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Estimating Advance of Built-Up Area in Desert-Oasis Ecotone of Cholistan Desert Using Landsat

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Abstract: There have been few attempts to estimate the effects of land use and land cover (LULC) on ecosystem services in desert-oasis ecotones, which are recognized as critical ecological barriers and buffers that prevent deserts from expanding into oases. This research investigated how remote sensing and geographic information technology may be used to monitor changes in LULC in the Cholistan desert and the Bahawalpur region of Pakistan between the years 2015 and 2022. The objective of this research was to identify thematic and statistical shifts in LULC in the study area due to various human interventions in the area. Landsat-8 images were processed using the maximum likelihood supervised classification technique using 500 training samples to categorize the study area into four LULC classes, i.e., desert/barren land, waterbodies, vegetation, and built-up areas, with an overall accuracy of 93% and 98% for 2015 and 2022, respectively. Results indicate a significant expansion in built-up area in 2022, which is up to 43%, agriculture and vegetation area declined by 8%, waterbodies decreased by 41%, and desert area decreased by 2% when compared with 2015. The change detection approach revealed that agricultural land was directly encroached on by rapidly increasing built-up area and urbanization as the area had an overall 19% rise in population growth within eight years with an annual growth rate of more than 3%. This study will be helpful to assess the quantity of spatial and temporal changes in the desert ecosystem, which is usually ignored by policymakers and governments due to less economic activity, although it plays a huge role in biodiversity conservation and balancing the regional ecosystem.

Keywords: remote sensing; land use; land cover; arid; ecosystem; desert

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1. Introduction

Land use/land cover (LULC) has affected 'almost a third' of the world's terrain since 1960 [1]. However, the scale, speed, and intensity of LULC change today have never been seen before [2]. Deforestation, habitat loss, climate change, and an increase in catastrophic floods are all on the rise as a direct consequence of human and natural change [3], thus, consequently, rapid spatial and temporal variation in land use trends are being observed [4]. LULC is an important indicator and an early warning of ecological changes with the largest relative impact on global terrestrial ecosystems [5]. Due to the intensification of land-use activities, i.e., over-cultivation, over-grazing, and fuelwood collection, along with recent shifts in climates [6], this trend is expected to continue, particularly in arid ecosystems, which are more fragile and easily affected by land use changes [7]. Oases are the basis of human life and economic development in arid regions [8] and are highly sensitive to external environmental and human disturbances, especially land use changes [9]. This high pressure of human development and extensive encroachment of desert-oasis ecotones continuously increasing [10] may result in a persistent loss of ecosystem services and pose a serious threat to hydrology [11], biodiversity, vegetation cover [12], food security, and even livelihood in arid areas [13].

Even though Cholistan is one of the driest deserts, it has wide biodiversity because of the varied terrain in the desert comprised of trees, bushes, and a huge number of medicinal plants [14]. However, encroachment due to increased demand for agricultural land, intensive grazing, fuel-wood overcollection, frequent heat waves, and droughts is causing the severe destruction of vegetation or loss of oasis in this rainfed desert-oasis ecosystem, and the same is happening in other parts of the world [15,16]. Thus, a spatially explicit assessment of the rates and patterns of LULC changes in this area needs to be carried out for the development of informed land policy to maintain or recover the ecological integrity of this fragile ecosystem in Pakistan and others throughout the world. However, there are few studies on LULC and its ecological effect on such desert-oasis ecotones [5,16]. Administratively, areas such as Cholistan are ignored due to their lower level of economic activity and growth, although they serve as a backbone for the environmental sustainability of these areas around the globe. In recent years, data obtained from remotely sensed satellites have become an increasingly important resource for mapping the patterns and structures of the Earth. Earth observation platforms are used to track the progression of environmental change [17] and various land elements at a regional scale [12,18] to assess the LULC changes [19] all around the world including Africa, Malaysia, China, Brazil, and Egypt [19–24]. In this context, an assessment of temporal LULC change over time due to recent significant economic and anthropogenic activities was conducted in the Cholistan desert of Pakistan using RS and GIS tools.

2. Materials and Methods

2.1. Study Area

The study area is the Bahawalpur division, an administrative unit within the Punjab Province of Pakistan (Figure 1) with a total land area of 44,912 km^2, out of which 26,300 km^2 is the Cholistan desert, which stretches between the 'Thar' desert in the Sindh province to the south and the Rajasthan desert of India to the east. This represents 26% of the entire desert area in the country, typically comprising drought-tolerant flora [25], sandy steep slopes, and huge low-lying flat regions (Figure 2). The region has a dry and arid climate, with large temperature variations between day and night temperatures, which average 45 °C to 20 °C, respectively, with very little precipitation, intense sunlight, and a high rate of evaporation and transpiration [26]. May-July experiences the highest average temperatures, ranging from 47–51 °C, and January is the coolest month with temperatures of 27–28 °C. Two months of the monsoon season (July–Sep.) receive 80% of the annual rainfall (88–135 mm), and the rest of the year it remains dry (https://www.pmd.gov.pk/en/accessed on 5 April 2023). The groundwater is salty and 80–100 m below the surface, so the only source where people and animals can obtain water are dugouts and natural ponds filled after rain [26].

Even though Cholistan is one of the driest deserts, it has rich biodiversity because of the varied terrain in the desert comprised of trees, bushes, and even a wide range of medicinal plants [14]. Many species of animals and birds thrive in the desert such as Blackbuck, Indian gazelle, Indian wild ass, and Great Indian bustard, which are just a few of the endangered wildlife species that can only be seen in the Cholistan area. People in the area make their living through livestock; however, recently, agriculture activities are increasing due to government subsidies for the installation of solar-powered deep tube wells and drip irrigation. Loss of vegetation due to recent droughts and overgrazing are major threats to indigenous wildlife and the desert's flora [27].

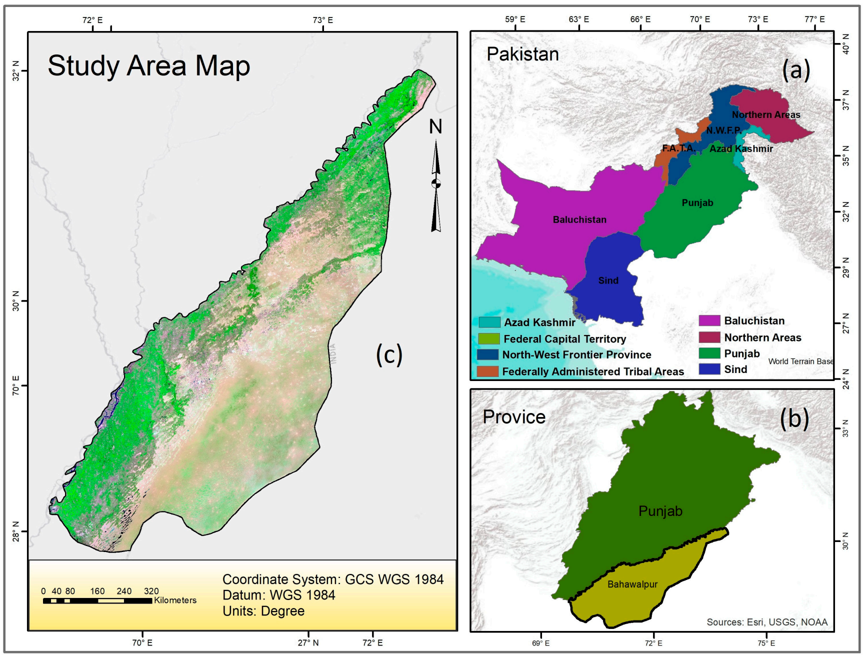

Figure 1. Geographical location map of the study area (**c**), province (**b**) and administrative division of the country (**a**) in subset.

2.2. Datasets

In this study, land use data were generated from multisource datasets comprised of remotely sensed imagery, baseline maps, and topographic features. The satellite remote data were acquired using multispectral images of Landsat-8 (OLI/TIRS L2 C2) downloaded freely from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/ accessed on 16 January 2023) for two study periods 2015 and 2022. The study area was covered in five image tiles in three cycle dates (Table 1). After retrieving the images, they were pre-processed for band composition, mosaicking, image enhancement, etc., in ERDAS Imagine® v14 (developed by Hexagon Geospatial, Madison, AL, USA) and the free open-source software QGIS v3.28 (developed by Open Source Geospatial Foundation Project, Austin, TX, USA (available and downloaded from http://qgis.osgeo.org, accessed on 5 April 2023).

Table 1. Characteristics of Landsat-8 datasets used.

Dates	Path/Row	Cloud Coverage	Spatial Resolution	Band Used	Band Width (µm)
5,12,19 May 2015 12,19,26 October 2015	149/39–40 150/40 151/40–41	Less than 5%	30 m	1–7	0.435–2.294
5,12,19 May 2022 12,19,26 October 2022	149/39–40 150/40 151/40–41	Less than 5%	30 m	1–7	0.435–2.294

Figure 2. Pictorial overview of Cholistan desert and its LULC categories as described in Table 2, range land (**a**), green vegetation after rainfall (**b**), mud houses of native residents (**c**), water ponds refilled with rainfall locally called 'Toba' (**d**), grazing of sheep and goat on natural vegetation (**e**), sand dunes (**f**), arid conditions along with water supply tanks from some NGO for locals (**g**), and diversity of vegetation in desert (**h**).

2.3. Pre-Processing and Classification

This study applies pixel-based supervised image classification with a maximum likelihood classification algorithm using ArcGIS 10.8 for the LULC classification to estimate the LULC shift in the study area [24]. Two visual interpretations of satellite images were performed: A false-color composite and natural color and a 'natural' rendering provided by a 'false-color composite'. Bands 4, 3, and 2 of Landsat 8 provide natural color repetitions similar to what the human eye perceives. Unhealthy vegetation appears darker, whereas desirable growth is green. Water seems gray or black, while urban features are pale and white [28]. This helped to generate spectral signatures of recognized categories. Different band combination patterns were employed during the signature extraction to visualize each land cover type. Four LULC classes were established based on the DN value of landscape elements, designated as built-up area, waterbodies, desert area, and agricultural area as described in Table 2. For each of the predetermined LULC types, training samples were selected by delimiting polygons around representative sites [18,29]. A total of 500 training samples were randomly chosen from the images, 100 from desert area, 150 from urban area, 200 from agricultural area, and 50 from waterbodies for spectral signature development of LULC categories. Before the selection of training samples, an empirical analysis of satellite imagery, google earth images, and a toposheet of the study area was investigated carefully along with additional information through group discussions. A total of 44 individuals were interviewed individually and in focus groups to evaluate their knowledge of LULC changes and trends in the area. Most of the respondents (16 of them) were from the land administration office and researchers at the Cholistan Institute of Desert Studies, IUB, Pakistan, along with 11 local residents who have been living in the study area for more than 10 years, while the rest of the respondents were shepherds or sheepherders who were interviewed individually. They were asked about various aspects such as sand dunes, slopes, grazing lines, etc., to ensure better representativity of each category and verify the accuracy of classified images as described by Yonaba et al. [30], as well as to prioritize the driving factors and causes of LULC changes based on their observation and perceptions of the area.

Table 2. Categorization of LULC classes observed in the study area with their description.

Classes	Description
Agricultural and vegetation area	Crop fields, natural vegetation, vegetation, range land
Built up area	Residential, commercial, industrial, roads, mixed urban area
Waterbodies	Lakes, ponds, rivers, reservoirs, wetlands, open water
Desert area	Desert land, barren land

2.4. Accuracy Assessment

The accuracy assessment of satellite images plays a vital role in evaluating the dependability of extracted information from classification for change detection. Accuracy analysis was performed in QGIS v3.28 (developed by Open Source Geospatial Foundation Project, Austin, TX, USA (available and downloaded from http://qgis.osgeo.org, accessed on 5 April 2023) to generate the error matrix, kappa coefficient, user's accuracy, and producer's accuracy for the classified images of 2015 and 2022. The Kappa coefficient was calculated for the classified images based on reference points extracted from Google Earth images for the accuracy assessment. The various land cover classes of the research region were represented using the random selection technique. Based on visual interpretation, the accuracy was assessed out of 100 polygons [24,29]. Twenty-five polygons from each land cover class were used as reference data. Every polygon was enclosed by the pixels of a specific land cover class. Confusion error matrices were used to statistically compare the classification outcomes with the reference data (ground truth). The following statistics pertaining to the overall user's and producer's classification accuracy values were based on this formulation:

$$\text{Producer's accuracy} = \frac{A}{A+C} \tag{1}$$

$$\text{User's accuracy} = \frac{A}{A+B} \tag{2}$$

where:

A = number of times a classification agreed with the observed value.
B = number of times a pixel was classified as Z when it was observed to not be Z.
C = number of times a pixel was not classified as Z when it was observed to be Z.

Kappa analysis is the accuracy assessment and quality of the classification [31]. The Khat index is calculated as

$$K = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+} \times x_{+i})} \tag{3}$$

where:

r = number of rows in the matrix, N = total number of observations (pixels)
x_{ii} = number of observations in row i and column i.
x_{i+} and x_{+i} = the marginal total of row i and column i respectively.

2.5. Land Use/Land Cover Change Detection

The land cover changes in the last eight years (2015–2022) were examined to determine the location, character, and pace of these changes. To identify the quantitative conversion of one specific land cover class to another land cover class throughout the evaluated period on a pixel-to-pixel basis, a confusion matrix was developed. This matrix was produced by multiplying each column in the matrix by the area of the associated land cover class in the later image. As a result, a new thematic layer was created by combining the two maps with four classes, each of which had a unique combination of land cover change classes ranging from "from" to "into". This percentage calculator was used to compute both the change in the area and the percentage of increase and decrease.

$$\text{AC} = \text{Total area of each class in 2015} - \text{Total area of each class in 2022} \tag{4}$$

$$\text{PD} = \frac{\text{Area of each class in 2015} - \text{Area of each class in 2022}}{\text{Area of each class in 2022}} \times 100 \tag{5}$$

AC = Area change from 2015 to 2022
PD = Percentage of area difference from 2015 to 2022.

3. Results

3.1. Spatial Distribution of Classes

The resulting land use/land cover maps for 2015 and 2022 are shown in Figure 3. The recent LULC classification and spatial distribution showed that the total area of Bahawalpur is 44,912 km^2 and desert is the major type, covering 26,957 km^2 and accounting for 60% of the total area, while the area covered by built-up areas was 8115 km^2, which accounted for 18% of the total area (Table 3). Agricultural and vegetation area covers approximately 21% and waterbodies constitute only 0.5% of the total area in 2022. The major change in the spatial distribution of these LULC types was expansion and increase in regard to built-up area and a reduction in agricultural land and waterbodies when compared with 2015. Water bodies and desert area were the LULC types that decreased during the eight years of the study's time span.

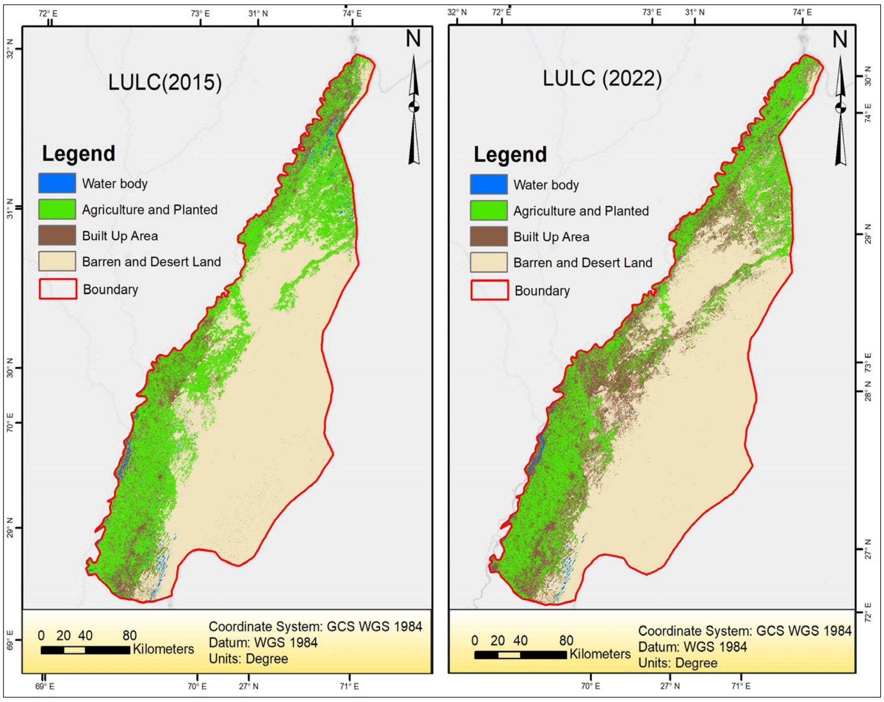

Figure 3. LULC maps of the Cholistan desert for 2015 and 2022.

Table 3. Extent and rate and trends of LULC change (2015–2022) in the Cholistan desert.

LULC Types	2015		2022		Change (km^2)	Relative Change **	Overall Gain/Loss
	km^2	% Age	km^2	% Age			
Waterbodies	412	0.9	240	0.5	−172 *	−41%	−0.5%
Built-up area	4280	9.5	6115	13.7	+1835	+43%	+4%
Desert & barren land	27,593	61.4	26,957	60	−636	−2.3%	−2%
Agriculture & vegetation area	12,627	28.1	11,600	25.8	−1027	−8%	−2.3%

* minus (−) or plus (+) signs with values indicate decrease or increase, respectively. ** represents the relative change within same LULC type from initial (2015).

3.2. Dynamic Land Use/Land Cover Change

According to the findings of this study, during this period of eight years, the land cover category that experienced the greatest amount of LULC change was the conversion of agricultural area into built-up area (Table 3). The overall changes in LULC of the area are presented below in a Sankey diagram (Figure 4) or supplementary Table S1.

This category went through a significant alteration and increased to 8115 km at an increased rate of 89% when compared with 2015, with an overall 8% proportional gain in LULC of the area. This indicated that there had been a significant land cover shift, and built-up areas are encroaching on other land covers, especially agricultural fields. As can be seen in Table 3 and Figure 4, the total area of agricultural and vegetation land shrunk by approximately 8% from 12,627 km^2 to 11,600 km^2, representing a significant reduction of more than 1027 km. Waterbodies were reduced by 41% over eight years with the total area cover decreasing from 412 km^2 to 240 km^2. The desert area, which covers more than 60% of the total study area, showed a minor reduction; however, 636 km^2 has disappeared. The tough climate and access to the area were the main reasons for the decrease in desert area, bringing it down to 26,957 from 27,593 km^2 at a pace of 2.3%. Overall, the biggest increase or expansion was found in built-up area with an increase of 1835 km^2, and this conversion was at the cost of agricultural area or natural vegetation, which decreased 1027 km^2. The loss of 172 km^2 of waterbodies is also transformed into built-up areas. This conversion of waterbodies, which are already limited in such an arid ecosystem and provide a lifeline for both flora and fauna, is a major threat to this ecosystem. The transformation that took place for this 8-year period can be visualized by the thematic LULCC map in Figure 5 showing that there was only a moderate shift in the desert region but there was an obvious shift in the built-up area.

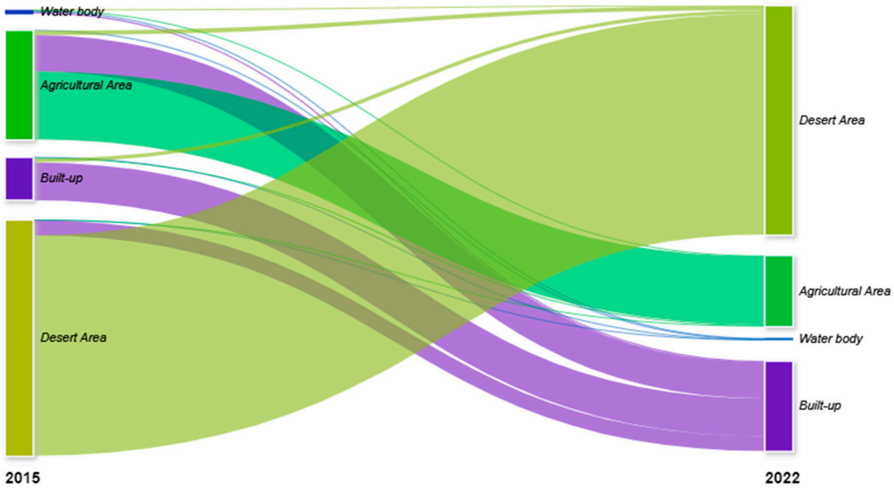

Figure 4. Sankey diagram of LULC changes (2015–2022) in Cholistan Desert, Pakistan.

The emergence of this rural–urban fringe zone, with its complex problems of adjusting between the various ways of life in urban and rural areas, has caused the emergence of serious land use problems, such as the loss of agricultural land and unauthorized urban sprawl.

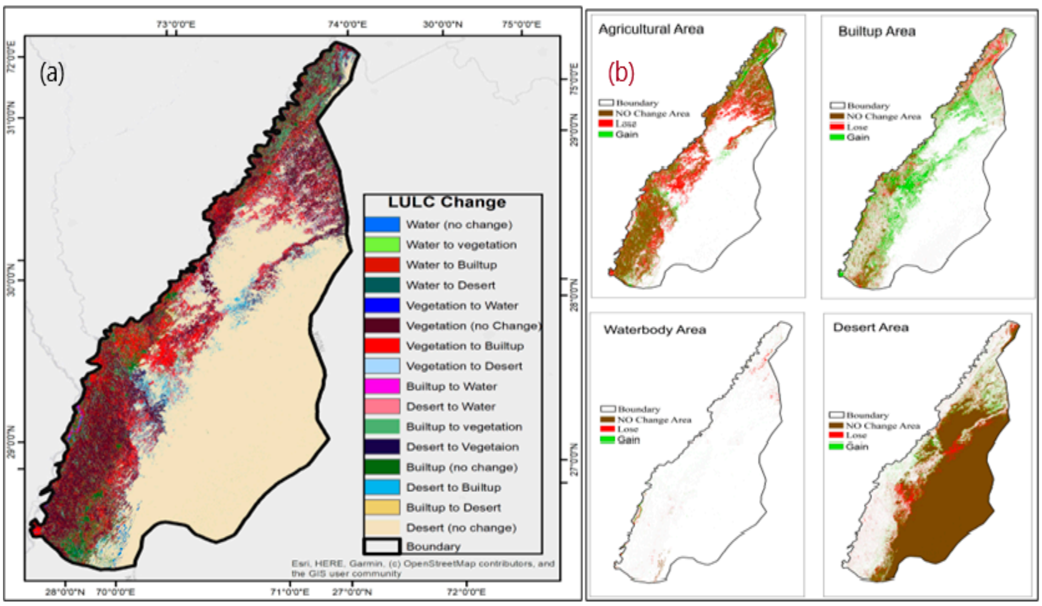

Figure 5. Thematic map of change detection in LULC (**a**) and overall gains and losses in LULC types from 2015–2022 (**b**).

3.3. Driving Factors of LULC Change

One of the major driving factors for this expansion in urban areas is the population increase, which has increased by approximately 18% since 2015, causing pressure on the sub-urban area and unplanned expansions in residential areas. Such uncontrolled housing societies and suburbs are encroaching on the land and degrading the natural ecosystem. According to the data obtained from group discussions and interviews regarding their perception of these changes, the major drivers that influenced the change in LULC and overall dynamics in this dry desert-oasis (Table 4) showed that the population increase was ranked as the primary reason (32%), followed by frequent droughts (25%), nature's work (18%), and government policies (14%).

Table 4. Drivers of recent LULC change in Cholistan desert.

No.	Driving Factors	No. of Respondents (out of Total 44)	Percentage (%)
1	Drought or climate change	11	25
2	Increase in population	14	32
3	Governess and policies	6	14
4	Nature's work	8	18
5	Agricultural activities	2	4
6	Tourism in the area	3	7

3.4. Accuracy Assessment

The accuracy assessment of image data processing and classification was performed using the Kappa coefficient test. The image data of 2015 was classified with an overall accuracy of 93% and the calculated Kappa coefficient was 0.86 (Table 5). In the 4 × 4 error matrix columns, the number of pixels for reference image land use classes was used to assess the accuracy and rows represented the pixel counts for land cover classes of the 2015 classified image, while the accuracy assessment figures derived from the 2022 classification image indicated that the overall accuracy was 98% and the kappa hat coefficient was 0.97, as presented in Table 6.

Table 5. Classification accuracy assessment error matrix (2015).

LULC Types	Waterbodies	Agriculture & Vegetation Area	Built-Up Area	Desert Area
Waterbodies	3779	0	0	6
Agriculture & vegetation Area	73	1095	0	22
Built-up Area	0	0	868	840
Desert Area	0	0	0	452,879
Total pixels	3852	1095	868	453,747
Producer Accuracy (%)	70.3421	100	100	92.102
User Accuracy (%)	99.8415	92.0168	50.8197	100
Kappa hat	0.9984	0.8927	0.4827	1
			Overall accuracy (%)	93.01
			Overall Kappa classification	0.8637

Table 6. Classification accuracy statistics (2022).

LULC Types	Waterbodies	Agriculture & Vegetation Area	Built-Up Area	Desert Area
Waterbodies	5903	0	0	3
Agriculture & vegetation Area	0	710	0	0
Built-up Area	9	0	820	70
Desert Area	0	0	0	400,785
Total pixels	5912	710	820	400,858
Producer Accuracy (%)	74.	100	100	92.10
User Accuracy (%)	99.94	100	91.2125	100
Kappa hat	0.9984	0.8927	0.4827	1
				Overall accuracy (%) = 98.41
				Overall Kappa classification = 0.97

4. Discussion

4.1. LULC Change Dynamics in the Cholistan Desert

Globally, approximately 60% of LULC change is attributed to social and human development, while climatic change is responsible for 40% of this change [2,19,32]. Arid and semi-arid regions constitute approximately 41% of the world's total land area, where precipitation and water resources are scarce. Desert oases play an important role in sustainable development; however, they are fragile areas and are very sensitive to degradation and desertification [33]. Both physical conditions and anthropic activities are regarded as potential driving forces for semi-natural land change in such areas, including the Cholistan desert in Pakistan. This study found some key observations that may constitute risks to the sustainability and survival of this ecotone. The major LULC type was vegetation/agricultural land after desert area; however, it was found that the urban area is expanding rapidly and encroached on approximately 2000 km^2 over 8 years, which shows that more area is being taken by settlements [34]. This expansion of urban areas was mostly in agricultural and desert lands. This trend was alarming as, previously in such areas, there was primarily the conversion of natural vegetation into arable land [5,16], but this change in land use into built-up area will severely ruin ecological systems and affect their services. Consequently, there are risks to productivity and ultimately environmental degradation and sustainability of the desert ecosystem as this is interconnected [32,35]. Another obvious LULC change was a reduction of 41% in area of waterbodies and its conversion into agricultural land and built-up areas. This trend may lead to more prominent conflicts in the future regarding the water supply and demand in such a fragile ecosystem, which is already facing water scarcity and droughts, posing further threats to the rich biodiversity and habitats of rare flora and fauna. It is worth mentioning that there are no permanent, natural bodies of surface water in Cholistan [26], and rainwater is collected in man-made dug-out water ponds called 'Tobas', which serve as a source of drinking water for both nomads and their livestock because underground water is at a depth of 30–50 m and is generally salty. This encroachment of water resources not only increases the vulnerability and food insecurity of residents, called 'nomads', who depend on natural assets of the ecosystem services of this desert [13] but also causes the species richness and abundance to decrease in the region [36].

Moreover, the expansion of built-up area into agricultural lands occurs in a transitional manner. It was observed and confirmed by visual observations and interviews with local inhabitants that the encroachment of the desert starts initially from suitable area with respect to natural resources such as water availability, climate, and vegetation, which are occupied for agriculture, livestock farming, hunting, and other activities, and then, with time, such areas are converted into other economic activities and end up as built-up area. In addition, this area contains many plants that have medicinal importance [14,37] and food for the fauna living in the range land of the Cholistan desert [38,39], which has decreased as observed in previous studies [40,41], resulting in desertification of the area [15]. Several species of plants and animals in the area are going extinct because of the region's natural environment being fragmented, degraded, and continuously lost [26,39].

4.2. Driver of Change in LULC of Desert

Expansion in urban areas may have either beneficial or detrimental consequences on the surrounding environment, depending on how it is planned, but unmanaged growth in urban areas will always have negative effects. According to a previous study [34], the population has increased by approximately 18–20% since 2000, causing pressure on the sub-urban area and peripheral areas as it is common for the proportion of farmland and vegetation to decrease as the proportion of built-up land increases. Overall, an 18% increase in growth since 2015 has been found in the study area, resulting in the development of new colonies and uncontrolled societies being constructed on fertile agricultural land, consequently degrading the natural ecosystem.

The major drivers that have influenced the change in LULC and overall dynamics in this dry desert-oasis were population increases, followed by frequent droughts and nature's work. Government policies have also had an impact on such LULC changes and the livelihoods of pastoralists, as some residents argue that the development of road networks and encouraging foreigners' activities also contribute to the transformation of rangeland into urban or semi-settlement areas. Another factor as indicated by residents is the activities and interests of Arab royals in this desert. Every year, millions of birds such as Houbara bustard migrate from Siberia in search of moderate waters and stopovers in the sprawling deserts of Cholistan and Thar in Pakistan, thus making these deserts a favorite hunting ground for Arab expeditions. They frequently visit at the invitation of government officials for hunting safaris. In return, as a courtesy, Arab royals do contribute to local development, especially in terms of the construction of hospitals, mosques, and other infrastructure such as their own palaces, private runways, farmhouses, etc. Tourism activities such as Jeep Safaris and historical forts are also another driving force for the change in LULC and the forging of built-up areas in the desert.

5. Conclusions

The spatial and temporal changes in the Cholistan desert were studied as this area is a key biodiversity pool in the region but is, at the same time, fragile and very sensitive to land degradation and desertification. This study improved the understanding of LULC changes and their driving factors in an arid desert-oasis ecosystem in order to develop policies and measures to protect biodiversity and other natural resources in such ecosystems. The results showed that considerable change occurred over the eight-year period from 2015 to 2022, and built-up area is increasing due to population growth at the cost of agricultural land and desert area. There is also encroachment of waterbodies, initially for agricultural activities and then later for transformation into urban settlements. Due to the low economic importance, the government seems to be less interested, so no conservation plans or measures are in place in the area. Natural calamities such as droughts and climate change are adding to the degradation and aridity of the area in its move toward desertification. This costs the life and health standards of flora/fauna and the wellbeing of natives in the desert. In future development, it is necessary to improve the monitoring and implementation of conservation measures for desertification to maintain an ecological equilibrium and promote harmonious coexistence between human beings and nature.

It was observed that our findings could provide a more conclusive direction of urban sprawl and its impact on land cover, which could be analyzed in future research. We suggest that future research is conducted to understand the inter-relationships between ecosystem services provided by the desert and LULC changes to forecast and highlight future scenarios for sustainability and the protection of natural systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12051009/s1, Table S1: LULC change dynamics in study area (2015–2022).

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Data Availability Statement: The dataset used in this research can be provided upon request.

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