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Dramatic Loss of Agricultural Land Due to Urban Expansion Threatens Food Security in the Nile Delta, Egypt

Taher M. Radwan [1,2,*], G. Alan Blackburn [1], J. Duncan Whyatt [1] and Peter M. Atkinson [1,3,4,5]

1 Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK; alan.blackburn@lancaster.ac.uk (G.A.B.); d.whyatt@lancaster.ac.uk (J.D.W.); pma@lancaster.ac.uk (P.M.A.)
2 Department of Soil and Water Sciences, Faculty of Agriculture (El-Shatby), Alexandria University, Alexandria 21545, Egypt
3 School of Natural and Built Environment, Queen's University Belfast, Belfast BT7 1NN, UK
4 Geography and Environmental Science, University of Southampton, Southampton SO17 1BJ, UK
5 Institute of Geographic Science and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
* Correspondence: t.radwan@lancaster.ac.uk or taher.radwan88@gmail.com; Tel.: +44-738-083-0383

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Abstract: Egypt has one of the largest and fastest growing populations in the world. However, nearly 96% of the total land area is uninhabited desert and 96% of the population is concentrated around the River Nile valley and the Delta. This unbalanced distribution and dramatically rising population have caused severe socio-economic problems. In this research, 24 land use/land cover (LULC) maps from 1992 to 2015 were used to monitor LULC changes in the Nile Delta and quantify the rates and types of LULC transitions. The results show that 74,600 hectares of fertile agricultural land in the Nile Delta (*Old Lands*) was lost to urban expansion over the 24 year period at an average rate of 3108 ha year^{-1}, whilst 206,100 hectares of bare land was converted to agricultural land (*New Lands*) at an average rate of 8588 ha year^{-1}. A Cellular Automata-Markov (CA-Markov) integrated model was used to simulate future alternative LULC change scenarios. Under a Business as Usual scenario, 87,000 hectares of land transitioned from agricultural land to urban areas by 2030, posing a threat to the agricultural sector sustainability and food security in Egypt. Three alternative future scenarios were developed to promote urban development elsewhere, hence, with potential to preserve the fertile soils of the Nile Delta. A scenario which permitted urban expansion into the desert only preserved the largest amount of agricultural land in the Nile Delta. However, a scenario that encouraged urban expansion into the desert and adjacent to areas of existing high population density resulted in almost the same area of agricultural land being preserved. The alternative future scenarios are valuable for supporting policy development and planning decisions in Egypt and demonstrating that continued urban development is possible while minimising the threats to environmental sustainability and national food security.

Keywords: land use/land cover; change detection; agricultural land sustainability; CA-Markov; remote sensing

1. Introduction

Egypt, with a population of approximately 100 million people, is the 14th most populated country in the world, the 3rd largest in Africa and the largest Arab country [1]. It has a total land area of almost 1 million km^2 of which nearly 96% is uninhabited desert. The majority (96%) of the national population is located within the River Nile valley and the Delta [2]. The combination of unbalanced distribution and dramatic population growth (around 2% annually) has caused severe socio-economic problems including a reduction in living standards, high levels of unemployment, and increasing crime rates [2–4].

The ratio between human resources and land resources is a critical issue in Egypt. Such a high annual rate of increase in population means that considerable attention need to be given to preserve the limited land resources to optimize agricultural productivity, and to help conserve the highly fertile soil of the Nile Delta which is the primary source of staple cereal crops for the nation [5].

The agricultural sector in Egypt is the main source of income for around 60% of the population [6]. Agricultural land in Egypt can be divided into two main categories; *Old Lands* and *New Lands* [2]. The *Old Lands* are areas of highly fertile clayey soils, which have been cultivated intensively for thousands of years in the Nile Valley and the Delta. Due to the fertile nature of the soil, these areas have traditionally been used to cultivate staple cereal crops such as wheat, maize and rice, maintaining agricultural sustainability and preserving food security for the Egyptian people, with the River Nile being the primary water source for crop irrigation by flooding irrigation. The *New lands* are desert areas outside the eastern and western fringes of the Nile Delta, which have been reclaimed over the last 50 years and cultivated with fruit trees (Orchards) such as oranges, grapes, apples, mangoes and bananas, and vegetables such as cherry tomatoes and bell pepper aimed for lucrative export markets with modern irrigation techniques used such as sprinkler and drip irrigation which is pumped from groundwater boreholes [2,5,7].

Urban expansion is a widespread process in Egypt due to economic development and exponential population growth. Rapid urban expansion, mainly at the expense of agricultural land, has critical consequences for agricultural productivity and the condition of the environment. It has already been recognized that in Egypt the mismanagement and overexploitation of land resources have negatively affected national GDP, the agricultural sector and the sustainability of the economic development of the country [3,4]. Urbanisation is a complicated process which not only negatively impacts sociological, cultural and economic aspects but also creates significant changes in the environmental conditions [8–10]. Widespread urbanisation as a result of rapid population growth is now recognized as a critical phenomenon in many developing counties [11].

Remote sensing (RS) and Geographic Information Systems (GIS) are robust, useful and efficient tools for assessing the temporal and spatial dynamics of land use/land cover (LULC) change, analysing and mapping these dynamics and providing valuable historical data for monitoring the condition of the environment [8,11,12]. LULC change is currently considered one of the most critical environmental issues across the globe [13]. New tools and techniques for monitoring and detecting changes on the Earth's surface at various scales have been developed in response to increased availability of remotely sensed data and technical advances in spatial, spectral and temporal resolution [14,15]. LULC change analysis is based on historical LULC data where past land transitions are monitored and assessed [15–18]. Predicting LULC change is useful for understanding, highlighting and quantifying potential alterations that might occur over landscapes in the future. Such predictions are helpful to urban planners, agriculturalists, and land use planners as they try to manage and reduce possible adverse impacts on the environment [15,16]. Recently, different types of models and methods within the fields of RS and GIS have been applied to model trends in urban growth [19,20]. These include studies that have used Cellular Automata (CA) and Markov chain analysis models [20–22].

Markov chain analysis is a powerful modelling approach that has been widely utilized to investigate the dynamics of LULC change at various scales. It can simulate and quantify future LULC change effectively [17,23–25] and is particularly useful method for modelling LULC change, particularly over large areas [26]. The model is built around producing a transition probability matrix of LULC change between two different dates. The transition probability matrix provides an estimate of the probability of each pixel of a specific LULC class being converted to another class or remaining in its current class [17,19]. The Markov chain analysis model does not simulate the spatial changes in LULC [27] but can be used to quantify and predict LULC changes efficiently [28,29].

CA modelling is dynamic, discrete and may be integrated with other models to project and simulate urban growth patterns [21,22]. It has been used extensively to simulate urban sprawl dynamics and predict future LULC change over recent years [13,21,26,30]. CA and Markov Chain analysis models (CA-Markov) may be integrated to quantify simulate and model spatio-temporal patterns. This integration can overcome the limitations of Markov chain analysis and provide increased understanding of LULC change dynamics, due to the addition of spatial dimensions by the CA model [13,22,31,32]. Hence, these integrated models consider the temporal and spatial aspects of LULC change patterns [33].

The aim of this paper was to monitor, understand and quantify historical LULC changes in the Nile Delta and predict future changes based on different assumed scenarios. To meet this aim, the following objectives were set:

- Monitor historic changes in LULC in the Nile Delta from 1992 to 2015;
- Quantify the rates and types of LULC transitions that have occurred;
- Evaluate the extent of urban sprawl and its implications for the loss of productive agricultural land in the Nile Delta;
- Simulate LULC changes to 2030 for a series of different scenarios designed to reduce the amount of fertile land lost to urban development in the Nile Delta.

2. Materials and Methods

2.1. Study Area

The Nile Delta in Egypt is considered to be one of the oldest agricultural areas in the world; it has been under continuous cultivation since 3000 B.C [2,5,34]. The River Nile and its associated sediments made the Delta soils fertile and highly productive, forming a visible green triangular area within a vast desert. This area supported the settlement, the prosperity and the expansion of one of the oldest and greatest civilizations in world history [2,34]. The Nile Delta is located in the north of Egypt and stretches from Alexandria governorate in the west to Port Said governorate in the east [35]. The study area (Figure 1) consists of 12 administrative divisions (governorates). It covers a total area of approximately 40,000 km^2 and characterized by a Mediterranean semi-arid climate. About 60% of Egypt's population is currently living in the Nile Delta region, which occupies 4% of the total land area of the country [6]. Recently, this region has experienced significant LULC change due to rapid and continuous urban expansion linked to exponential population growth. Figure 2 shows population and urban LULC in Egypt from 1992 to 2015 [1].

2.2. Data Collection and Processing

2.2.1. Land Use/Land Cover (LULC) Change Analysis

Twenty-four LULC maps based on a multi-sensor dataset were available and downloaded from the European Space Agency-Climate Change Initiative (ESA-CCI) land cover viewer (http://maps.elie.ucl.ac.be/CCI/viewer/). These maps provide access to consistent global LULC coverage at 300 m spatial resolution on an annual basis from 1992 to 2015 based on the processing of ENVISAT MERIS, SPOT-VEGETATION, PROBA-V and AVHRR images [36]. The original data were supplied in global coordinates (WGS84) hence they were projected into UTM (Zone 36N) coordinates for the purpose of this analysis using ArcGIS Desktop 10.5 [37]. These maps were analyzed to reveal LULC changes for the period 1992 to 2015 inclusive.

The ESA-CCI dataset covers the longest period available to date and it is considered the first time-series of global LULC coverage at 300 m. The original dataset classifies the global LULC into 37 classes (22 global classes and 15 regional classes) based on the Land Cover Classification System developed by the Food and Agriculture Organization (FAO) with an overall accuracy of about 75%.

The dataset has been validated against the GlobCover 2009 dataset. A more detailed validation is currently under development by the ESA-CCI project team [36].

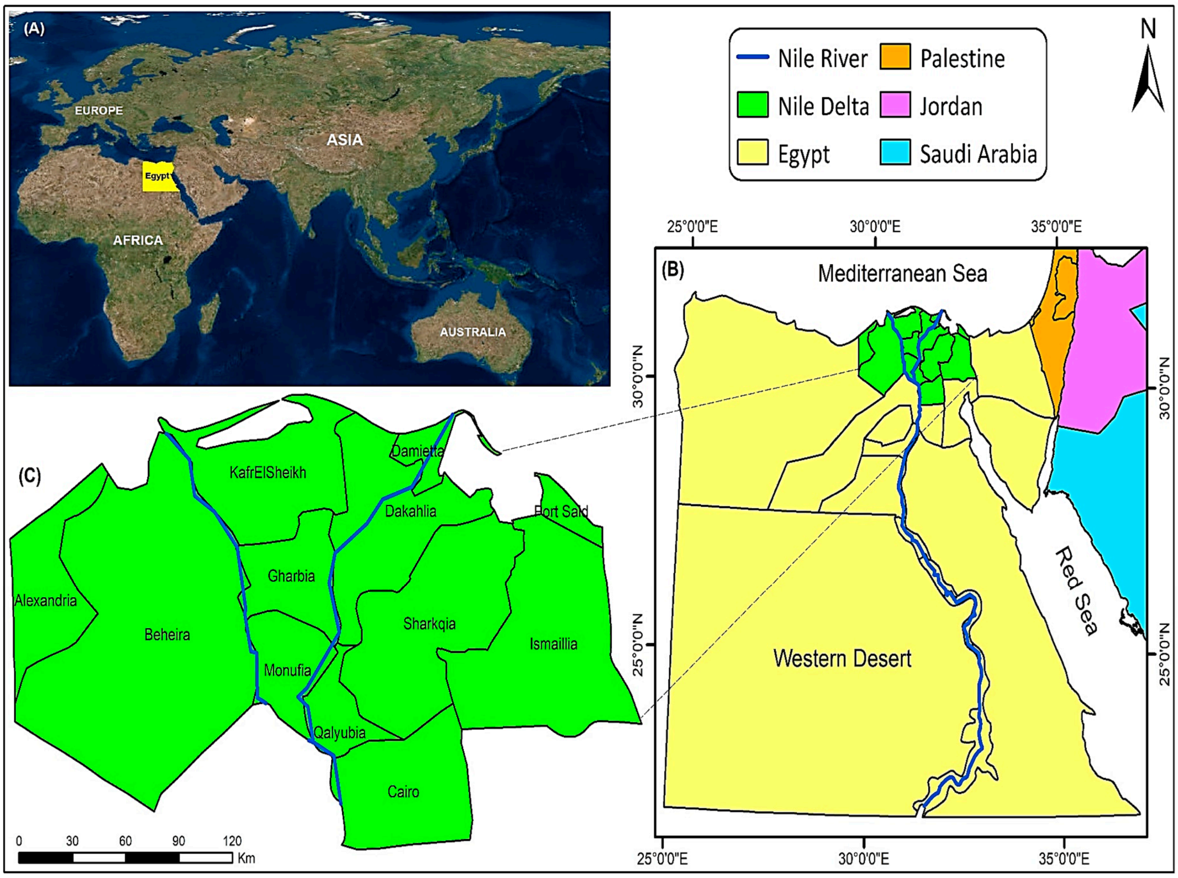

Figure 1. Location of the study area: (**A**) location of Egypt in the North of Africa; (**B**) location of the Nile Delta in the North of Egypt; (**C**) the study area (Nile Delta governorates).

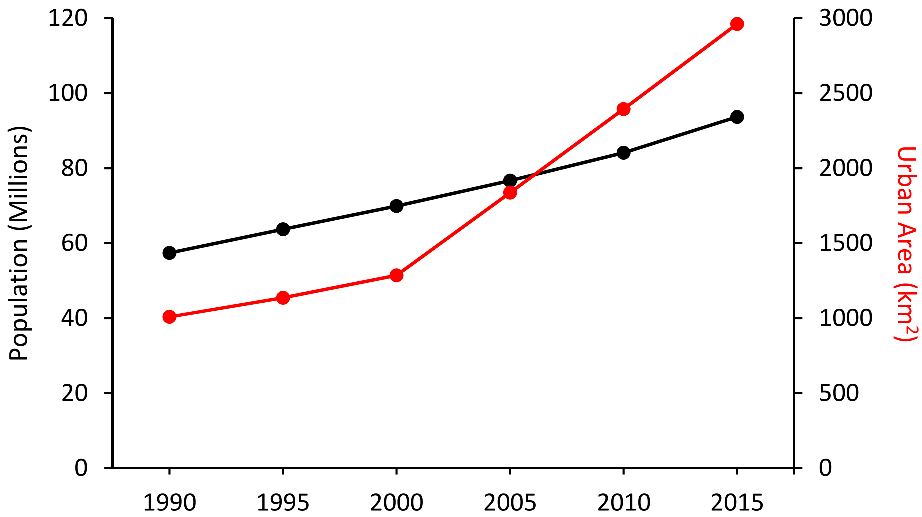

Figure 2. Urban land use/land cover (LULC) and population growth in Egypt [1].

2.2.2. Simulation of Future LULC Changes under Different Urban Growth Scenarios

A CA-Markov integrated model was used to model likely future LULC dynamics in the Nile Delta. CA-Markov is a change/time series model established within the TerrSet Geospatial Monitoring and Modeling System software [19,38]. In this model, a Markov chain analysis controls the temporal changes in LULC based on transition probabilities, while the spatial changes are controlled by the cell-based rules determined by a CA spatial contiguity filter [13,19,32,39]. In order to predict future LULC changes, the first step is to conduct the Markov chain analysis (a Markovian transition estimator), which requires two image data inputs: the first image for an earlier LULC period and the second image for a later LULC period. This generates a transition probability matrix and conditional probability images [17,19,38,40]. The second step is to implement the CA–Markov integrated model using the previously derived transition probability matrix and the later LULC image [19,38]. In this paper, LULC maps for the years 1999, 2000, 2014 and 2015 were used to derive transition probability matrices of LULC classes between 1999–2000 and 2014–2015 using the Markov model. These transition matrices were then used to simulate LULC changes to future periods. Figure 3 illustrates the primary steps carried out within the LULC change analysis using the Markov and CA–Markov models.

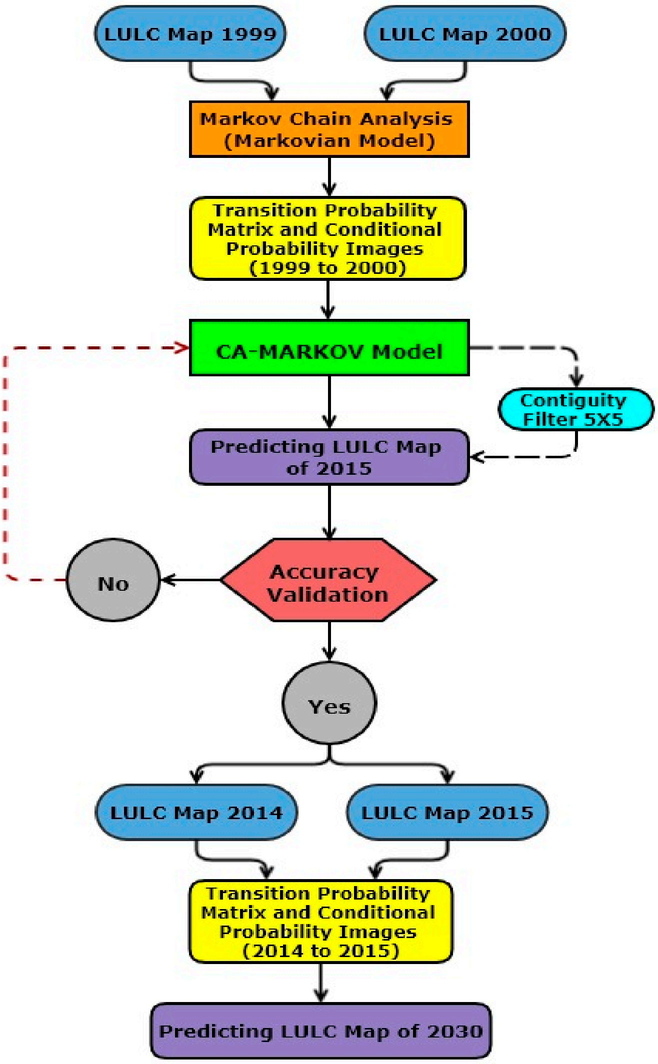

Figure 3. Workflow of the methodology used within CA-Markov LULC future analysis.

To assess the accuracy of a forwards prediction of 15 years (i.e. the length of prediction to be used in this study), we compared the actual LULC map in 2015 with the predicted map generated using a transition probability matrix derived from the 1999 and 2000 maps, with a 5 × 5 cell contiguity filter used to represent the neighbourhood rules for each cell. The VALIDATE module within TerrSet was used to calculate the overall agreement between actual and predicted LULC maps, using the Kappa index [25,41]. The importance of model validation prior to simulating future changes in LULC has been emphasized in the literature [19].

Based on the successful validation (see results section) we used the two most recent LULC maps (i.e., 2014 and 2015) to generate the transition probability matrix for the years 2014–2015 within the CA-Markov model to project LULC maps for 2030. Four scenarios of future urban expansion were used to assess their impact upon the loss of areas of fertile soils within the Nile Delta. These projected scenarios could be useful for aiding policy formulation and planning decisions in the country.

The 1st scenario, Business As Usual (BAU) assumes current patterns of urban growth continuing in the future. The subsequent scenarios were designed to generate the same increase in urban area by 2030 as the BAU, but to spatially distribute this urban expansion in different ways. Hence, the 2nd scenario, Desert Development Only (DDO) was conceived to prevent further urban development within the green zone of the Nile Delta (*Old Lands*), restricting it to the desert only. A binary image of bare land was used to drive this simulation, whilst, the agricultural land and waterways binaries were used as spatial constraints for future urban expansion.

The 3rd scenario, Population-Driven Expansion (PDE) assumes that areas of high population act as catalysts for further urban expansion. Population data were obtained from the WorldPop website for Egypt [42], at a spatial resolution of 100m, then aggregated to 300m to match the spatial resolution of the LULC data and maintain consistency within the model. The waterways binary then was used as a spatial constraint. This scenario encourages higher levels of urbanization adjacent to existing areas of higher population in an attempt to minimize the loss of agricultural land in the Delta region. Finally, the 4th scenario Desert and Population Expansion (DPE) was constructed using elements of scenarios 2 and 3 (DDO and PDE). The bare land binary and the population layer were used as driving factors for urban expansion. The waterways binary was used as a spatial constraining factor. This hybrid scenario encourages urban expansion in the desert adjacent to existing areas of higher population.

3. Results

3.1. LULC Change Analysis

The original LULC classes in the ESA-CCI dataset were regrouped and simplified into the five major LULC classes found in the Nile Delta namely: agricultural land, aquatic/terrestrial vegetation, urban land, bare land and water bodies [43] as shown in Figure 4.

Urban areas increased significantly over the 24 year period in the Nile Delta, from 755 km^2 in 1992 to 1890 km^2 in 2015 (Table 1) at an average rate of 47 km^2 year^{-1}. Agricultural LC increased over this period from 24,053 km^2 in 1992 to 25,576 km^2 in 2015 at an average rate of 63 km^2 year^{-1}. However, all of this additional agricultural land was created in the *New Lands* (formerly desert) through government incentives. Four governorates were selected to explore the process of urban expansion in the Nile Delta in more detail: Dakahlia, Gharbia, Sharkqia and Cairo (Figure 1). The first three governorates are considered the largest areas of highly productive soils located in the fertile delta zone (*Old Lands*), and the fourth encompasses the capital city. The amount of urban LC in Dakahlia governorate more than doubled over the 24-year period from 108 km^2 to 237 km^2. Similarly, the amount of urban LULC in Gharbia governorate almost doubled over the study period, from 94 km^2 to 170 km^2, and more than tripled in Sharkqia governorate, from 59 km^2 in 1992 to 205 km^2 in 2015. The most significant urban growth occurred in Cairo governorate over the study period, increasing from 188 km^2 to 449 km^2. Urban expansion over the study period from 1992 to 2015 has been plotted for the four selected governorates; Dakahlia, Gharbia, Sharkqia, and Cairo (Figure 5). This demonstrates differing trajectories of LULC changes between various governorates. Maps showing different patterns and rates of urbanization over the productive agricultural land (*Old Lands*) for the four selected governorates are shown in Appendix A.

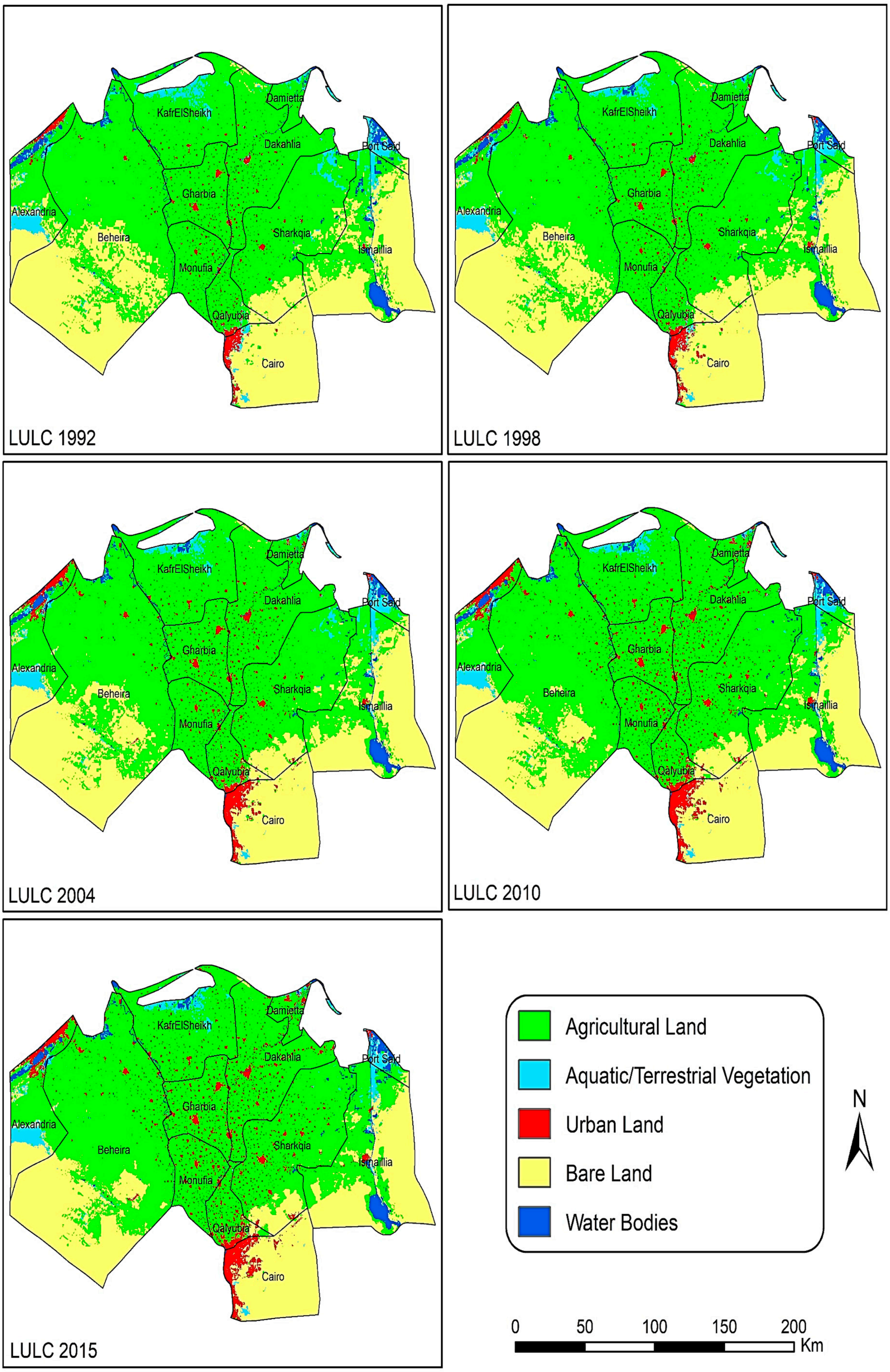

Figure 4. The major five LULC classes in the Nile Delta over the study period.

Table 1. LULC classes total areas across the Nile Delta over the study period.

LULC Class	Area (km^2)					Change
	1992	**1998**	**2004**	**2010**	**2015**	**1992–2015 (%)**
Agricultural Land	24,053	24,427	24,959	25,430	25,576	6.3
Natural Vegetation	1435	1301	1147	1031	989	−31.1
Urban Land	755	873	1266	1597	1890	150.3
Bare Land	13,031	12,696	11,947	11,243	10,795	−17.2
Water Bodies	841	818	797	815	866	2.9

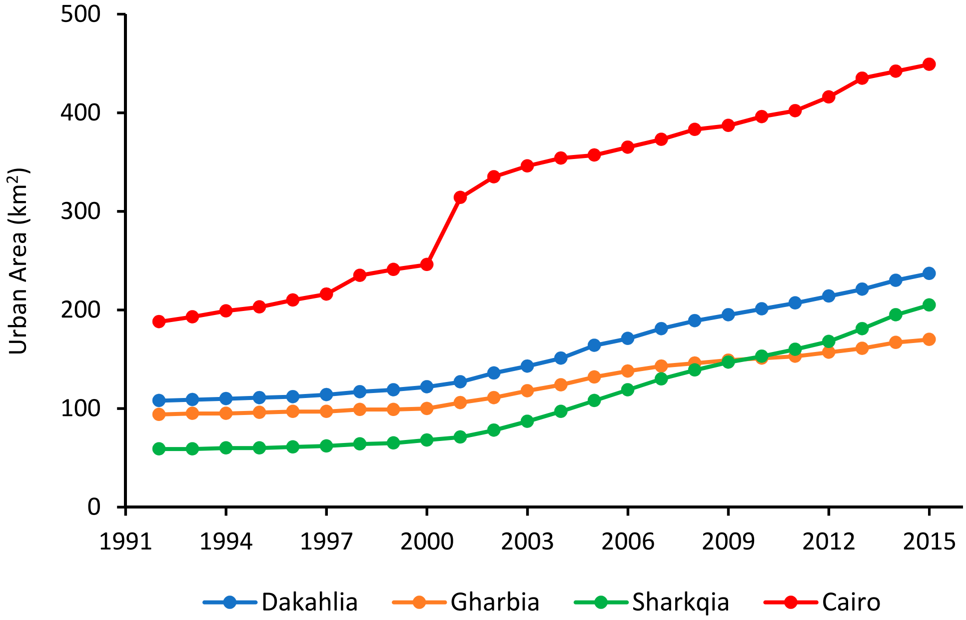

Figure 5. Urbanization in Dakahlia, Gharbia, Sharkqia and Cairo over the study period.

Transitions between different LULC classes in the Nile Delta between 1992 and 2015 are shown in Table 2. A change map illustrating the spatial distribution of LULC transitions from 1992 to 2015 is shown in Figure 6. Table 2 indicates that more than 90% of the total land area in the Nile Delta did not change over the 24-year period. However, around 2061 km^2 was converted from bare land to agricultural land, which reflects the government's efforts to reclaim new lands outside the Delta to cater for the exponential population growth, achieve self-sufficiency of food production and maximize national GDP by delivering fruits and vegetables to export markets [34,44]. Over 900 km^2 of land was converted into urban areas at the expense of fertile agricultural land and natural vegetation in the Nile Delta. This amount of land is 1.16 times the size of New York City and almost the same size as Berlin, representing a significant loss of crucial natural resources. As Figure 6 shows, most of this transition occurs in relatively small patches scattered throughout the Delta. In contrast, 205 km^2 of the desert was converted into urban areas, including New Cairo city, which was established in the year 2000 by a presidential decree.

Table 2. Areas of transitions changes within LULC classes in the Nile Delta from 1992 to 2015.

LULC Transition	Area	
	(km^2)	Hectares (ha)
Agriculture to Urban	746	74,600
Vegetation to Urban	170	17,000
No Change	36,352	3,635,200
Vegetation to Agriculture	266	26,600
Bare to Urban	205	20,500
Bare to Agriculture	2061	206,100
Other LC classes changes	315	31,500

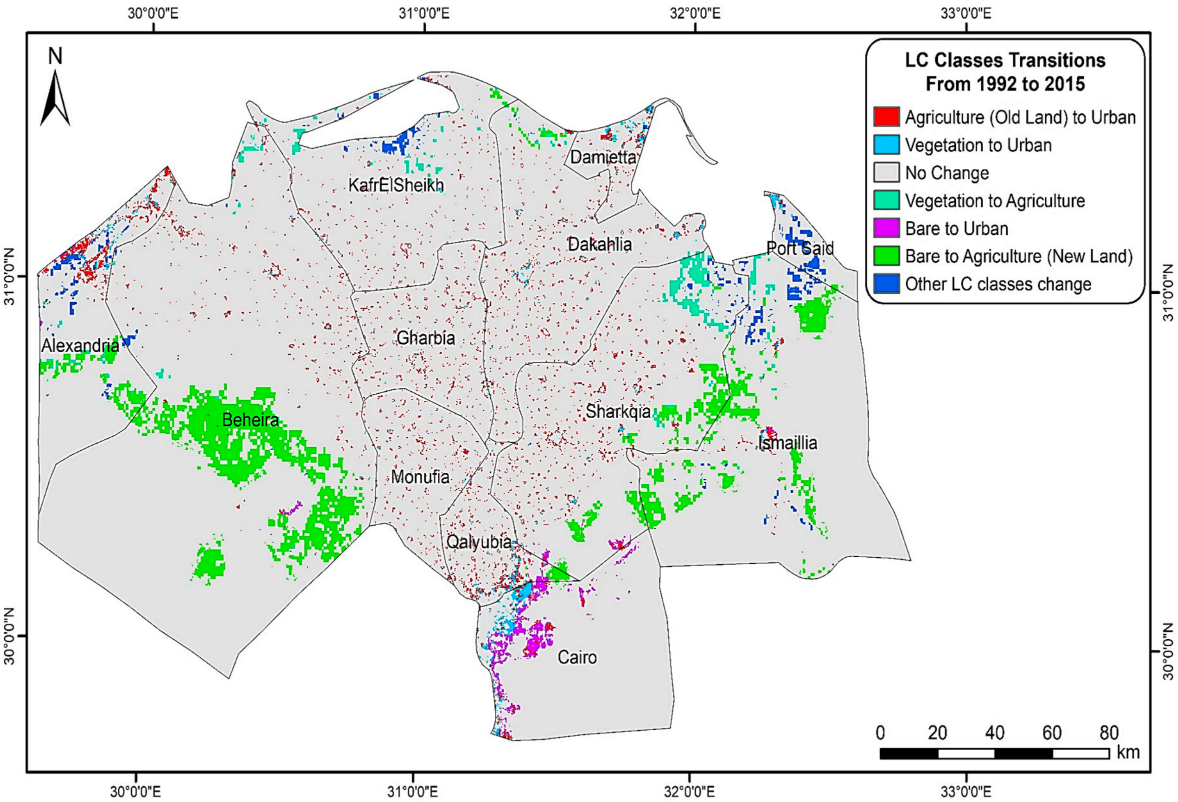

Figure 6. Change map between the 1992 and 2015 LULC distributions.

3.2. Prediction of Future LULC Dynamics

3.2.1. Validation and Application of the CA-Markov Integrated Model

The Markov model outputs, probability matrix and the conditional probability images were combined using the CA-Markov integrated model to simulate LULC change for 2015 using a 5 × 5 contiguity filter. To validate the CA-Markov model, the actual LULC map in 2015 was compared with the predicted map generated using maps from 1999 and 2000 (Figure 7). For this forwards prediction of 15 years, the validation results showed a high level of correspondence between the actual and the simulated LULC maps in 2015 where the Kappa index value was 0.94. This Kappa value is significantly higher than the value of 0.80 considered acceptable [45] and in line with other studies which have applied the CA-Markov model in LULC change predictions [13,38,46,47]. Hence, after achieving this level of predictive accuracy, the CA–Markov model was considered suitable for use in simulating future LULC change to 2030. This high *K*-index value could be attributed to the large amount of land that did not transition at all which was about 90% of the total land area, or the number of LULC classes used in the analyses (five classes). Parsa et al. [48], have previously achieved an overall accuracy of 0.98 based on three LULC classes.

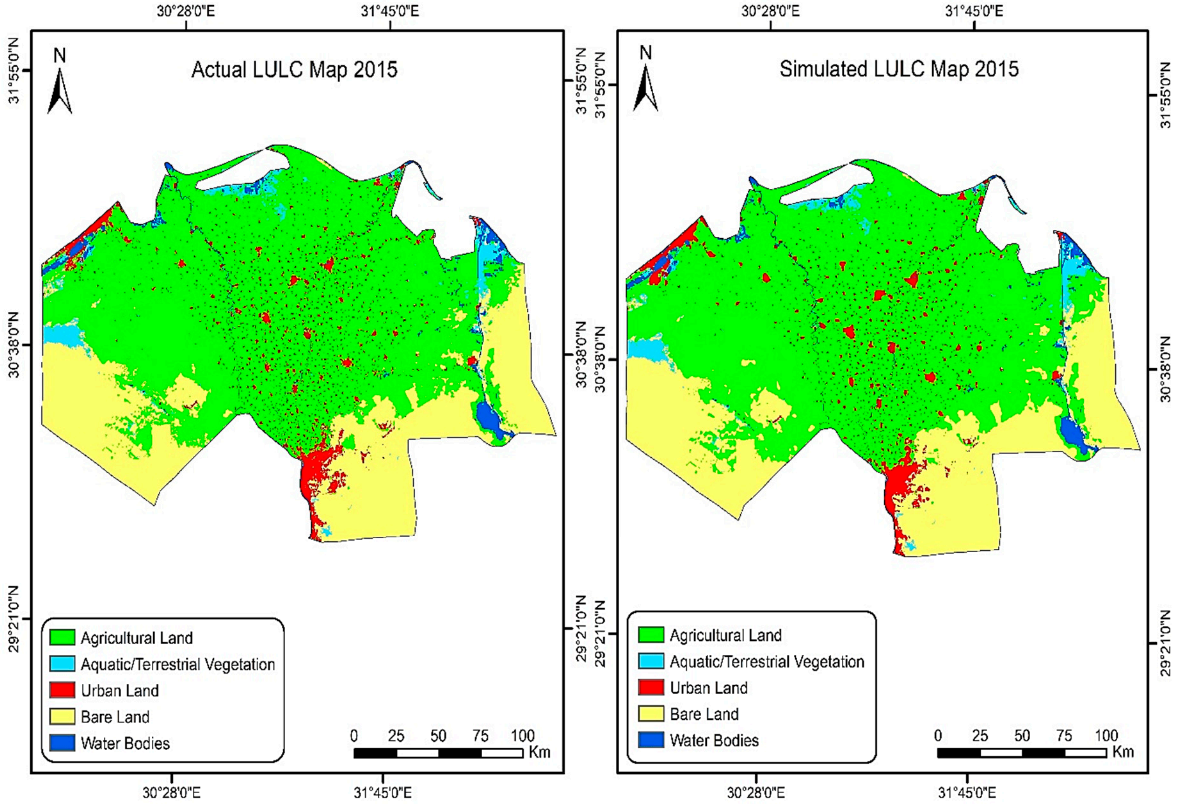

Figure 7. Actual (to the left) and simulated (to the right) LULC maps for 2015.

3.2.2. Simulation of LULC in 2030 Based on Different Scenarios of Urban Expansion

Under the BAU scenario, the simulation revealed that there was a significant increase in urban land, from 1890 km^2 in 2015 to 2759 km^2 in 2030 at an average growth rate of 58 km^2 year^{-1}. The majority of this increase occurred at the expense of productive agricultural land in the Nile Delta, hence constitutes a significant loss of natural resources (Table 3). The BAU simulation results also showed that agricultural land increased by 405 km^2 from 2015 to 2030, at an average rate of 27 km^2 year^{-1}. The majority of this growth occurred in the desert (*New Lands*) outside the fertile Delta region (Table 3). The amount of bare land decreased from 10795 km^2 in 2015 to 9570 km^2 in 2030 at an average rate of 81 km^2 year^{-1}. Most of these areas are expected to be converted to agricultural land (*New lands* reclamation). However, some of these areas will change to urban land particularly as Cairo and New Cairo expand over time.

Table 3. LULC classes change (gains and losses) over the Nile Delta from 1995 to 2030 (Business As Usual, BAU).

LULC Class	**Area Change (km^2)**		
	1995–2005	**2005–2015**	**2015–2030**
Agricultural Land	730	595	405
Aquatic/Terrestrial Vegetation	−234	−138	−116
Urban Land	539	556	869
Bare Land	−1,022	−1,083	−1,225
Water Bodies	−14	73	66

Comparing the three alternative future scenarios (Figure 8) with the BAU scenario (Table 4), we found that agricultural land increased by 410 km^2 in the DDO scenario, with no loss of agricultural land in the Nile Delta, as expected. In contrast, bare land decreased by 325 km^2, as a result of further urbanisation particularly in the zone of Cairo and New Cairo, since this scenario restricts urban development to the desert only. In the PDE scenario, agricultural land increased by 254 km^2 compared to BAU. Finally, 346 km^2 of agricultural land is likely to be saved in the DPE scenario. Most of the agricultural land saved in the DDO, PDE and DPE scenarios is located in the (*Old Lands*) zone.

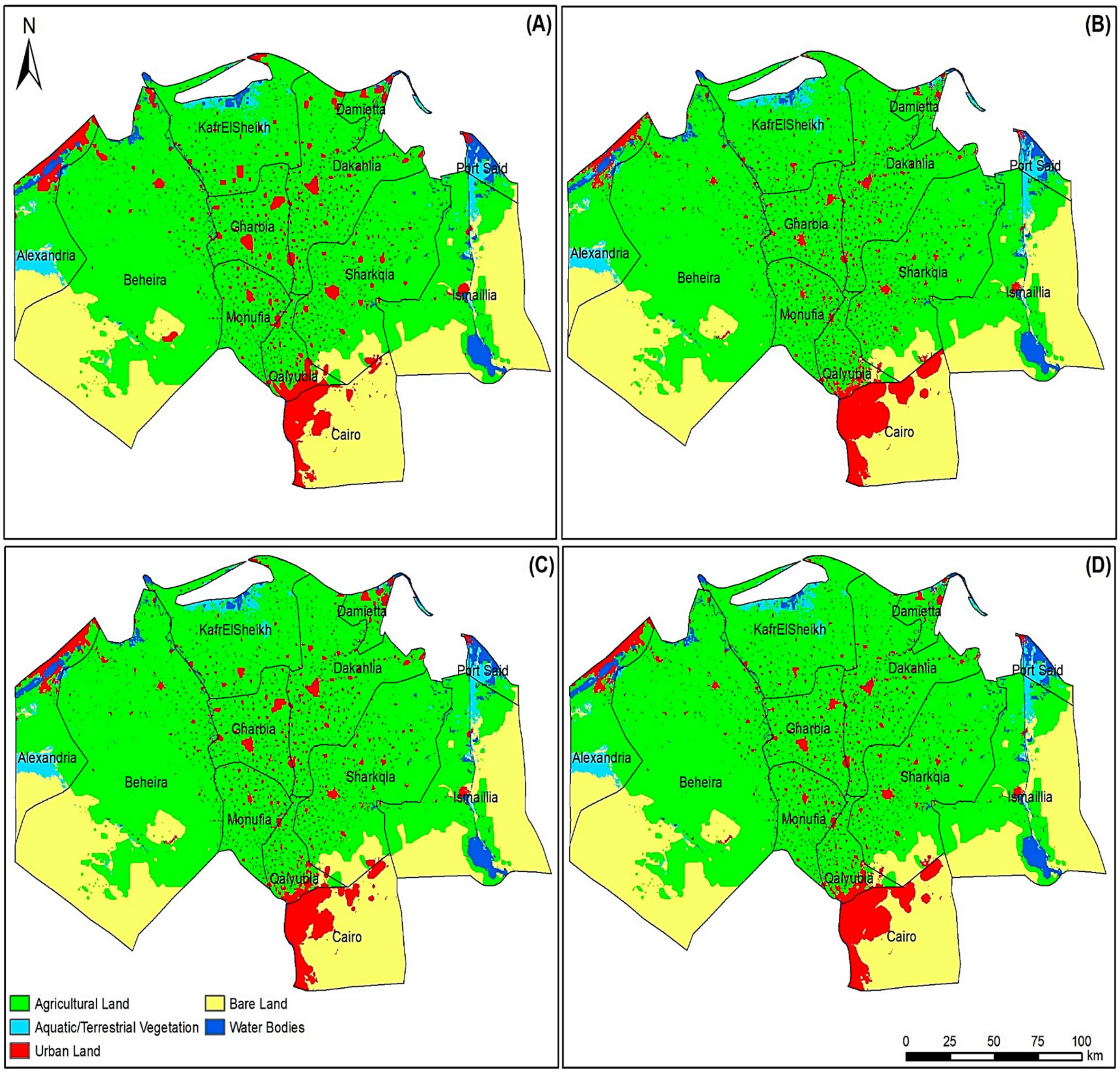

Figure 8. Simulated LULC scenarios: (**A**) BAU, (**B**) DDO, (**C**) PDE, (**D**) DPE.

Table 4. The simulated future scenarios LULC total areas over the Nile Delta.

LULC Class	Predicted Area (km^2)			
	BAU	**DDO**	**PDE**	**DPE**
Agricultural Land	26,078	26,488	26,332	26,424
Aquatic/Terrestrial Vegetation	832	814	806	826
Urban Land	2683	2680	2678	2681
Bare Land	9572	9247	9403	9293
Water Bodies	951	887	897	892

Three governorates (Sharkqia, Dakahlia and Gharbia) with the largest amount of fertile agricultural land (*Old Lands*) in the Nile Delta were selected to explore the impacts of the four simulated scenarios in more detail (Figure 9). This demonstrates how substantial areas of agricultural land will be lost under BAU, and how the alternative scenarios can preserve significant amounts of agricultural land, particularly under DDO and DPE. Maps showing the patterns of LULC in the three selected governorates under different urban growth scenarios are shown in Appendix B.

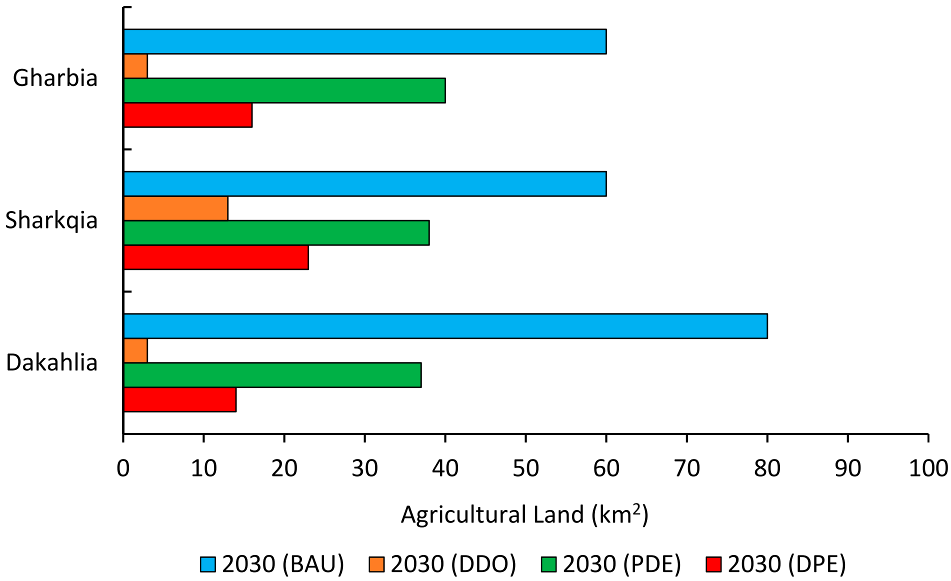

Figure 9. Amount of agricultural land lost in three governorates under the different urban growth scenarios between 2015 and 2030.

4. Discussion

4.1. Previous Nile Delta LULC Studies

In Egypt, several smaller-scale LULC studies have focussed on the Nile Delta. Compared to these studies, we found that fertile agricultural land loss due to urban development is a more critical issue than previously suggested. Shalaby et al. [49] assessed the effect of urban expansion on the productive agricultural land in Qalubia governorate between 1992 and 2009 and found that 151 km^2 of agricultural land had been lost to urban development over this period, accounting for 13% of the total land area of the governorate. Shalaby and Moghanm [50] assessed the effect of urban sprawl on the fertile agricultural soils of the northern Nile Delta between 1984 and 2006 and found that around 280 km^2 of productive agricultural land had been lost to urban areas, with urban land expanding by 689 km^2, 41% of which was at the expense of fertile agricultural land. Megahed et al. [51] mapped, analysed and modelled urban expansion over the Greater Cairo Region from 1984 to 2014, revealing that 357 km^2 of agricultural land had been lost to urban development. The results of the present study were in accordance with recent work by Bratley and Ghoneim [5] who monitored the urban expansion in the Eastern Nile Delta (Sharkqia, Qalubia and Cairo governorates) from 1988 to 2017 using Landsat imagery. They found that urban land increased by 223% over the 30-year period, mainly at the expense of agricultural land. For a corresponding study area, we found that urban areas increased by 160% from 1992 to 2015. Furthermore, their simulations indicated urban growth of 277 km^2 from 2017 to 2026, and under BAU scenario we predicted an increase of 346 km^2 from 2015 to 2030. Hence, both studies confirm the substantial threats to agricultural land in the Eastern Nile Delta.

4.2. Current and Possible Future Alternative Land-Use Strategies

In the present study, we have highlighted a significant loss of agricultural land to urban development across all governorates of the Nile Delta. This will become even more problematic in future if current land use policies are continued. However, we have also shown that alternative land-use scenarios can potentially accommodate current rates of urban expansion while also preserving valuable agricultural land. The results demonstrate that implementing the DPE scenario, where urban development in desert areas and locations adjacent to existing areas of high population density is likely to save 346 km^2 in the Nile Delta (*Old Lands*) compared to the BAU scenario. This is almost as effective in preserving fertile agricultural land as the more extreme and difficult to implement the DDO scenario. Hence, the DPE scenario is considered the more realistic and achievable scenario.

Rapid urban expansion, mainly at the expense of agricultural land may have critical consequences for agricultural productivity and the condition of the environment. It has already been recognized that in Egypt the mismanagement and overexploitation of land resources has negatively affected national GDP, the agricultural sector and the sustainability of the economic development of the country [3,4]. Recently, the Egyptian government instigated a number of projects to reclaim new desert land (*New Lands*) in response to the rapid national population increase and high demand for food. This resulted in over 12,000 km^2 of bare land being converted to agricultural land [5,52]. These efforts could be considered as a potential solution to the current problem. However, this is a very challenging process, and not necessarily a sustainable solution because the soils of these newly reclaimed areas are not only less fertile, but also less effective at holding water than soils in the Nile Delta and have much lower nutrient levels [43,44]. Furthermore, reclaimed areas require substantial resource inputs including water, power and vast amounts of chemical fertilizers to enhance soil fertility, in addition to labour inputs and secure transportation to distant markets [34,43]. This translates into the requirement for significant financial investment to develop fertile soils. As a result, most of the newly reclaimed areas (*New Lands*) are cultivated with fruit trees and vegetables aimed for lucrative export markets, which undoubtedly do not contribute to agricultural sustainability and self-sufficiency of the country [43,44]. Therefore, it is important for the government to consider alternative strategies to tackle both the exponential population growth and rapid urban expansion. These strategies could include:

(1) Preserving current areas of fertile soils in the Nile Delta and constructing new cities, such as New Cairo, outside the delta fringes to accommodate the increasing population, although this is also associated with significant financial and environmental challenges.

(2) Maximizing the agricultural productivity of existing cultivated areas by crop intensification, including the use of higher yielding varieties of cereal crops which are resistant to pathogens and environmental stresses.

4.3. Global LULC Change Studies

Urban sprawl is an issue of a global concern, which has severe negative impacts on the sustainability of the environment. Many studies around the world have illustrated the conflict between urban expansion and loss of fertile agricultural land and the related critical consequences for environmental sustainability. In Kenya, Mundia and Aniya [53] analysed the LULC changes of Nairobi city from 1976 to 2000. They found that the amount of urban area increased substantially from 14 km^2 in 1976 to 61 km^2 in 2000. In contrast, forest land significantly decreased from 100 km^2 to 23 km^2 over the study period. In Bangladesh, Dewan and Yamaguchi [9] evaluated LULC changes in Greater Dhaka between 1975 and 2003. They found that cultivated land decreased from 120 km^2 in 1975 to 84 km^2 in 2003 and 62 km^2 of cultivated land was lost to urbanisation over the study period. In India, Sahana et al. [54] analysed the trends of urban growth in Kolkata from 1990 to 2015. They found that agricultural land area decreased from 621 km^2 in 1990 to 405 km^2 in 2015, whilst urban land area increased from 537 km^2 in 1990 to 779 km^2 in 2015, with urban growth accounting for the loss of the productive agricultural land. In China, Shi et al. [55] studied the conflict between agricultural land loss and urban expansion at the national-level between 2001 and 2013. They found that 33,080 km^2 of agricultural land were lost to urban land and that urban areas had grown substantially from 31,076 km^2 to 80,887 km^2 over the study period, at a growth rate of 13.36% per year. Hence, the present study provides a further example of a process that is significant in many developing countries, and it highlights the seriousness of the threat in Egypt.

4.4. Egypt's Wider Challenges

Egypt faces a number of critical environmental and anthropogenic challenges in relation to both land and water resources. Since 1959, it has received a fixed share of water from the River Nile (equal to 55.5 billion m^3 $year^{-1}$) regardless of the rapid growth in the population. There is limited precipitation in coastal zones in the northern region and there is sea-water intrusion into the Nile Delta [34,43]. Sea level rise presents a continuing threat in the Nile Delta and recent construction of dams in southern countries of the Nile basin, such as the Ethiopian Grand Renaissance Dam, present further pressures on the country. In addition, there are multiple anthropogenic challenges, in particular, the exponential increase in the population of the country [34,43], which, as this study has demonstrated, has given rise to urban development occurring at the expense of the fertile agricultural land in the Nile Delta. This is particularly problematic given the geographically constrained nature of fertile agricultural land in the country and the very high rates of LULC transition to urban areas. Hence, there is a pressing need to develop appropriate land-use strategies. The land-use strategies proposed in this paper could inform policy development and planning decisions within the Ministry of Agriculture and Land Reclamation, and the Ministry of Housing, Utilities and Urban Communities in Egypt. These strategies could contribute to long-term sustainability and assure national food security.

5. Conclusions

In this research, consistent historical data were used to determine the magnitude and dynamics of LULC changes over the Nile Delta region and to quantify the agricultural and urban land change in different governorates. The results showed that 74,600 hectares of productive agricultural land were lost to urban development between 1992 and 2015. In addition, 206,100 hectares of the desert was converted to high input agriculture (*New Lands*). These rapid large-scale transitions represent a significant threat to environmental sustainability and food security in Egypt. A CA-Markov integrated model for simulating future LULC changes was validated and used to analyse the implications of a range of different land use scenarios. The simulated distribution of the LULC classes in 2030 under the BAU scenario suggests that, if the current patterns and rates of urban development continue, then 86,900 hectares of fertile agricultural land (*Old Lands*) in the Nile Delta will be lost. Three alternative simulated scenarios were developed to assess the potential impacts of different land-use policies on the loss of fertile agricultural land. The DDO scenario indicates that by restricting urban expansion into the desert only, 41,000 hectares of productive agricultural land could be preserved in the Nile Delta. However, in the more realistic and achievable DPE scenario, urban development in desert areas and locations adjacent to existing areas of high population density could preserve almost as much fertile agricultural land as the DDO scenario. Hence, the simulated scenarios derived from our analysis demonstrate that continued urban development is possible while minimising the threats to the national agricultural sector sustainability and food security, informing a more sustainable land-use strategy for decision makers and appropriate authorities in Egypt.

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Appendix A

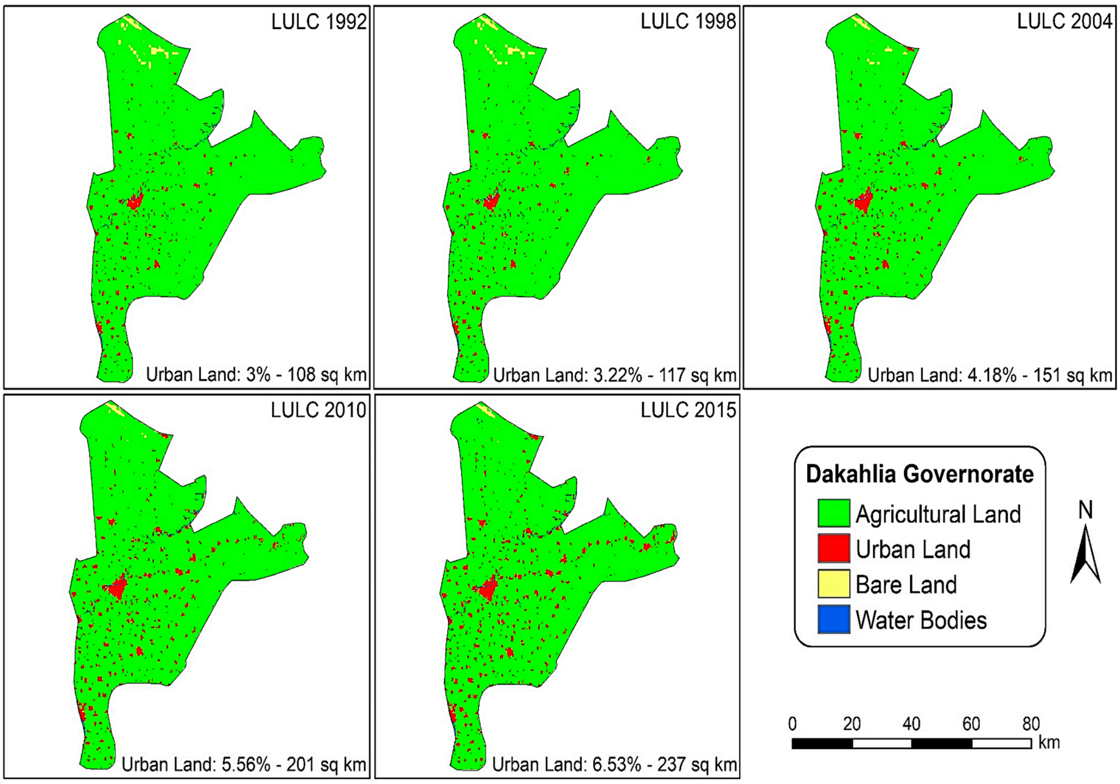

Figure A1. Urban expansion over Dakahlia governorate.

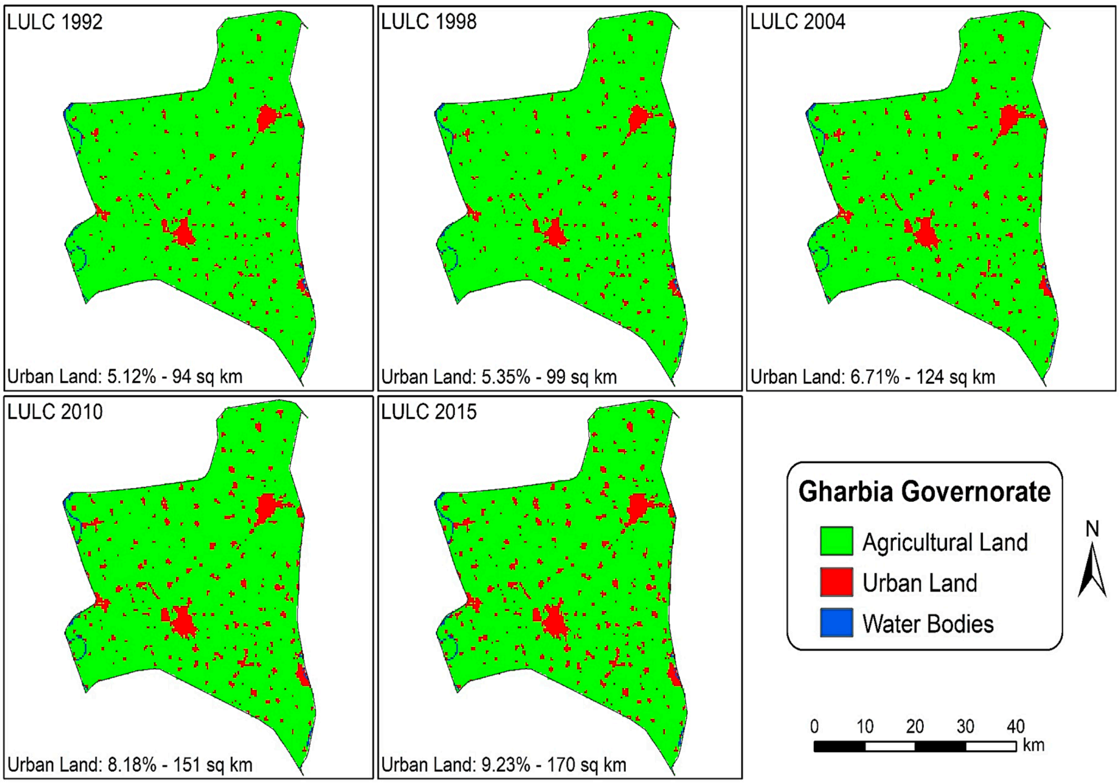

Figure A2. Urban expansion over Gharbia governorate.

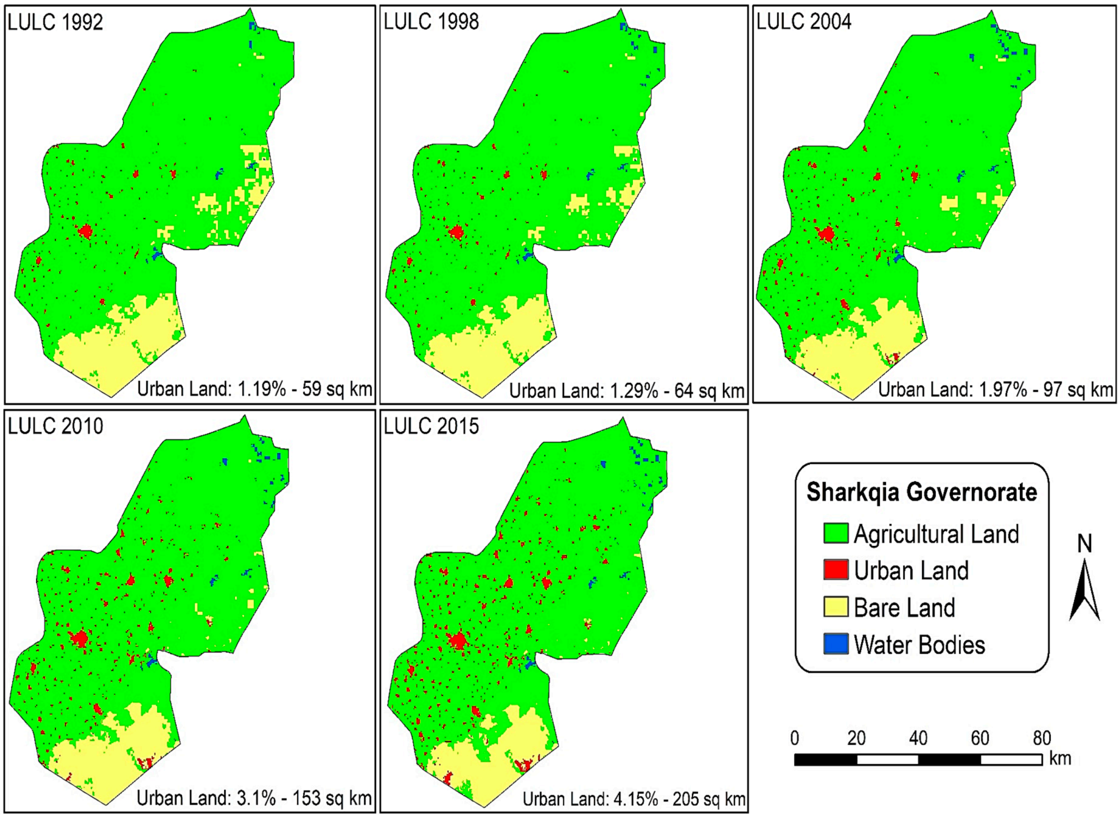

Figure A3. Urban expansion over Sharkqia governorate.

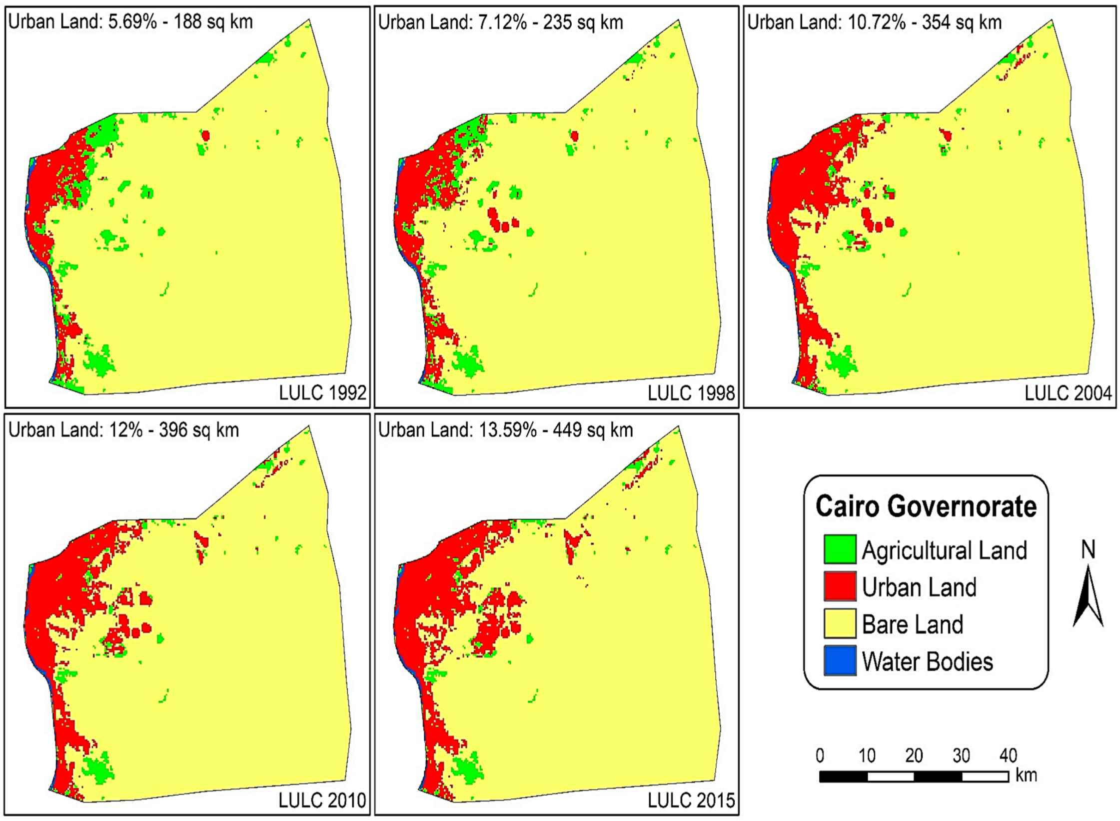

Figure A4. Urban expansion over Cairo governorate.

Appendix B

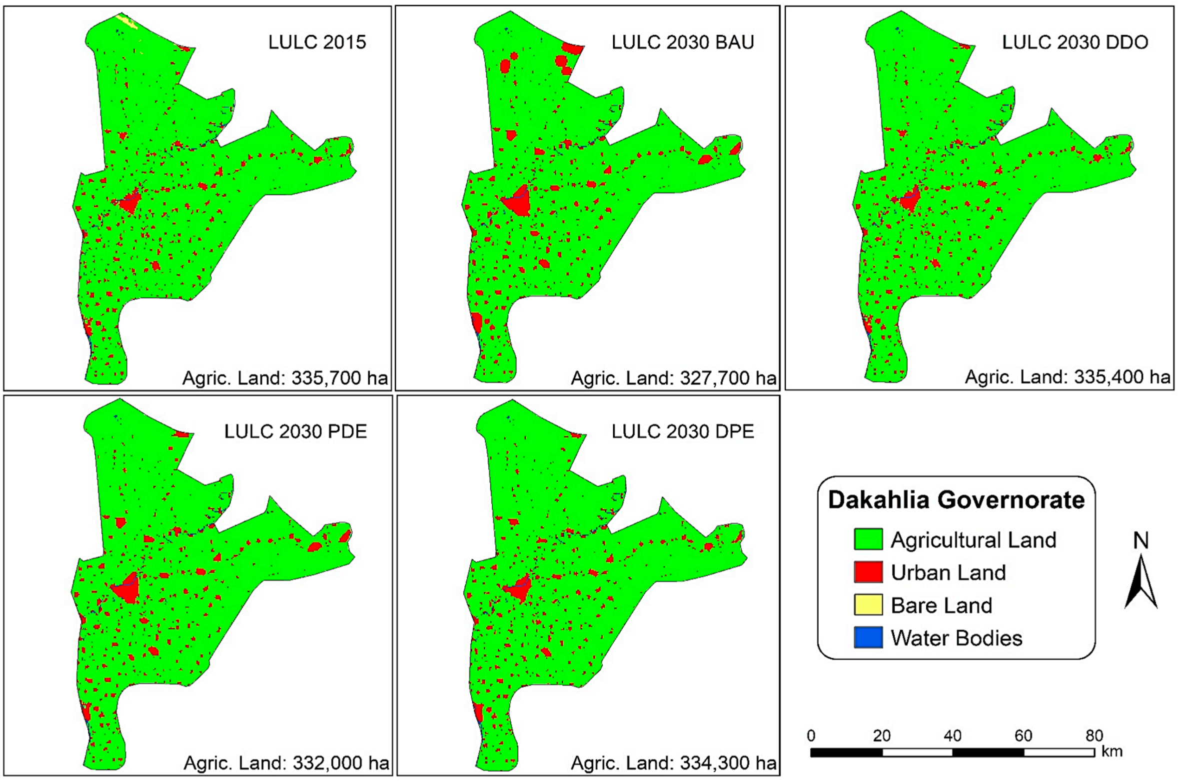

Figure A5. Amount of agricultural land over Dakahlia governorate within the simulated scenarios relative to the state in 2015.

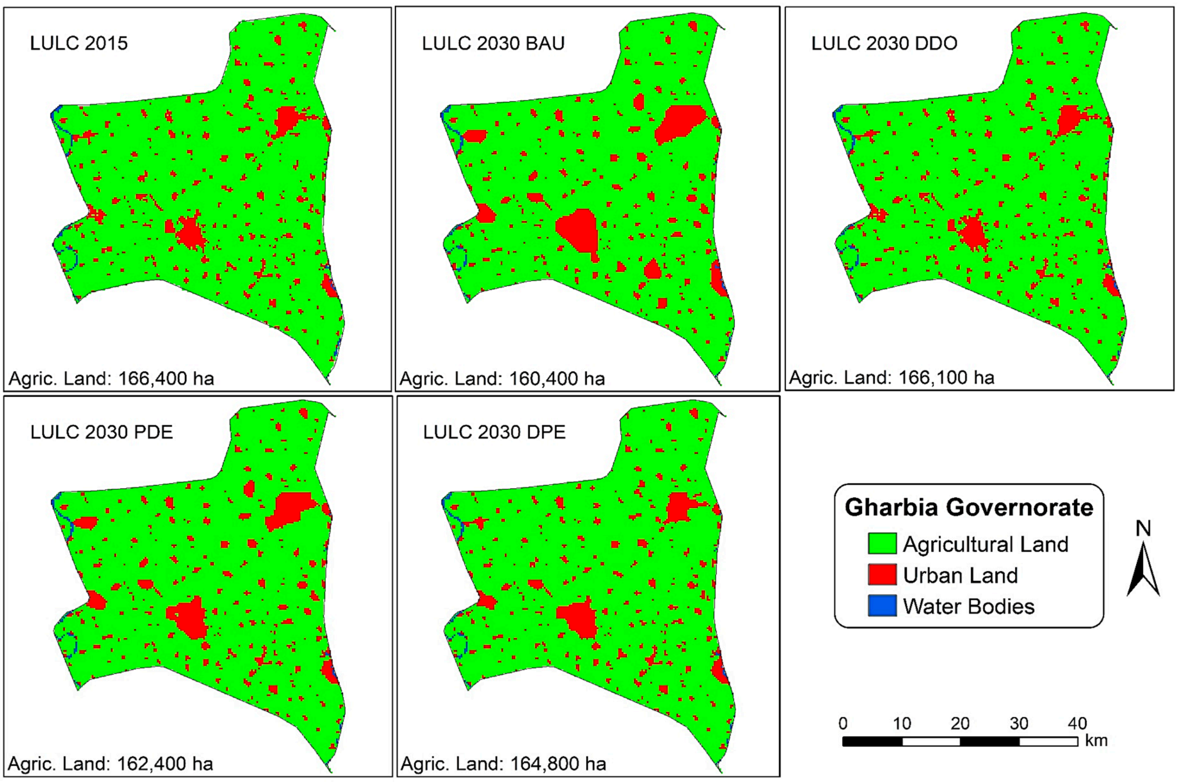

Figure A6. Amount of agricultural land over Gharbia governorate within the simulated scenarios relative to the state in 2015.

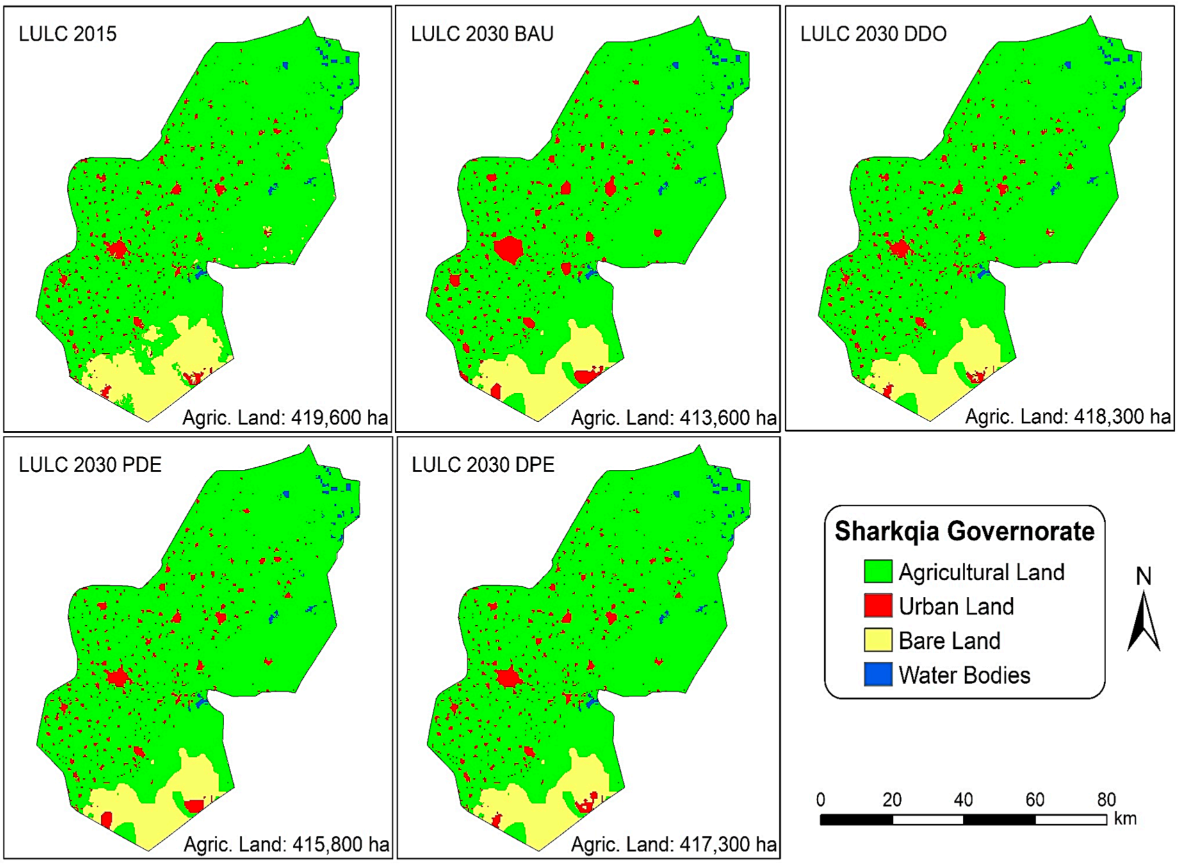

Figure A7. Amount of agricultural land over Sharkqia governorate within the simulated scenarios relative to state in 2015.

References

1. Worldometers. Available online: http://www.worldometers.info/world-population/egypt-population/ (accessed on 6 June 2018).
2. Bakr, N.; Bahnassy, M.H. Egyptian Natural Resources. In *The Soils of Egypt*; El-Ramady, H., Alshaal, T., Bakr, N., Elbana, T., Mohamed, E., Belal, A.A., Eds.; World Soils Book Series; Springer: Cham, Switzerland, 2019; pp. 33–49.
3. Abd El-Kawy, O.R.; Rød, J.K.; Ismail, H.A.; Suliman, A.S. Land use and land cover change detection in the western Nile delta of Egypt using remote sensing data. *Appl. Geogr.* **2011**, *31*, 483–494. [CrossRef]
4. Shalaby, A.; Tateishi, R. Remote sensing and GIS for mapping and monitoring land cover and land-use changes in the Northwestern coastal zone of Egypt. *Appl. Geogr.* **2007**, *27*, 28–41. [CrossRef]
5. Bratley, K.; Ghoneim, E. Modeling Urban Encroachment on the Agricultural Land of the Eastern Nile Delta Using Remote Sensing and a GIS-Based Markov Chain Model. *Land* **2018**, *7*, 114. [CrossRef]
6. CAPMAS. The Central Agency for Public Mobilization and Statistics. The Arab Republic of Egypt. 2018. Available online: http://www.capmas.gov.eg/ (accessed on 6 June 2018).
7. Food and Agriculture Organization of the United Nations. *FAOSTAT Database*; FAO: Rome, Italy, 2018; Available online: http://www.fao.org/faostat/en/#data/QC (accessed on 11 November 2018).
8. Lambin, E.F.; Turner, B.L.; Geist, H.J.; Agbola, S.B.; Angelsen, A.; Bruce, J.W.; Coomes, O.T.; Dirzo, R.; Fischer, G.; Folke, C.; et al. The causes of land-use and land-cover change: Moving beyond the myths. *Glob. Environ. Chang.* **2001**, *11*, 261–269. [CrossRef]
9. Dewan, A.M.; Yamaguchi, Y. Land use and land cover change in Greater Dhaka, Bangladesh: Using remote sensing to promote sustainable urbanization. *Appl. Geogr.* **2009**, *29*, 390–401. [CrossRef]
10. Wu, K.Y.; Zhang, H. Land use dynamics, built-up land expansion patterns, and driving forces analysis of the fast-growing Hangzhou metropolitan area, eastern China (1978–2008). *Appl. Geogr.* **2012**, *34*, 137–145. [CrossRef]

11. Wu, Y.; Li, S.; Yu, S. Monitoring urban expansion and its effects on land use and land cover changes in Guangzhou city, China. *Environ. Monit. Assess.* **2016**, *188*, 1–15. [CrossRef] [PubMed]
12. Bakr, N.; Weindorf, D.C.; Bahnassy, M.H.; Marei, S.M.; El-Badawi, M.M. Monitoring land cover changes in a newly reclaimed area of Egypt using multi-temporal Landsat data. *Appl. Geogr.* **2010**, *30*, 592–605. [CrossRef]
13. Guan, D.; Li, H.; Inohae, T.; Su, W.; Nagaie, T.; Hokao, K. Modeling urban land use change by the integration of cellular automaton and Markov model. *Ecol. Model.* **2011**, *222*, 3761–3772. [CrossRef]
14. Rogan, J.; Chen, D.M. Remote sensing technology for mapping and monitoring land-cover and land-use change. *Prog. Plann.* **2004**, *61*, 301–325. [CrossRef]
15. Wu, Q.; Li, H.Q.; Wang, R.S.; Paulussen, J.; He, Y.; Wang, M.; Wang, B.H.; Wang, Z. Monitoring and predicting land use change in Beijing using remote sensing and GIS. *Landsc. Urban Plan.* **2006**, *78*, 322–333. [CrossRef]
16. Pijanowski, B.C.; Brown, D.G.; Shellito, B.A.; Manik, G.A. Using neural networks and GIS to forecast land use changes: A Land Transformation Model. *Comput. Environ. Urban Syst.* **2002**, *26*, 553–575. [CrossRef]
17. 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. [CrossRef]
18. Van Soesbergen, A. A Review of Land-Use Change Models. 2016. Available online: https://www.researchgate.net/publication/308515089_A_review_of_land_use_change_models (accessed on 8 February 2019).
19. Eastman, J.R. *Terrset Geospatial Monitoring and Modeling System*; Clark University: Worcester, MA, USA, 2016.
20. Aburas, M.M.; Ho, Y.M.; Ramli, M.F.; Ash'aari, Z.H. The simulation and prediction of spatio-temporal urban growth trends using cellular automata models: A review. *Int. J. Appl. Earth Obs. Geoinf.* **2016**, *52*, 380–389. [CrossRef]
21. Aburas, M.M.; Ho, Y.M.; Ramli, M.F.; Ash'aari, Z.H. Improving the capability of an integrated CA-Markov model to simulate spatio-temporal urban growth trends using an Analytical Hierarchy Process and Frequency Ratio. *Int. J. Appl. Earth Obs. Geoinf.* **2017**, *59*, 65–78. [CrossRef]
22. Clarke, K.C.; Hoppen, S.; Gaydos, L.J. A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. *Environ. Plan. B* **1997**, *24*, 247–261. [CrossRef]
23. Baker, W.L. A review of models of landscape change. *Landsc. Ecol.* **1989**, *2*, 111–133. [CrossRef]
24. Muller, M.R.; Middleton, J. A Markov model of land-use change dynamics in the Niagara Region, Ontario, Canada. *Landsc. Ecol.* **1994**, *9*, 151–157.
25. Kamusoko, C.; Aniya, M.; Adi, B.; Manjoro, M. Rural sustainability under threat in Zimbabwe—Simulation of future land use/cover changes in the Bindura district based on the Markov-cellular automata model. *Appl. Geogr.* **2009**, *29*, 435–447. [CrossRef]
26. Weng, Q. Land use change analysis in the Zhujiang Delta of China using satellite remote sensing, GIS and stochastic modelling. *J. Environ. Manag.* **2002**, *64*, 273–284. [CrossRef] [PubMed]
27. Balzter, H. Markov chain models for vegetation dynamics. *Ecol. Model.* **2000**, *126*, 139–154. [CrossRef]
28. Yang, X.; Zheng, X.Q.; Lv, L.N. A spatiotemporal model of land use change based on ant colony optimization, Markov chain and cellular automata. *Ecol. Model.* **2012**, *233*, 11–19. [CrossRef]
29. Mishra, V.N.; Rai, P.K. A remote sensing aided multi-layer perceptron-Markov chain analysis for land use and land cover change prediction in Patna district (Bihar), India. *Arab. J. Geosci.* **2016**, *9*, 4. [CrossRef]
30. Santé, I.; García, A.M.; Miranda, D.; Crecente, R. Cellular automata models for the simulation of real-world urban processes: A review and analysis. *Landsc. Urban Plan.* **2010**, *96*, 108–122. [CrossRef]
31. Memarian, H.; Kumar Balasundram, S.; Bin Talib, J.; Teh Boon Sung, C.; Mohd Sood, A.; Abbaspour, K. Validation of CA-Markov for Simulation of Land Use and Cover Change in the Langat Basin, Malaysia. *J. Geogr. Inf. Syst.* **2012**, *4*, 542–554. [CrossRef]
32. Nouri, J.; Gharagozlou, A.; Arjmandi, R.; Faryadi, S.; Adl, M. Predicting Urban Land Use Changes Using a CA-Markov Model. *Arab. J. Sci. Eng.* **2014**, *39*, 5565–5573. [CrossRef]
33. Houet, T.; Hubert-Moy, L. Modeling and projecting land-use and land-cover changes with Cellular Automaton in considering landscape trajectories. *EARSeL eProceedings* **2006**, *5*, 63–76.
34. Negm, A.M.; Saavedra, O.; El-Adawy, A. Nile Delta Biography: Challenges and Opportunities. In *The Nile Delta*; Negm, A., Ed.; The Handbook of Environmental Chemistry; Springer: Cham, Switzerland, 2016; Volume 55.
35. Shalaby, A. Assessment of Urban Sprawl Impact on the Agricultural Land in the Nile Delta of Egypt Using Remote Sensing and Digital Soil Map. *Int. J. Environ. Sci.* **2012**, *1*, 253–262.

36. European Space Agency (ESA). Land Cover CCI Product User Guide Version 2.0. 2018. Available online: http://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf (accessed on 14 January 2019).
37. Environmental Systems Research Institute (ESRI). *ArcGIS Desktop 10.5*; ESRI: Redlands, CA, USA, 2016.
38. Hyandye, C.; Martz, L.W. A Markovian and cellular automata land-use change predictive model of the Usangu Catchment. *Int. J. Remote Sens.* **2017**, *38*, 64–81. [CrossRef]
39. Wu, F. Calibration of stochastic cellular automata: The application to rural-urban land conversions. *Int. J. Geogr. Inf. Sci.* **2002**, *16*, 795–818. [CrossRef]
40. Pontius, G.R.; Malanson, J. Comparison of the structure and accuracy of two land change models. *Int. J. Geogr. Inf. Sci.* **2005**, *19*, 243–265. [CrossRef]
41. Wang, S.Q.; Zheng, X.Q.; Zang, X.B. Accuracy assessments of land use change simulation based on Markov-cellular automata model. *Procedia Environ. Sci.* **2012**, *13*, 1238–1245. [CrossRef]
42. WorldPop. Available online: http://www.worldpop.org.uk/data/summary/?doi=10.5258/SOTON/WP00078 (accessed on 6 June 2018).
43. Bakr, N.; Bahnassy, M.H. Land Use/Land Cover and Vegetation Status. In *The Soils of Egypt*; El-Ramady, H., Alshaal, T., Bakr, N., Elbana, T., Mohamed, E., Belal, A.A., Eds.; World Soils Book Series; Springer: Cham, Switzerland, 2019.
44. Ghar, M.A.; Shalaby, A.; Tateishi, R. Agricultural land monitoring in the Egyptian Nile Delta using landsat data. *Int. J. Environ. Stud.* **2004**, *61*, 651–657. [CrossRef]
45. Viera, A.J.; Garrett, J.M. Kappa_statisitc_paper. *Fam. Med.* **2005**, *37*, 360–363. [PubMed]
46. Kityuttachai, K.; Tripathi, N.K.; Tipdecho, T.; Shrestha, R. CA-Markov analysis of constrained coastal urban growth modeling: Hua hin Seaside City. Thailand. *Sustainability* **2013**, *5*, 1480–1500. [CrossRef]
47. El-hallaq, M.A.; Habboub, M.O. Using Cellular Automata-Markov Analysis and Multi Criteria Evaluation for Predicting the Shape of the Dead Sea. *Adv. Remote Sens.* **2015**, *4*, 83–95. [CrossRef]
48. Amini Parsa, V.; Yavari, A.; Nejadi, A. Spatio-temporal analysis of land use/land cover pattern changes in Arasbaran Biosphere Reserve: Iran. *Model. Earth Syst. Environ.* **2016**, *2*, 1–13. [CrossRef]
49. Shalaby, A.A.; Ali, R.R.; Gad, A. Urban sprawl impact assessment on the agricultural land in Egypt using remote sensing and GIS: a case study, Qalubiya Governorate. *J. Land Use Sci.* **2012**, *7*, 261–273. [CrossRef]
50. Shalaby, A.; Moghanm, F.S. Assessment of urban sprawl on agricultural soil of northern Nile Delta of Egypt using RS and GIS. *Chin. Geogr. Sci.* **2015**, *25*, 274–282. [CrossRef]
51. Megahed, Y.; Cabral, P.; Silva, J.; Caetano, M. Land Cover Mapping Analysis and Urban Growth Modelling Using Remote Sensing Techniques in Greater Cairo Region—Egypt. *ISPRS Int. J. Geo-Inf.* **2015**, *4*, 1750–1769. [CrossRef]
52. Barnes, J. Pumping possibility: Agricultural expansion through desert reclamation in Egypt. *Soc. Stud. Sci.* **2012**, *42*, 517–538. [CrossRef]
53. Mundia, C.N.; Aniya, M. Analysis of land use/cover changes and urban expansion of Nairobi city using remote sensing and GIS. *Int. J. Remote Sens.* **2005**, *26*, 2831–2849. [CrossRef]
54. Sahana, M.; Hong, H.; Sajjad, H. Analyzing urban spatial patterns and trend of urban growth using urban sprawl matrix: A study on Kolkata urban agglomeration, India. *Sci. Total Environ.* **2018**, *628–629*, 1557–1566. [CrossRef] [PubMed]
55. Shi, K.; Chen, Y.; Yu, B.; Xu, T.; Li, L.; Huang, C.; Liu, R.; Chen, Z.; Wu, J. Urban expansion and agricultural land loss in China: A multiscale perspective. *Sustainability* **2016**, *8*, 790. [CrossRef]