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Dynamics of the Oasis–Desert–Impervious Surface System and Its Mechanisms in the Northern Region of Egypt

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Abstract: Arid oasis ecosystems are susceptible and fragile ecosystems on Earth. Studying the interaction between deserts, oases, and impervious surfaces is an essential breakthrough for the harmonious and sustainable development of people and land in drylands. Based on gridded data such as land use and NDVI, this article analyzes the interaction characteristics between oases, deserts, and impervious surfaces in northern Egypt and examines their dynamics using modeling and geographic information mapping methods. The results show the following: In terms of the interaction between deserts and oases, the primary manifestation was the expansion of oases and the reduction of deserts. During the study period, the oases in the Nile Delta and Fayoum District increased significantly, with the area of oases in 2020 being 1.19 times the area in 2000, which shows a clear trend of advance of people and retreat of sand. The interaction between oases and impervious surfaces was mainly observed in the form of the spread of impervious surfaces on arable land into oases. During the study period, the area of impervious surfaces increased 2.32 times. The impervious surface expanded over 1903.70 km^2 of arable land, accounting for 66.67% of the expanded area. The central phenomenon between the impervious surface and the desert was the encroachment of the covered area of the impervious surface into the desert, especially around the city of Cairo. Population growth and urbanization are the two central drivers between northern Egypt's oases, deserts, and impervious surfaces. The need for increased food production due to population growth has forced oases to move deeper into the desert, and occupation of arable land due to urbanization has led to increasing pressure on arable land, creating a pressure-conducting dynamic mechanism. Finally, countermeasures for sustainable regional development are suggested.

Keywords: desert; oasis; northern Egypt; interaction characterization; dynamical mechanisms

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1. Introduction

Oases are natural geographical landscapes found in dry areas around the world. On a global scale, oases are mainly distributed in the middle and low latitudes controlled by subtropical high pressure, where there is little rainfall, the climate is dry, and the habitat is fragile, and it is the world's leading distribution area of deserts. Since the 1970s, environment and development have become two significant issues of concern to the international community, and the interrelationship between population, environment, and development in drylands has received considerable attention [1]. Oasis formation and desertification are the two most fundamental geographical processes in dryland zones [2]. With a deeper understanding of global terrestrial ecosystems and sustainable development, land use, and terrestrial desertification in dry areas, the development of oases has received significant attention from scientists at home and abroad [3]. Oases are mainly the result of a combination of anthropogenic factors in dry areas disturbed by human activities and natural factors aimed at increasing the productivity of the land [4]. Oasis formation directly manifests environmental change in drylands and positively stabilizes oases, preventing desertification and maintaining ecological stability [5]. Among other things, Sun et al. [6]

investigated the spatial and temporal patterns, structural changes, and their causes of oases in the Shule River Basin from 1975 to 2020, based on Landsat series data and a combination of object-oriented random forests and visual interpretation methods. Sun et al. [7] analyzed the relationship between the expansion of arable land and the ability of vegetation to sequester carbon within the oasis, using the Weiku Oasis in Xinjiang as the study area. Liu et al. [8] used a coupled deep learning model to simulate the value of ecological services in the Wuwei arid oasis in the next ten years and analyzed the driving factors. The process of mutual transformation between oasis and desert has essential functions, such as preventing the spread of deserts, maintaining the ecological security of oases, and occupying a special status in the dry zone [9,10]. For oases, desertification is characterized by poor water quality, severe soil salinization, the destruction of vegetation cover, and limitations on ecosystem productivity [11]. In particular, in the last hundred years, due to the unique water, soil, and gas conversion processes and the intervention of human activities on the oasis in the dry zone, the changes in the transition zone between the oasis and the desert have been particularly highlighted [12]. At the same time, the oasis is the most critical activity site for human production and life in the dry zone, and human activities disrupt the development of the oasis to some extent. Some scientists have also conducted extensive research on this topic, including Yin et al. [13], who analyzed the expansion of construction land in Urumqi, an oasis city in Li, based on three Landsat remote sensing images from 2000, 2010, and 2018. Zhang et al. [14] used dynamic change, focal point, and coordination analysis to examine the relationship between urban expansion and people–land coordination in 13 cities in Xinjiang, China. Pai et al. [15] selected two typical oasis cities, Urumqi and Kashgar, and studied the changes between the development of oasis cities and the ecological environment. However, few scientists have studied the small-scale interaction in typical oasis–desert–impervious surface systems and their pressure-transmitting dynamic mechanism.

The delta region is a vital oasis ecosystem that provides an essential source of fresh water and food for a growing population [16]. The Nile Delta and Fayoum District are typical dry-zone oases that occupy an important position in global oasis research, and the rich water resources and fertile sediments of the Nile Delta, as well as the favorable transportation conditions, have had a significant impact on Egypt's agriculture, economy, culture and religion [17]. The Nile Delta accounts for only 3% of Egypt's land area but is home to more than 90% of Egypt's population, living in the fertile lands along the Nile and the Nile Delta, the birthplace of ancient Egyptian civilization [18]. The Nile Delta accounts for about two-thirds of Egypt's total arable land, and it is the center of Egypt's agricultural production and an area that has been subject to very significant changes due to human activities [19]. With this in mind, this article analyzes the interaction characteristics of the oasis–desert–impervious surface system in northern Egypt. It examines the dynamics and mechanisms using the modeling and geomorphological information mapping methods to provide a basis for optimizing human–land relationships in drylands and the sustainable development of the region. The purpose of this study was to (1) characterize the spatial and temporal evolution of deserts, oases, and impervious surfaces in northern Egypt from 2000 to 2020; (2) analyze the characteristics of deserts, oases, and impervious surfaces in the northern region of Egypt from 2000 to 2020 using geomorphological information mapping; and (3) explore the dynamics of oasis–desert–impervious surface interaction in northern Egypt.

2. Methods and Data

2.1. Study Area

The northern part of Egypt was selected as the study area, which is located between 28°51′~33°7′ E longitude and 28°27′~31°35′ N latitude (Figure 1). The northern region of Egypt is mainly dominated by the Nile Delta, characterized by solid sunlight; abundant water; flat terrain; fertile land; and a Mediterranean climate with hot, dry summers and mild, rainy winters. Cairo is located in the delta, which has one of Egypt's highest population densities and numbers. The spread of agriculture has not only impacted the Egyptian

desert, but the eastward expansion of Cairo's cities has further exacerbated environmental problems. Many of the Egyptian government's desert restoration programs have been implemented over the past 50 years in response to increasing food shortages and urban population density [20].

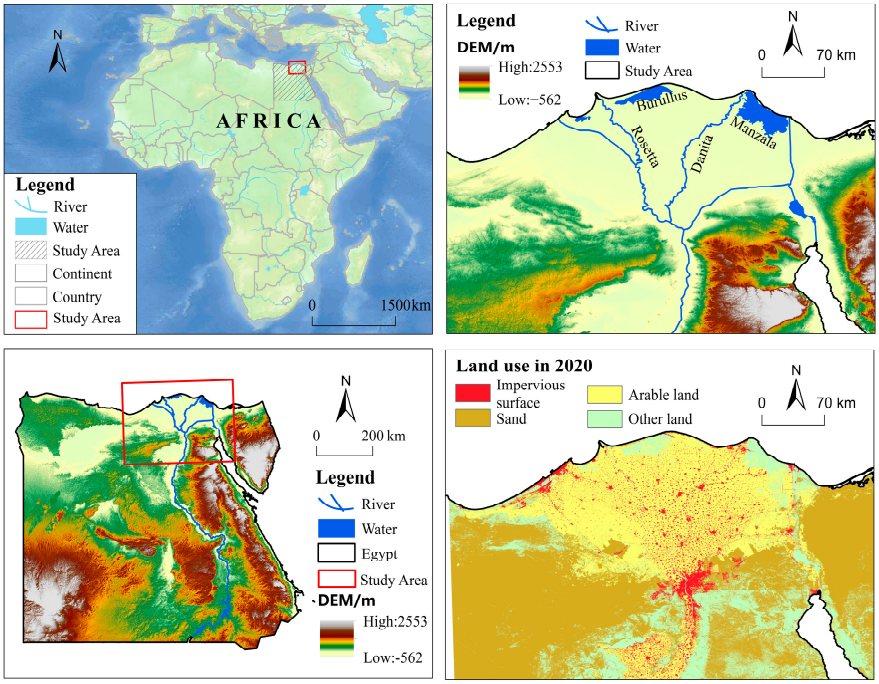


Figure 1. Scope of the study area (produced based on the base map of a standard map with the Remote Sensing and Geographic Information Cloud Service Platform website. (https://engine.piesat.cn/dataset-list (accessed on 5 December 2023)). No modifications were made to the base map, the same for maps at the bottom.

2.2. Methodology

2.2.1. Model Analysis Method

(a) Single land use dynamics: Single land use dynamics is the frequency of changes in land types over time, quantified using land use dynamics [21,22]. The formula is as follows:

$$N = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\%$$

In the above formula, N is the annual rate of change of a land use type in the study area, and U_a and U_b are the areas of land use types at the beginning and the end of the study period; the larger the N is, the more the land type is converted out, and the greater the relative degree of change is. T is the study period $t_b - t_a$ in years.

(b) Comprehensive land use dynamics: Comprehensive land use dynamics are used to reflect changes in the overall land use in the study area [23]. The formula is as follows:

$$LC = \frac{\sum_{i=1}^{n} \Delta LU_{i-k}}{2\sum_{i=1}^{n} LU_i} \times \frac{1}{T} \times 100\%$$

In the above formula, LC is the combined land use dynamics; $\Delta LU_{i\text{-}j}$ is the absolute value of the area of land use type I that was converted to land use type j during the study period; LUi is the area of land use type I in the initial period; T is the study period $t_b - t_a$ in years.

(c) Land use transfer matrix: Land use transfer matrices can not only quantify the transformation between different land use types but also reveal the rate of transfer between different land use types [24]. The formula is as follows:

$$K = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix}$$

In the above formula, K is the area of the initial land use type converted to the terminal land use type; n is the number of land use types; in the transfer matrix, the rows are the initial land use types, and the columns are the terminal land use types.

2.2.2. Methods for Analyzing Geographical Information Mapping

Geographic information mapping is a geospatial–temporal composite analysis method that can simultaneously express spatial structural features and practice dynamic changes [25]. The map has the dual nature of graph and spectrum; graphrepresents the spatial location characteristics, and spectrumrepresents the process change information; the combination of map and spectrum and analysis can solve the complex problem of spatial and process integration research. The mapping unit is the basic unit of the geological information map, which contains information about the spatial variability of geographical units and phenomena, as well as information about the temporal changes of geographical processes, and it represents a combination of geographical and temporal units with internal homogeneous characteristics [26]. Based on raster data, geographic information system (GIS), and spatial analysis methods, impervious surfaces and arable land areas in the study area were extracted, and change information on impervious surfaces and arable land areas was determined.

2.3. Data Source

The primary data sources used were land use/cover data, digital elevation model (DEM) data, roads, water systems, etc. (Table 1), and some vector data were obtained by vectorization based on the literature. Among others, the land use data were derived from the Global 30 m Land Cover Change Dataset from 1985 to 2020 (GLC_FCS30D) [27], developed by Liu Liangyun's group, which has an overall accuracy of 80.88% for land cover types. Land use types were categorized into arable land, impervious land, sand, and other land use types based on ArcGIS 10.8 software, which is the version released in 2020 by ESRI Corporation of United States (Redlands, CA, USA). The space reference was GCS_WGS_1984.

Table 1. Information about the different types of data used in this study.

Data Name	Source	Resolution
Land-use/cover change raster data for 2000 and 2020	https://essd.copernicus.org/articles/16/1353/2024/ [27] (accessed on 28 December 2023)	90 m
Digital elevation model data	https://download.gebco.net (accessed on 31 December 2022)	30 m
Water systems and global continental boundary data	https://gaohr.win/site/blogs/2017/2017-04-18-GIS-basic-data-of-China.html (accessed on 15 April 2024)	1:1,000,000
Normalized difference vegetation index	https:/www.earthdata.nasa.gov (accessed on 16 July 2024)	250 m
Vector data	https://engine.piesat.cn/dataset-list (accessed on 5 December 2023)	1:1,000,000

3. Results

3.1. Characterization of Oasis–Desert–Impervious Surface Interaction Dynamics in Northern Egypt

3.1.1. Oasis–Desert–Impervious Surface Mass Structure Change

Significant changes were found in land types in northern Egypt from 2000 to 2020. The largest area is sand, which accounts for about 50 percent of the total study area, followed by more extensive arable land and a smaller proportion of impervious surfaces. The northern region of Egypt is flat and fertile, and long-term stable water sources provide unique conditions for agriculture. In 2010, the arable land reached a maximum of 28,900 km^2, and then, with the strong population growth, which puts pressure on arable land and natural resources, the arable land decreased, and the overall arable land growth in the northern part of the Egyptian region was reduced to 2.5 percent. Egypt is a typical arid zone with many sand areas and scarce water resources, and the area of sand has decreased from 53,400 km^2 to 50,500 km^2, indicating a decrease of 2900 km^2, which corresponds to 5.34%. Impervious surfaces have expanded with the increase in population, and the area has increased by 2900 km^2, up to 2.3 times (Figure 2).

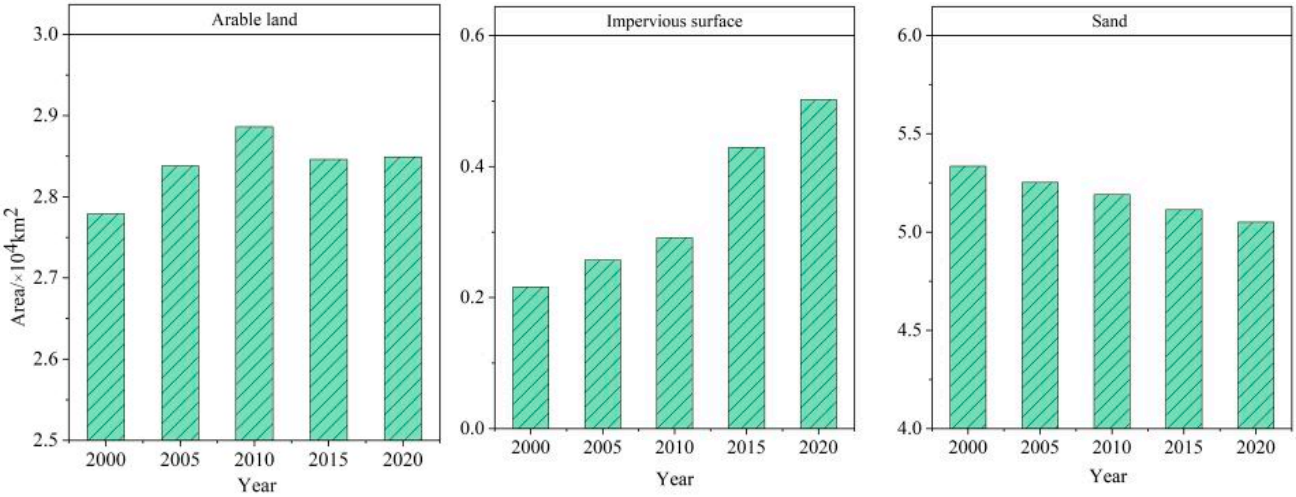


Figure 2. Statistical map of changes in the area of arable land–impervious surface–sand in the northern region of Egypt from 2000 to 2020.

3.1.2. Basic Characteristics of the Oasis–Desert–Impervious Surface Dynamics

Significant differences were observed in the dynamics of individual land use between categories in the northern region of Egypt from 2000 to 2020. The single land use dynamics values for impervious surfaces were highest between 2010 and 2015, reaching 9.47 percent, indicating a dramatic expansion of impervious surfaces. The single land use dynamic for sand has been shrinking; arable land had the most significant single dynamic of 0.42% from 2000 to 2005, which reduced to 0.28% from 2010 to 2015. Arable land, sand, and impervious surfaces combined with the land use dynamic exhibited positive values from 2010 to 2015. The combined dynamic was the largest, amounting to 0.003%, indicating that the changes in arable land, sand, and impervious surface were drastic from 2000 to 2010. The smallest combined dynamic was from 2015 to 2020, amounting to 0.0017%, indicating that the trend of change in the land, sand, and impervious surface from 2005 to 2010 was relatively stable (Figure 3).

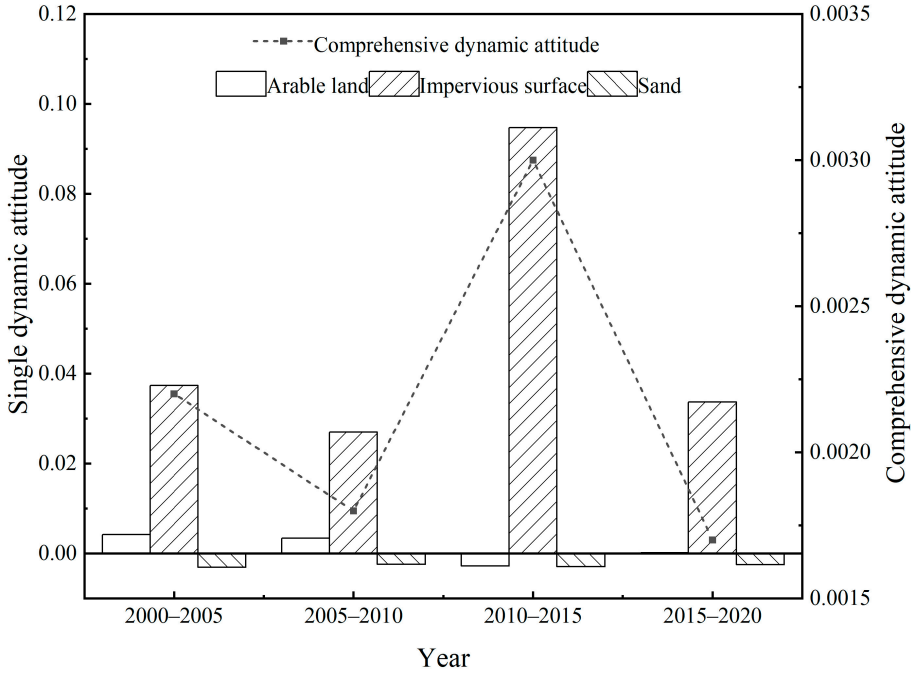


Figure 3. Dynamic map of single and integrated land use in the northern region of Egypt from 2000 to 2020.

3.1.3. The Transfer Flow Characteristics of the Oasis–Desert–Impervious Surface Interaction

Land use transfer flow is one of the proposed methods by Ma Caihong et al. for tracking land use changes [28,29]. It was found that there are significant phase differences in the transformation of arable land, sand, and impervious surface interactions in the northern part of Egypt. From 2000 to 2005, the most extensive arable land was converted to impervious surfaces, with 0.76% of the total area transferred. The largest area of sand was converted to arable land, with 1.34% of the total area transferred, indicating a more significant demand for arable land and a more drastic trend of change from arable land to sand. From 2005 to 2010, the sand area was converted into arable land. The land area was 665.8 km^2, with the transferred area accounting for 1.27% of the total area, while the area of arable land converted into impervious areas was 210.2 km^2, with the transferred area accounting for 0.74% of the total area. From 2010 to 2015, the arable land converted to impervious areas accounted for 3.49% of the total area, indicating that human activities were more disruptive to the land during this study period. From 2015 to 2020, the area of arable land converted into impervious areas was 499.42 km^2, and the sand area converted into arable land was 564.1 km^2. Impervious areas continued to increase throughout the study period without any shifts across land types (Figure 4).

3.2. Spatial Characterization of Oasis–Desert–Impervious Surface Interactions in Northern Egypt

3.2.1. Spatial Characterization of Oasis and Desert Change

Vegetation cover in northern Egypt generally improved from 2000 to 2020, but there were significant spatial differences (Figure 5). Every five years, the mean spectrogram of NDVI was calculated. The results indicate that as the Nile flows through the delta area, which is well irrigated and suitable for plant growth, the mean NDVI value is in the high-value range [0.4, 1). The NDVI value in the transition zone increased from [0.003, 0.2) to [0.4, 0.8], mainly due to the disturbance of human activities, which resulted in significantly increased NDVI. At each 5-year interval, the difference spectrogram of NDVI was calculated, and it was found that the NDVI differences in the Nile Delta and Fayoum District from 2000 to 2005 and from 2015 to 2020 were mainly in the range of [0.02, 0.11), indicating that the condition of the vegetation cover in the Nile Delta is gradually improving.

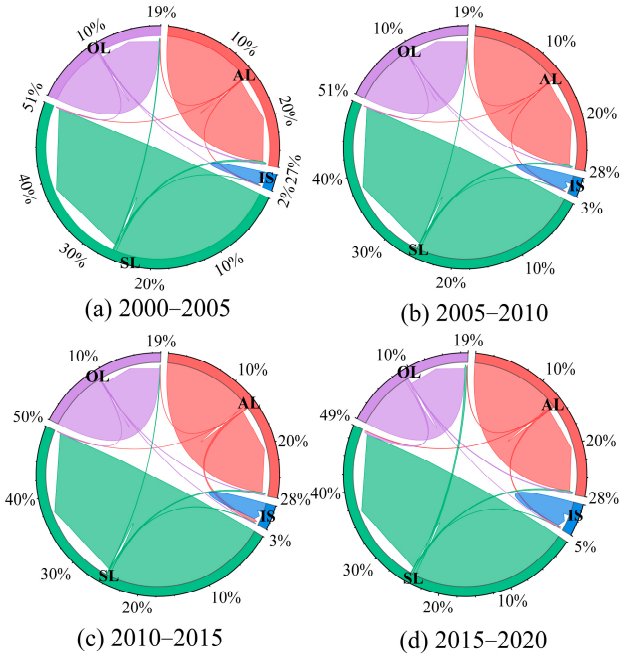


Figure 4. Arable land–impervious surface–sand-other transfer flow chords in northern Egypt from 2000 to 2020.

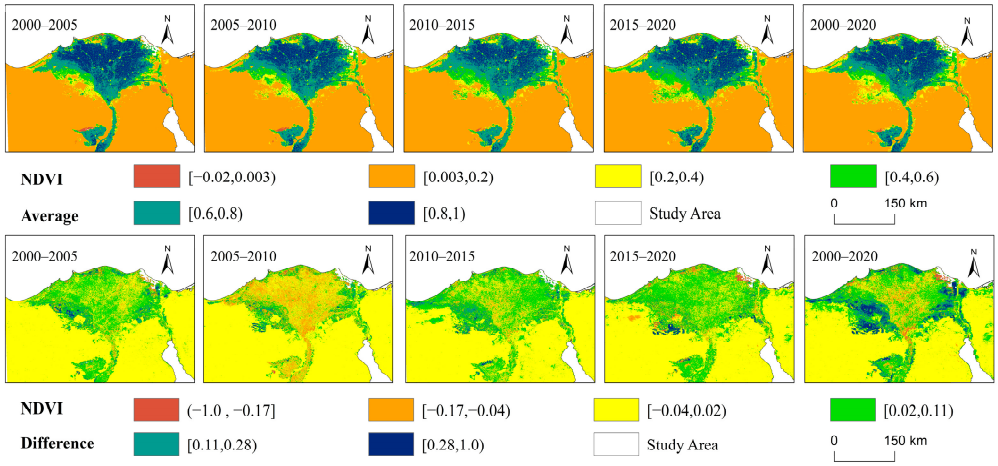


Figure 5. Spatial distribution of normalized vegetation index (NDVI) in northern Egypt from 2000 to 2020.

From 2000 to 2020, land use types in the Nile Delta and Fayoum District were dominated by arable land (Figure 6). The large expanses of water in the Nile Delta are more suitable for agricultural land. The arable land in 2020 was estimated to be 1.19 times larger than that in 2000, with the most significant expansion occurring in the southwestern part of the Nile Delta.

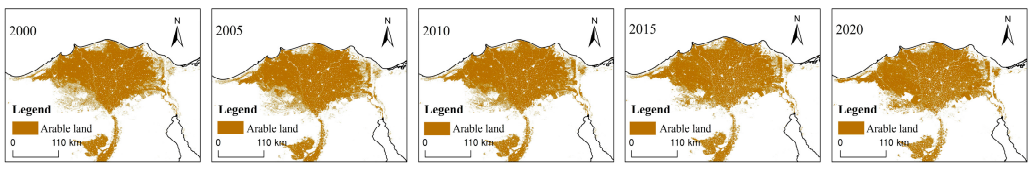


Figure 6. Changes in arable land in northern Egypt from 2000 to 2020.

3.2.2. Characterization of Spatial Variation in Impervious Surfaces

From 2000 to 2020, the impervious surfaces and arable lands in the northern region of Egypt changed significantly due to rapid economic development, generally showing a trend of rapid expansion of impervious surface encroachments on arable land towards the delta region and an increase in arable encroachment on sand in the west(Figure 7). The population proliferated over the study period, with population growth in 2020 being 0.98 times that in 2000. The demand for population growth drives the expansion of the impervious area, with the impervious area in 2020 being 2.32 times the area in 2000, representing a discrepancy between both growth rates and suggesting weak population intensification in northern Egypt. The nighttime light index is an index that reflects the degree of change in human activities. The nighttime light index from 2000 to 2020 indicates that people mainly concentrated in Cairo and then expanded to the Nile Delta and Fayoum District, which is consistent with the general characteristics of urbanization development [30].

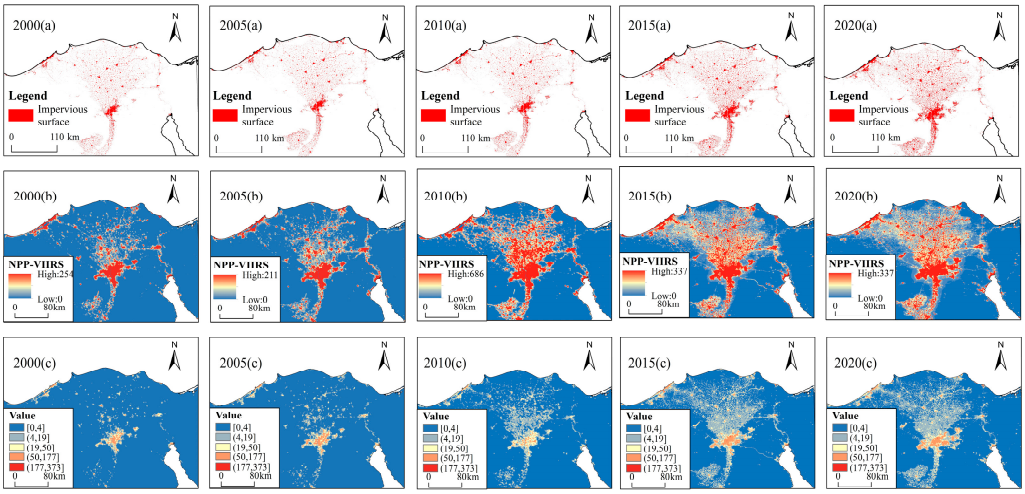


Figure 7. Map of impervious surface and nighttime light index in northern Egypt from 2000 to 2020: (**a**) change in impervious surface; (**b**) genealogy of nighttime light index; (**c**) change in nighttime light index.

3.3. Study of Drivers of Oasis–Desert–Impervious Surface Interaction Evolution

3.3.1. Characteristics of Spatial Changes in Oasis–Desert Interaction Lines

The northern region of Egypt is a typical agricultural desert oasis area. To investigate the extension of the oasis in the southwest direction, we calculated the center of the Nile Delta in 2000 and 2020. Measured in the direction of 207.5° from the center, the distances from the center to the edge of the oasis were 51 km and 120.54 km, and the oasis penetrated a total of 69.54 km into the desert, mainly through encroachment on cultivated land into the sand. The extension of the Nile Delta, mainly in the southwest direction, is evident because the southwest direction is topographically located in a low-lying area with abundant water resources, which makes it more suitable for human activities and exchanges. Impervious surfaces expanded over 1903.70 km^2 of arable land, accounting for 66.67% of the expansion area, and it was most significant near Cairo (Figure 8).

3.3.2. Dynamic Mechanisms of Oasis–Desert–Impervious Surface Interaction Evolution

The analysis reveals that human activities were the key driving force that changed Egypt's arable land, sand, and impervious surfaces through land use changes during the study period. The process of interactive evolution between oasis, desert, and impenetrable surface results from a spatial game between the three. The power factor of the development of things includes internal power and external power; internal power is inherent in things, whereas external power is the external conditions for the development of things, and internal and external power interact to form a power mechanism and jointly promote

the development of things. Therefore, a result layer was created with the interactive development of oases, deserts, and impervious surfaces, and a response layer was created with the transfer flow between oases, deserts, impervious surfaces, and other land uses. A power layer was proposed with economic development, population size, food demand, and scientific and technological progress considered external drivers, and water scarcity and national policies considered the internal drivers, to form the power–response–outcome driving mechanism (Figure 9). The drivers are interdependent and limited. First, rapid economic development triggers urbanization, expanding impervious areas and resulting in population growth. Second, population growth accelerates the demand for food, encouraging the development of oasis agriculture. Technological progress in oasis agriculture results in the transformation of a large area of sand, inevitably leading to water shortages and forcing the state to take appropriate measures to promote economic development. Therefore, the changes that occur in the dynamic factors are correlated in space and time.

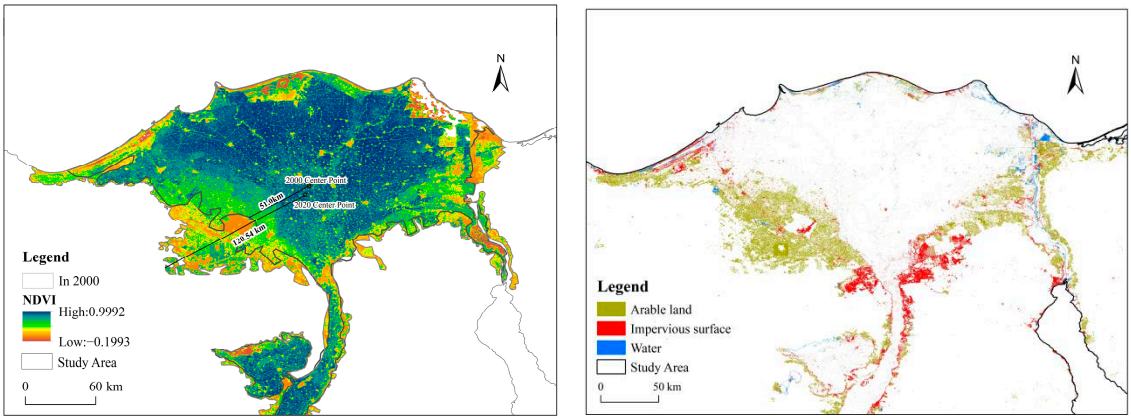


Figure 8. Map of NDVI change lines and land use change lines in the northern region of Egypt from 2000 to 2020.

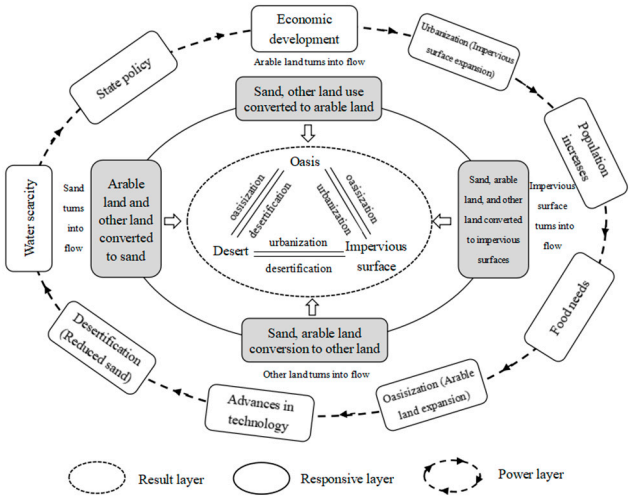


Figure 9. Schematic diagram of the dynamic mechanism of oasis–desert–impervious surface interaction evolution (image by the authors).

4. Discussion and Conclusions

4.1. Discussion

The harmonious development of oases and deserts, oases and impervious surfaces is a global problem. Land use interactions occur in the northern part of Egypt, where improvement in environmental quality is accompanied by degradation [31]. The rapid spread of impervious surfaces influenced by human activities has led to a dramatic process

of ossification and desertification. With the construction of the Aswan Dam in 1970, a large amount of arable land was reclaimed, totaling more than 10 million hectares of reclaimed land. During the same period, Egypt lost almost as much agricultural land to industrial and urban development [32]. Recognizing the need to protect and increase the area of arable land, the Egyptian government began to encourage the establishment of new settlements in desert areas and the cultivation of large areas of sand. This has led to a continuous advance of the oasis line in the delta area towards the desert, which is more pronounced in the southwest and southeast directions of the oasis. The oasis extends nearly 69.54 km to the southwest, and the land use type is dominated by agricultural land, which has the apparent characteristic of oasis advance and sand retreat. This significantly reduces the risk of exposure of oasis ecosystems to wind and sand, prevents the country's desertification, and protects the development of agricultural oasis areas [33].

At the same time, Egypt's population growth led to a massive expansion of impervious surfaces. Spatially, the expansion was most pronounced to the west and northeast, showing a clear pattern of population growth driving the decline of the oases. This reflects the contradiction between human–land relationships and the laws of natural evolution. The northern region of Egypt is in the oasis development phase, and by revealing the oasis–desert impervious surface interactions over two decades, it has been found that oases and impervious surfaces in the northern region of Egypt have expanded significantly, and deserts have shrunk, a finding consistent with the global trend of land use change [34]. The expansion of oases in the northern region of Egypt needs to be improved in two ways: Firstly, the proximity of the northern region of Egypt to the Mediterranean Sea and the lack of natural drainage for wastewater treatment in remote areas for long periods, coupled with the excessive use of irrigation water and inadequate drainage systems, have led to the shallow evaporation of groundwater and gradual salinization of soils [35], which in turn affects the sustainable development of agriculture and the stability of the ecosystem as a whole. Subsequently, soil properties can be restored through rice cultivation, underground drainage system installation, and land improvement programs to promote oasis development. Second, the expansion of impervious surfaces affects oases and forces them to expand, requiring large amounts of water recharge. Due to the scarcity of water resources in the northern region of Egypt, it is crucial to rationalize the use of these oases. Water resources provided by the Nile in Egypt should be exploited to promote the development of oases in the northern region of Egypt. In contrast, China has achieved some success in conserving and intensively using water resources [36]. The protective measures taken include regulating the balance between the supply and demand of water resources through market mechanisms and actively promoting advanced water-saving irrigation technologies (sprinklers, micro-irrigation, and drip irrigation), the rational adjustment of planting structure, promoting the use of treated water, etc. China's water conservation measures can be used as a reference for the northern region of Egypt to improve the use of water resources and promote the development of oases.

4.2. Conclusions

This article analyzes the interaction characteristics between oases, deserts, and impervious surfaces in northern Egypt based on gridded data such as land use and NDVI and examines their dynamics using modeling and geographic information mapping methods. The main conclusions are as follows:

1. Considering the interaction between deserts and oases, the primary manifestation is the expansion of oases and the reduction of deserts. During the study period, the oases in the Nile Delta and Fayoum District increased significantly, with the area of oases in 2020 being 1.19 times the area in 2000, which shows a clear trend of advance of people and retreat of sand.
2. The interaction between oases and impervious surfaces was mainly observed in the form of the spread of impervious surfaces on arable land into oases. During the study period, the area of impervious surfaces increased 2.32 times. The impervious

surface expanded over 1903.70 km^2 of arable land, accounting for 66.67% of the expanded area.

3. Regarding the interaction between the impervious surface and the desert, the central phenomenon is the encroachment of the covered area of the impervious surface into the desert, especially around the city of Cairo.
4. The need for increased food production due to population growth has forced oases to move deeper into the desert, and the occupation of arable land due to urbanization has led to increasing pressure on arable land, creating a pressure-conducting dynamic mechanism. It is recommended that the intensification of impervious surfaces in land use be mitigated to reduce pressure on arable land.

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Data Availability Statement: The data used to support the findings of this study can be made available by the first author upon request. The data are not publicly available due to privacy restrictions.

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

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