

Article

Dynamics of Urban Expansion and Agricultural Land Loss in the Trnava District (Slovakia): A CORINE Land Cover-Based Modelling Approach

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Abstract

This study analyses long-term land cover changes in the Trnava District, Slovakia, with particular emphasis on urban expansion and agricultural land loss. CORINE Land Cover datasets from 1990, 2006 and 2018 were analysed in the TerrSet Land Change Modeler environment, and future land cover development up to 2064 was simulated using a CA–Markov modelling framework. The model incorporated four spatial explanatory variables: distance from built-up areas, distance from the road network, distance from water courses, and elevation. Between 1990 and 2018, Non-irrigated arable land recorded the largest absolute net loss, decreasing by 962 ha (−1.9%). Urban and industrial categories expanded during the same period: Industrial or commercial units increased by 456 ha (+75.2%), Discontinuous urban fabric by 378 ha (+7.7%), and Continuous urban fabric by 70 ha (+175.0%). Broad-leaved forest increased by 796 ha (+6.9%), whereas Transitional woodland-shrub decreased by 487 ha (−76.7%), demonstrating that gross gains and losses within individual categories did not necessarily correspond to their net area changes. The scenario-based projection to 2064 indicates a continued reduction in arable land and further expansion of discontinuous urban fabric and industrial or commercial areas, particularly around existing settlements and transport corridors. The results demonstrate the simultaneous effects of urbanisation, agricultural land conversion and changes in semi-natural and forest categories. The study highlights the importance of distinguishing gross land cover turnover from net area change and provides spatially explicit information to support agricultural land protection, spatial planning and sustainable landscape management in rapidly urbanising regions.

Keywords: land cover change; urban expansion; agricultural land loss; suburbanisation; Land Change Modeler

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1. Introduction

One of the most significant and most dynamic forms of environmental change is land use change. In particular, urbanisation and industrialisation rank among the main factors leading to the loss of agricultural land, the reduction in biodiversity and the degradation of soil resources [1–3]. The dynamics of these processes are especially pronounced in rapidly growing urban regions, where there is a continuous conversion of fertile arable land and an increase in impervious surfaces [4,5]. The importance of these changes has also been emphasised in the European context [6,7]. The most recent analyses indicate that urbanisation and infrastructure expansion remain the dominant driving forces of agricultural land loss, not only in Europe [8,9]. The suburbanisation of metropolitan areas such as Bratislava, Prague or Budapest has led to a significant increase in the categories Continuous and Discontinuous urban fabric, and it is precisely these classes that most frequently expand at the expense of arable land [10–12].

In addition, land use transformation is also influenced by secondary processes, such as the succession of abandoned areas, which leads to the expansion of the categories Transitional woodland-shrub and forests [13,14].

An equally serious problem is soil degradation, which is closely linked to urbanisation and the decreasing extent of areas with vegetation cover. The European Environment Agency (EEA) [15] points out that approximately one quarter of the European Union (EU) territory is affected by erosion. The most recent predictive models confirm that the continuing expansion of urbanised areas will further intensify this problem [16]. This is also confirmed by the works of [7,17], who state that European soils are exposed to intensive pressure, with urbanisation being among the main factors of the permanent loss of their production potential. This trend is particularly serious in areas with high soil quality, where fertile land is converted into built-up areas at a faster rate than elsewhere. A similar problem is faced, for example, by the Danubian Lowland, which is the subject of our study.

Land cover changes rank among the key processes shaping the spatial and functional structure of a territory. The identification and quantification of trends therefore require the application of modelling approaches which enable not only retrospective analysis but also the development of future predictions.

From a methodological perspective, several modelling approaches are used for the prediction of land cover changes, combining historical data with simulation techniques. Among the most frequently applied is the Markov Chains and Cellular Automata (CA–Markov) model, which combines Markov Chains and cellular automata, thereby enabling the simulation of the spatio-temporal dynamics of land cover changes [18–23]. Its effectiveness has also been confirmed in hybrid approaches combining Random Forest modelling [20], in applications focused on soil degradation using Trends.Earth [24], as well as in the prediction of functional urban areas [25]. A review study [26] emphasises the ability of the CA–Markov model to capture non-linear and autonomous landscape change processes.

Another widely applied approach is the CLUE-S model (Conversion of Land Use and its Effects at Small regional extent), which integrates socio-economic and environmental variables and is particularly suitable for the simulation of scenarios conditioned by policy or management measures [27,28]. In addition to the classical CLUE-S model, modern applications employ its various advanced variants; for example, Ref. [29] applied CLUE-S with a geographic information systems (GIS) application in an industrial area. Ref. [30] developed the trans-CLUE-S variant, enabling a more detailed allocation of transitions according to land use types. Ref. [31] implemented scenario planning for the simulation of territorial changes up to 2040, while [32] demonstrated the capability of the CLUE-S

model to simulate regional land use and predict impacts on carbon emissions with high accuracy.

For the purposes of this paper, the LCM tool implemented in the TerrSet (v.20) software environment was used for the analysis and prediction of land cover changes. Its basis is the combination of CA–Markov model, which enables the capture of both temporal and spatial dynamics of changes. For the creation of transition potentials, LCM employs statistical and machine-learning approaches, primarily logistic regression or the Multi-Layer Perceptron (MLP) neural network, enabling the modelling of complex relationships between environmental and socio-economic factors [33,34].

These approaches have become a standard in the assessment of long-term trends and scenarios, their advantage being the combination of statistical evaluation of past changes with spatially explicit prediction [35,36]. Applications focus not only on urbanisation and agricultural land loss, but also on forest succession, soil degradation, climate change impacts and infrastructure development scenarios [37,38].

In the Slovak context, however, the number of case studies linking long-term assessment of changes with future prediction remains relatively limited. Most available research is oriented to the national level, while analyses work with CLC data and primarily map general trends of urbanisation, succession and afforestation [11,12,39]. More detailed studies at the district or local level are significantly less frequent, although it is precisely these levels that enable the capture of specific trajectories of change and their consequences for fertile soil, local ecosystems or landscape structure. This shortcoming underlines the importance of case analyses such as the assessment of the Trnava District.

The paper fills this gap through a case study of the Trnava District, which combines CLC data with modelling in the LCM environment. The originality of the work lies in linking historical analysis (1990–2018) with prediction up to 2064, which makes it possible to capture not only past trends but also potential future scenarios of landscape transformation in a region with high soil fertility and intensive urbanisation pressure.

The objective of the paper is to analyse land cover changes and land use in the Trnava District in the period 1990–2018 and, by means of the LCM model, to simulate their future development up to 2064. Hypothesis 1 assumes that the main factor of change is urbanisation, which conditions the most significant agricultural land loss, particularly in the category Non-irrigated arable land. Hypothesis 2 is based on the assumption that the greatest losses in terms of area will occur precisely on fertile arable land, which will be transformed into built-up areas.

The originality of the study lies in linking the historical analysis of CLC with predictive modelling up to 2064, which makes it possible not only to quantify past changes but also to assess their future consequences for agricultural production, spatial planning and soil protection in one of the most rapidly urbanising regions of Slovakia.

2. Materials and Methods

2.1. Case Study

The model locality for the assessment of land cover changes is the Trnava District (Figure 1). It is a territory with a long-standing tradition of intensive agriculture, which is simultaneously exposed to strong urbanisation pressure due to its location in the core of western Slovakia and in proximity to the capital city of Bratislava. The Trnava District extends at the interface between the Danubian Hilly Land and the Little Carpathians in the lowland area of Slovakia and is one of the seven districts of the Trnava Self-Governing Region (Trnava, Galanta, Dunajská Streda, Hlohovec, Piešťany, Skalica, Senica). A total of 45 municipalities divided into 58 cadastral territories are located in the Trnava District. It extends from a very warm, very dry lowland climatic area to a moderately warm, moderately humid climatic area. Very deep loamy chernozems, brown earths and cambisols on

plains and gentle slopes prevail, with a minimum altitude in the south-eastern part of the territory of 122.09 m above sea level and a maximum in the north-western part of the territory of 799.71 m above sea level. Almost the entire territory is suitable for agriculture. In 2025, a total of 78 different crops were cultivated across the district, mainly commercial crops such as maize, durum wheat and spring wheat, oilseed rape, sunflower, etc. In the more sloping areas of the district, manifestations of water erosion occur in the categories of moderately to catastrophically endangered soils.



Figure 1. Location and administrative division of the Trnava District.

2.2. Corine Land Cover

Land cover categories were derived from the CLC database Copernicus Land Monitoring Service (<https://land.copernicus.eu/en/products/corine-land-cover>, accessed on 1 January 2021). For the model territory, 19 layers were harmonised, representing individual land types at Level 3. The following categories were included in the analysis: Continuous urban fabric (111), Discontinuous urban fabric (112), Industrial or commercial units (121), Road and rail networks and associated land (122), Mineral extraction sites (131), Sport and leisure facilities (142), Non-irrigated arable land (211), Vineyards (221), Fruit trees and berry plantations (222), Pastures (231), Complex cultivation patterns (242), Agricultural land with natural vegetation (243), Broad-leaved forest (311), Coniferous forest (312), Mixed forest (313), Transitional woodland-shrub (324), Inland marshes (411), Water courses (511), and Water bodies (512).

2.3. Time Horizons of the Analysis

Land cover changes were modelled between two land cover maps across three time horizons: 1990 (past), 2006 (past), and 2018 (present). All datasets employ the same hierarchical CLC classification scheme and identical mapping specifications, including a minimum mapping unit of 25 ha for areal features and a minimum mapping width of 100 m for linear features, ensuring temporal comparability. Although the production methodology has been progressively refined across successive releases, these improvements preserve the consistency of the datasets while enhancing their overall quality, making them suitable for long-term land cover change analysis. Although the CLC dataset provides a

harmonised and consistent database for long-term regional land cover analyses, its minimum mapping unit and spatial resolution limit the detection of small and fragmented land cover changes, such as isolated buildings or local urban infill. Consequently, the presented results should be interpreted at the regional scale rather than for individual land parcels. Future studies could improve the representation of local-scale dynamics by employing higher-resolution satellite imagery and independently validated land cover classifications.

The year 1990 represents the baseline state of the landscape following the period of intensive socialist agricultural production, when large-scale arable land predominated and the share of successional and urbanised areas was low. This horizon is key for capturing the original landscape structure prior to major socio-economic changes. The year 2006 reflects the period following Slovakia's accession to the European Union (2004), when new approaches in agricultural policy began to manifest more significantly, including the retreat from certain traditional forms of farming. At the same time, this period is characterised by an increase in successional areas and the first more pronounced manifestations of urbanisation. The year 2018 represents the current state of the landscape after more than two decades of transformation. Typical processes of this horizon include the continuing decline in arable land at the expense of urbanised categories. This horizon enables the assessment of the long-term trend of landscape–ecological transformation in the model territory.

2.4. Change Prediction

The prediction of the future state of the landscape was carried out using the LCM, which forms part of the TerrSet geospatial monitoring and modelling software package. It was developed at Clark University (<https://www.clarku.edu/centers/geospatial-analytics/terrset/>, accessed on 1 January 2021).

The prediction of future land cover development was carried out using a hybrid CA–Markov modelling framework implemented in the LCM within the TerrSet software environment for the Tnava District (Slovakia). The overall modelling workflow is illustrated in Figure 2.

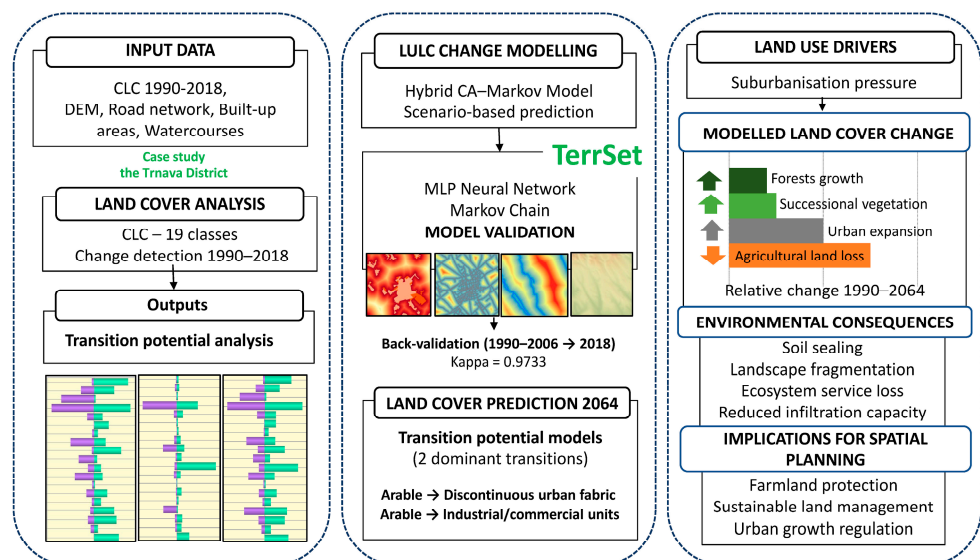


Figure 2. Workflow of suburbanisation-driven land cover change modelling using the CA–Markov approach implemented in TerrSet LCM in the Tnava District.

Within the change analysis, we compared three time horizons: 1990, 2006, and 2018. Based on an exploratory analysis of observed land cover changes, seven major transition categories were initially selected for detailed evaluation to verify the proposed hypotheses:

1. Non-irrigated arable land TO Discontinuous urban fabric;
2. Non-irrigated arable land TO Continuous urban fabric;
3. Non-irrigated arable land TO Industrial or commercial units;
4. Pastures TO Discontinuous urban fabric;
5. Mixed forest TO Discontinuous urban fabric;
6. Transitional woodland-shrub TO Discontinuous urban fabric;
7. Agricultural land with natural vegetation TO Discontinuous urban fabric.

Subsequently, gross gains, gross losses, net area changes, and class-to-class transitions were calculated separately. Figure 3A presents the contributions of individual land cover categories to the net change in Non-irrigated arable land, while Figure 3B shows the spatial distribution of the two selected class-to-class transitions. Table 1 reports the total area of each land cover class at the individual time points and supports the calculation of net area changes; therefore, these outputs quantify different aspects of land cover dynamics and should not be interpreted as directly equivalent. For model calibration and the modelling of transition potentials, only two sub-models representing the conversion of Non-irrigated arable land to Discontinuous urban fabric and to Industrial or commercial units were selected. These transitions represented the dominant modelled processes of agricultural land loss and suburbanisation and provided sufficient training samples for MLP calibration. The remaining transitions were evaluated but were not included as separate sub-models because they were infrequent, spatially fragmented, or contained too few transition pixels for reliable calibration.

1. From Non-irrigated arable land to Discontinuous urban fabric;
2. From Non-irrigated arable land to Industrial or commercial units.

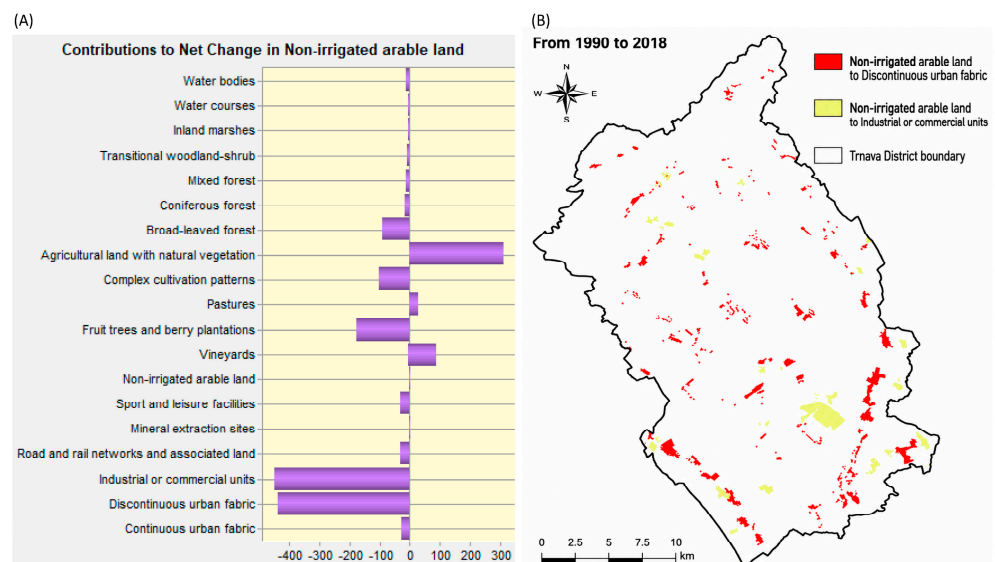


Figure 3. Land cover changes involving Non-irrigated arable land between 1990 and 2018: (A) contributions of individual land cover categories to the net change in Non-irrigated arable land, expressed in hectares; and (B) spatial distribution of the observed transitions from Non-irrigated arable land to Discontinuous urban fabric and Industrial or commercial units in the Trnava District.

Table 1. Absolute areas in hectares of all land cover classes in years 1990, 2006, 2018, and 2064.

Class Name	Area [ha]			
	1990	2006	2018	2064
Agricultural land with natural vegetation	2249	1570	1595	1595
Broad-leaved forest	11,517	12,058	12,313	12,314
Complex cultivation patterns	157	340	276	276
Coniferous forest	261	371	370	370
Continuous urban fabric	40	80	110	110
Discontinuous urban fabric	4904	4989	5282	6369
Fruit trees and berry plantations	26	26	200	201
Industrial or commercial units	606	991	1062	1797
Inland marshes	74	26	26	26
Mineral extraction sites	103	115	116	117
Mixed forest	652	689	731	730
Non-irrigated arable land	51,146	50,840	50,184	48,363
Pastures	741	548	585	584
Road and rail networks and associated land	53	84	60	60
Sport and leisure facilities	207	240	258	257
Transitional woodland-shrub	635	356	148	148
Vineyards	618	464	468	467
Water bodies	84	276	278	279
Water courses	37	47	48	47
Sum	74,110	74,110	74,110	74,110

Figure 3A shows the contribution of individual land cover categories to the net change in Non-irrigated arable land, while Figure 3B presents the spatial distribution of the two selected transitions used for MLP calibration. The mapped transitions do not represent the total net area change in the destination classes. For the prediction of land cover change, the MLP neural network was applied. The model was calibrated for the period 1990–2018 using four explanatory variables. All variables, as used in comparable studies (e.g., [40,41]), were resampled to a common spatial resolution of 100 m corresponding to the CLC grid. The following explanatory variables were used:

1. Distance from built-up areas is understood as urban expansion, which tends to occur in the immediate vicinity of already existing built-up areas. This variable therefore represents the core effect of the growth of towns and municipalities (so-called urban sprawl) and is key in modelling suburbanisation. A similar approach is presented, for example, by [42], who identified “proximity to built-up areas” as one of the strongest predictors of urbanisation processes.
2. Distance from the transport network, i.e., accessibility of transport infrastructure, is one of the main factors in the spatial organisation of settlement. The variable captures the attractiveness of locations in proximity to transport corridors for residential and commercial as well as industrial development. According to studies by [43], transport accessibility is systematically one of the most significant factors in predicting urbanisation.
3. Water courses and distance from water courses represent both an attraction and a limiting factor. Proximity to water courses may increase attractiveness for recreation or housing, but at the same time represents a risk of degradation processes and flooding, which influences the spatial distribution of development. Inclusion of hydrological variables is recommended by [44], who point out that rivers shape urban development patterns, both through resource availability and hazard risks.

4. Terrain morphology significantly influences land use—flat and gently sloping areas are more suitable for development, whereas slopes and higher elevations limit expansion. The inclusion of the Digital Elevation Model (DEM) enables the consideration of topographic constraints of urbanisation as well as links to soil stability. This practice is also recommended by [45], who consider topography to be one of the fundamental factors in modelling landscape change.

Two MLP models were developed within the LCM. The first model was developed exclusively for model validation. It was calibrated using the 1990–2006 land cover datasets and subsequently validated by simulating the 2018 land cover map, which was compared with the observed CLC 2018 dataset. The second model was calibrated using the complete 1990–2018 dataset and employed for the final projection of land cover to 2064. This two-stage modelling approach enabled an independent assessment of the predictive performance of the modelling framework while simultaneously maximising the amount of historical information available for the final long-term projection.

Both models employed the same MLP architecture, consisting of four input neurons, three hidden neurons, and three output neurons. The four input neurons corresponded to distance from built-up areas, distance from the road network, distance from water courses, and elevation represented by the Digital Elevation Model. The three output neurons represented the two modelled transitions—Non-irrigated arable land to Discontinuous urban fabric, and Non-irrigated arable land to Industrial or commercial units—and persistence of the originating Non-irrigated arable land class. Model training was performed using 1000 sampled cells per class, with 50% of the samples allocated for training and 50% for testing. The training process used a final learning rate of 0.0005, a momentum factor of 0.5, a sigmoid constant of 1, an acceptable RMS threshold of 0.01, and a maximum of 10,000 iterations. The validation model calibrated for the 1990–2006 period achieved a training RMS of 0.1966, a testing RMS of 0.2071, an accuracy of 91.28%, and a skill measure of 0.8692. The final projection model calibrated using the 1990–2018 period achieved a training RMS of 0.2961, a testing RMS of 0.3047, an accuracy of 81.82%, and a skill measure of 0.7274. The lower accuracy and skill of the final projection model indicate greater uncertainty associated with the long-term projection to 2064. The back-validation was evaluated primarily using change-focused measures. The Figure of Merit (FoM) was calculated from a three-map comparison of the observed 2006 map, the observed 2018 map, and the simulated 2018 map as $H/(H + M + F + W)$, where H denotes correctly predicted change, M is the missed observed change, F is the false-alarm change, and W represents change predicted in an incorrect destination category. Correctly predicted persistence was excluded from the calculation. Quantity disagreement and grid-cell-level allocation disagreement were also calculated. Whole-map Kappa was retained only as a supplementary statistic because it is strongly influenced by the large proportion of persistent pixels.

Following the back-validation, the final CA–Markov simulation was recalibrated using the complete 1990–2018 land cover dataset to maximise the historical information available for estimating transition probabilities. For the simulation of future land cover development, the Markov Chain approach was applied to estimate transition probabilities between land cover categories based on observed historical changes. The year 2064 was selected as the projection horizon in accordance with the objectives of the research project. The resulting land cover map should therefore be interpreted as a scenario-based projection representing the continuation of historical land cover dynamics under the assumption of stationary transition probabilities rather than as a deterministic prediction of future landscape development [36].

Within the Change Allocation module, the soft prediction option was used to generate spatially explicit transition potential maps, with probability values ranging from 0 to 1 for each pixel. These transition probability surfaces were subsequently allocated using

the Cellular Automata algorithm to produce the final hard-classified land cover map for 2064. This approach combines the quantity of expected land cover changes estimated by the Markov transition matrix, with their spatial allocation based on transition suitability. Only the dominant transitions from Non-irrigated arable land to Discontinuous urban fabric and Industrial or commercial units were modelled using MLP-derived transition potential maps. The remaining land cover classes were not individually modelled because their transition frequencies were low and did not provide sufficient samples for reliable MLP calibration. Nevertheless, all land cover classes were included in the Markov transition probability matrix. During the prediction stage, the CA–Markov algorithm allocated all classes according to the transition probabilities and the available transition potential maps, resulting in a complete 19-class land cover map for 2064.

Reverse transitions specifically from urban or industrial classes back to Non-irrigated arable land were not included as separate transition sub-models because they were absent or too infrequent and spatially fragmented to provide sufficient training samples for robust MLP calibration. This statement does not imply that all outflows from Discontinuous urban fabric or Industrial or commercial units were absent. Gross inflows and outflows may occur simultaneously, whereas Table 1 reports only the resulting net area change. The modelling framework therefore focused on the dominant transitions from arable land to urban and industrial classes.

3. Results

The analysis of gross gains and losses revealed considerable differences in the turnover of individual land cover categories between 1990 and 2006 (Figure 4A). The largest gross gains and losses were associated particularly with Transitional woodland-shrub, Inland marshes, Water bodies, Complex cultivation patterns and several urban and infrastructure-related categories. However, the gross gains and losses shown in Figure 4 should not be interpreted as net changes in the total area of the respective classes. According to the absolute areas reported in Table 1, Non-irrigated arable land decreased from 51,146 ha in 1990 to 50,840 ha in 2006, representing a net loss of 306 ha (−0.6%). More substantial net declines were recorded for other categories: Agricultural land with natural vegetation decreased by 679 ha (−30.2%), Transitional woodland-shrub by 279 ha (−43.9%), Pastures by 193 ha (−26.0%), Vineyards by 154 ha (−24.9%), and Inland marshes by 48 ha (−64.9%). In contrast, Industrial or commercial units increased by 385 ha (+63.5%), Continuous urban fabric by 40 ha (+100.0%), Discontinuous urban fabric by 85 ha (+1.7%), and Road and rail networks and associated land by 31 ha (+58.5%). Forest categories also increased: Broad-leaved forest increased by 541 ha (+4.7%), Coniferous forest by 110 ha (+42.1%), and Mixed forest by 37 ha (+5.7%).

During the period 2006–2018 (Figure 4B), the gross gains and losses indicate continued turnover among several land cover categories. However, the net area changes derived from Table 1 show that Non-irrigated arable land decreased by 656 ha (−1.3%), Transitional woodland-shrub by 208 ha (−58.4%), Complex cultivation patterns by 64 ha (−18.8%), and Road and rail networks and associated land by 24 ha (−28.6%). In contrast, Fruit trees and berry plantations increased by 174 ha (+669.2%), Discontinuous urban fabric by 293 ha (+5.9%), Continuous urban fabric by 30 ha (+37.5%), Industrial or commercial units by 71 ha (+7.2%), and Mixed forest by 42 ha (+6.1%). The simultaneous decline in arable land and expansion of urban and industrial categories indicates continuing urbanisation pressure during this period.

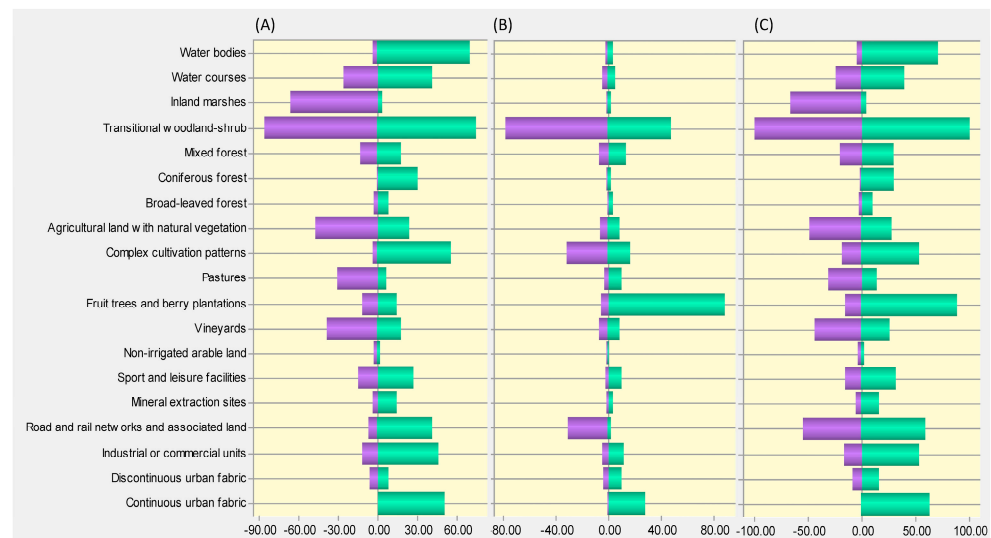


Figure 4. Gross gains and losses by land cover category, expressed as percentage change, for (A) 1990–2006, (B) 2006–2018, and (C) 1990–2018. Positive values represent gross gains, whereas negative values represent gross losses.

Over the entire period 1990–2018 (Figure 4C), Non-irrigated arable land recorded the largest absolute net loss, decreasing by 962 ha (−1.9%). Substantial declines were observed in other categories: Agricultural land with natural vegetation decreased by 654 ha (−29.1%), Transitional woodland-shrub by 487 ha (−76.7%), Pastures by 156 ha (−21.1%), Vineyards by 150 ha (−24.3%), and Inland marshes by 48 ha (−64.9%). In contrast, Broad-leaved forest increased by 796 ha (+6.9%), Industrial or commercial units by 456 ha (+75.2%), Discontinuous urban fabric by 378 ha (+7.7%), Water bodies by 194 ha (+231.0%), Fruit trees and berry plantations by 174 ha (+669.2%), Coniferous forest by 109 ha (+41.8%), Mixed forest by 79 ha (+12.1%), and Continuous urban fabric by 70 ha (+175.0%). Although some categories show very high relative increases because of their small initial areas, the absolute changes confirm the simultaneous expansion of urbanised areas and the reduction in agricultural land. Absolute areas for all land cover categories and years are presented in Table 1.

Overall, the results indicate two simultaneous landscape-transformation processes: the net decline of Non-irrigated arable land and several other agricultural and semi-natural categories; and the expansion of urban, industrial, forest, and water-related categories. Figure 4 presents gross gains and losses, while Table 1 reports class areas and the resulting net area changes.

Figure 5 illustrates the spatial persistence of land cover, i.e., territories that retained the same type of use or cover throughout the entire monitored period, thereby indicating the core stable elements of the landscape.

To evaluate the predictive performance of the modelling framework, an independent back-validation was performed. The model was calibrated using the 1990 and 2006 CORINE Land Cover datasets and subsequently used to simulate land cover for 2018. The simulated 2018 map was compared with the observed CLC 2018 dataset (Figure 6). The three-map comparison yielded a Figure of Merit of 0.125 (12.5%), indicating modest performance in predicting the spatial occurrence of land cover change. The comparison also yielded a quantity disagreement of 0.0044 (0.44%) and a grid-cell-level allocation disagreement of 0.0125 (1.25%), while allocation disagreement at the strata level was 0.0000. The whole-map Kappa coefficient was 0.9733; however, it was interpreted only as a supplementary measure because the landscape is dominated by persistent pixels.

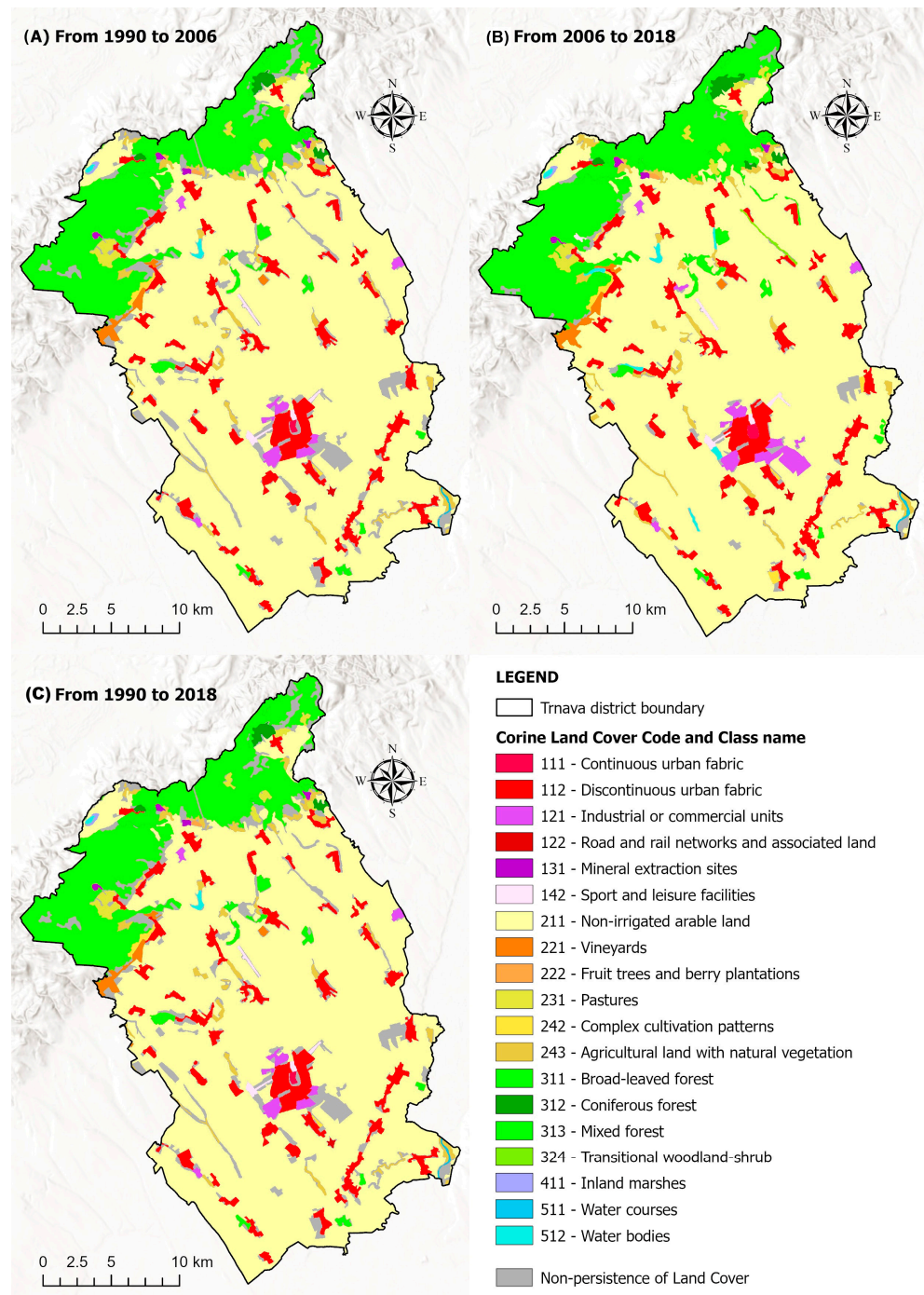


Figure 5. Spatial distribution of land cover persistence and change (non-persistence) in the Trnava District. Comparisons between (A) 1990 and 2006, (B) 2006 and 2018, and (C) 1990 and 2018.

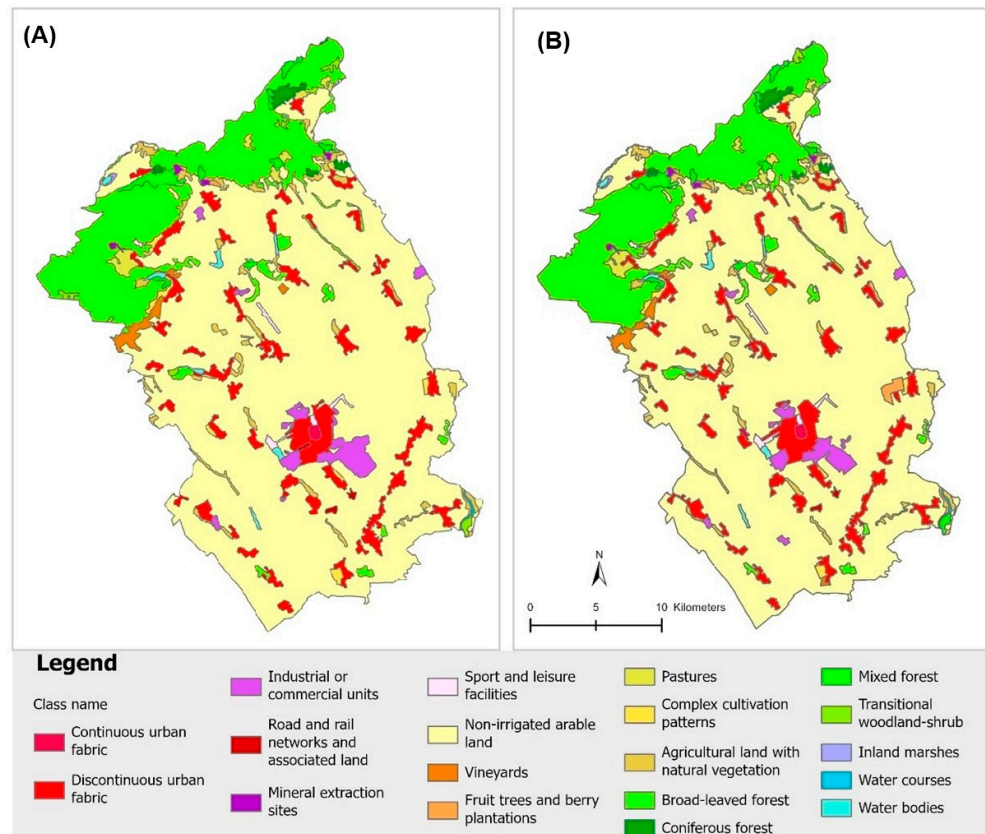


Figure 6. Back-validation of the CA-Markov model: comparison between (A) the simulated land cover map for 2018 generated using the 1990–2006 calibration period and (B) the observed CLC 2018 map.

Figure 7 presents the expansion of built-up areas (urban fabric) in the territory of the Trnava District that occurred at the expense of the Non-irrigated arable land category. Areas where agricultural land was transformed into urbanised areas are marked in pink, with the most significant changes concentrated around the city of Trnava and other settlement centres. The result of the distance analysis expresses the spatial distribution of built-up area expansion in relation to the original arable land. Values cover a range from 0 to 6413 m, while dark areas (0—low values) indicate the zones closest to built-up areas and lighter shades (higher values) represent more distant areas that are, so far, less affected by urban expansion.

Figure 8 presents the spatial accessibility of water and its potential impact on land use change. In the agricultural landscape of the Trnava District, water courses are of fundamental importance as they influence the production potential of the soil and the hydrological regime, as well as the ecological stability of the territory. The hydrographic network of water courses represents the category Water courses according to the CLC classification. The result of the distance analysis quantifies the distance of individual parts of the territory from the nearest water course. Distance values range from 0 to 3331 m; dark purple and blue areas (0–500 m) indicate zones closest to water courses, green areas represent medium distances, and yellow to red areas (above 2000 m) express territories most distant from water courses.

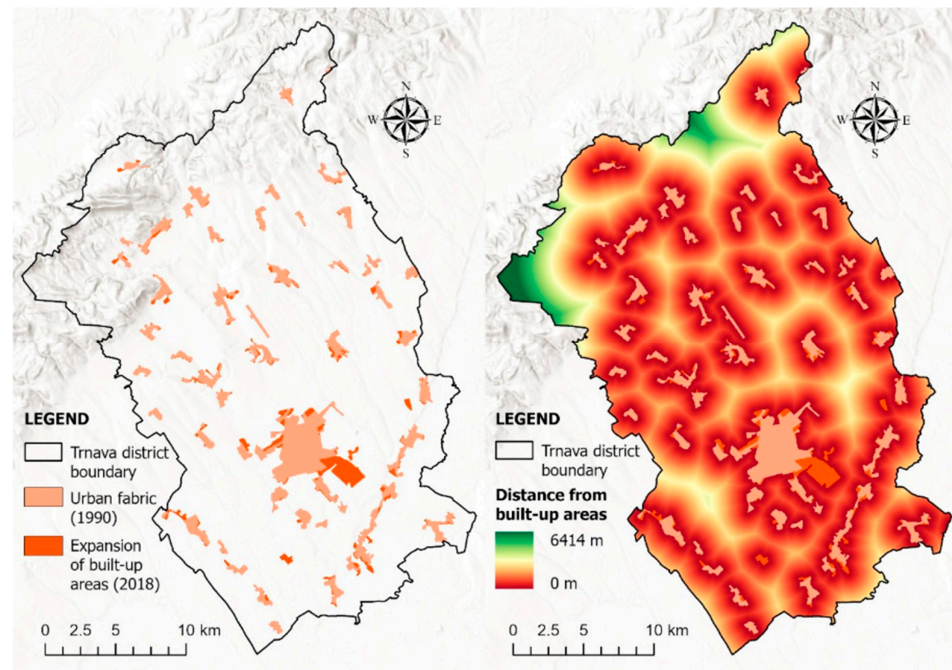


Figure 7. Expansion of built-up areas (urban fabric) and distance analysis from built-up areas.

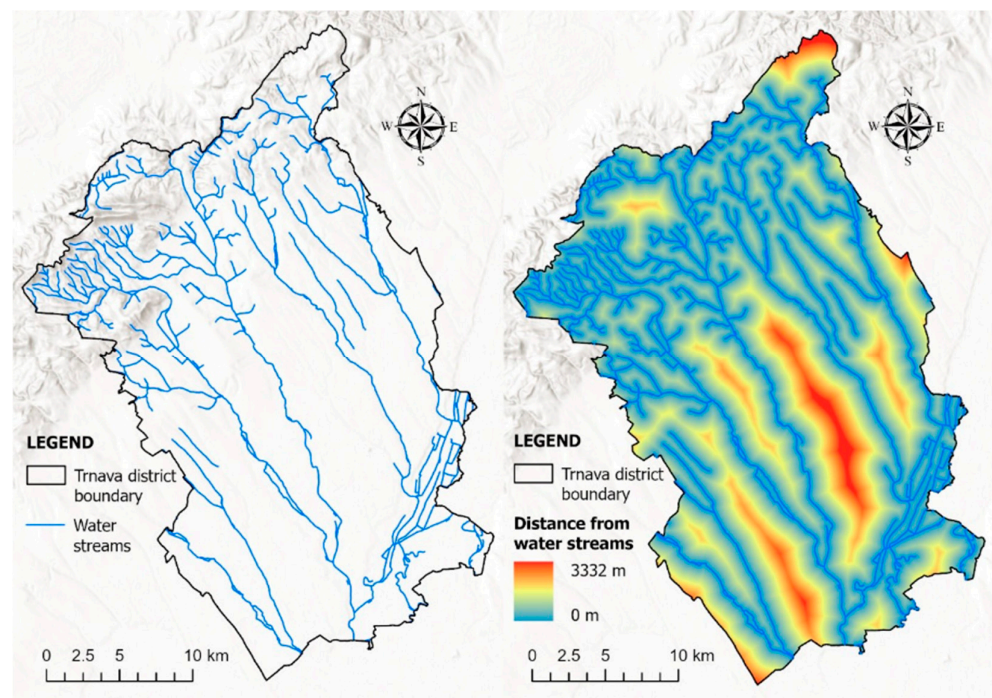


Figure 8. Water courses and distance analysis from water courses (distance analysis).

Accessibility of the territory in terms of transport infrastructure is a key factor in modelling land use change. Distance from roads particularly influences urban expansion (Continuous and Discontinuous urban fabric, Industrial or commercial units). The results of the distance analysis express the distance of individual parts of the territory from the nearest road communication. The range of values varies from 0 to 1787 m. Dark purple and blue areas (0–200 m) indicate zones directly adjacent to roads, green shades represent medium distances, and yellow to red areas (above 1500 m) represent territories most dis-

tant from the road network. The results clearly indicate that the Trnava District has a very dense road network, which significantly increases the probability of the expansion of built-up areas, particularly in the vicinity of the city of Trnava and along the main transport corridors (Figure 9).

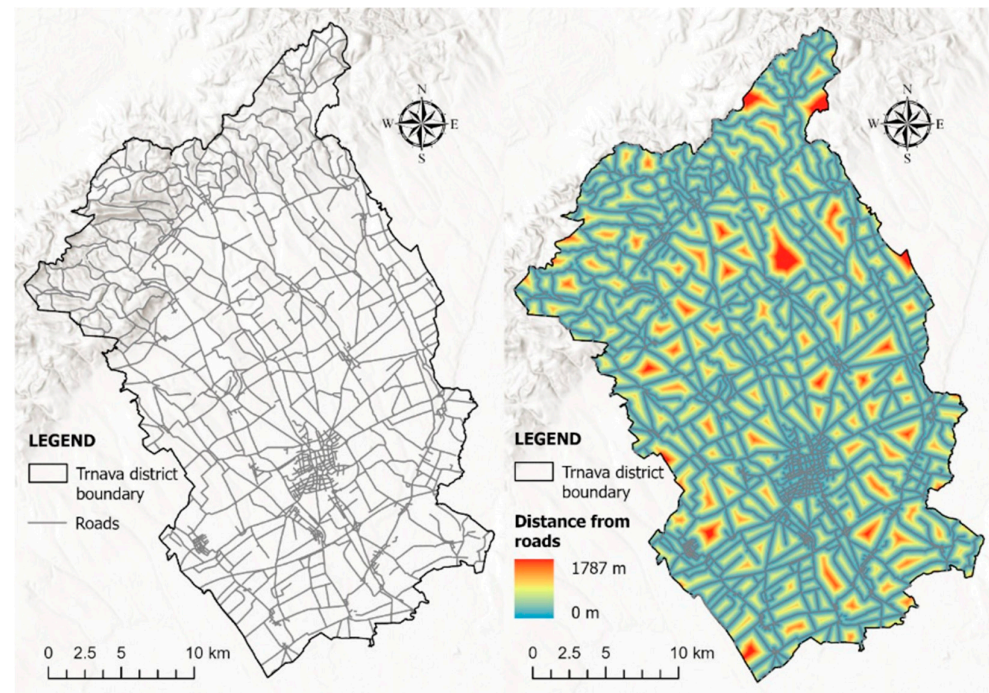


Figure 9. Road network and distance analysis from transport networks (distance analysis).

The DEM (Figure 10) represents one of the fundamental environmental factors influencing the spatial dynamics of land use change. The DEM for the model territory of the Trnava District captures altitudes ranging from 122.85 to 765.76 m a.s.l. Lower lying parts of the territory, typical particularly for the Danubian Lowland, are predominantly used as Non-irrigated arable land, and at the same time represent the area with the highest pressure of urban expansion (Continuous urban fabric, Discontinuous urban fabric). Conversely, higher altitudes in the north-western part of the territory, extending into the Little Carpathians, are characterised by a higher proportion of forest stands (Coniferous forest, Mixed forest, Broad-leaved forest) and successional areas (Transitional woodland-shrub). The inclusion of the DEM in the model makes it possible to better reflect topographic conditions, which influence both the production potential of agricultural land as well as the limits for urbanisation and construction.

The Markov Chain prediction transition probability matrix between land cover classes (Transition Probability Matrix), which was generated on the basis of historical data (past 1990 (Figure 11A), past 2006 (Figure 11B), present 2018 (Figure 11C)) indicates the probability that a given CLC class will change into another class by the year 2064 (Figure 11D). The results show that Continuous urban fabric has a 96.2% probability of persistence, while at the same time expanding at the expense of other classes (e.g., 3.37% from Discontinuous urban fabric). This means that urban built-up areas will continue to expand and densify in a stable manner. Discontinuous urban fabric maintains 85.5% stability, but also has a high probability of transformation into Continuous urban fabric (8.4%), which signals gradual compactisation of suburban development. Non-irrigated arable land has a high rate of preservation (93%); however, part of it (approximately 2–3%) is transformed into urban fabric, fruit trees and complex cultivation patterns, which confirms the long-

term pressure leading to agricultural land loss. Transitional woodland-shrub is to a large extent converted into forest stands (19.5% to Mixed forest), documenting the trend of succession and afforestation of abandoned areas. Forest stands (Coniferous forest, Mixed forest, Broad-leaved forest) show a high probability of persistence (92–97%), which means that in the prediction up to 2064, they will form a stable landscape matrix. Fruit trees and berry plantations show 79.5% stability; however, up to 18.4% may convert to Agricultural land with natural vegetation, indicating that part of these areas is threatened by a return to more extensive forms of agriculture. Vineyards show a stability of 72.4%, but more frequently change into Fruit trees or arable land, which may indicate continuing restructuring of vineyards in the region. Road and rail networks show a high rate of transition to Discontinuous urban fabric (67.5%), meaning that in the model prediction, transport infrastructure is strongly interconnected with suburban urban expansion. The model assumes that in the Trnava District, the expansion of urban and industrial areas will continue, primarily at the expense of Non-irrigated arable land. At the same time, abandoned areas will continue to be overgrown by successional and forest communities. The most endangered category remains agricultural land, while forests and water bodies remain relatively stable. These transition probabilities describe gross class-to-class flows and should not be interpreted as net area changes; the projected net class areas are reported in Table 1.

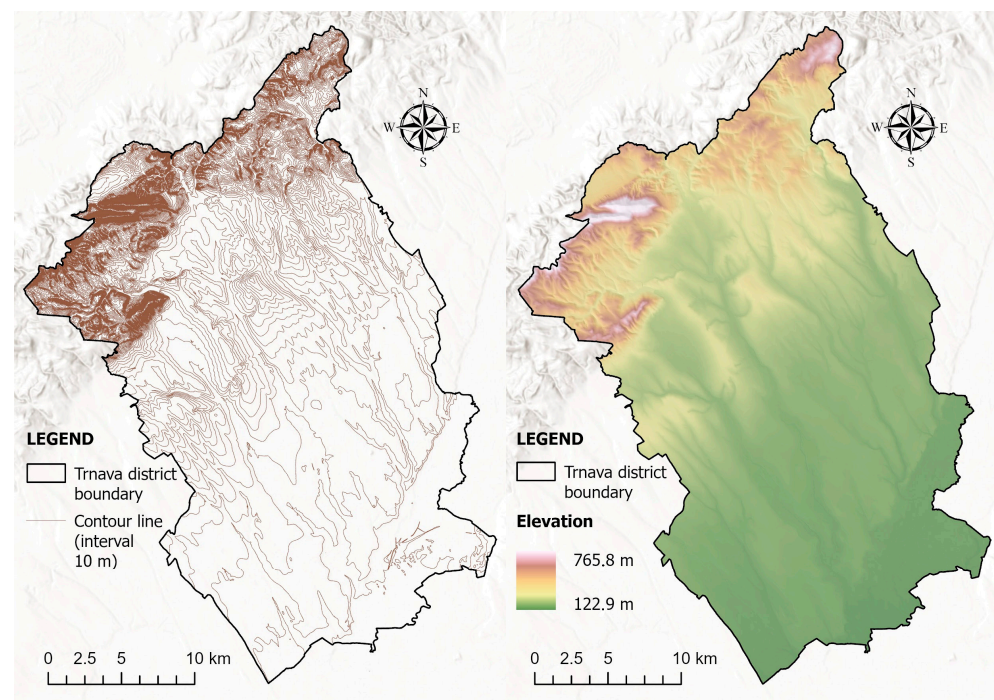


Figure 10. Digital Elevation Model.

An example of the predicted land use development for the year 2064 is visualised through a web-based mapping application within the territorial information system available at ArcGIS Experience Builder (v1.21.0)—Prediction of Land Use Development in the Trnava District until 2064. The interactive map enables the spatial visualisation of predicted land cover changes in the Trnava district based on future development modelling. The visualisation highlights expected urbanisation encroachments on agricultural land, the expansion of built-up and industrial areas, as well as stable forest stands. The web application also allows comparison of historical CLC layers from 1990, 2006, and 2018 with the predicted state for 2064, thereby providing a comprehensive overview of land-

scape change dynamics and suburbanisation processes in the studied area. The application further includes the possibility of switching between different basemaps, including orthophoto maps, enabling a more detailed visualisation and interpretation of spatial landscape changes within the real territorial context.

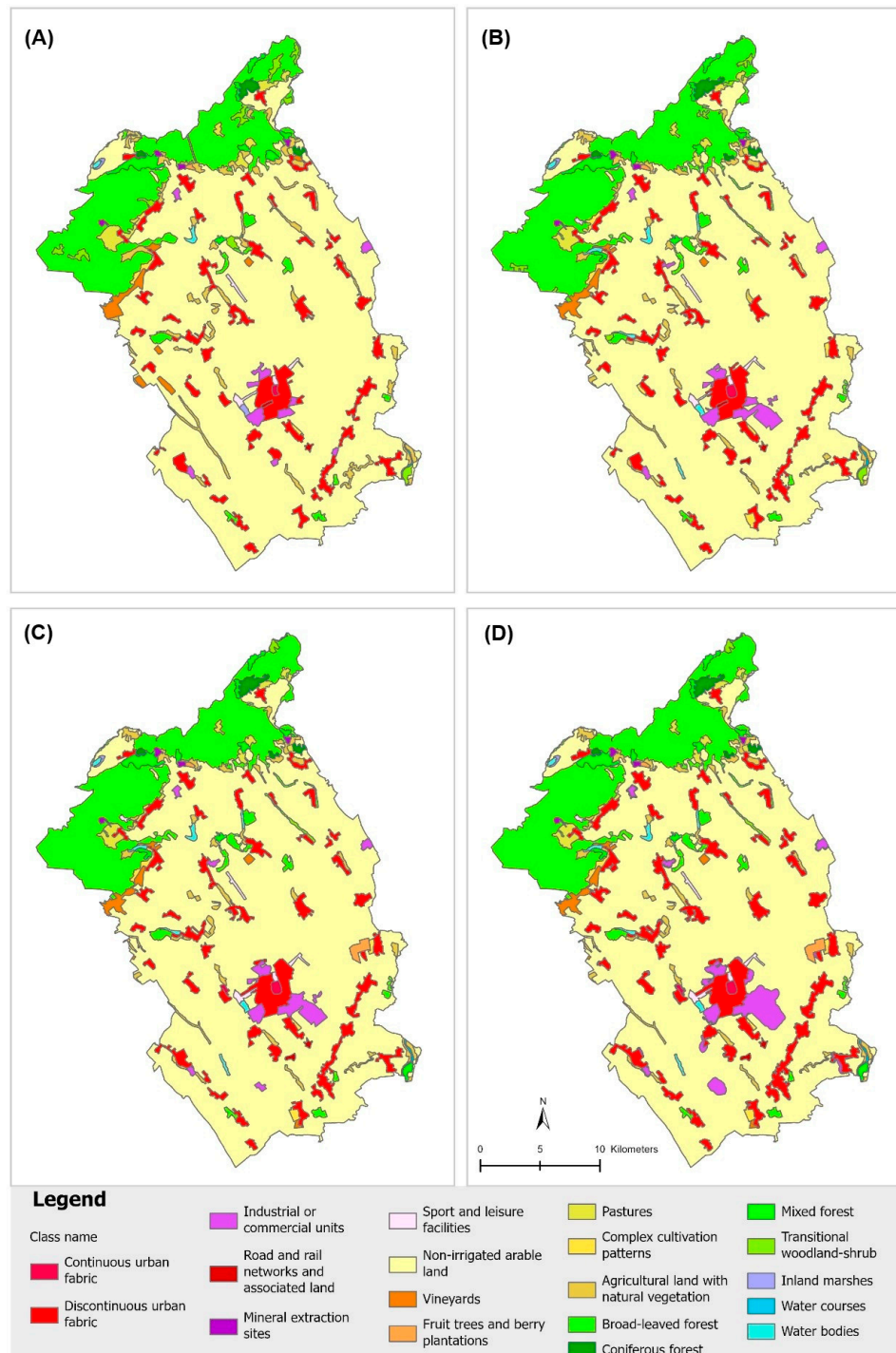


Figure 11. Land use for the studied years (A) 1990, (B) 2006, (C) 2018, and (D) 2064.

The results of Markov Chain prediction modelling indicate that by the year 2064, the following trends will be dominant:

- Continuous urban fabric is highly persistent. Although the transition matrix indicates gross inflows from other classes, its projected net area remains 110 ha between 2018 and 2064.
- Non-irrigated arable land remains the dominant category but is projected to decrease by 1821 ha (−3.6%) between 2018 and 2064, while Discontinuous urban fabric increases by 1087 ha (+20.6%) and Industrial or commercial units by 735 ha (+69.2%).
- Transitional woodland-shrub may undergo gross transitions to forest classes, but its projected net area remains 148 ha. Broad-leaved forest changes by +1 ha, Mixed forest by −1 ha, and Coniferous forest remains unchanged, indicating no substantial net afforestation in the 2064 scenario.
- Water bodies are highly stable. Inland marshes, however, are markedly dynamic, with a high proportion of transformations into Transitional woodland-shrub and Broad-leaved forest, which indicates their ecological vulnerability.

4. Discussion

The historical analysis and the 2064 scenario indicate that urban expansion and agricultural land loss are the dominant quantitative processes. Between 1990 and 2018, Non-irrigated arable land recorded the largest absolute net loss (−962 ha), whereas Broad-leaved forest (+796 ha), Industrial or commercial units (+456 ha), and Discontinuous urban fabric (+378 ha) recorded the largest gains. In the 2018–2064 scenario, the principal changes are the decline in arable land (−1821 ha), and the expansion of Discontinuous urban fabric (+1087 ha) and Industrial or commercial units (+735 ha), while forest and transitional categories remain nearly stable in net area. The Markov chain assumes stationary transition probabilities derived from historical changes; consequently, the 2064 map should be interpreted as a scenario-based extrapolation rather than a deterministic forecast.

The present study represents a regional case study focused on the Trnava District, one of the most rapidly urbanising agricultural regions in Slovakia. Although the identified trends are consistent with those reported in other Central European regions, the results should not be directly extrapolated to other areas because land cover dynamics are strongly influenced by local socioeconomic conditions, spatial planning policies, environmental characteristics, and historical development. Consequently, the findings should be interpreted as region-specific while providing methodological guidance for similar analyses in comparable landscapes.

Urban expansion appears to be the most significant factor in land cover change in the Trnava District. The 2064 scenario projects a decline in Non-irrigated arable land, together with expansion of Discontinuous urban fabric and Industrial or commercial units, while Continuous urban fabric remains unchanged in net area at 110 ha. According to [46], urbanisation leads to a gradual and often permanent loss of arable land, with serious consequences for regional production potential. Similarly, the CA-Markov model projects a 3.6% decline in Non-irrigated arable land between 2018 and 2064 (1821 ha). Although this scenario covers a longer horizon than the global projection of 1.8–2.4% by 2030 [47], both indicate a continuing downward trend in agricultural land availability. In the Trnava District, the projected decline is associated particularly with growth of Discontinuous urban fabric (+20.6%) and Industrial or commercial units (+69.2%).

This trend is particularly evident in metropolitan and suburbanised regions, where a dramatic loss of productive agricultural land occurs. It is expected that the expansion of built-up areas will lead to the loss of millions of hectares of agricultural land, including approximately 34% of converted areas into high-density urban forms—with the most serious consequences occurring precisely in the peripheral parts of large cities [48]. The re-

sults of our model, which records a continuous increase in urbanisation at the expense of arable land, are therefore consistent with this broader scientific knowledge. These data together indicate that, without the implementation of regulatory measures, urban expansion in Trnava will in the long term weaken the production and ecological potential of the landscape.

A secondary process concerns gross transitions among semi-natural and forest classes. Transitional woodland-shrub can represent an initial stage of forest regeneration or natural vegetation recovery [49,50], and the transition matrix indicates that 19.5% of this class may convert to Mixed forest. However, this percentage represents a gross transition flow rather than a net increase in forest area. Table 1 projects Transitional woodland-shrub to remain at 148 ha between 2018 and 2064, while Broad-leaved forest changes by +1 ha, Mixed forest by −1 ha, and Coniferous forest remains unchanged. The scenario therefore suggests relative stability of forest classes rather than substantial afforestation. This stability is broadly consistent with the wider European tendency towards stable or improving forest conditions reported by [51].

The projected conversion of agricultural land to urban areas may contribute to a reduction in ecosystem services and landscape ecological stability, as reported in previous studies. However, these variables were not directly assessed in the present study and should therefore be interpreted as potential consequences rather than measured outcomes. The 2064 land cover map represents a scenario-based continuation of historical trends rather than a deterministic forecast. The back-validation yielded a Figure of Merit of 0.125 (12.5%), showing that the model had only modest ability to reproduce the exact spatial occurrence of observed land cover changes despite the high whole-map Kappa value. This result, together with the quantity disagreement of 0.0044 and the grid-cell-level allocation disagreement of 0.0125, indicates that Kappa should be interpreted only as a supplementary statistic because it is strongly influenced by persistence. The simulation also assumes stationary transition probabilities and does not account for future changes in agricultural policy, spatial planning, demographic development, economic conditions, or climate.

In addition to urbanisation, soil degradation also represents a serious problem, particularly water erosion, which is one of the most significant degradation processes in Slovakia [52]. Arable land, which in the Trnava region ranks among the most fertile in the country, is threatened by topsoil loss that directly reduces its production potential and increases the risk of further ecological instability. The EEA points out that approximately 25% of the EU territory is affected by water or wind erosion, which has a fundamental impact on soil ecosystem services [7,15]. In the context of the model up to the year 2064, it may be expected that continuing landscape fragmentation and the increase in built-up areas may indirectly increase erosion risk in the agricultural landscape of Trnava, particularly in exposed areas with reduced vegetation cover.

The 2064 scenario indicates that urban expansion will remain the dominant force of land cover change in the Trnava District, while agricultural land declines in favour of discontinuous urban and industrial development. Forest and semi-natural categories remain broadly stable in net area. Consequently, the principal planning implication is the protection of agricultural land and the regulation of settlement and industrial expansion rather than an expectation of substantial natural regeneration.

5. Conclusions

The analysis of land cover change in the Trnava District demonstrates a long-term reduction in agricultural land together with expansion of urban and industrial categories. Between 1990 and 2018, Non-irrigated arable land recorded the largest absolute net loss, decreasing by 962 ha (−1.9%), while Industrial or commercial units increased by 456 ha

(+75.2%), Discontinuous urban fabric by 378 ha (+7.7%), and Continuous urban fabric by 70 ha (+175.0%). The 2018–2064 scenario projects a further reduction in Non-irrigated arable land by 1821 ha (−3.6%), accompanied by increases of 1087 ha (+20.6%) in Discontinuous urban fabric and 735 ha (+69.2%) in Industrial or commercial units. Forest and transitional categories remain almost unchanged in net area during the projection period. These results indicate that urban expansion represents the dominant process captured by the modelling framework and that fertile arable land experienced the largest absolute historical loss. Because the projection assumes stationary transition probabilities, it should be interpreted as a scenario of continued historical dynamics rather than a deterministic forecast. The findings underline the importance of agricultural land protection and effective regulation of urban and industrial expansion.

Potential environmental implications include soil degradation, landscape fragmentation, and the loss of ecosystem services. These impacts were not quantified directly in the present study and are therefore discussed as plausible consequences of agricultural land conversion and urban expansion based on previous research, rather than as independently validated outcomes of the model.

From the perspective of verification of the established hypotheses, the following can be concluded:

Hypothesis 1. *assuming urbanisation as the main factor of change, was confirmed, as built-up areas expanded primarily at the expense of agricultural land.*

Hypothesis 2. *expecting the greatest losses on fertile arable land, was confirmed, since the category Non-irrigated arable land recorded the most significant decrease in area.*

The results of this research have direct significance for the formulation of regional as well as national land use policy. They emphasise the need to strengthen the protection of the highest-quality agricultural soils through stricter regulatory mechanisms in spatial planning, as well as the support of adaptation strategies. At the same time, they demonstrate that modelling tools such as LCM provide an effective framework for the simulation of future scenarios and support qualified decision-making in the field of landscape planning and management. It may be concluded that the Trnava District represents a representative example of a territory where conflicting interests of urban development and agricultural land protection intersect. The experience from this study may be beneficial not only for the Slovak context but also for the broader Central European and European discussion on sustainable land use and effective landscape planning.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CLC	CORINE Land Cover
LCM	Land Change Modeler
EEA	European Environment Agency
EU	European Union
CA-Markov	Markov Chains and Cellular Automata
CLUE-S	Conversion of Land Use and its Effects at Small regional extent
GIS	Geographic information systems
KIA	Kappa Index of Agreement
MLP	Multi-Layer Perceptron
DEM	Digital Elevation Model

References

- Seto, K.C.; Güneralp, B.; Hutya, L.R. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 16083–16088.
- European Environment Agency (EEA). *State of the Environment Report*; European Environment Agency: Copenhagen, Denmark, 2017.
- IPCC. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security and Greenhouse Gas Fluxes in Terrestrial Ecosystems*; Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., et al., Eds.; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2019.
- Angel, S.; Parent, J.; Civco, D.L.; Blei, A.M. *Making Room for a Planet of Cities*; Lincoln Institute of Land Policy: Cambridge, MA, USA, 2011.
- Güneralp, B.; Seto, K.C. Futures of global urban expansion: Uncertainties and implications for biodiversity conservation. *Environ. Res. Lett.* **2013**, *8*, 014025.
- Prokop, G.; Jobstmann, H.; Schönbauer, A. *Report on Best Practices for Limiting Soil Sealing and Mitigating its Effects*; European Commission, Directorate-General for the Environment: Luxembourg, 2011.
- Panagos, P.; Borrelli, P.; Poesen, J.; Ballabio, C.; Lugato, E.; Meusburger, K.; Montanarella, L.; Alewell, C. The new assessment of soil loss by water erosion in Europe. *Environ. Sci. Policy* **2015**, *54*, 438–447.
- Liu, X.; Huang, Y.; Xu, X.; Li, X.; Li, X.; Ciaia, P.; Lin, P.; Gong, K.; Ziegler, A.D.; Chen, A.; et al. High-spatiotemporal-resolution mapping of global urban expansion from 1985 to 2015. *Nat. Sustain.* **2020**, *3*, 564–573.
- Ustaoglu, E.; Williams, B. Institutional Settings and Effects on Agricultural Land Conversion: A Global and Spatial Analysis of European Regions. *Land* **2023**, *12*, 47.
- Hersperger, A.M.; Oliveira, E.; Pagliarin, S.; Palka, G.; Verburg, P.H.; Bolliger, J.; Grădinaru, S.R. Urban land-use change: The role of strategic spatial planning. *Glob. Environ. Change* **2018**, *51*, 32–42.
- Naumann, S.; Frelih-Larsen, A.; Heuser, I.; Kasimbazi, E.; Markus, T.; Qin, T. Land take and soil sealing—Drivers, trends and policy (legal) instruments: Insights from European cities. In *International Yearbook of Soil Law and Policy 2018*; Ginzky, H., Dooley, E., Heuser, I., Kasimbazi, E., Markus, T., Qin, T., Eds.; Springer: Cham, Switzerland, 2019; pp. 83–112.
- Kryczka, P.; Sikorski, D.; Figlus, T.; Lisowska-Kierepka, A.; Musiaka, Ł.; Spórna, T.; Sudra, P.; Szymytkie, R. Defining suburbanization in Central and Eastern Europe: A systematic literature review. *Cities* **2025**, *158*, 105626.
- Kuemmerle, T.; Levers, C.; Erb, K.; Estel, S.; Jepsen, M.R.; Müller, D.; Plutzer, C.; Stürck, J.; Verkerk, P.J.; Verburg, P.H.; et al. Hotspots of land use change in Europe. *Environ. Res. Lett.* **2016**, *11*, 064020.
- Prévosto, B.; Kuiters, L.; Bernhardt-Römermann, M.; Dölle, M.; Schmidt, W.; Hoffmann, M.; Van Uytvanck, J.; Bohner, A.; Kreiner, D.; Stadler, J.; et al. Impacts of land abandonment on vegetation: Successional pathways in European habitats. *Folia Geobot.* **2011**, *46*, 303–325.
- European Environment Agency (EEA). *Land Degradation in Europe*; EEA Report No. 2/2019; Publications Office of the European Union: Luxembourg, 2019.
- Borrelli, P.; Robinson, D.A.; Panagos, P.; Lugato, E.; Yang, J.E.; Alewell, C.; Wuepper, D.; Montanarella, L.; Ballabio, C. Land use and climate change impacts on global soil erosion by water (2015–2070). *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 21994–22001.

17. Kristensen, S.B.P.; Busck, A.G.; van der Sluis, T.; Gaube, V. Patterns and drivers of farm-level land use change in selected European rural landscapes. *Land Use Policy* **2016**, *57*, 786–799.
18. Halmy, M.W.A.; Gessler, P.E.; Hicke, J.A.; Salem, B.B. Land use/land cover change detection and prediction in the north-western coastal desert of Egypt using Markov-CA. *Appl. Geogr.* **2015**, *63*, 101–112.
19. Eastman, J.R. *TerrSet Geospatial Monitoring and Modeling System Manual*; Clark Labs, Clark University: Worcester, MA, USA, 2021.
20. Asif, M.; Khan, I.; Khan, W.; Jan, A.; Ullah, S. Modelling of land use and land cover changes and prediction using CA-Markov and Random Forest. *Geocarto Int.* **2023**, *38*, 1–19.
21. Taloor, A.K.; Sharma, S.; Parsad, G.; Jasrotia, R. Land use land cover simulations using integrated CA-Markov model in the Tawi Basin of Jammu and Kashmir India. *Geosyst. Geoenviron.* **2024**, *3*, 100268.
22. Tahir, Z.; Haseeb, M.; Mahmood, S.A.; Batool, S.; Ullah, S.; Tariq, A. Predicting land use and land cover changes for sustainable land management using CA-Markov modelling and GIS techniques. *Sci. Rep.* **2025**, *15*, 3271.
23. Tárniková, M.; Muchová, Z. Ecological stability over the period: Land-use land-cover change and prediction for 2030. *Land* **2025**, *14*, 1503.
24. Zimba, H.M.; Banda, K.E.; Mbewe, S.; Nyambe, I.A. Integrated use of the CA-Markov model and the Trends. Earth module to enhance the assessment of land cover degradation. *Environ. Syst. Res.* **2024**, *13*, 25.
25. Hu, X.; Zhu, W.; Shen, X.; Bai, R.; Shi, Y.; Li, C.; Zhao, L. Exploring the predictive ability of the CA-Markov model for urban functional area in Nanjing old city. *Sci. Rep.* **2024**, *14*, 18453.
26. Sun, Q.; Huang, L.; Meng, H.; Chi, L.; Wu, J.; Zhou, X. Review of simulations on land use change: A methodology based on bibliometric analysis. *Front. Sustain. Food Syst.* **2025**, *9*, 1548565.
27. Verburg, P.H.; Soepboer, W.; Veldkamp, A.; Limpiada, R.; Espaldon, V.; Mastura, S.S.A. Modeling the spatial dynamics of regional land use: The CLUE-S model. *Environ. Manag.* **2002**, *30*, 391–405.
28. Halpern, A.B.W.; Meadows, M.E. Fifty years of land use change in the Swartland, Western Cape, South Africa: Characteristics, causes and consequences. *S. Afr. Geogr. J.* **2013**, *95*, 38–49.
29. Herrera-Franco, G.; Escandón-Panchana, P.; Montalván, F.J.; Velastegui-Montoya, A. CLUE-S model based on GIS applied to management strategies of territory with oil wells—Case study: Santa Elena, Ecuador. *Geogr. Sustain.* **2022**, *3*, 366–378.
30. Kiziridis, D.A.; Mastrogrianni, A.; Pleniou, M.; Tsiftsis, S.; Xystrakis, F.; Tsiripidis, I. Improving the predictive performance of CLUE-S by extending demand to land transitions: The trans-CLUE-S model. *Ecol. Model.* **2023**, *478*, <https://doi.org/10.1016/j.ecolmodel.2023.110307>.
31. Mamanis, G.; Vrahnakis, M.; Chouvardas, D.; Nasiakou, S.; Kleftoyanni, V. Land Use Demands for the CLUE-S Spatiotemporal Model in an Agroforestry Perspective. *Land* **2021**, *10*, 1097.
32. Wei, T.; Yang, B.; Wang, G.; Yang, K. County land use carbon emission and scenario prediction in Mianyang Science and Technology City New District, Sichuan Province, China. *Sci. Rep.* **2024**, *14*, 9310.
33. Janus, J.; Božek, P.; Taszakowski, J.; Doroż, A. Assessment of long-term canopy height changes across the Białowieża Primeval Forest using historical stereoscopic images and aerial laser scanning data. *Sylvan* **2023**, *167*, 397–414.
34. Colditz, R.R.; Llamas, R.M.; Ressler, R.A. Land cover change analysis in Mexico using 30 m Landsat and 250 m MODIS data. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *XL-7/W3*, 367–374.
35. Veldkamp, A.; Verburg, P.H. Modelling land use change and environmental impact. *J. Environ. Manag.* **2004**, *72*, 1–3.
36. Pontius, R.G.; Malanson, J. Comparison of the structure and accuracy of two land change models. *Int. J. Geogr. Inf. Sci.* **2005**, *19*, 243–265.
37. Dendoncker, N.; Rounsevell, M.; Bogaert, P. Spatial analysis and modelling of land use distributions in Belgium. *Comput. Environ. Urban Syst.* **2007**, *31*, 188–205.
38. Muchová, Z.; Daxnerová, S.; Hafezi, S.M.; Moradi, E. Comments on some evaluation criteria for the official prioritization of land consolidation projects in Slovakia. *J. Ecol. Eng.* **2025**, *26*, 15–23.
39. Feranec, J.; Soukup, T.; Hazeu, G.; Jaffrain, G.; Jindřichová, M.; Kopecký, M.; Orlitová, E.; Jupová, K. *European Landscape Dynamics: CORINE Land Cover Data*; CRC Press (Taylor & Francis Group): Boca Raton, FL, USA, 2016.
40. Zhang, X.; Chen, P.; Cai, Y.; Lin, J. Prediction of PM2.5 Concentrations in the Pearl River Delta by Integrating the PLUS and LUR Models. *Land* **2026**, *15*, 240.
41. Ma, L.; Xiao, J.; Teng, G.; Zhang, T.; Chen, L. An Integrated Model Based on CNN-Transformer and PLUS for Urban Expansion Simulation in the Yangtze River Delta, China. *Remote Sens.* **2026**, *18*, 1071.

42. Clarke, K.C.; Gaydos, L.J. Loose-coupling a cellular automaton model and GIS: Long-term urban growth prediction for San Francisco and Washington/Baltimore. *Int. J. Geogr. Inf. Sci.* **1998**, *12*, 699–714.
43. Koomen, E.; Stillwell, J.; Bakema, A.; Scholten, H.J. *Land-Use Modelling in Planning Practice in GeoJournal Library*; Springer: Dordrecht, The Netherlands, 2011; Volume 101.
44. Park, S.-R.; Lee, H.-J.; Lee, S.-W.; Hwang, S.-J.; Byeon, M.-S.; Joo, G.-J.; Jeong, K.-S.; Kong, D.-S.; Kim, M.-C. Relationships between land use and multi-dimensional characteristics of streams and rivers at two different scales. *Ann. Limnol. Int. J. Limnol.* **2011**, *47*, S107–S116.
45. Halászová, K.; Lackóová, L.; Panagopoulos, T. Long-term evaluation of surface topographic and topsoil grain composition changes in an agricultural landscape. *Front. Environ. Sci.* **2024**, *12*, 1445068.
46. Scalenghe, R.; Ajmone Marsan, F. The anthropogenic sealing of soils in urban areas. *Landsc. Urban Plan.* **2009**, *90*, 1–10.
47. Bren d'Amour, C.; Reitsma, F.; Baiocchi, G.; Barthel, S.; Güneralp, B.; Erb, K.-H.; Haberl, H.; Creutzig, F.; Seto, K.C. Future urban land expansion and implications for global croplands. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 8939–8944.
48. Tóth, A.; Slobodníková, K.; Bellérová, S.; Hus, M. Sustainable landscape approaches and solutions in small municipalities in rural landscapes of Slovakia. *Acta Hortic. Regiotect.* **2026**, *29*, 70–79.
49. Fuchs, R.; Herold, M.; Verburg, P.H.; Clevers, J.G.P.W.; Eberle, J. Gross changes in reconstructions of historic land cover/use for Europe between 1900 and 2010. *Glob. Change Biol.* **2015**, *21*, 299–313.
50. Cegielska, K.; Noszczyk, T.; Kukulska, A.; Szylar, M.; Hernik, J.; Dixon-Gough, R.; Jombach, S.; Valánszki, I.; Filepné Kovács, K. Land use and land cover changes in post-socialist countries: Some observations from Hungary and Poland. *Land Use Policy* **2018**, *78*, 1–18.
51. EEA. *State of Nature in the EU: Results From Reporting Under the Nature Directives 2013–2018*; EEA Report 2020, No. 10/2020; Publications Office of the European Union: Luxembourg, 2020.
52. Petlušová, V.; Petluš, P.; Hreško, J. Vplyv zmien využívania krajiny na eróziu pôdy v katastrálnych územiach Lubá a Belá (Hronská pahorkatina). *Geogr. Čas./Geogr. J.* **2017**, *69*, 245–262.

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