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A Scenario-Based Analysis for the Selection of Post-Mining Land Uses Applying a Cellular Automata Model †

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Abstract: In line with the European Green Deal, Greece plans to achieve climate neutrality by 2050. In this context, the country aims to cease all lignite mines by 2028 and transition away from coal. Effective strategic planning is crucial for mine closure, considering technical, environmental, and social factors. Cellular automata models, known for their adaptability to dynamic environments, are widely used for land use simulation. This research focuses on the surface mining area of Ptolemais in Western Macedonia, Greece, using a cellular automata model to predict new land uses in two scenarios: industrial and agricultural development. The interpretation of the results proved that the applied model could be a helpful tool for the planning and analysis of new land uses considering the spatiotemporal aspect of each scenario.

Keywords: mine closure; cellular automata; strategic planning; simulation model; spatiotemporal; land use change

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1. Introduction

The mining phase-out regards a set of multidimensional and complex procedures that should have been incorporated into the early mining strategic planning. Some standard stages are generally followed, but they are appropriately adjusted depending on each country's local characteristics and legislation. Considering the current energy transition policies, the mine closure should be accompanied by circular economy principles [1]. Some general aspects of the mining phase-out are (a) the preparatory stage, (b) the legislative and policy framework, (c) the economic diversification, (d) the social and labor transition, (e) mine closure and environmental rehabilitation, (f) renewable energy development, and (g) monitoring and evaluation. The present article focuses on the environmental aspect of mining phase-out and the reclamation works. This framework develops a methodology for the post-mining land use allocation.

The land use allocation in a specific area is a complex and multiparametric procedure, as it is affected by the local and topographical characteristics, as well as by socioeconomic factors. In addition, land use allocation is a dynamic procedure, especially when it regards a continuously changing mining area. For this reason, developing "what-if" scenarios is considered a favorable approach for predicting and determining future conditions. This approach is expressed by a widely used method called "cellular automata (CA)", which aims to simulate multiple land use allocations under different scenarios in a continuously changing environment through spatial simulation and modeling process [2,3]. According to Yang et al. (2016), CA is a discrete-time, space, and state grid dynamic model with local spatial interaction and temporal causality [4]. Usually, CA is applied in combination with other methods, such as the Markov model [5,6]. The main advantage of this particular method is that it incorporates the spatial and temporal dimensions in land use prediction [7,8]. The CA is also used for land use change detection and suitability assessment in urban planning and respective decision-making projects [9].

The present research aims to forecast the land use allocation in a mining area and in correlation with time and space by adopting two different scenarios that will cover the needs of the Just Transition Plan. The methodology emphasizes the dynamic behavior that characterizes the mining areas.

2. Materials and Methods

2.1. Research Area

This study examines the Ptolemais mining area, located in the Kozani Province of Western Macedonia, where lignite extraction has been carried out for over six decades [10]. Over the years, the Public Power Corporation (PPC) of Greece has utilized both continuous and non-continuous mining methods to operate multiple mines located within the extensive lignite fields of Western Macedonia [11]. Figure 1 depicts three distinct maps representing the existing land uses, predetermined land uses, and the land uses employed within the model. The predetermined land uses refer to areas where their designated use has already been established, taking into account either the mining planning or the final configuration of the pit. These areas are the Renewable energy sources, the Water bodies, and the agricultural land south of the boundary of environmental limits which is outside the limit of expropriation. Moreover, the aforementioned areas cannot be changed in the model because their use has already been defined.

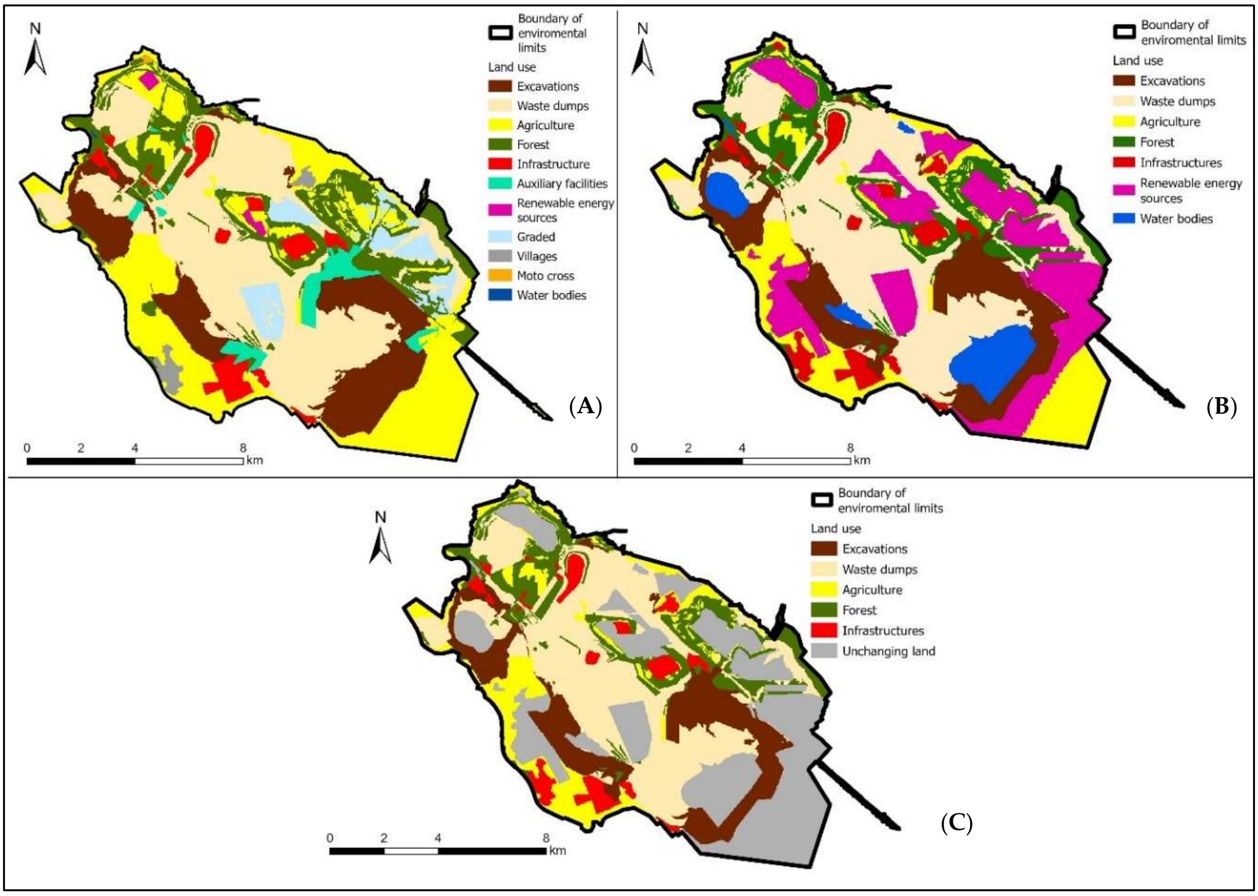

Figure 1. Research area. (**A**) Represents the existing land uses, (**B**) depicts the existing land use with the predetermined areas, and (**C**) the land uses that were used in the model.

2.2. Data Collection

Table 1 presents the dataset employed in this research to simulate the land use changes. The information regarding land use patterns, in conjunction with the Digital Elevation Model (DEM), was obtained through the combination of the PPC database and the Corine land cover data. This process combined the datasets from these two sources to comprehensively and accurately represent the land use characteristics. Integrating the PPC data with the Corine land cover data generated a more robust and reliable dataset, facilitating a more precise simulation of land use changes.

Table 1. Data sources.

Data	Type (Spatial Resolution in Meters)	Source	Date
Land use	Shapefile	PPC database	1 June 2022
Corine land cover	Shapefile	ESA Copernicus https://scihub.copernicus.eu (accessed on 2 May 2023)	2018
Roads	Vector	PPC database	1 June 2022
Cities	Points	PPC database	1 June 2022

2.3. Methods

In order to simulate the land use changes, several transition rules were established for each scenario. This research considers the distance from the cities, the expected lake expansion, the roads, the predetermined Renewable Energy Sources, and the neighborhood effect. There are two most commonly used methods for the neighborhood effect; Von Neumann (4 cells observed around a particular cell) and Moore's quadrature (8 cells observed around a particular cell) [12,13]. This research uses the Moore neighborhood effect with a larger radius (500 × 500 m). Furthermore, the spatial resolution or patch size that was used in the model is 25 × 25 m. In addition to the land use categories mentioned in Figure 1, three additional land use categories were added for each scenario to map the changes. These categories are "New agriculture", "Nature", and "Industrial". The diagram of Figure 2 depicts the logic of the simulation model. Finally, the simulation was carried out in a NetLogo environment.

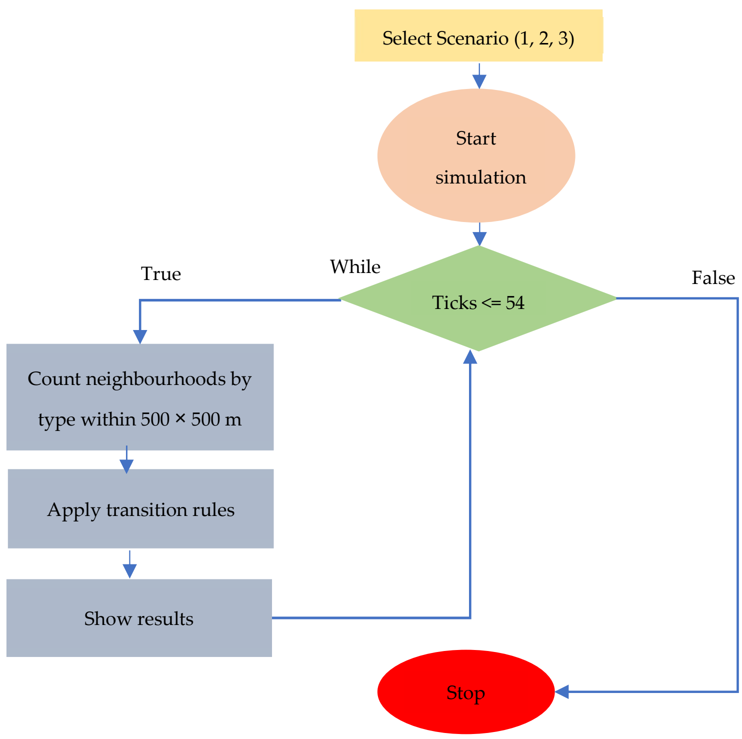

Figure 2. Flow chart depicting the logic and sequence of operations in the simulation model.

After the scenario selection, the model starts and runs until it reaches 54 ticks (A NetLogo expression, which can keep track of the number of times the model runs). Each tick represents a two-month time interval, symbolizing the progress of months within the model. The model runs for nine years, covering the period from 2022 to 2031, after which it automatically stops. Following that, the model calculates the number of neighboring cells for each examined cell and land use type in an area of 500 × 500 m and applies the designated transition rules. Subsequently, it visualizes the progress and changes made within the model. The logic for each of the two scenarios (1) Industrialization, (2) Agricultural development], and land use type is based on applied transition rules regarding (a) The permitting expansion according to the existing land uses, (b) the favorable distance which assesses the benefits of a cell's proximity to predefined locations, and (c) the favorable presence of specific neighboring cells, where the concentration of a particular land use type within a 500 × 500 m area plays a crucial role.

3. Results and Discussion

Figure 3 depicts the simulation results, for the first (Industrialization), and the second (Agricultural development) scenarios. For the first scenario, agriculture, waste dumps, excavations, and infrastructure are allowed to shrink while the forest and unchanging land are not. Furthermore, in the second scenario, the waste dumps, excavations, and infrastructure are allowed to shrink while the agriculture, forest, and unchanging land stay the same. Figure 3 also presents the three-time intervals of 2023, 2025, 2027, 2029, and 2031 simulation results for the first and the second scenarios.

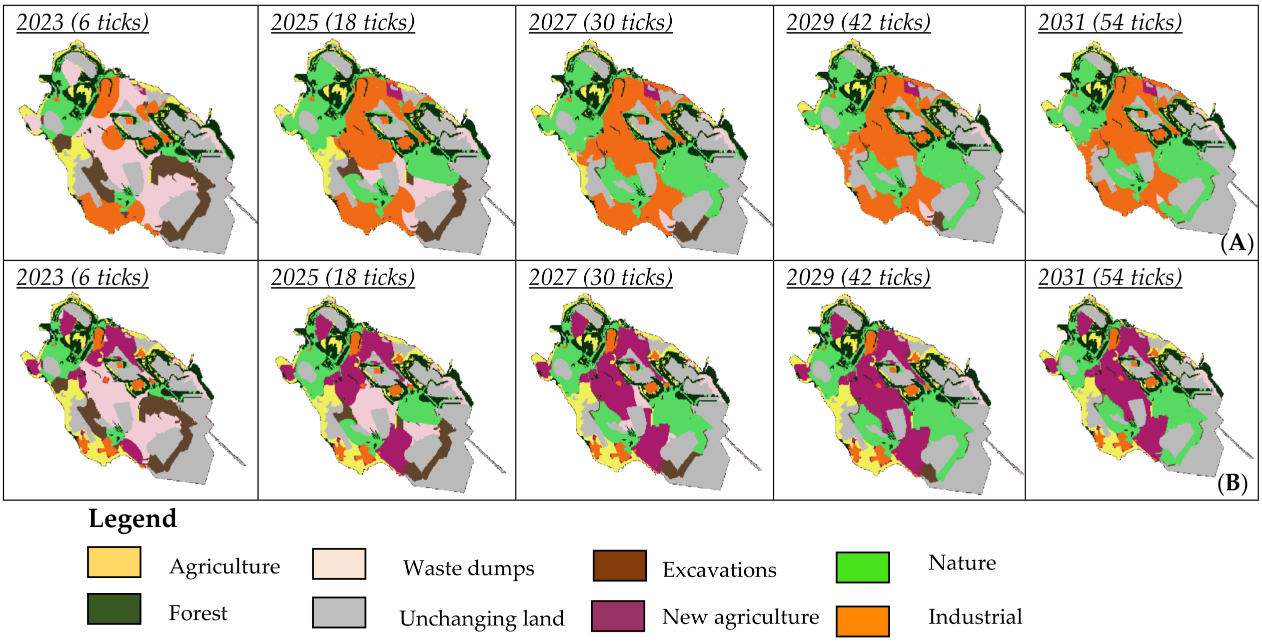

Figure 3. Simulation results. The first row (**A**) presents the industrialization scenario while the second row (**B**) shows the agricultural development scenario.

In the first scenario, industrial areas replaced most waste dumps and agricultural land, while nature was promoted in excavated areas near lakes. Small patches of agriculture were also established. In the second scenario, agricultural land was developed in former waste dump areas. "Nature" took over the excavation sites, and industrial areas replaced the previous infrastructure areas.

It is worth noting that the excavated areas, characterized by steep slopes, are most suitable for transforming into natural areas and promoting biodiversity. The challenging topography restricts the possibilities for other land uses, making the preservation and enhancement of nature and biodiversity the most feasible option for these areas.

4. Conclusions

The selection of new land uses after mine closure is a challenging task, made even more complex due to the numerous factors that must be considered. The design of new land uses in such large areas should take into account not only the topographic characteristics of the area but should also align with the development directions of each country as well as the needs and aspirations of the local community. This paper demonstrates the effectiveness and utility of a land use simulation model. Specifically, a cellular automata model was employed to forecast and analyze the allocation of new land uses based on two distinct scenarios: industrial activities and agricultural uses.

The model results showed that each scenario promoted different land uses within the study area. The land-use changes were influenced by two key parameters: the transition rules and the neighborhood effect. This result indicates that modifying the transition rules and neighborhood effect would form distinct land use patterns in the study area. Moreover, the interaction between these parameters highlights the dynamic nature of land use changes and the importance of carefully considering them when planning for the future development of the area. Finally, the adopted cellular automata-based methodology can be extended as a valuable tool in the decision-making processes within diverse domains, including urban planning, environmental management, agriculture, and resource allocation. Its applicability is rooted in its capacity to model and simulate complex spatial dynamics, providing scientifically informed insights and aiding in rational decision-making.

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