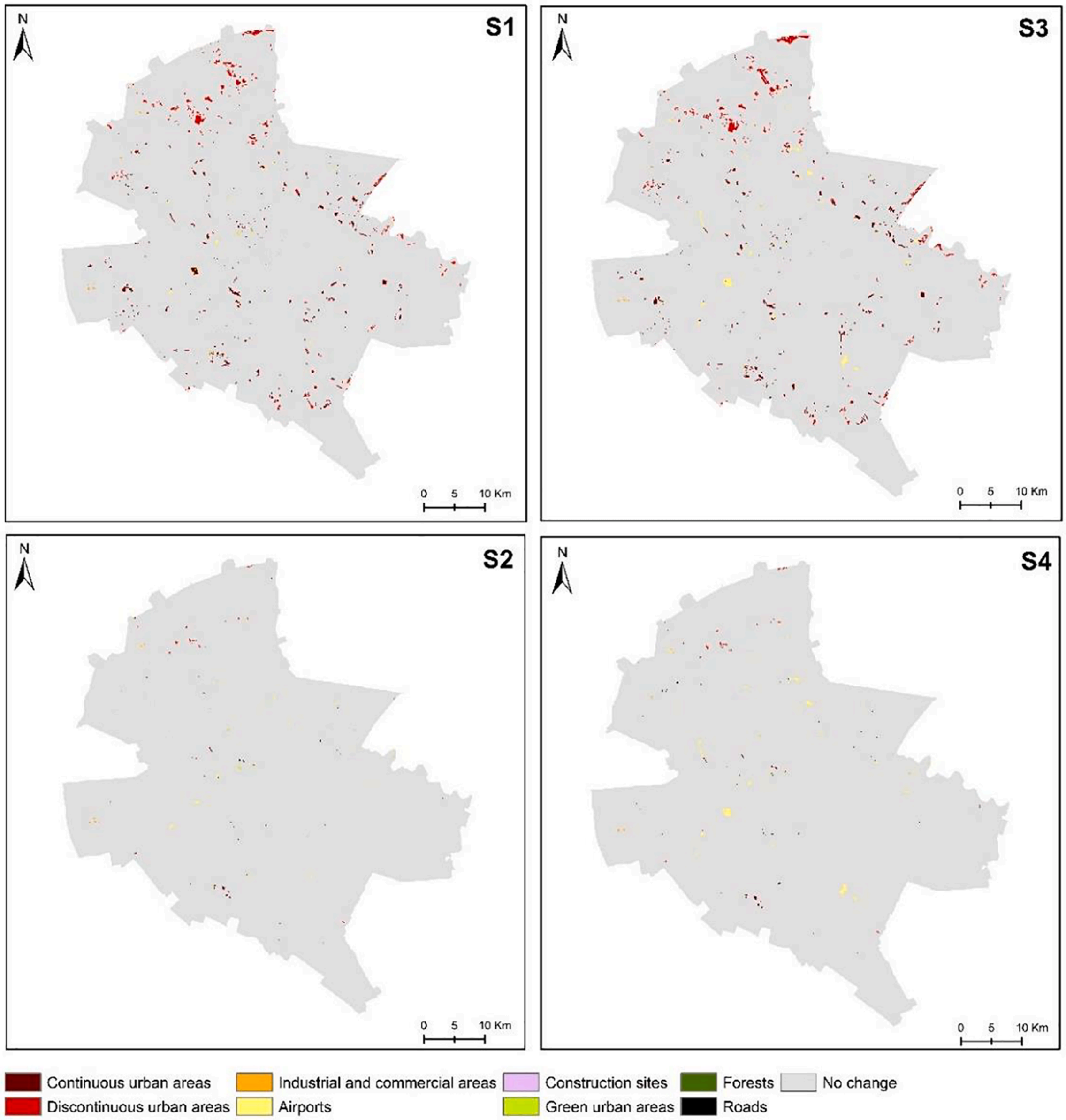

Fig. 4. The spatial distribution of land-use types in the city of Bucharest in the year 2040 for the four defined scenarios (S1–S4). The most extreme changes towards urbanization are simulated under scenario S3 (i.e. increasing future demands and inclusion of planning).

and three described the proximity to (semi-)natural areas, including the distance to water bodies, forests and urban parks. For the transport system, the distance to major roads included all motorways, primary, secondary and tertiary roads; distance to cycling and pedestrian trails considered all cycling lanes, pedestrian and residential paths; distance to transport lines encompassed the public transport network, including metro, tram and railways; and distance to public transport stations considered the proximity of metro, tram and bus stops. Finally, three socioeconomic drivers were included to characterize the demographic and economic profile. Population density was derived from the Global Human Settlement Population layer, whereas the job density and housing prices were provided by the NIS and computed at neighborhood level. Four environmental drivers were included in the regional simulations to help predict future land uses and to satisfy demands for agricultural areas, i.e. annual mean temperature, annual mean precipitation and soil and geology classes (Table 6 in Appendix).

Multivariate logistic regression models (MLR) were then used to estimate the probability of occurrence of each land-use type based on all drivers for any given pixel (Ornetsmüller et al., 2016). First, random samples were taken, ensuring a minimum distance of two pixels between each selected pixel to reduce spatial autocorrelation (Dungan et al., 2002) and to balance the presence and absence observations for each land system type (Ornetsmüller et al., 2016). To determine a final model for each land-use type, we modeled all combinations of the explanatory variables and selected the set of variables with the best fit according to the AIC value (Price et al., 2015). Finally, we evaluated all models using a split-sample approach, in which a group of randomly selected sites was divided into training and testing samples (Pazúr & Bolliger, 2017). Explanatory power of the models was measured with the Area under the Receiver Operating Curve (AUC) (Pontius & Schneider, 2001). We used the same probability models for all scenarios, which were all performed in R version 4.0.2.

2.3.3. *Spatial allocation in CLUMondo*

The demands and the weighted planning intention layers, together with the initial land use and the location suitability maps for each land use were transposed into the CLUMondo model settings. In addition, to run CLUMondo, permitted land-use conversions were specified in a

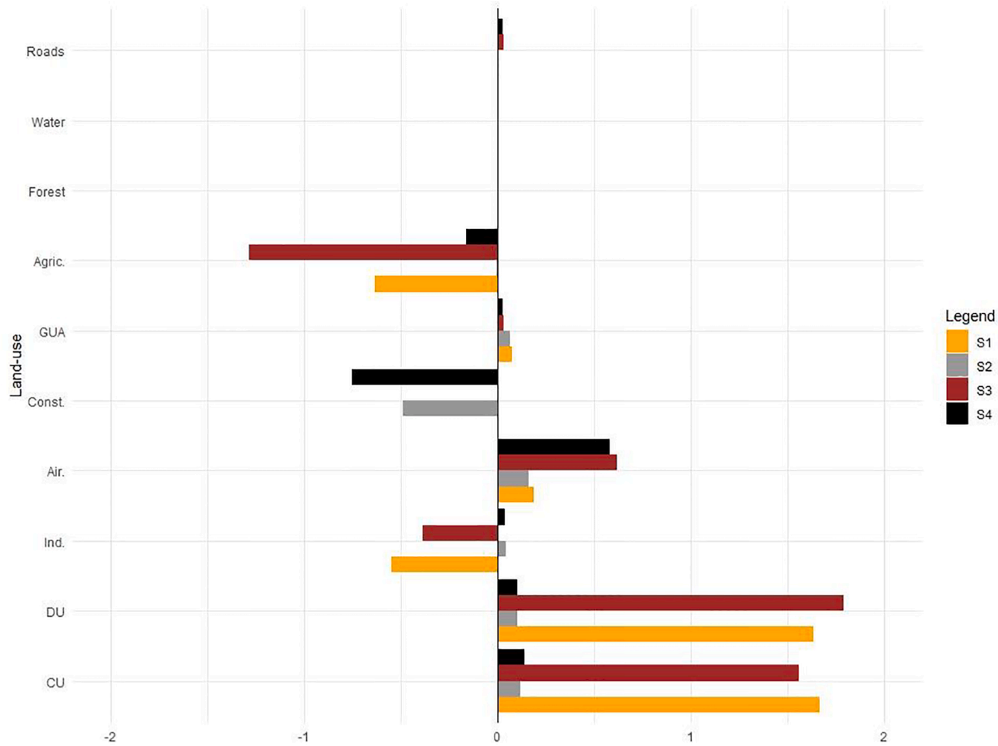

Fig. 5. The changes in areas of land-use types from 2006 to 2040 at the city scale, shown in km^2 for each land-use type under the four defined scenarios. Land uses were abbreviated as follows: Agric = Agricultural areas, GUA = Green Urban Areas, Const = Construction sites, Air = Airports, Ind = Industrial and commercial areas, DU = Discontinuous Urban areas, CU = Continuous Urban areas.

conversion matrix for each scale of the analysis (Tables 7 and 8 in Appendix). The conversion matrices indicated the initial land use and how much time must pass before conversion to another land use is permitted (Ornetsmüller et al., 2016). As built-up areas are not easy to transform into other land uses, we first allowed densification of continuous urban, discontinuous urban, industrial and commercial land uses, assuming that the remaining land-use types (e.g. cultivated land or forest) can be converted from and to one another in a given time (Domingo et al., 2021; Zhu et al., 2020).

2.4. Accuracy assessment

Uncertainty in simulations is inevitable, emerging from a variety of sources, such as accuracy of the initial land-use data used to simulate, to the accuracy of driving factors and simulation performance. Thus, to acknowledge the uncertainty of simulations, we first ran CLUMondo using data from 2006 to predict the land uses for 2012 and 2018 for both the city and regional scales. This run calibrates the simulations with information from the past in order to simulate a map of the present and then uses those observations to anticipate how the model will simulate for the future (Pontius & Schneider, 2001). The validation procedure includes: (i) the initial land-use maps from 2006, (ii) the available UA and CLC datasets from 2012 to 2018, and (iii) the simulated maps for 2012 and 2018 (Pontius et al., 2018). This level of accuracy is then used to further compute simulations up to 2040.

We conducted independent validations at both pixel and patch levels to assess the location accuracy (Pontius & Schneider, 2001; Pontius and Spencer, 2005; Pontius et al., 2018) and pattern accuracy (Power, Simms & White, 2001) of each simulation. Location accuracy at pixel level was summarized using the Figure of Merit's components: Misses, Hits, Wrong Hits and False Alarms at three aggregation levels (Varga et al., 2019; Zhai et al., 2020). Moreover, since pixel-by-pixel comparisons do not capture the similarity of patterns between maps, we also performed pattern validations comparing the simulated and available reference maps of 2012 and 2018. This was carried out using hierarchical fuzzy pattern matching, which measures both map similarities and land-use change between maps (Power et al., 2001). Validations at pixel level were performed in R version 4.0.2 and validation at patch level in Map Comparison Kit.

3. Results

3.1. Performance of the location suitability models

The logistic regression performed well for all land uses at both scales, with an average AUC value of 0.83 at the city scale and 0.90 at the regional scale. The AUC values ranged from 0.68 for roads to 0.99 for water at the city scale (Fig. 10 in Appendix) and from 0.79 for pastures to 0.98 for roads and airports at the regional scale (Fig. 11 in Appendix). Overall, the highest model performance was identified when modeling continuous urban areas, airports, forests, water, and agricultural areas whereas the model had lowest accuracy for industrial and commercial areas, trees and vineyards and pastures.

The performance of each variable impacts the overall accuracy of simulations and spreads uncertainty in the final results. Nevertheless, they are acknowledged and included in land change modeling research (Pazúr & Bolliger, 2017; Daunt et al., 2021). Thus, the number of drivers selected to assess land-use change, using the MLR regression, depended upon the scale considered. At city scale, the number of independent drivers ranged from three (for water land-use) to nine (for dense urban and green urban areas) (Table 9 in Appendix). Whereas, at regional scale independent drivers ranged from three (for transport land use) to ten (for water and green urban areas) (Table 10 in Appendix). Of the drivers, proximity variables, especially distances to major roads, trails for non-motorized transport and transport lines were most often selected at city scale, along with population density. At regional scale, topographical and environmental drivers such as elevation, slope, geology, mean temperature and precipitation, as well as distance to water and forests

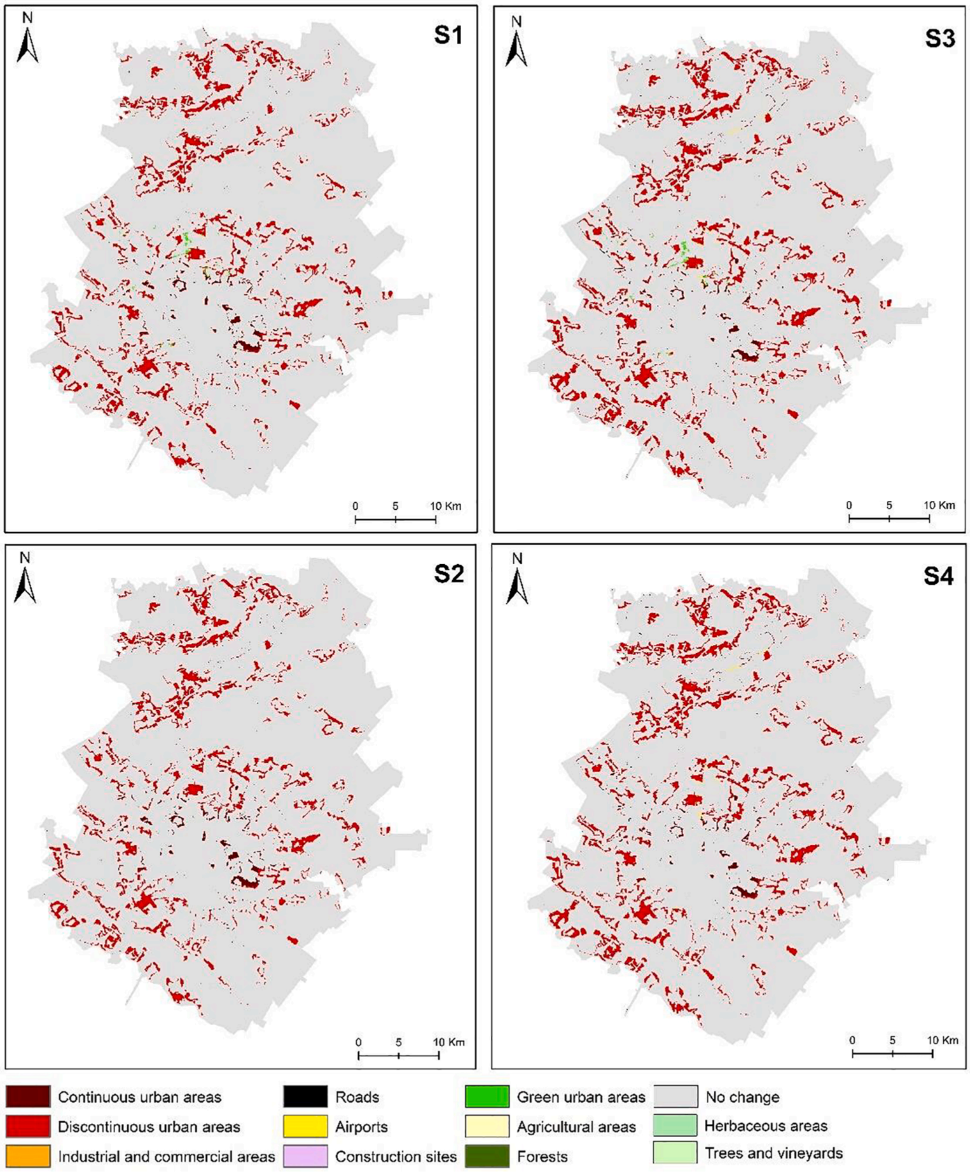

Fig. 6. The spatial distribution of land-use types in the Bucharest-Ilfov Development Region in the year 2040 for the four defined scenarios (S1–S4). Similar to the city scale, scenario S3 will produce the highest land consumption in order to meet all land-use demands.

were commonly included.

3.2. Integration of spatial planning

Within the four selected plans we found a total of 12 PIs suited for our analysis (Table 11 in Appendix). At city scale, eight PIs were selected from the General Urban Plan of Bucharest, whereas at regional scale, PIs were selected from all four plans, to differentiate their statutory and non-statutory characters at city and regional level respectively. Although some PIs were only present in one plan, most of them were present in all four plans, indicating a high degree of consistency amongst the plans (Bacău et al., 2020). Among PIs, eight addressed built-up areas, one related to the overall transport network and three concerned (semi-)natural areas.

The PIs encompass both the overall development of the city and region, as well as specific spatial transformations. Specifically, half of the PIs target large-scale developments, such as polycentric, linear or compact development, or the establishment of a green-yellow belt around Bucharest. Moreover, the large-scale PIs also target major investments for transport infrastructure and the conservation of natural and cultural areas. The remaining PIs, which target small-scale transformations, focus on the provision of social housing, education facilities or technical infrastructures, and measures for improving the quality of life, e.g. conversions of former industrial sites or the expansion of urban green areas within the city.

All PIs were spatially computed based on the spatial information available in plans. They were represented either as buffers around existing structures, or as new digitized and rasterized features for the proposed new developments. The weightings obtained from the expert survey used to compute the planning contribution range from 0.48 for PIs for (semi-)natural areas to 0.5 for PIs concerning built-up areas and 0.53 for PIs relating to transport infrastructure (Fig. 12 in Appendix). The PIs related to these three categories of land use, transport, built-up areas and (semi-)natural areas, received the corresponding weight obtained from the survey.

3.3. Simulated land uses under the defined scenarios

3.3.1. City scale

At city scale, all simulations show an overall increase in built-up

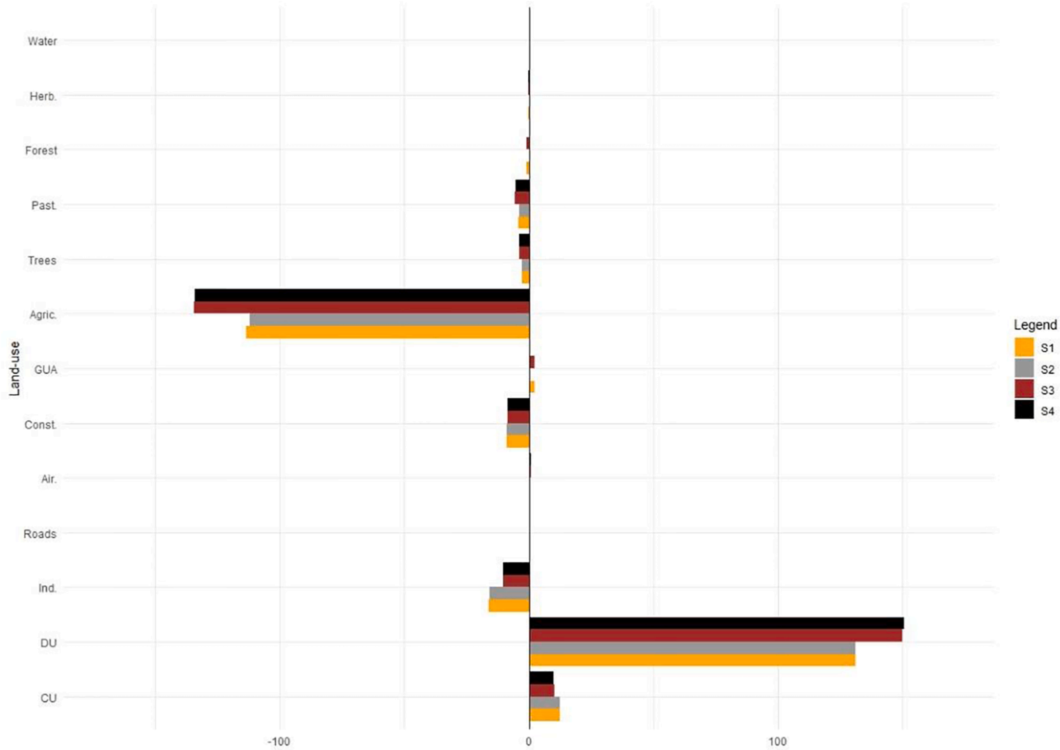

Fig. 7. The changes in areas of land-use types from 2006 to 2040 at the regional scale, shown in km^2 for each land-use type under the four defined scenarios. Land uses were abbreviated as follows: Herb = Herbaceous areas, Past = Pastures, Agric = Agricultural areas, GUA = Green Urban Areas, Const = Construction sites, Air = Airports, Ind = Industrial and commercial areas, DU = Discontinuous Urban areas, CU = Continuous Urban areas.

Table 3
An overview of the results of location and pattern accuracy validations in 2012 and 2018, at the city and regional scales for the four defined scenarios. All accuracy values in the table are given in percentage. WPP = Well Predicted Performance, OMP = Overall Model Performance and FIS = Fuzzy Inference System.

Scale	Scenario	Validation year	Location accuracy							Pattern accuracy
			Misses	Hits	Wrong hits	False alarms	Correct rejections	WPP	OMP	FIS
City	S1	2012	2.79	0.04	0.32	0.09	96.76	99.91	96.8	81.2
		2018	4.3	0.16	1.61	0.07	93.85	99.92	94.01	70.8
	S2	2012	2.79	0.04	0.32	0.09	96.76	99.91	96.8	81.2
		2018	4.42	0.07	1.55	0.03	93.93	99.97	94	70.9
	S3	2012	2.69	0.04	0.44	0.13	96.7	99.86	96.75	81.2
		2018	4.18	0.17	1.75	0.1	93.79	99.89	93.97	70.8
	S4	2012	2.69	0.04	0.44	0.13	96.7	99.87	96.75	81.2
		2018	4.31	0.08	1.68	0.06	93.87	99.94	93.96	70.8
Region	S1	2012	12.94	0.18	2.3	0.57	84.02	99.33	84.2	72.8
		2018	12.24	0.46	2.77	1.55	82.99	98.17	83.45	72.2
	S2	2012	12.95	0.18	2.29	0.56	84.03	99.34	84.21	72.9
		2018	12.26	0.46	2.73	1.52	83.02	98.2	83.49	72.3
	S3	2012	12.88	0.19	2.35	0.69	83.89	99.19	84.08	72.7
		2018	12.17	0.47	2.82	1.75	82.79	97.93	83.25	72
	S4	2012	12.89	0.19	2.34	0.68	83.9	99.19	84.09	72.8
		2018	12.19	0.47	2.8	1.73	82.81	97.95	83.28	72

areas, regardless of the scenario considered (Fig. 4). Irrespective of future population increases or decreases in Bucharest until 2040, the need for more living space per person will continue to increase over time, resulting in higher amounts of built-up areas in the city. Urbanization mostly happens at the expense of agricultural areas, however in scenarios S1 and S3 the industrial areas will also diminish (Fig. 5).

The unrestricted development scenario (S1) implies an increase in the population, resulting in demands for living space per person and consequently green space per person to increase over time. S1 shows an increase in built-up areas, with slightly more continuous than discontinuous densities. This scenario would provide both infill development and expansion, densifying the existing areas before creating new developments in the periphery (mostly in the northern part of the city). S1 also simulates the creation of new green areas, satisfying the demands for green areas per person. All demands are provided at the expense of industrial and agricultural areas, which show decreases in 2040. As expected with scenario S1, without planning intervention future developments might be prone to conflicting situations emerged from the need for both built-up and green areas.

Conversely, as expected with scenario S2, since population size is decreasing, land might be prone to abandonment in the absence of planning. In the scenario S2 the industrial and agricultural areas are maintained and only a low increase in built-up areas is seen. Since the population is expected to decrease in this scenario, the demand for living space per person will also decrease, meaning that the existing amount of built-up area is almost enough to satisfy demands in 2040. Under scenario S2, more industrial and commercial areas are predicted along with an increase in green areas.

Scenario S3, following past trends, takes into account the eight weighted PI layers in order to simulate for growing future demands. Although the General Urban Plan used in this analysis is statutory and aims to balance future developments, scenario S3 shows the most extreme changes towards urbanization, simulating the highest loss of agricultural areas. Urbanization under S3 will take place both as infill and expansion, creating medium and low density urbanized areas far from the city center. S3 predicts more discontinuous areas than any other scenario and even more than the predicted continuous areas. Since the PI layers contain statutory goals, S3 is also able to predict the transport infrastructures required by the General Urban Plan of Bucharest in terms of new roads and airport developments.

In scenario S4 a decrease in the population is expected along with decreasing demands for living space and green spaces, which together with expected planning interventions results in a rather low increase in built-up areas and roads. Nonetheless, scenario S4 did express the defined PIs from the spatial plan related with the planned airport developments, showing an increase in this land use type. As assumed with S4, it shows a sustainable development with less land consumption since that the growth of new built-up areas would happen at the expense of construction sites.

3.3.2. Regional scale

At the regional scale, simulations of the four scenarios resulted in similar spatial patterns and changes (Fig. 6), although the amount of change differed slightly (Fig. 7). The regional simulations showed that future requirements for built-up areas will increase, either in form of living, working or service spaces, irrespective of future population increases or decreases. Overall, the regional simulations show increases in built-up areas, especially regarding the discontinuous urban land-use type, which are expected to take place mostly at the expenses of agricultural and industrial areas.

For the regional simulations, the plans used to extract the spatial PI layers are strategic and mostly indicative, showing a rather low increase in continuous built-up areas and an extremely high increase in discontinuous built-up areas for 2040. Scenarios without planning, S1 and S2, showed a slightly higher increase in continuous urban areas than S3 and S4, whereas the latter two scenarios showed a higher increase in discontinuous urban areas than the first two. Continuous areas showed an expected edge development of 10–15 km^2 in the eastern part of Bucharest. Contrastingly, discontinuous areas showed expected increases of ca. 150 km^2, situated around the city and in the northern part of the region in linear forms, alongside rivers and close to forests. Regarding the demand for green areas, it was met in both scenarios implying growing demands, namely S1 and S3. In S2 and S4, since the population is expected to decrease, no further additional green spaces would be required.

All gains in built-up areas mostly happened at the expense of agricultural land, which is expected to witness a loss of about 130 km^2 by the year 2040. The most extreme decrease in agricultural areas arose in S3 and S4, the two scenarios in which planning was included. The strategic PIs included in these two simulations would require a high amount of agricultural land to be able to place all intended development found in the four spatial plans. For instance, large developments at the regional level, such as polycentric or linear development will require extreme decreases in the amount of agricultural areas to be implemented. All four scenarios also showed losses of industrial and construction sites of about 15–20 km^2, and S1 and S3 also showed a slight loss of forested areas.

3.4. Location and pattern accuracy assessments

Validation results varied on the scale considered, the defined scenario and the year of validation (Table 3). At the city scale, location accuracy at the pixel level showed the highest agreement between simulated and observed land uses with Well Predicted Performance (WPP) values above 99% for all scenarios and Overall Model Performance (OMP) values ranging from 93% to 96%. The pattern accuracy validation showed that simulations also predicted patches of change at city scale with relatively high accuracy, with pattern accuracy ranging from 71% to 81%.

Validation results showed an overall lower accuracy at the regional scale than the city scale. The regional simulations WPP values ranged from 97 to 99% and the OMP from 83 to 84%, while the pattern accuracy validation showed moderate accuracy in predicting patterns of change, with pattern accuracy ranging from 72 to 73%.

Overall, the location accuracy was higher for scenarios S1 and S2 than for S3 and S4, where the highest performance is attributed to scenarios that do not consider PIs in order to meet the future demands. Validations showed a decrease in accuracy over time between 2012 and 2018, which is commonly the case in land-change simulations where the accuracy decays over time (Pontius & Schneider, 2001). Using datasets from 2012 to 2018 to validate the simulated land uses demonstrated the growing uncertainty of simulations, which tend to perform well for shorter periods of time than for broader timeframes (Verburg et al., 2019). Finally, the disagreements between simulated and reference changes were present. These disagreements might be related to the relatively small amount of change between the initial year (2006) and the validation years (Pontius et al., 2018); alternatively disagreements could be due to the different number of classes in the datasets from the initial and the two validation years.

4. Discussion

We designed four plausible scenarios of development for Bucharest and Bucharest-Ilfov Development Region and implemented them in CLUMondo modeling framework in order to simulate and assess the contribution of planning to land change and in meeting future land-use demands up to 2040. The four scenarios represent a wide range of developments, taking into account possible increases or decreases in the population size and the associated demands for built-up areas, green spaces and agricultural areas. The scenario simulations highlighted the role of different types of plans and planning processes in future land uses, the role of scale when planning for a multi-level systems and, finally, provided a methodology to quantitatively integrate planning into scenario-based land change simulations. The simulated scenarios are not a certain reality, but describe a considerable part of the uncertainty in future land use trajectories and enable policy makers to focus on critical issues (Verburg et al., 2008(Verburg, Eickhout and van Meijl, 2008)), identify key locations of change and indicate likely hotspots or risk areas (Price et al., 2015).

4.1. The role of planning among drivers of change

The simulated land uses for 2040 differ on the scale of analysis and scenario considered, but overall, all simulations indicate decreases in agricultural areas in favor of built-up areas. Previous research showed that in Romania, significant shifts of areas from agricultural uses to urban uses are associated with legislative and institutional changes, especially from the post socialist period (Kuemmerle, Müller, Griffiths & Rusu, 2009). This pattern in land-use change was previously found in other post socialist countries, such as Slovakia, where agriculture is reported among the most sensitive landscape elements when considering political or economic changes (Pazúr & Bolliger, 2017). Changes in land property after 1989 (Iojă, Niţă, Vânău, Onose & Gavrilidis, 2014) and the passive and permissive land management that followed, strongly influenced the evolution of urban areas, especially in Bucharest region (Ianoş et al., 2017). Thus, the agricultural intensification, which dominated the socialist period, was in subsequent periods substituted by spontaneous built-up areas to meet market demands (Ianoş, Sîrodoev, Pascariu & Henebry, 2016). Among them, a rapid expansion of service areas was reported (Suditu, 2012), which has driven urban sprawl (Suditu, 2009) and increased land abandonment (Grădinaru et al., 2015). Such developments are not particular to Bucharest. Similar occurrences of urban sprawl have been reported, for example, in the Czech Republic by the expansion of shopping malls and logistic centres near motorways (Pazúr et al., 2017).

The location suitability models, with high model performances (Ornetsmüller et al., 2016), indicate that the shifts from agricultural to urban uses are mostly influenced by population density and proximity variables. Similar findings were found for other countries, including Spain (Domingo et al., 2021), China (Zhou et al., 2020) and Iran (Dadashpoor et al., 2019). Among drivers, population density appears as the main driving force of change, strongly linked with the development of built-up land-uses. However, in Bucharest the population size is expected to decrease, which may generate an unnecessary waste of land (Van Vliet, Verburg, Grădinaru & Hersperger, 2019). Nevertheless, the built-up area will still increase over time because the demand of built-up/person is increasing, especially at regional scale. Previous findings regarding the Bucharest-Ilfov region highlight that the Ilfov County has become the place for second residences of inhabitants of Bucharest (Iojă et al., 2014). Whereas in other countries, such as Switzerland, initiatives on limiting the construction of second homes are emerging (Price et al., 2015), in Romania the private interest still plays an important role, pressuring the demands for built-up (Nae & Turnock, 2011). A similar case was previously reported for Italy, where urban expansion was inversely proportional to the demographic growth and in the absence of real estate demand (Saganeiti, Mustafa, Teller & Murgante, 2021). Nonetheless, there is an European tendency towards weak correlations between population size and urban growth (Siedentop & Fina, 2012).

Since land change is usually influenced by neighbourhood characteristics (Verburg, Schot, Dijst & Veldkamp, 2004), it is more likely that the built-up areas will occur in the urban fringe (Anputhas et al., 2016). Thus, as the regional simulations show, the expansion is more likely to occur as edge expansion close to Bucharest's boundaries. Similarly, in Italy the general trend is to construct new buildings in the vicinity of low-density areas (Saganeiti et al., 2021) and in Iran the edge growth pattern is dominant over the entire region of Tabriz (Dadashpoor et al., 2019).

The outputs of all four scenario simulations show that among drivers, in the distribution of future land uses, planning makes little contribution. Whereas at the city scale, the statutory General Urban Plan is expected to balance the provision of future land-use demands, its inclusion in simulations show the most extreme changes towards urbanization, simulating the highest loss of agricultural areas among scenarios. At the regional level, the inclusion of non-statutory planning intentions shows an even higher land consumption than in the absence of planning. Thus, a paradox of the analysis remains that scenarios integrating planning intentions simulate a higher loss of agricultural lands than scenarios without planning intentions. Although spatial planning is responsible for better spatially-arranged future developments, in this case integrating planning into simulations showed the opposite outcome. Similar results have been reported for the Shenyang metropolis in Northeast China, where simulated outcomes including planning did not verify the achievement of the plan's main goals to increase urban land use efficiency (Huang et al., 2019). Conversely, findings from Redland, Florida show that planning matters, since agricultural zoning reduced urban growth more than areas zoned for development (Onsted & Chowdhury, 2014). Similarly, evidence from the Netherlands indicates that strong planning measures can reduce urban sprawl (Van Vliet et al., 2017). Similar findings were also found for Spain and China, where integrating zoning plans into simulations proved to help maintaining compactness and urban sustainability (Domingo et al., 2021; Zhou et al., 2020). In Bucharest, however, planning has little contribution and it was previously found incoherent and even able to amplify land-use conflicts (Ianoş et al., 2017; Iojă et al., 2014).

Nonetheless, only 20 years have passed since the first plan of Bucharest plan was issued and it certainly could not have anticipated the dynamics that were to follow in the next decade. The ambitious visions of the first plans, combined with the fact that they were continuously undermined by hundreds of derogative Zonal Urban Plans (Nae & Turnock, 2011), have led Bucharest and the surrounding area to confront many challenges in planning and overall land management. Moreover, since the regional level was created as a requirement for EU accession (Dobre, 2009), spatial plans coping with the regional development are mostly indicative, though not binding to local authorities from counties or municipalities (Benedek, 2013). In this regard, planning is definitely not the only aspect to be criticized (Liu, Huang, Tan & Kong, 2020), but there has clearly been insufficient regulation and all land-use changes have undermined the current plans (Nae & Turnock, 2011).

4.2. The role of scale in multi-level planning systems

The Romanian multi-level planning system is relatively new and rarely the focus of current research (but see Grădinaru et al. 2017). The two scales of analysis allowed to assess not only the contribution of plans and planning to an individual scale but to make a point for the efficacy of planning in the multi-level system. In multi-level planning, relationships among plans and planning processes should be understood as dialectical and not dualistic (Mäntysalo, Kangasoja & Kanninen, 2015). Since all planning instruments coexist 'as a part of a wider context, interacting with others' (Lieu et al., 2018), the analysis also showed that plans are aligned with each other, especially in terms of goals, in order to commonly design and guide sustainable and coherent transformations.

Therefore, choosing the scales of analysis had an influence on selecting the type and number of plans. Thus, for the simulations at city scale, one statutory plan, the General Urban Plan was used, whereas at the regional level, four non-statutory spatial plans were implemented in simulations. Although the General Urban Plan is statutory, it only covers the city of Bucharest, whereas it only gives general directions for the regional developments; this is why it was considered non-statutory for the regional simulations. The remaining three plans included in the regional simulations are strategic and mostly indicative. Despite their differences, the analysis showed that plans are well aligned with each other, especially in terms of goals, in order to commonly design and guide sustainable and coherent transformations. This finding is supported by previous research conducted by Bacău et al. (2020) who analyzed the external consistency among plans of Bucharest region and found that they are highly connected in terms of goals. However, since plans referring to the regional level are mostly indicative, a high level of consistency does not yet mean a better influence of land change.

Nevertheless, the impact of the various plans on land change is noticeable on the simulated amount of land consumption. Specifically, integrating the four plans in the regional simulations showed a higher land consumption than in the case of the one plan integrated into the city-scale simulations. Indeed, all simulations are prone to uncertainty, but findings on how planning favors sprawl in Bucharest were previously reported (see Grădinaru et al. 2015, Suditu 2009). In the same direction, it has been noted that spatial plans referring to Bucharest do not contain any future prediction or simulation to account for what they plan for in the future. This is probably one reason why plans do not match real land-use demands and simulate a higher land consumption than demanded. As plans envision a rather economic development translated into a high increase of buildable land after the EU accession, to fulfill both planning goals and future demands, a higher land consumption is expected in the scenarios involving planning, with differences between types of planning as well. These plans were previously found only to comply with EU requirements, rather than focusing on actual demands for future development (Garcia-Ayllon, 2018; Ianăși, 2008). Nevertheless, previous research indicated that the regional plans of Bucharest are central within the network of plans as they contain important information referenced in order to access EU funding (Bacău et al., 2020), with potential to influence land change. Thus, in the future, for a sustainable urban development, attention should be devoted to search for sustainable urban forms that minimize agricultural land consumption. It will be thus appropriate to design the new generation of plans by encouraging densification processes and limiting further dispersion of urbanized areas in the region.

4.3. The uncertainty of simulations

Land-use models are valuable tools for analyzing land-use changes and assessing potential outcomes of plans and policies (Van Vliet et al., 2019). However, simulating future land use change is subject to increased uncertainty emerging from a variety of sources. First, regarding the land-use data, European Environmental Agency (EEA) spatial datasets, previously validated were used in the analyses. Although the accuracy of both UA and CLC datasets is above 80%, it is doubtful that EEA data with different spatial resolutions and number of classes will reflect all changes. For instance, since the number of land-use classes in the databases increased from 2006 to 2012, it might be that there are no actual changes, but just a difference in the reclassification of classes. Consistently, aggregation of classes for the homogeneity and comparability over time might lead to an underestimation of built-up land (Pazúr & Bolliger, 2017), especially because changes in urban land use come in small increments rather than sudden large-scale conversions (Ornetsmüller et al., 2016; Van Vliet et al., 2019).

Second, the limited number of driving forces selected, particularly the scarce socioeconomic data are challenging for inclusion into simulations. In Romania, data on social and economic issues are handled by the National Institute of Statistics. Data are freely available online, but lack accuracy at large scales, such as the district or neighborhood level, adding uncertainty in the analysis. Moreover, it is likely that the inclusion of additional variables, such as variables related to the real estate market would have improved the modelled outcomes, but they were not available (Daunt et al., 2021). Furthermore, most of the variables are dynamic and will potentially change over time, but the assumption that their influence will continue identically in the future enabled longer forecasts (Gerecke et al., 2019).

Third, the translation of the selected planning intentions into model settings was challenged by fuzzy definitions found in strategic spatial plans and limited spatial information. For instance, regional plans used in the analysis are rather descriptive and lack spatial databases, so the plan data were manually digitized and translated into spatial information. Nevertheless, our procedure produced good results (Palka et al., 2018), easily identified when simulating roads and airport developments in scenarios with planning, which were otherwise absent. Furthermore, whilst it is clear that both planning intentions and weights might change over time, it is plausible that other generations of plans will be issued and that the strength of planning efficacy will vary; this might cause deviations from the simulations presented (Gerecke et al., 2019).

Lastly, land change is uncertain by itself (Verburg et al., 2019). Although simulations might reveal the trends and patterns of change and the potential contradictions of land use (Zhou et al., 2020), unexpected events can drastically influence land change. For instance, a particular case in Bucharest is the rapid densification of the north-eastern part of the city in the close vicinity of Băneasa airport. Since densification was so intense and the residencies were too close to the airport, the airport was closed in 2011. Indeed, our simulations could not have predicted such a development, regardless of the drivers or demands included in the analysis.

Despite the integration of the aforementioned datasets in simulations that may spread uncertainties in the results, simulations accuracy assessments showed good performances, with overall model performances ranging from 83% at regional scale to 96% at city scale (Pontius et al., 2018; Pontius et al., 2008), which denotes the usefulness of simulations for urban growth management.

Land change models could be improved by including more accurate data, more nuanced representations of urban land, spatially explicit plan data and more socioeconomic variables (Van Vliet et al., 2019). For instance, a way to improve models is to increase the spatial resolution of input data, which is increasingly possible as a result of recent advances in remote sensing (Zhao, Weng & Hersperger, 2020). However, a higher spatial resolution does not necessarily increase the accuracy of the data, nor does it necessarily increase the accuracy of the model (Van Vliet et al., 2019). At the same time, other planning instruments, such as zoning plans (Geneletti, 2013; Lin & Li, 2019), could be further integrated into models along with the increasingly available digital plan data (Domingo et al., 2021; Fertner et al., 2019) to further simulate urban growth at city, regional and at national scales or for other European regions. Furthermore, simulations can further account for property ownership, at least in terms of public vs. private to allow conversions in land use or for land use intensity to better promote future conversions and account for densification. Finally, societies no longer only demand built-up, green spaces and food products from the land but also a wide range of ecosystem services and biodiversity protection. Thus, various demands and services could be integrated to broaden the picture of the goods and services that land systems can provide and reduce the number of competing claims made on land resources that shape landscapes (Ornetsmüller et al., 2016).

5. Conclusions

We designed four scenarios of development and implemented them in the CLUMondo model, in order to simulate and analyze if and how future land-use demands for living space, built up, green and agricultural areas will be met in Bucharest and the Bucharest-Ilfov Development Region. The results of our simulations indicate that future demands, as expressed in the four scenarios, will be met at both scales, but that planning will have a rather low influence. Moreover, integrating planning into the simulations revealed a less sustainable form of development than simulations run in its absence. These findings are crucial for understanding the efficacy of the entire multi-level planning system and could be the basis for designing new plans, with planning intentions that better match future sustainable land-use demands.

With this study, we explored future land uses and revealed the importance of integrating strategic planning intentions into land-change simulations. The analysis can thus be seen as an advancement in translating and integrating strategic planning intentions into land-change models. Furthermore, while scenarios and simulations have proven useful in anticipating future land uses, it is often difficult to link these back to policies and management decisions. Results of scenario-based simulations further offer decision support for urban planning and policy makers (Feng et al., 2012; García-Ayllón, 2018), for instance through determining desired locations for urban development or minimizing negative impacts on other land uses (Karakus, Cerit & Kavak, 2015; Li & Yeh, 2000; Saganeiti et al., 2021; Zhai et al., 2020). Thus, simulations results could be further integrated into future plans as a way to perceive the future and to engage stakeholders in discussions and decision-making processes.

Declaration of Competing Interest

None.

Acknowledgments

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Appendix

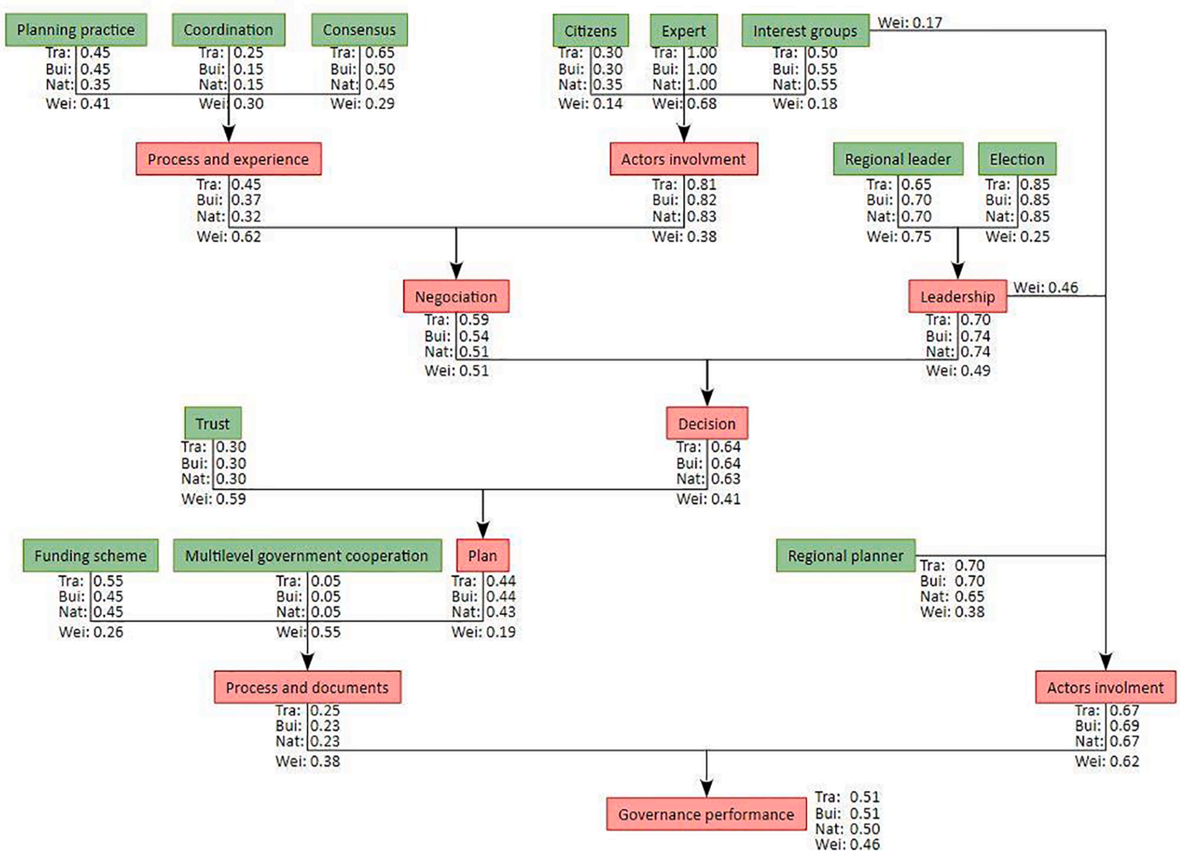

Fig. 8. Weights of the governance performance affecting plan implementation in Bucharest as provided by the ten local experts. Wei stands for the average weight of each component. Values showed consider the three categories of land use, where Tra = transport infrastructures, Bui = built-up areas and Nat = (semi-)natural areas.

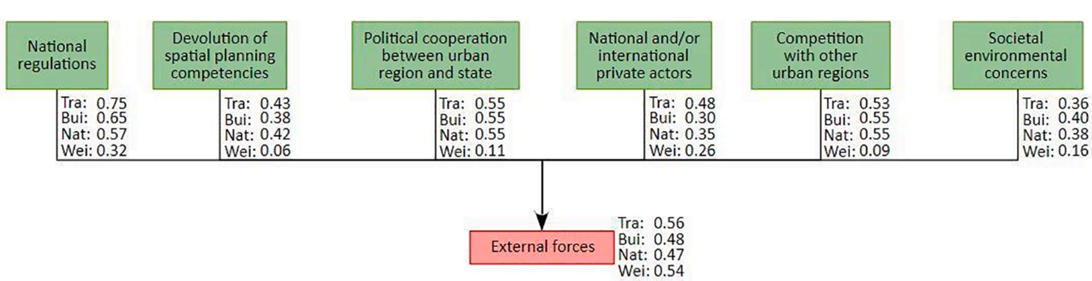

Fig. 9. Weights of the external forces affecting plan implementation in Bucharest as provided by the ten local experts. Wei stands for the average weight of each component. Values showed consider the three categories of land use, where Tra = transport infrastructures, Bui = built-up areas and Nat = (semi-)natural areas.

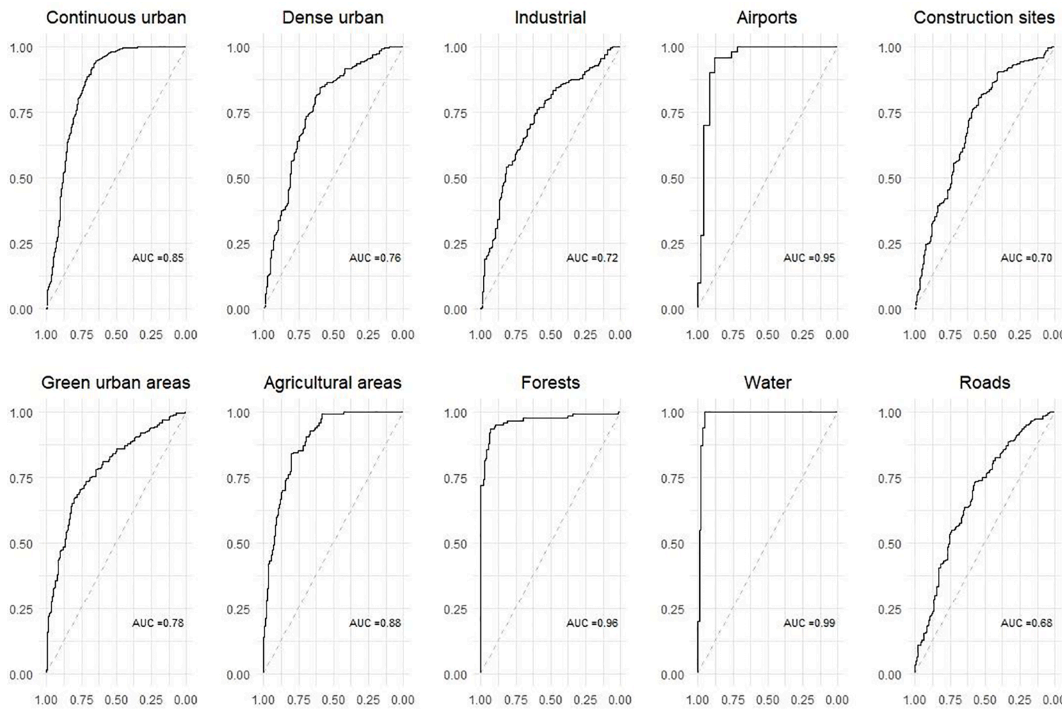

Fig. 10. AUC logistic regression performance values for land-uses at city scale.

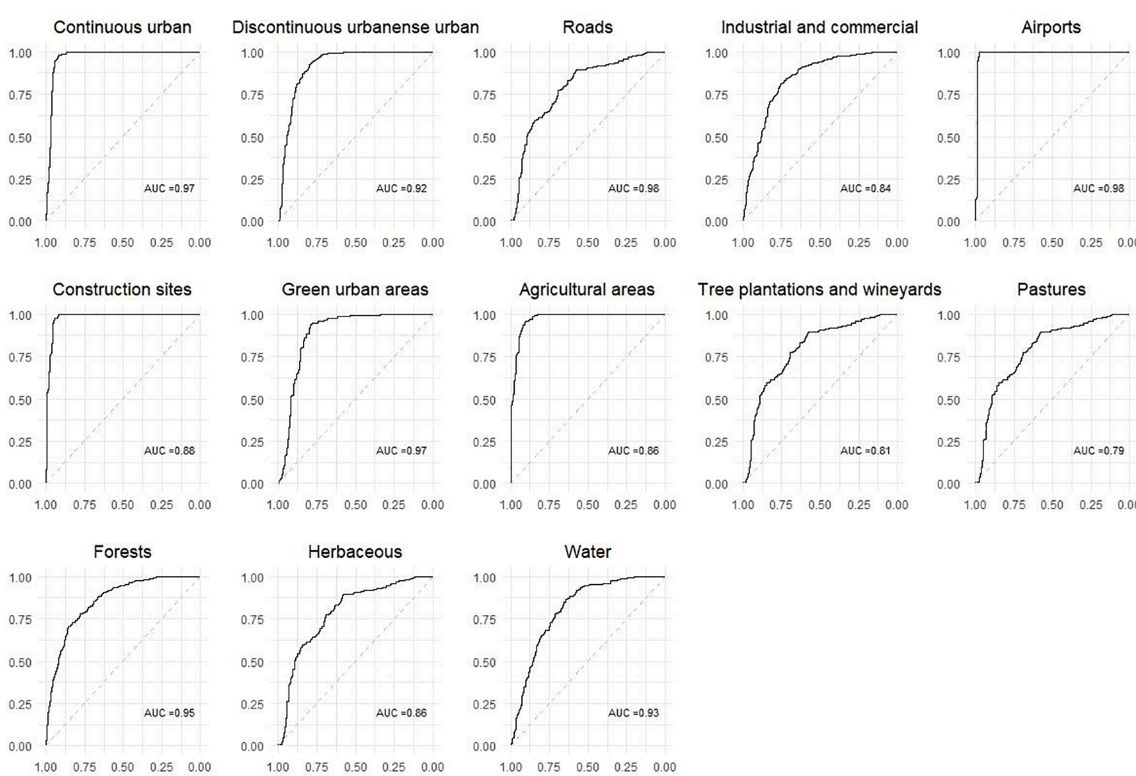

Fig. 11. AUC logistic regression performance values for land-uses at regional scale.

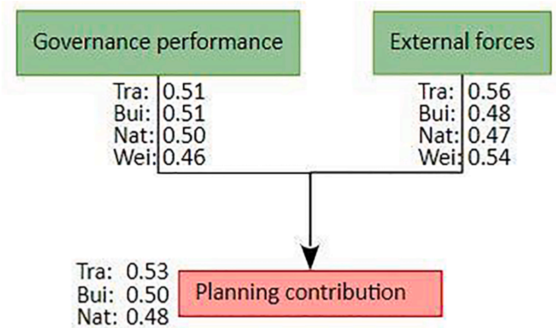

Fig. 12. Values of planning contribution in Bucharest, concerning both governance performance and external forces, as obtained from interviews with local experts; Wei stands for the average weight of each component. Values showed consider the three categories of land use, where Tra = transport infrastructures, Bui = built-up areas and Nat = (semi-)natural areas. Values were used for both scales of the analysis in scenarios S3 and S4.

Table 4
Changes in population number and demands from 2006 to 2040 for each scenario and scale.

Trend	Scenario	Scale	Population size		Living space (m^2/person)		Built-up area (m^2)		Green space (m^2/person)		Agricultural area (m^2)	
			2006	2040	2006	2040	2006	2040	2006	2040	2006	2040
Growth	S1, S3	City	1,930,400.00	2,013,143.84	22,040,843.9	49,299,315.92	Not included		18,666,968	21,092,714.63	Not included	
Decrease	S2, S4	City	1,930,400.00	1,647,515.00	22,040,843.9	40,345,533.53	Not included		18,666,968	17,261,838.41	Not included	
Growth	S1, S3	Region	2,315,700.00	2,431,638.17	Not included		390,809,366	500,849,924	21,425,819	25,477,488.94	1,181,300,000	908,574,887
Decrease	S2, S4	Region	2,315,700.00	2,295,272.00	Not included		390,809,366	500,849,924	21,425,819	24,048,712.38	1,181,300,000	908,574,887

Table 5
Initial land-use classes and classes they were reclassified into for the city and regional scale simulations.

Initial UA and CLC land-use classes	Reclassified land use classes for the city-scale simulations	Reclassified land use classes for the regional-scale simulations
Continuous urban fabric	Continuous urban	Continuous urban
Discontinuous/Dense urban fabric	Discontinuous urban	Discontinuous urban
Isolated structures	Industrial and commercial	Industrial and commercial
Industrial, commercial, public, military and private units		
Sports and leisure facilities		
Airports	Airports	Airports
Mineral extraction and disposal sites	Construction sites	Construction sites
Construction sites		
Lands without current use		
Green urban areas	Green urban areas	Green urban areas
Agricultural, semi-natural areas, wetlands	Agricultural areas	Agricultural areas
Pastures		Pastures
Grasslands		Herbaceous
Woodland-shrub		
Vineyards		Trees and vineyards
Fruit trees and berry plantations		
Forests	Forests	Forests
Water courses	Water	Water
Water bodies		
Other roads and associated land	Transport	Transport
Railways and associated land		

Table 6
Driving factors used in the city and regional simulations. Abbreviations are as follows: DEM = digital elevation model, USGS = United States Geological Survey agency.

Driving factor	Description
Topographical variables	
Elevation	DEM, 25 m from USGS
Slope	DEM, 25 m from USGS
Aspect	DEM, 25 m from USGS
Proximity variables	
Distance to major roads	Distance (m) to the closest motorway, primary, secondary or tertiary road
Distance to cycling and pedestrian trails	Distance (m) to the closest cycling and pedestrian trail
Distance to public transport lines	Distance (m) to the closest metro, tram, railway line
Distance to public transport stations	Distance (m) to the closest metro, tram, bus stop
Distance to city center	Distance (m) to the closest main city center
Distance to settlements	Distance (m) to the closest center of a settlement
Distance to commercial areas	Distance (m) to the closest shopping center
Distance to education facilities	Distance (m) to the closest education facility, including kindergartens, schools, high schools and universities
Distance to water	Distance (m) to the closest water body
Distance to parks	Distance (m) to the closest urban park or green area
distance to forests	distance (m) to the closest forest
socioeconomic variables	
Population density	Global Human Settlement Population Layer at 250 m resolution
Job density	Job density values at neighborhood level
Average housing price	Average housing price at neighborhood level
Environmental variables	
Annual mean temperature	Interpolated average temperature from Worldclim
Annual mean precipitation	Interpolated average precipitation from Worldclim
Soil classes	National soil classification
Geology classes	National geology classes

Table 7
Allowed conversions between land-uses at city scale. The matrix determines whether the conversion from one land-use to another is allowed (1), restricted (0) or allowed after 10 timesteps (110).

	Continuous urban	Dense urban	Industrial	Airports	Construction	Green urban areas	Agricultural	Forests	Water	Roads
Continuous urban	1	0	0	0	0	0	0	0	0	0
Dense urban	1	1	0	0	0	0	0	0	0	0
Industrial	1	1	1	0	0	0	0	0	0	0
Airports	0	0	0	1	0	0	0	0	0	0
Constructions	1	1	1	1	1	1	0	0	0	1
Green urban areas	0	0	0	0	1	1	0	0	0	1
Agricultural	1	1	1	1	1	1	1	110	0	1
Forests	0	0	0	0	1	1	1	1	0	1
Water	0	0	0	0	0	0	0	0	1	0
Roads	0	0	0	0	0	0	0	0	0	1

Table 8
Allowed conversions between land-uses at regional scale. The matrix determines whether the conversion from one land-use to another is allowed (1), restricted (0) or allowed after 10 timesteps (110).

	Continuous urban	Dense urban	Industrial	Roads	Airports	Construction	Green urban areas	Agricultural	Trees and vinewards	Pastures	Forests	Herbaceous	Water
Continuous urban	1	0	0	0	0	0	0	0	0	0	0	0	0
Discontinuous urban	1	1	0	0	0	0	0	0	0	0	0	0	0
Industrial	1	1	1	0	0	0	0	0	0	0	0	0	0
Roads	0	0	0	1	0	0	0	0	0	0	0	0	0
Airports	0	0	0	0	1	0	0	0	0	0	0	0	0
Constructions	1	1	1	1	1	1	0	0	0	0	0	0	0
Green urban areas	0	0	0	1	0	1	1	0	0	0	0	0	0
Agricultural	1	1	1	1	1	1	1	1	1	1	110	110	0
Trees and vinewards	1	1	1	1	1	1	1	1	1	1	110	110	0
Pastures	1	1	1	1	1	1	1	1	1	1	110	110	0
Forests	0	0	0	1	0	1	1	1	1	1	1	1	0
Herbaceous	1	1	1	1	1	1	1	1	1	1	110	1	0
Water	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 9
Independent drivers per land use at city scale.

Land use	Drivers	AUC
Continuous urban	Distance to major roads, Distance to cycling and pedestrian trails, Distance to city center, Distance to education facilities, Distance to water, Job density, Population density	0.85
Dense urban	Elevation, Distance to major roads, Distance to cycling and pedestrian trails, Distance to transport lines, Distance to public transport stations, Distance to city center, Distance to education facilities, Distance to water, Job density	0.76
Industrial and commercial	Aspect, Distance to cycling and pedestrian trails, Distance to transport lines, Distance to city center, Distance to commercial areas, Distance to water, Population density	0.72
Airports	Elevation, Distance to major roads, Distance to commercial areas, Distance to water	0.95
Construction sites	Slope, Aspect, Distance to cycling and pedestrian trails, Distance to transport lines, Distance to city center, Distance to commercial areas, Distance to water, Distance to parks	0.70
Green urban areas	Elevation, Slope, Distance to major roads, Distance to transport lines, Distance to public transport stations, Distance to city center, Distance to commercial areas, Distance to parks, Population density	0.78
Agricultural areas	Distance to major roads, Distance to transport lines, Distance to education facilities, Distance to parks	0.88
Forests	Elevation, Distance to transport lines, Distance to public transport stations, Distance to commercial areas, Distance to water, Population density	0.96
Water	Distance to cycling and pedestrian trails, Distance to education facilities, Distance to water	0.99
Roads	Distance to cycling and pedestrian trails, Distance to transport lines, Housing price, Job density	0.68

Table 10
Independent drivers per land use at regional scale.

Land use	Drivers	AUC
Continuous urban	Elevation, Mean temperature, Mean precipitation, Soil, Geology, Distance to major roads, Distance to cycling and pedestrian trails, Distance to parks, Population density	0.97
Discontinuous urban	Aspect, Soil, Distance to major roads, Distance to cycling and pedestrian trails, Distance to transport lines, Distance to commercial areas, Distance to parks, Distance to forests, Population density	0.92
Industrial and commercial	Elevation, Slope, Geology, Distance to major roads, Distance to public transport stations, Distance to commercial areas, Distance to water, Distance to forests, Population density	0.84
Roads	Elevation, Distance to transport lines, Distance to water	0.98
Airports	Elevation, Mean temperature, Mean precipitation, Distance to major roads, Distance to cycling and pedestrian trails	0.98
Construction sites	Elevation, Mean precipitation, Distance to major roads, Distance to cycling and pedestrian trails, Distance to transport lines, Distance to settlements, Distance to commercial areas, Distance to education facilities, Distance to parks	0.88
Green urban areas	Elevation, Slope, Mean precipitation, Distance to cycling and pedestrian trails, Distance to transport lines, Distance to public transport stations, Distance to education facilities, Distance to water, Distance to forests, Population density	0.97
Agricultural areas	Elevation, Slope, Geology, Distance to settlements, Distance to commercial areas, Distance to water, Distance to parks, Distance to forests, Population density	0.86
Trees and vineyards	Mean temperature, Soil, Distance to major roads, Distance to cycling and pedestrian trails, Distance to public transport stations, Distance to commercial areas, Distance to education facilities, Distance to water, Population density	0.81
Pastures	Slope, Geology, Distance to major roads, Distance to cycling and pedestrian trails, Distance to education facilities, Distance to water, Distance to parks, Distance to forests, Population density	0.79
Forests	Elevation, Slope, Mean temperature, Mean precipitation, Distance to major roads, Distance to city settlements, Distance to education facilities, Distance to water, Distance to forests	0.95
Herbaceous	Aspect, Mean temperature, Geology, Distance to transport lines, Distance to public transport stations, Distance to education facilities, Distance to parks, Distance to forests	0.86
Water	Elevation, Mean temperature, Mean precipitation, Geology, Distance to major roads, Distance to cycling and pedestrian trails, Distance to education facilities, Distance to water, Distance to parks, Population density	0.93

Table 11
An overview of the planning intentions used in simulations, where GUP = General Urban Plan of Bucharest (2001), CSP = County Spatial Plan (2004), RSP1 = Regional Spatial Plan (2007), RSP2 = Regional Spatial Plan (2013).

Planning Intention (PI)	Plan(s) in which the PI is present	Description of the PI	Weight of PI	Simulation (s) in which the PI was included
Polycentric development	GUP	Promotes built-up and transport land uses	0.5	city
Linear development	CSP	Promotes development of built-up land uses along specific transport corridors	0.5	regional
Limited linear development	GUP	Hinders built-up land uses along specific transport corridors	0.5	regional
Compact development	GUP	Promotes built-up land uses inside the existing boundaries	0.5	city
Provision of social housing	GUP	Promotes built-up land uses in specific locations	0.5	city
Provision of educational and cultural facilities	GUP, CSP, RSP1, RSP2	Promotes built-up land uses in specific locations	0.5	city and regional
Promoting functional conversion	GUP, CSP, RSP1, RSP2	Promotes built-up land uses in specific locations	0.5	city
Development of transport infrastructures	GUP, CSP, RSP1, RSP2	Promotes transport infrastructures in specific locations	0.53	city and regional
Development of technical infrastructures	GUP, CSP, RSP1, RSP2	Promotes built-up land uses in specific locations	0.5	regional
Conservation of (natural/ cultural) protected areas	GUP, CSP, RSP1, RSP2	Hinders built-up land uses in specific locations	0.48	city and regional
Development of a green-yellow belt	GUP, CSP, RSP1, RSP2	Promotes (semi-) natural areas, hinders built-up and transport land uses	0.48	regional
Expansion of urban green areas	GUP, RSP1, RSP2	Promotes (semi-) natural areas, hinders built-up and transport land uses	0.48	city and regional

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