Spatial analysis of biodiversity and ecosystem dynamics in Lal Sohanra Biosphere Reserve, Pakistan

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Abstract. This study examines how livelihood pressures, environmental variability, and changes in land use/land cover (LULC) affect ecosystem dynamics and biodiversity in Lal Sohanra National Park (LSNP) in Pakistan. Remote sensing (RS) and geographic information system (GIS) methods were used to process multi-temporal Landsat images spanning from 1990 to 2023. The normalized difference vegetation index (NDVI), the normalized difference water index (NDWI), and the bare soil index (BSI) were used to assess the dynamics of vegetation, water, and bare soil, respectively. The photos covered a wide range of years, from 1990 to 2023. Local reliance on park resources was assessed using household survey data from 100 respondents. At the same time, climatic variability was examined using the Mann-Kendall trend test, Sen's slope estimator, and Pettitt's change-point analysis. Over the course of the research period, the results reveal significant changes in land cover. Barren land and shrubland varied widely, alternating between stages of degradation and vegetation regeneration, whereas forest cover declined at times but recovered partially in later years. While BSI indicates that soil remains exposed in critical zones, NDVI shows that vegetation is improving in some areas. Despite non-significant or fluctuating trends in precipitation and temperature, climate research reveals a notable rise in soil moisture and a notable fall in wind speed. In the late 90s and early 2000s, when land use changed and environmental stress was at its worst, change-point analysis primarily found structural shifts. According to socioeconomic data, local communities rely heavily on park resources, including fuelwood, grazing, and livelihood assistance, which strains habitat quality and vegetation. The study found that land-cover change, climate variability, and human resource use all play a role in shaping ecosystem dynamics in the Lal Sohanra Biosphere Reserve. To manage biodiversity sustainably, it is advised to implement integrated conservation planning, regulate resource use, and provide community-based livelihood options.

Keywords: land use/land cover change, biodiversity dynamics, remote sensing and GIS, climate variability, anthropogenic pressure, Lal Sohanra Biosphere Reserve.

1. Introduction

Lal Sohanra National Park is 36 kilometers east of Bahawalpur in Punjab province, at 29°12′0″N 71°48′0″E. The government proclaimed Lal Sohanra National Park (LSNP) on October 26, 1972, following recommendations from the 1971 Wildlife Inquiry Committee. It was originally 333.549 km^2 in size, including 209.339 km^2 of desert, 84.880 km^2 of irrigated forest plantation, and a 19.339 km^2 reservoir; it was later expanded by 226.80 km^2. It is known for its diverse animal population, including blackbuck, Nilgai antelope, and rhinoceros. LSNP is Pakistan's first biosphere reserve. LSNP was added to the World Network of Biosphere Reserves in 1977 as part of UNESCO's Man and the Biosphere (MAB) Program, making it Pakistan's first Biosphere Reserve to be so declared. UNESCO's "Man and the Biosphere" (MAB) Program recognizes biosphere reserves as locations that encourage sustainable development. It is a UNESCO-designated Biosphere Reserve, recognized for its diverse ecosystems, including desert, wetland, and forest habitats. Spanning over 65,000 hectares, the park supports a variety of flora and fauna, including endangered species such as the blackbuck and houbara bustard. As a critical ecological site, it plays a significant role in conserving biodiversity and sustaining ecosystem services, which benefit both the environment and local communities (Khan et al., 2023).

There are biosphere reserves worldwide. In 2021, 727 biosphere reserves in 131 countries made up the World Network of Biosphere Reserves, reflecting the increasing worldwide dedication to sustainable development and biodiversity conservation, according to UNESCO. These protected areas demonstrate how to balance human needs with those of ecosystems.

There are 168 locations in 40 countries throughout Asia and the Pacific. There are 132 sites in 22 countries in Latin America and the Caribbean. There are 86 locations in 33 African countries. There are 35 sites in 14 Arab nations. This year saw the establishment of the first biosphere reserves in Mozambique and Moldova, as well as one new site in India. This year, seven sites were removed from the World Network of Biosphere Reserves. One participant was from Australia, one from the Netherlands, and one from the US. Spain now has the most biosphere reserves of any country in the world (Mariye et al., 2022). Biodiversity, the diversity of life at all scales of biological organization, is a key element of ecosystem dynamics. Ecosystem dynamics refers to the natural changes over time in the structure and function of a given ecosystem driven by biological and abiotic interactions. Explaining this connection between biodiversity and ecological processes is the focus of ecological theory and is crucial to effective policy-making for conservation and sustainability. The relation between biodiversity and ecosystem functioning (BEF) is a long-standing issue that has been extensively researched over the last several decades. It has been suggested that biodiversity is often associated with greater productivity, stability, and resilience in ecosystems (Cardinale et al., 2012). Longitudinal research on grassland ecosystems by Tilman and Downing (1994) revealed that communities with greater species diversity were better able to withstand drought, demonstrating how biodiversity can improve ecosystem stability under environmental stress.

Biodiversity dynamics, as used in this research, refer to changes over time and space in the diversity, abundance, distribution, and ecological functions of the various biological communities found in Lal Sohanra National Park. Alterations to land use/cover, vegetation condition, water availability, soil exposure, climate variability, and anthropogenic pressures that impact habitat quality and species persistence provide an indirect means of evaluating biodiversity dynamics. Biodiversity dynamics in this study thus reflect the ecological reactions of plants and animals to changing habitats, human activities, and the passage of time.

However, the growing human population in surrounding regions has posed substantial challenges to the park's biodiversity and ecosystem dynamics (Ge et al., 2022). Habitat degradation, illegal resource extraction, and the encroachment of agricultural and settlement activities are among the most pressing issues. These anthropogenic pressures are leading to habitat fragmentation, biodiversity loss, and disruption of ecological processes. Understanding the interplay between human population growth and ecological health is essential for developing strategies to sustainably manage the park's resources while safeguarding its unique biodiversity (Kuuluvainen, 2009).

This research examines the effects of climate change, human reliance on natural resources, and changes in land use and land cover on ecosystem dynamics and biodiversity in Lal Sohanra National Park. The study examines environmental changes from 1990 to 2023 using data from household surveys, climatic trend assessments, GIS analysis, and remote sensing. We postulate that the biosphere reserve's biodiversity and ecosystem functioning have been significantly affected by substantial alterations in habitat conditions driven by rising anthropogenic pressure and environmental variability.

All technical acronyms are defined at the point in the article where they appear for consistency. Land use/land cover (LULC), normalized difference vegetation index (NDVI), normalized difference water index (NDWI), bare soil index (BSI), geographic information system (GIS), remote sensing (RS), Lal Sohanra National Park (LSNP), Mann–Kendall (MK) test, Sen's slope estimator (SSE), and root-mean-square error (RMSE) are the primary acronyms used in this study.

Research Hypothesis:

It is hypothesized that the combined effects of land-use/land-cover transformation, environmental variability, and anthropogenic pressure have significantly affected biodiversity and ecosystem dynamics in the Lal Sohanra Biosphere Reserve. This hypothesis is based on prior research showing that protected dryland ecosystems are extremely vulnerable to land-use change, climate variability, and human reliance on natural resources. Habitat degradation, ecological instability, and increased vulnerability in buffer and transition zones are likely to be spatially related to changes in forest cover, shrubland, barren land, vegetation condition, water availability, soil exposure, and climate trends. To ensure sustainable management, the study suggests that community-oriented conservation planning and integrated spatial monitoring are crucial. This is because local dependence on park resources, such as grazing and fuelwood gathering, leads to vegetation stress and a decrease in biodiversity.

1.1. Background of the Study

Protected areas like Lal Sohanra National Park serve as biodiversity hotspots, hosting a wide range of species adapted to specific ecological niches. The park's location in an arid region makes its ecosystems particularly sensitive to external pressures. Population growth in nearby areas has led to increasing dependence on the park's resources for fuelwood, grazing, and water, exacerbating environmental degradation (Abbass et al., 2022). Studies have shown that human-induced changes, such as habitat destruction and pollution, are among the leading causes of biodiversity loss globally (Pimm et al., 2014). In Lal Sohanra, these impacts are evident in the decline of native wildlife populations and the degradation of critical habitats. The park's designation as a Biosphere Reserve underscores the need to balance conservation and sustainable human development. Despite conservation agencies' efforts to mitigate human impacts, challenges persist due to inadequate policy enforcement, limited community engagement, and limited resources for ecological restoration (Jin et al., 2022). A comprehensive understanding of how population dynamics influence biodiversity and ecosystem services in Lal Sohanra is vital for formulating effective conservation strategies that address both ecological and socio-economic dimensions. This study investigates the impacts of population pressures on the biodiversity and ecosystem dynamics of Lal Sohanra National Park. By examining the factors driving ecological change, it aims to provide insights into sustainable management practices that can harmonize human activities with biodiversity conservation (Díaz et al., 2019).

1.2. Specific objectives

The main goals of this research are to:

(i) Using multi-temporal Landsat imagery and GIS-based classification, we will analyze land-use/land-cover changes in the Lal Sohanra Biosphere Reserve from 1990 to 2023.

(ii) Using NDVI, NDWI, and BSI indices, we will evaluate the dynamics of vegetation, water, and soil exposure.

(iii) Using the Mann-Kendall trend test, Sen's slope estimator, and Pettitt's change-point analysis, we will assess the long-term environmental variability.

(iv) Using household survey data, we will examine the local community's dependence on park resources.

(v) Finally, we will relate spatial, climatic, and socio-economic indicators to biodiversity and ecosystem dynamics to support sustainable conservation planning.

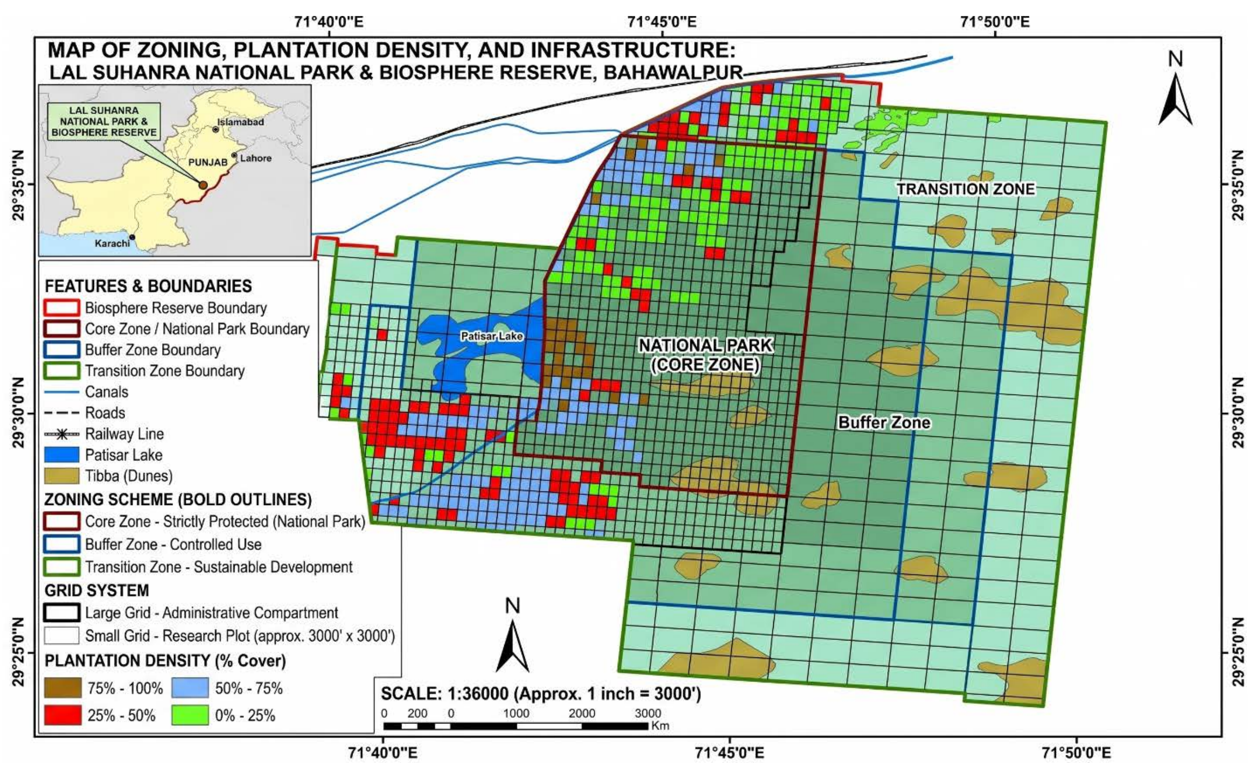


Figure 1. Location map of Lal Sohanra National Park/Biosphere Reserve, Punjab, Pakistan, showing the spatial extent of the study area used for LULC, vegetation index, climate, and socio-economic analysis

2. Literature Review

Human population expansion often leads to habitat degradation, fragmentation, and loss, particularly in buffer zones of protected areas. Studies show that increasing population pressures near Lal Sohanra National Park contribute to resource exploitation, overgrazing, and illegal hunting, negatively impacting biodiversity and ecosystem services (Sandifer et al., 2015). Population-driven land-use changes, such as the conversion of natural habitats to agriculture or settlements, have been documented as critical stressors on biodiversity. Globally, around 75-83% of natural land has been impacted by human activity, emphasizing the urgent need for sustainable land management practices to protect natural ecosystems (Pendrill & Persson, 2017). Increased human activity affects species diversity and abundance. For instance, in Lal Sohanra, changes in vegetation due to human interference disrupt the habitat for native and migratory species, including the highly sensitive desert ecosystem inhabitants (Sachs et al., 2022).

Conservation strategies have been proposed to mitigate these impacts by restoring degraded habitats. Ecosystem services, such as water filtration, carbon sequestration, and soil fertility, are under threat from overexploitation driven by population growth. Studies emphasize the interdependence of human well-being and ecosystem health, advocating for community-based conservation efforts (Shahabfar & Eitzinger, 2011). Sustainable practices, including eco-tourism, reforestation, and local community engagement, have proven effective in reducing the adverse impacts of human populations on biodiversity. Research highlights the importance of integrating local knowledge into biodiversity conservation policies to balance ecological and human needs (Sustainable Land Management Project II, 2017).

The changes in the landscape, shifting cultivation, and land transformation are important parts of LULC changes; the application of Change detection is very significant in these kinds of studies. The human population is increasing day by day, and people are moving from natural to artificial environments. As a result, urban researchers and environmentalists are actively working to sustain the environment (Shahid et al., 2022). The human population is increasing day by day, and they are moving from a natural environment to an artificial one. As a result, urban researchers and environmentalists are actively working to sustain the environment. They know the consequences of LULC change and its effects on humans. Greenhouse gases have a significant impact on the climate, and after this, the most severe factor is land-use change. The developing countries are severely affected by this change. This is because population growth and urbanization are at peak levels in developing countries. LULC research is very meaningful for understanding the impact on climate and for sustainable management of urban areas (Arsiso et al., 2018). Field assessments across LSNP's geographic regions during October to December 2015 were conducted to assess vertebrate richness. They recorded 17 mammals, including the Asiatic Wolf, considered an endangered species; five amphibians; and 27 reptiles, of which *Chitra indica* is endangered (Ali Khan et al., 2014).

Furthermore, 7423 individuals from 74 species across 35 families were accounted for in our studies. Some of the threats encountered included hunting, deforestation, and habitat loss; the authors requested conservation of these species (Sial, 2024). The feeding habits of the translocated blackbuck population in LSNP. They determined the animals' dietary preferences and the amount of dry matter each consumed through direct observation. This study identified eight most favored plants in one stockade and ten in the other; this knowledge helped assess the quality of the habitat and the availability of resources in the park (Afzal et al., 2025)**.** Our study also indicated that ecosystems are better able to function under a changing environment with greater functional diversity. This has been supported by empirical evidence indicating that high rates of productivity and nutrient cycling are usually maintained by communities with high functional diversity (Chapin III**)** (Díaz & Cabido, 2001)**.** The basic forces of ecosystem dynamics are how species interact with one another: predation, competition, mutualism, and facilitation. The interactions are mediated by biodiversity, since it shapes food webs and alters energy flow (Loreau et al., 2001). A more sophisticated ecosystem, comprising more species assemblages, will usually have more complex and stable food webs that insulate against population collapses and maintain ecological balance. More recently, meta-analyses have shown that species richness can enhance multiple ecosystem processes, known as multifunctionality (Gamfeldt et al., 2008). This means that diverse communities play a greater array of ecological roles, including biomass production, nutrient cycling, and carbon storage.

Human activities such as deforestation, pollution, and climate change have exacerbated biodiversity loss, with profound implications for ecosystem dynamics. According to a report in the Millennium Ecosystem Assessment update (2005), more than 60 percent of ecosystem services are being degraded, mainly due to biodiversity decline. The effects of biodiversity loss include simplified ecological networks, decreased resilience, and a presumed heightened susceptibility to environmental perturbations (Isbell et al., 2011).

Specifically, climate change alters the distribution and phenology of species, as well as species interactions and ecosystem feedbacks. For example, temperature variations may alter pollinator availability, reducing plant reproductive fitness and eventually leading to ecosystem erosion (Folke et al., 2004)**.** The resilience of an ecosystem is its ability to absorb disturbances and reorganize in response to change. This resilience with respect to biodiversity stems from a reservoir of available functional traits and genetic diversity, enabling the community to recover following disruptions (Tsuruta, 2018). The idea of diversity of responses, i.e., the variability in species responses to environmental change, provides another reason to focus on the preservation not only of biodiversity in terms of the number of species, but also of the fulfillment of ecological functions. In addition, many systems have greater adaptive capacity, in that they can deal with slow changes or recover after slumps, better than simpler systems (Elmqvist et al., 2003). Therefore, the conservation of Biodiversity is part and parcel of helping ecosystems cope with changing environments over long periods of time.

Therefore, the conservation of Biodiversity is part and parcel of helping ecosystems cope with changing environments over long periods of time. These studies establish the importance of spatial approaches for understanding the distribution of biological diversity and the processes shaping ecosystems in Lal Sohanra National Park.

3. Data Sources and Data Acquisition

Before starting the research, data and data sources are searched across various departments, and their availability is confirmed. The data sources for the two variables differ—afforestation data collected by the Lal Sohanra Biosphere Reserve Forest office and the Bahawalpur Forest office, Government of Pakistan. To study land-use changes in the Lal Sohanra Biosphere Reserve, Landsat data are obtained from the USGS (United States Geological Survey). Four multi-date and cloud-free satellite images from Landsat 5 TM and one Landsat 8 OLI are obtained from the United States Geological Survey (USGS) online service, with a spatial resolution of 30 m, and processed in Erdas Imagine and ArcGIS (Farooq et al., 2023). Landsat 4-5TM (Thematic Mapper) is the selected sensor for analyzing land-use change from the year 1900 to 2010, and Landsat 8 (Operational Landsat Imagery) in 2023. The details are shown in (Table 1). Primary data were collected through field surveys to fill out the questionnaire and analyze the impacts on the indigenous population.

Table 1. Characteristics of Satellite data used in the study

Satellite	Sensor	Bands	Resolution	Cloud Cover	Acquisition date	Path/row
Landsat 5	TM	1,2,3,4,5	30 m	Less than 10%	1990/09/15 1995/10/25 2000/09/10 2005/11/10	150/40
Landsat 8	OLI	1,2,3,4,5,6,7	30 m	Less than 10%	2010/11/25 2015/11/11 2020/10/10 2023/11/06	150/40

Satellite images from Landsat 5 and 8 have been utilized in this study. Landsat 7 data were also available, but due to a technical error in the imagery, it was deemed inaccurate for land transformation analysis. Landsat data sets are freely available on the official website, so they were easily acquired from there (Table 2). Images were used to investigate land transformations in the Lal Sohanra Biosphere Reserve from 1990 to 2023. Images were downloaded, with the study area kept cloud-free during capture. This can be checked from the metadata available with each image, which provides some basic information about that tile.

Table 2. Description of Landsat imagery and its Spectral Resolution

Satellite	Bands	Wavelength (micrometers)	Resolution (meters)	Swath
Landsat 4-5 Thematic Mapper (TM) Launched 03/1/1984	Band 1 –Blue	0.45-0.52	30	185 km
	Band 2 –Green	052-0.60	30	
	Band 3 –Red	063-0.69	30	
	Band 4 –Near Infrared (NIR)	0.76-0.90	30	
	Band 5 –Shortwave Infrared (SWIR) 1	1.55-1.75	30	
	Band 6 – Thermal	10.40-12.5	120*(30)	
	Band 7 - Shortwave Infrared (SWIR) 2	2.08-2.35	30	
Landsat 8	Band 1-Coastal Aerosol	0.43-0.45	30	
	Band 2- Blue	0.45-0.51	30	

Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) Launched 02/11/2013	Band 3- Green	0.53-0.59	30	185 km
	Band 4- Red	0.64-0.67	30	
	Band 5- Near Infrared (NIR)	0.85-0.88	30	
	Band 6-(SWIR) 1	1.57-1.65	30	
	Band 7- SWIR) 2	2.11-2.29	30	
	Band 8-Panchromatic	0.50-0.68	15	
	Band 9-Cirrus	1.36-1.38	30	
	Band 10- Thermal Infrared (TIRS) 1	10.60-11.19	100	
	Band 11- Thermal Infrared (TIRS) 2	11.50-12.51	100	

Source: United States Geological Survey.

Every table was double-checked to ensure uniform layout, full headers, units, and alignment. Data from the trend test, environmental variables, satellite characteristics, LULC change statistics, and geographical linkage were kept since they directly contribute to the study's goals and interpretation. Table captions were updated to identify the variables, time period, and content more precisely.

3.1. Data Collection

The data collection methodologies used in this research include satellite data acquisition, GIS techniques, maps, field surveys, GPS surveys, and related methods. Data was gathered using both primary and secondary methods. Secondary data on afforestation have been collected from the Lal Sohanra Biosphere Reserve Forest Office and the Bahawalpur Forest Office (Nation United, 2012). The Lal Sohanra (BR) is divided into three forest ranges, and each range is divided into different compartments (CPTs), where afforestation is carried out in different CPTs in different years. Satellite data is obtained from USGS for September to November, as these months provide a more accurate and detailed distribution of vegetation. The study area of the Lal Sohanra Biosphere Reserve is covered by one Landsat TM scene, path 150, row 40.

Raw Satellite images were downloaded from the USGS website: Landsat 4-5 and Landsat 8 (collection 2, Level-2, band Surface Reflectance (SR)), keeping in mind the specific parameters required for use in land transformation studies. Satellite images were downloaded with less than 10% cloud cover for the last three decades. Knowledge of the study area must be acquired before downloading and visually interpreting satellite images to improve training of signatures for supervised classification (Abdela, 2024). The primary aim of a well-thought-out fieldwork strategy was to collect data for land transformation analysis and validation.

The socio-economic component relies on household survey data gathered from communities surrounding the park boundaries, specifically in places where people have direct contact with water, pasture, and forest resources. A standardized questionnaire was used to survey 100 families. Farmers, livestock herders, fuelwood collectors, and residents living at various distances from the park's boundaries were among the livelihood groups represented in the sample. Household demographics, sources of income, reliance on park resources, intensity of grazing, collection of fuelwood, perception of vegetation change, observation of wildlife, and conservation awareness were among the topics included in the questionnaire. Clarity and consistency were ensured by reviewing the questionnaire before final data collection. Any unclear items were amended. To find missing or contradictory information, answers were reviewed as data were entered. Given the data requirements, a well-planned data collection methodology was adopted to achieve the aims and objectives outlined in the first chapter of this dissertation.

4. Research Methodology Framework

This study employs an integrated analytical framework that amalgamates remote sensing, statistical methodologies, and socio-economic evaluation to examine ecosystem dynamics in Lal Sohanra National Park. Multi-temporal Landsat data (1990–2023) were acquired and processed through geometric and atmospheric corrections. Land-use/land-cover maps were created using supervised classification with the maximum likelihood algorithm. Environmental conditions were evaluated using NDVI, NDWI, and BSI indices, and temporal variations were examined using post-classification comparison techniques. Climatic trends were assessed using the Mann–Kendall test, Sen's slope estimator, and Pettitt's change-point analysis. Socio-economic data from household surveys were analyzed employing descriptive statistics and regression methods to evaluate the influence of human activities on biodiversity and ecosystem stability.

4.1. Satellite data processing

Image preprocessing includes geometric and atmospheric corrections, as well as various image enhancement techniques. Before applying geometric corrections to the image, a subset of the study area is obtained by overlaying the district BWP vector layer. Image georeferencing and geometric corrections are performed by creating a master-slave relationship. Satellite images from 1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2023 were geometrically corrected using the satellite image UTM projection with datum WGS1984 and zone 43, as this best defines the location of Lal Sohanra Biosphere Reserve between 71E and 72E. Geometric correction is applied using 50 ground control points, which are easily identifiable in the image. The applied resampling method was nearest-neighbor, and the resulting root-mean-square error was less than 1 pixel. Image enhancements are applied to more effectively display the image and for subsequent visual interpretation.

Following the satellite-image categorization approach, an accuracy assessment was conducted to enhance methodological transparency. Field observations, GPS-collected ground data, high-resolution Google Earth images, and eye interpretation of stable land-cover elements were used to establish reference points. The main land-cover classes, such as forests, shrublands, barren ground, and bodies of water, were represented by these reference points. After comparing the labeled pixels with the reference data, an error matrix was generated. Following this, the Kappa coefficient, producer accuracy, user accuracy, and overall accuracy were computed to assess the reliability of the supervised classification. This evaluation was useful for determining whether the LULC maps were accurate enough to detect changes after classification and to compare them over time. A "new" image is created from an old image, providing more information for visual interpretation (Asif et al., 2026). Various spatial, spectral, and radiometric enhancement techniques are available to improve image clarity and vividness. Keeping the research objectives in view, after layer stacking and geometric corrections, spatial enhancement techniques are applied. All three Satellite images are spatially enhanced by applying a “sharpen filter and a 3 * 3 convolution for edge enhancement.

The maps and graphical outputs were all formatted using better cartographic standards to make them easier to read. Each time-series map had its legend, class names, scale bar, north arrow, and color scheme reviewed to ensure uniformity. To maintain legibility of spatial patterns, class boundaries, and labels in the final manuscript, the LULC, NDVI, NDWI, and BSI maps were exported at high resolution. We also updated the captions to clarify each picture's function, the variables displayed, the time frame covered, and the primary interpretation backed by the figure.

4.2. System of Land Cover Classification

An a priori land cover classification system has been adopted for this study, in which satellite images from 1990, 2000, 2010, and 2023 are categorized into classes based on the dominant land cover types in the study area. Land cover was classified into five main classes in the study area:

dark forest, light forest, shrubland, water bodies, and bare land. The categorization of land uses into different land covers was mainly based on Pakistan's land use and land cover scheme, which is also an adaptation of Anderson's land cover classification scheme, first presented in 1972 (Smith, 2011).

4.3. Classification Data Output and Analysis

Finally, satellite image output is produced as thematic maps, which are refined using post-classification smoothing (majority filter) in ERDAS. Thematic maps produced from classification are further analyzed by computing the area covered by each land-use category in hectares. We opted for the post-classification comparison method because it provides class-wise estimates of LULC conversion and allows us to compare photos classified independently across years directly. Class areas were calculated after using a majority filter to eliminate classification noise. To ensure that the main land-cover classes were consistent in space across all time series, the class maps were double-checked using reference data and visual interpretation. All classes' area changes, percentage changes, and dynamic change rates were computed using the final LULC statistics. That is how temporal land-use data are prepared for analyzing land cover and land use over 33 years. Aerial changes are analyzed over three time spans.

Land use changes are analyzed from 1990 to 2023 with a 33-year interval, including the recent 11 years, by computing the percentage cover for each land cover and land use category. Percentage changes and exact expansions and reductions in each land use are also calculated and presented in tables and graphs.

4.4. Change Rate of Classification

The change rate of Classification analysis includes a variety of methods for identifying and describing quantitative and qualitative differences between two multi-date images. The other change-detection procedure is to subtract the area coverage of each land-use class in the recent year from that in the previous year. Furthermore, the dynamic rate of change per cent for each land use is computed using Eq. (1). Using Eq. (1) and Eq. (2), we were able to determine the percentage change and yearly rate of change for each LULC class, respectively. These equations use hectares (ha) as the unit of area and years as the unit of time interval.

$$n \times LUA(i) \tag{1}$$

$$\frac{\mathrm{LUA}(i+n)-\mathrm{LUA}(i)}{\mathrm{LUA}(i)} \times 100 \tag{2}$$

In this context, LuA_{i+n} stands for the area of a specific land-use/land-cover class in the subsequent year, LuA^k for the area of the same class in the preceding year, and n for the number of years between the two. A negative value indicates a decrease in size, while a positive value indicates an increase in size. The unit of measurement for area is the hectare (ha).

5. Results and Discussion

5.1. Comparison of Results

Comparing results from supervised classification reveals land-use changes in the study area. The LANDSAT images, results, layouts, and statistics defined the changes in the study area. The three land covers used for supervised classification clearly explain the changes. The map shows the layouts of the results after classification for 1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2023. Map 1.2 shows that the LANDSAT images from 1990 to 2010 use the 5, 4, 3 band combinations, and those from 2015 to 2023 use the 7, 5, 4 band combinations. In front of these images, the results of supervised classifications are displayed. After reviewing these classification results, a layperson can see that the land use has changed. The forest and water area is increased, and the barren land area fluctuates, etc.

Now we detect changes based on land cover statistics, which clearly quantify them. Each image has an area in acres, and the percentages of land cover are also given.

Table 3. The comparison of land-use and land-cover change

LULC	1990-1995		1995-2000		2000-2005		2005-2010	
	change	**%**	**Change**	**%**	**Change**	**%**	**change**	**%**
Forest	-1327	-1.98	2122	3.12	-13745	-20.24	11328	16.68
Barren Land	-15121	-22.55	-17777	-26.18	19756	29.09	-17501	-25.77
Shrubs	16976	25.32	16164	23.8	-4455	-6.56	5677	8.36
Water Bodies	327	0.49	-507	-0.75	-1555	-2.29	494	0.73

LULC	2010-2015		2015-2020		2020-2023	
	change	**%**	**Change**	**%**	**Change**	**%**
Forest	-5854	-8.62	4360	6.42	-2588	-3.81
Barren Land	-3685	-5.43	5410	7.97	1347	1.98
Shrubs	7615	11.21	-9827	-14.47	1169	1.72
Water Bodies	1925	2.83	56	0.08	69	0.1

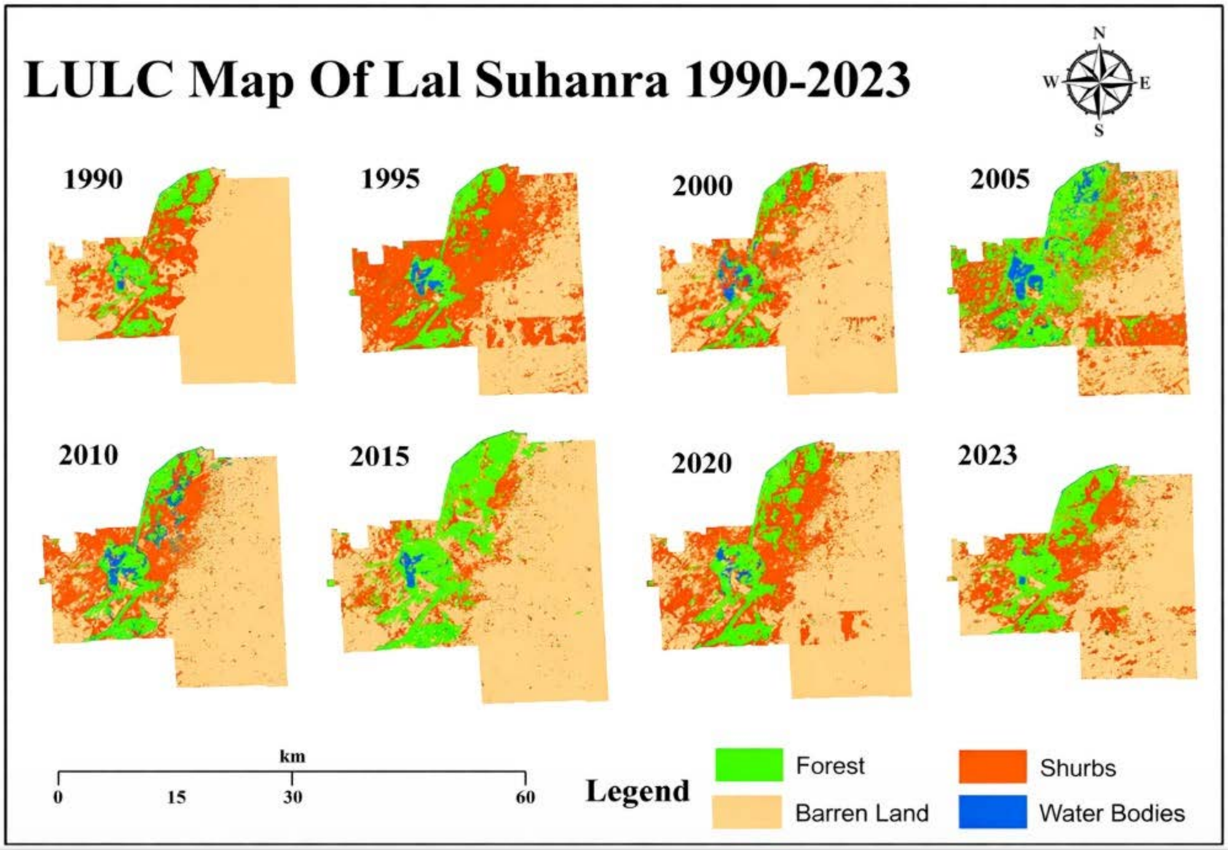


Figure 2. Supervised LULC classification maps of Lal Sohanra National Park/Biosphere Reserve from 1990 to 2023, showing temporal changes in forest, barren land, shrubland, and water bodies. The maps illustrate major land-cover transformations used for post-classification change detection.

(Table 3) illustrates the percentage changes in the different land use and land cover (LULC) categories—Forest, Barren Land, Shrubs, and Water Bodies—over the period from 1990 to 2023 (Fig. 2). It highlights how these land categories have fluctuated due to environmental and anthropogenic factors. Initially, forested areas declined between 1990 and 1995 (-1.98%) and experienced a drastic loss from 2000 to 2005 (-20.24%). However, there was a significant recovery from 2005 to 2010 (16.68%). After 2010, forest cover showed fluctuations, with a notable decline from 2010-2015 (-8.62%), an increase from 2015-2020 (6.42%), and another slight reduction from 2020-2023 (-3.81%). This category showed major variations. It significantly decreased in the early years, with large drops from 1990 to 1995 (-22.55%) and from 1995 to 2000 (Boussaada & Benabdelli, 2021). However, it surged by 29.09% from 2000 to 2005, indicating land degradation or deforestation. After another sharp decline from 2005 to 2010 (-25.77%), it fluctuated moderately in later years, showing minor reductions and increases, with the latest rise of 1.98% from 2020 to 2023. Shrubs expanded notably from 1990 to 2000, increasing by over 25% in 1990-1995 and 23.80% in 1995-2000. However, there was a decline of -6.56% from 2000 to 2005, followed by a moderate recovery in 2005-2010 (8.36%). The highest recent fluctuation was a major loss of 14.47% from 2015 to 2020, though shrubs slightly rebounded by 1.72% from 2020 to 2023. The percentage of water bodies showed minor fluctuations over the years. While there was a slight increase in 1990-1995 (0.49%) and 2010-2015 (2.83%), declines occurred in 1995-2005 (Sidky, 2015). The latest changes (2020-2023) show only a marginal increase of 0.10%, indicating stability in recent years. Overall, the data reveal significant land cover transformations, with forests and shrubs experiencing both expansion and depletion, barren land undergoing cycles of increase and decrease, and water bodies showing only minor variations. These changes likely reflect land management practices, climatic shifts, and human interventions over time.

Changes in LULC are in line with what is often observed in protected desert and semi-arid areas, where vegetation is particularly vulnerable to weather extremes and human interference. When vegetation recovers after a period of decline, it may be due to afforestation, improved water access, reduced local disturbance, or a combination of factors such as grazing pressure, fuelwood extraction, irregular rainfall, and water availability in these ecosystems. A common reaction in dryland ecosystems damaged by overgrazing, drought stress, and land-use conversion is a transient exacerbation of land degradation and soil exposure. The rise in barren land during some intervals suggests the same thing. Results from Lal Sohanra National Park's LULC should be seen as indicators of ecosystem vulnerability, recovery potential, and management efficacy in a dryland biosphere reserve environment, in addition to class-wise spatial changes.

The alterations in land use and vegetation dynamics reported in Lal Sohanra National Park align with prior research on dry and semi-arid areas. Similar patterns of deforestation, land degradation, and vegetation regeneration emphasize the influence of human activities and climate variability on ecosystem dynamics (Yi et al., 2008). The rise in barren land at certain times indicates that land-use patterns are unsustainable, while the rise in forest cover shows that afforestation efforts are working. Also, the drop in water bodies fits with the global trend of hydrological stress in dryland ecosystems. These results underscore the need to integrate land management policies with climate adaptation measures to ensure enduring ecological sustainability (Sayat et al., 2025).

5.2. Land cover/land use dynamics from 1990 to 2023

In this study, change detection is performed using a post-classification procedure. Landsat TM data from 1990 to 2010 with a five-year interval and Landsat 8 OLI data from 2015, 2020 & 2023 are individually classified using supervised classification (maximum likelihood classifier). The result of the supervised classification expresses and detects the overall changes that accrued over the defined 33 years. The graph of the results shows the changes in Lal Sohanra Biosphere Reserve. The combined graph based on statistics is given in Figure 3.

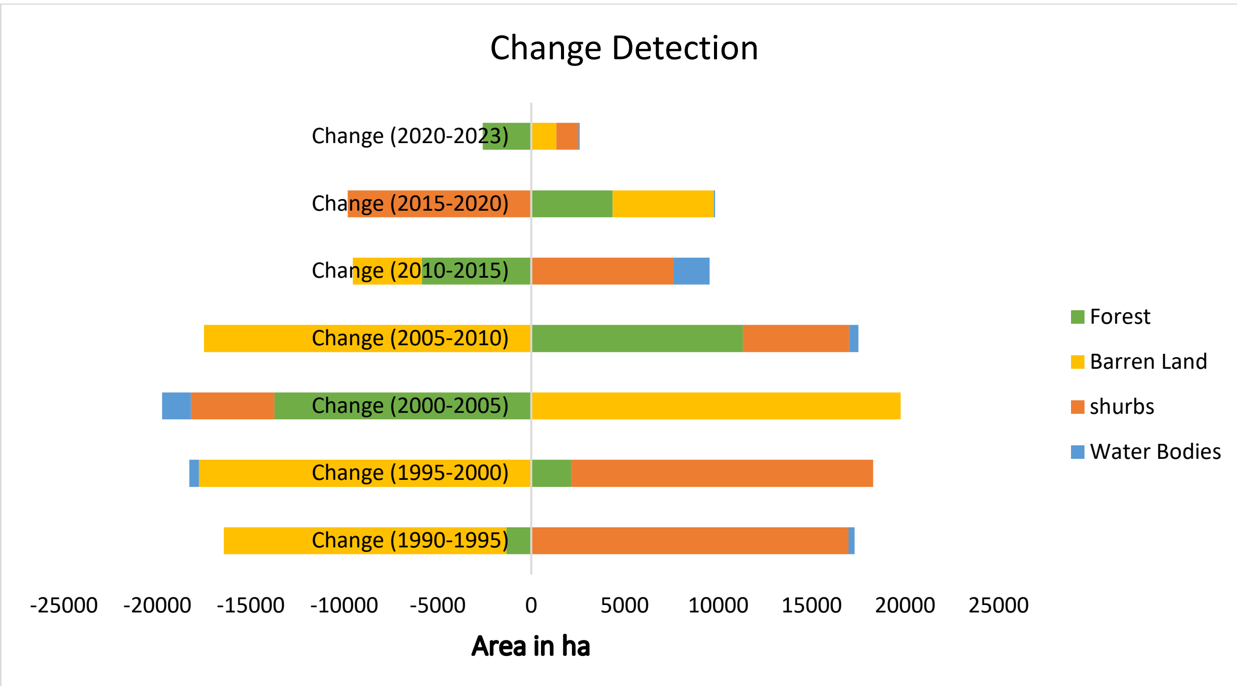


Figure 3. Land-cover change detection from 1990 to 2023 showing gains and losses in forest, barren land, shrubland, and water bodies across successive time intervals. Positive values indicate class expansion, whereas negative values indicate class reduction.

Figure 3 shows that the bar chart titled "Change Detection" illustrates the variations in land use and land cover (LULC) categories—Forest, Barren Land, Shrubs, and Water Bodies—across different time periods from 1990 to 2023. The changes are measured in hectares (ha) and presented in both positive and negative values, indicating gains and losses over time (Fig. 3).

Similar to other protected dryland and desert-margin habitats, where land-cover change is rarely linear, the change-detection data exhibit a fluctuating pattern. Instead, depending on factors such as rainfall variability, grazing intensity, plantation activity, and local management interventions, vegetation and bare land often undergo alternating episodes of degradation and recovery. Restorative and afforestation efforts have improved habitat conditions at times, with some regrowth of forest and vegetation cover; nonetheless, ecological pressures remain, as there has been a steady rise in bare land and a decline in shrub cover. According to this reading, natural variation and human-caused resource depletion are the primary drivers of biodiversity change in Lal Sohanra National Park.

From 1990 to 1995, there was a significant decline in barren land (orange) and a notable increase in shrubs (yellow), while forest cover (green) declined slightly. Water bodies (blue) showed a slight increase. Between 1995 and 2000, a further decline in barren land was observed, while shrubs continued to expand. Forest cover showed a minor recovery. The 2000-2005 period saw drastic changes, with a sharp decline in forested areas and a massive increase in barren land, indicating deforestation and land degradation (Yi et al., 2008). Shrubs also declined, while water bodies increased slightly. From 2005 to 2010, trends reversed: forest cover increased significantly, barren land decreased, and shrubs showed some recovery. Water bodies remained relatively stable. During the 2010-2015 period, shrub cover increased significantly, while forest cover declined. The barren land also saw a slight decrease, and water bodies showed some growth. Between 2015 and 2020, forested areas recovered, barren land increased, and shrubs declined sharply, suggesting vegetation loss. From 2020 to 2023, changes were minimal compared to previous years, with slight variations in forest, barren land, and shrub cover, while water bodies remained relatively stable. Overall, the chart highlights dynamic shifts in land cover over the decades, with major deforestation, regrowth cycles, and fluctuations in barren land and shrub cover (Fig. 4). These variations may be attributed to natural factors, conservation efforts, or land-use changes driven by human activities.

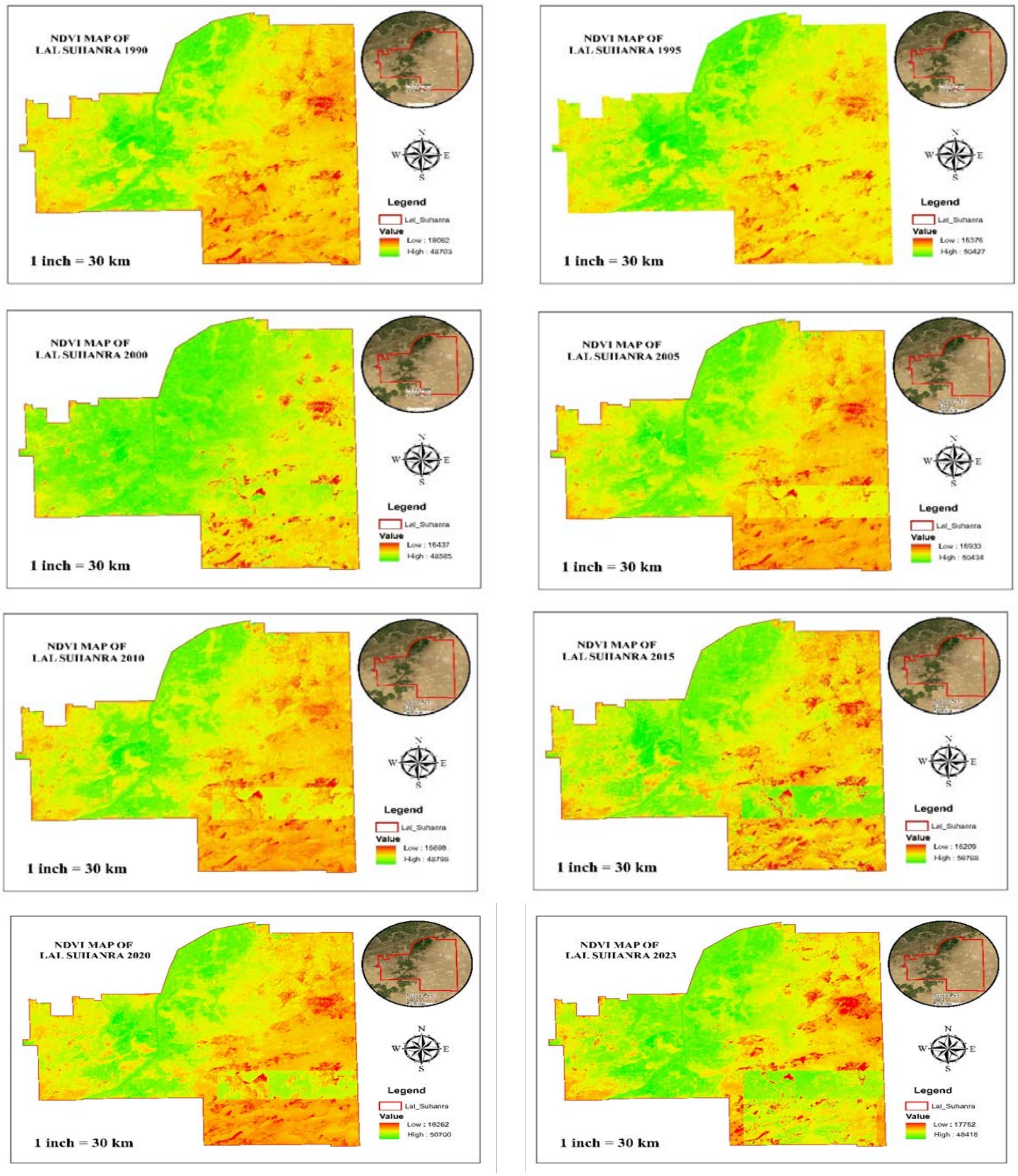


Figure 4. Normalized Difference Vegetation Index (NDVI) maps of Lal Sohanra National Park/Biosphere Reserve showing temporal variation in vegetation condition from 1990 to 2023. Higher NDVI values indicate denser or healthier vegetation, whereas lower values represent sparse vegetation, bare soil, or non-vegetated surfaces.

The normalized difference vegetation index results in Map 4.3 are explained and displayed using the Geographic Information System. The images of LANDSAT TM 1990, LANDSAT TM

2000, 2010, and LANDSAT OLI 2015, 2020, and 2023 show the results, and the key results are divided into five classes: no vegetation, low vegetation, Moderate vegetation, high vegetation, and very high vegetation. The 1990 image shows that vegetation and greenery are higher than in 2000. The water facility and the far reaches of the Lal Sohanra Biosphere Reserve are inaccessible, although vegetation is moderate during this period. The barren land is very high and completely white because there is no vegetation in the desert and dry areas.

The image of 2000 shows that vegetation decreased compared to 1990. The vegetation in 2010 and 2023 is higher than in 2000 because land cover has been converted to forest, and the barren area has decreased. The barren area also decreased in the NDVI results, as shown in the display. The patches of bare ground were also evident throughout the study area, which have been converted to other land covers. The result in 2023 differs from that in 1990. The vegetation increased, and as a result. Due to land-cover conversion, bare areas were converted into green areas. The overall view of the normalized difference vegetation index shows that vegetation increased over the 1990-to 2023 period. The 33-year period is a long time for vegetation in land cover areas. Due to increased water facilities, afforestation, and improved accessibility in remote areas of the Lal Sohanra Biosphere Reserve, land cover is changing. The vegetation increased across all similar land covers, including grassland, agriculture, and forest, during this period (Sayat et al., 2025).

5.3. Bare Soil Index (BSI) and Normalized Difference Water Index (NDWI)

The image result of the 2000 results is shown in Map 1.6. The image of 2000 shows that the canal rise area in the desert is not flowing properly, but stagnant water is shown in the layout. Due to the dryness of the Patisar Lake, the water is stagnant; it may have been rainwater or canal water. The second prominent water body, the canal discussed above, is highlighted in water. Small patches of other water bodies in desert areas were also observed. The third image in the layout is from 2010. Normalized difference water between 2000 and 1990 (Fig. 5). The desert areas' small patches of water are completely dry, and bodies have decreased compared to 1990 and 2000. The eight images from show23 show a significant difference between 1990 and 2023. The canal is flowing properly, and the small patches observed in other study areas are also present. The overan is clearly shown in the overall layout (Fig. 6). The results of the normalized difference water index help create a proper strategy for training the signatures for supervised classification, and the results are oriented. This index separates water from other land covers.

The NDWI results are significant for understanding ecosystem dynamics because water availability is a critical factor in dry protected areas. Vegetation production, animal habitat suitability, grazing distribution, and wetland persistence are all affected by changes in the extent of water bodies and moisture availability. In biosphere reserves, where desert, wetland, and forest ecosystems coexist, even small changes in surface water or seasonal moisture can have large ecological effects, according to similar dryland studies. Soil bareness, vegetation recovery, and habitat conditions that promote biodiversity can be seen using the NDWI pattern in Lal Sohanra National Park.

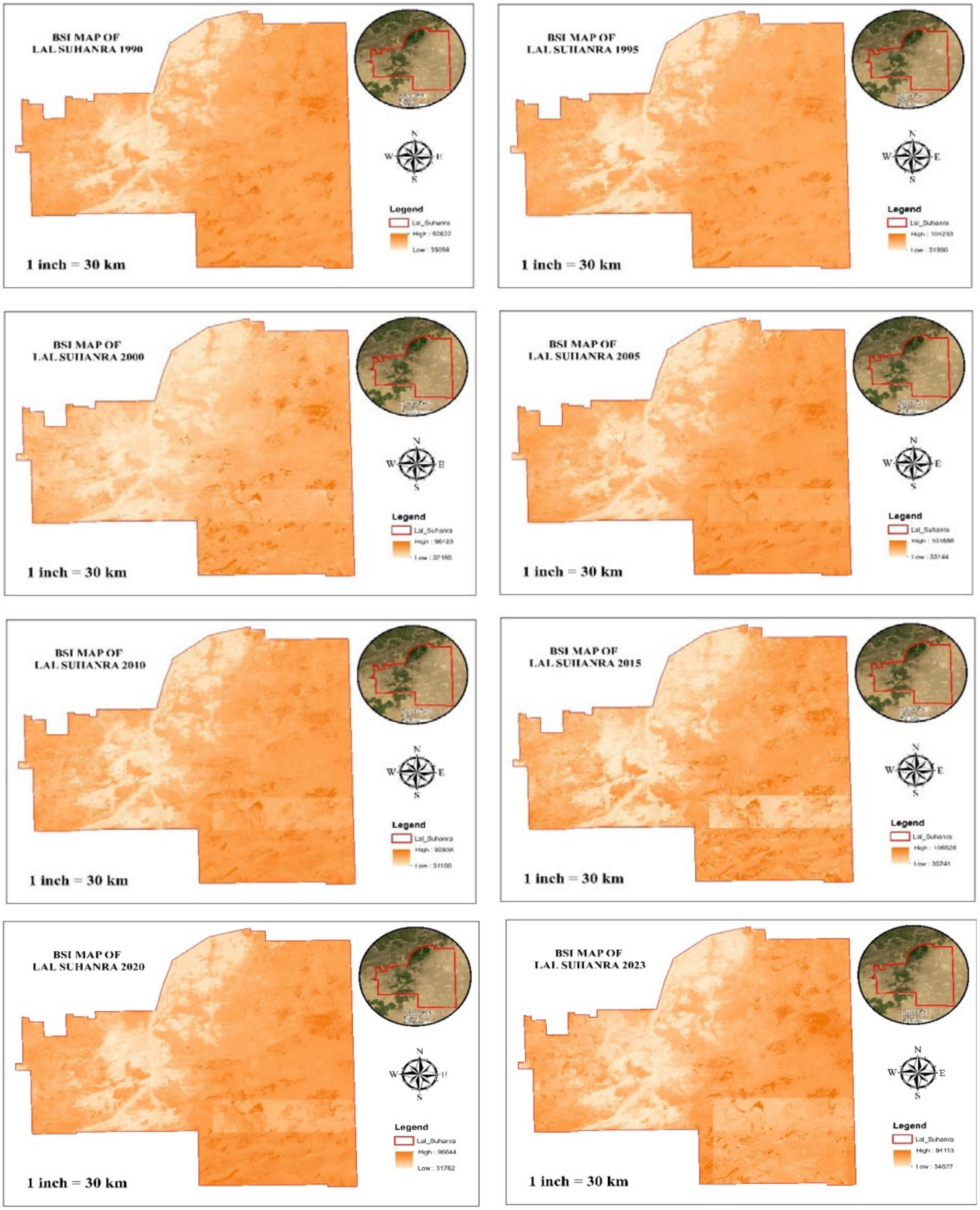
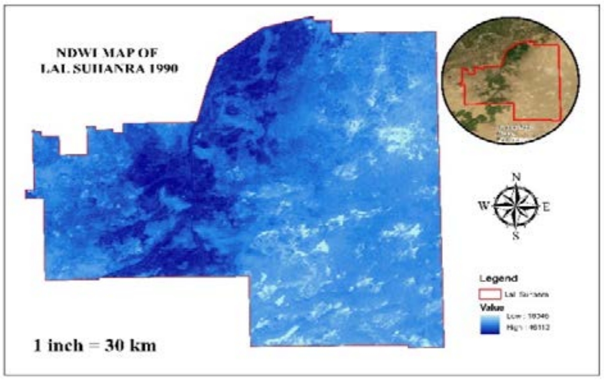
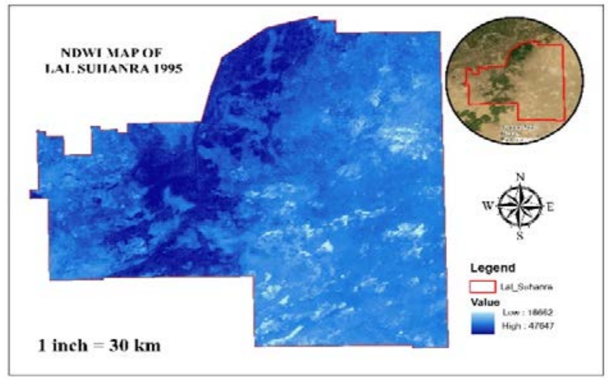


Figure 5. Bare Soil Index (BSI) maps of Lal Sohanra National Park/Biosphere Reserve from 1990 to 2023, showing spatial variation in exposed soil and land degradation risk. Higher BSI values indicate greater bare-soil exposure, whereas lower values indicate areas with vegetation cover or lower soil exposure.


NDWI MAP OF
LAL SUHANRA 1990
N
W
E
S
Legend
Value
1 inch = 30 km


NDWI MAP OF
LAL SUHANRA 1995
N
W
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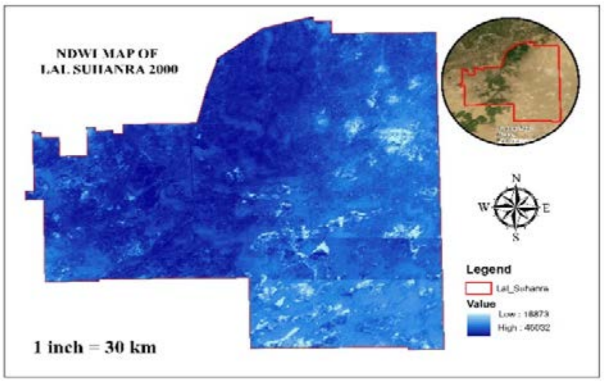
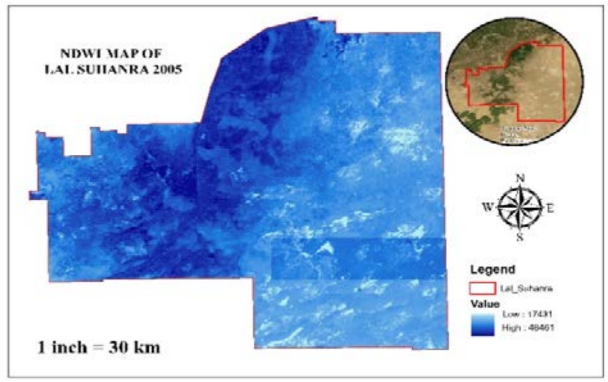
S
Legend
Lal_Suhanra
Value
High : 47647
1 inch = 30 km


NDWI MAP OF
LAL SUHANRA 2000
N
W
E
S
Legend
Lal_Suhanra
Value
Low : 16873
1 inch = 30 km


NDWI MAP OF
LAL SUHANRA 2005
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W
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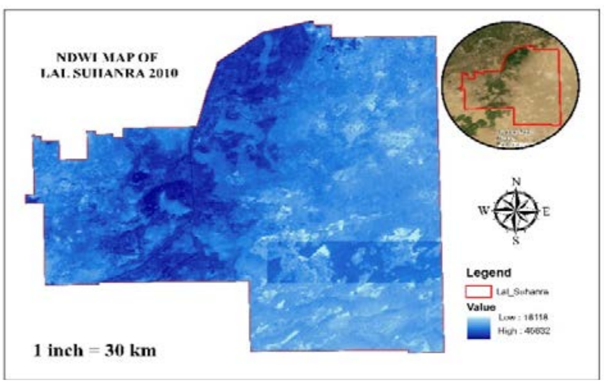
S
Legend
Lal_Suhanra
Value
Low : 17431
1 inch = 30 km


NDWI MAP OF
LAL SUHANRA 2010
N
W
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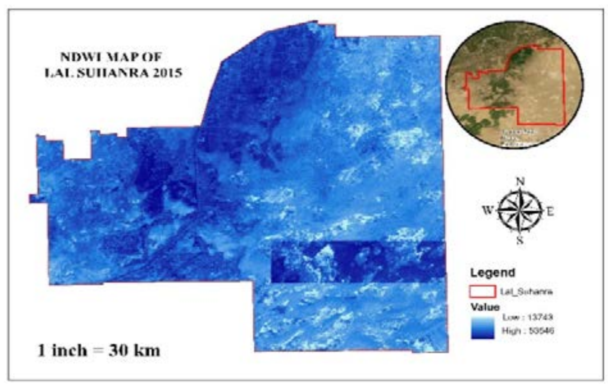
S
Legend
Lal_Suhanra
Value
Low : 16118
1 inch = 30 km


NDWI MAP OF
LAL SUHANRA 2015
N
W
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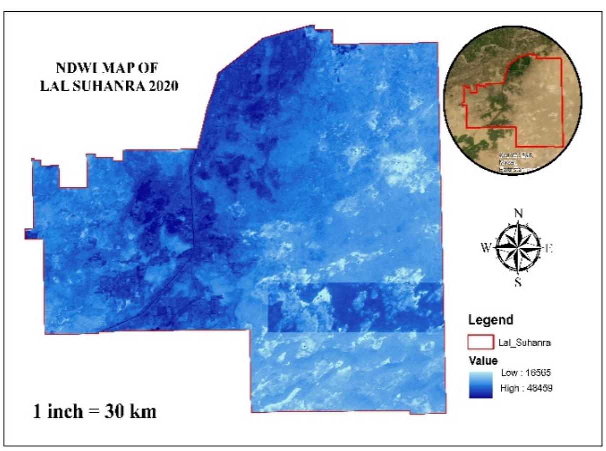
Legend
Lal_Suhanra
Value
Low : 13743
High : 53546
1 inch = 30 km


NDWI MAP OF
LAL SUHANRA 2020
N
W
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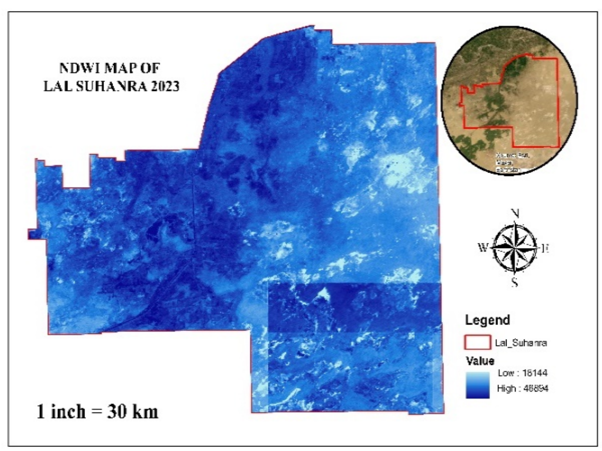
S
Legend
Lal_Suhanra
Value
Low : 16565
High : 48459
1 inch = 30 km


NDWI MAP OF
LAL SUHANRA 2023
N
W
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Legend
Lal_Suhanra
Value
Low : 16144
High : 46894
1 inch = 30 km

Figure 6. Normalized Difference Water Index (NDWI) maps of Lal Sohanra National Park/Biosphere Reserve from 1990 to 2023, showing temporal variation in water bodies and surface moisture conditions. Higher NDWI values indicate stronger water/moisture signals, whereas lower values represent dry or non-water surfaces.

The image presents a time series of Bareness Soil Index (BSI) maps for Lal Sohanra National Park covering 1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2023. These maps illustrate the spatial distribution and intensity of bare soil within the park, using a color gradient ranging from light to dark orange. Lighter shades represent lower BSI values, indicating areas with less exposed soil, likely covered by vegetation or organic matter. In comparison, darker shades indicate higher BSI values, indicating greater soil exposure and potential land degradation.

Each map includes a legend showing BSI values from low (around 17,000) to high (around 24,000), a scale bar (1 inch = 30 km), and a north arrow for orientation. An inset map in each panel highlights Lal Sohanra's location within a broader regional context, helping situate the study area geographically. Over the three-decade span, a clear trend emerges. In the earlier years (1990 to 2000), BSI values are generally moderate and more evenly distributed, suggesting relatively stable soil and vegetation conditions (Benzougagh et al., 2022). However, from 2005 onwards, the maps reveal a progressive increase in areas with higher BSI values. By 2015 and especially in 2023, darker orange shades dominate more of the park, indicating significant increases in soil bareness. This trend suggests growing land degradation, possibly due to deforestation, overgrazing, prolonged droughts, or other anthropogenic pressures. Overall, these BSI maps serve as a valuable tool for assessing environmental change and monitoring the ecological health of Lal Sohanra National Park. The consistent increase in bare soil over time raises concerns about desertification and highlights the need for effective land management and conservation strategies in the region.

Similar to other dry and semi-arid regions, this region is seeing an increase in BSI due to vegetation clearance, animal trampling, wind erosion, and extended periods of low precipitation. Higher BSI values in protected regions may indicate greater susceptibility to desertification, diminished soil protection, and habitat loss. In conjunction with changes in NDVI and LULC, the BSI data indicate that while certain areas of Lal Sohanra National Park are recovering due to improved vegetation, other areas are still under pressure to degrade. Ecosystem change in dryland protected areas is complicated and spatially complex, as this mixed response shows.

5.4. Environmental Drivers of Ecosystem Dynamics

Environmental drivers exert a critical influence on ecosystem dynamics by shaping vegetation productivity, habitat stability, and biodiversity patterns. In dry ecosystems, including the Lal Sohanra National Park, fluctuations in soil moisture, rainfall, extreme temperatures, and winds increase the ecosystem's sensitivity to land-use change. The Mann-Kendall trend test, the Sen slope estimator, and change-point analysis were used to measure trends and changes in these variables over long time periods, respectively, and to identify both gradual trend changes in climate and abrupt regime shifts (Fig 4). These environmental changes mediate land-cover changes, vegetation vitality, and habitat persistence, thereby determining biodiversity responses. The jeopardy of ecosystems and climate-adaptive conservation plans (Alexander & Hernández Álvarez, 2018): The combination of statistical trend analysis and spatial land-use dynamics provides a powerful framework for understanding ecosystem vulnerability. Using standard units, all environmental variables are presented. The dimensionless soil moisture index, millimeters (mm) for precipitation, degrees Celsius (°C) for maximum and minimum temperature, and meters per second ($m\ s^{-1}$) for wind speed are all used in meteorology. A p-value less than 0.05 was deemed statistically significant when evaluating statistical significance using the Mann-Kendall test.

Table 4. Descriptive statistics of environmental variables used for climate and ecosystem-dynamics analysis. Temperature is reported in °C, wind speed in $m\ s^{-1}$, precipitation in mm, and soil moisture index is dimensionless.

Variable	Mean	Std. Deviation	Minimum	Maximum
Soil Moisture Index	0.20	0.04	0.13	0.34
Precipitation	0.52	0.31	0.11	1.76
Maximum Temperature (°C)	48.92	1.00	46.23	51.12
Minimum Temperature (°C)	2.70	1.27	0.58	5.64
Wind Speed (ms^{-1})	2.07	0.12	1.49	3.39

These statistics show high thermal stress levels, uneven precipitation, and declining wind speeds, all of which directly affect the health of vegetation, habitat stability, and the distribution of biodiversity within Lal Sohanra National Park.

5.5. Mann–Kendall Trend Analysis with Sen’s Slope

To identify monotonic changes in environmental factors influencing the dynamics of the ecosystem (Table 5).

Table 5. Mann–Kendall trend-test results and Sen's slope estimates for environmental variables affecting ecosystem dynamics in Lal Sohanra National Park. Statistical significance was evaluated at $p < 0.05$

Variable	Kendall's Tau	Z-Value	Sen's Slope	p-Value	Trend
Soil Moisture Index	0.226	2.16	+0.0010	0.036	Significant Increase
Precipitation	0.178	1.70	+0.0040	0.091	Non-significant Increase
Maximum Temperature	−0.156	−1.49	−0.0159	0.137	No Significant Trend
Minimum Temperature	0.031	0.29	+0.0064	0.769	No Trend
Wind Speed	−0.414	−3.96	−0.0057	<0.001	Significant Decrease

Important trends in soil moisture and wind speed reveal changes in the structure of ecosystem processes. In contrast, the variability of temperature and precipitation shows instability at the climatic level rather than a linear transformation.

5.6.Seasonal Mann–Kendall Analysis

Seasonal Mann-Kendall Trend Analysis is used to measure intra-annual change, which is of concern for biodiversity and habitat continuity (Table 6).

Table 6. Seasonal Trends of Key Environmental Variables

Variable	Winter	Spring	Summer	Autumn
Soil Moisture	Low–Moderate	Moderate	High Variability	Moderate
Precipitation	Very Low	Moderate	Highest	Low
Minimum Temperature	Low	Rising	High	Moderate
Wind Speed	Low	Moderate	Highest	Low

The summer season dominates ecosystem processes due to monsoonal rainfall and extreme temperatures, directly controlling wetland persistence, vegetation productivity, and faunal breeding cycles.

5.7. Pettitt's Change-Point Analysis

Pettitt Non-Parametric Change-Point Test to test the occurrence of abrupt changes in environmental behavior, which indicate that an ecological regime has changed.

Table 7. Pettitt's Change-Point Detection Results

Variable	Change-Point Period	Significance	Ecological Implication
Soil Moisture Index	Late 1990s–Early 2000s	Significant	Irrigation & land-use impact
Precipitation	Early 2000s	Moderate	Altered rainfall regime
Wind Speed	Mid-1990s	Highly Significant	Reduced aeolian processes

Observed change points are associated with rapid land-use change and the spread of humans into buffers and transition areas, indicating anthropogenic impact on ecosystem processes (Table 7).

5.8. Spatial Linkage with LULC Dynamics

Spatial Overlay Analysis of LULC and Climatic Trends to make the relationship between land-use change and biodiversity and ecosystem behavior (Table 8).

Table 8. Spatial Linkage between LULC Change and Ecosystem Dynamics

Zone	Dominant LULC Change	Ecosystem Impact	Biodiversity Response
Core Zone	Stable vegetation	High resilience	Relatively stable
Buffer Zone	Agricultural expansion	Habitat fragmentation	Declining richness
Transition Zone	Built-up growth	Soil & habitat degradation	High vulnerability

The combined analyses show that the interaction between climate variability and land-use change drives ecosystem dynamics in Lal Sohanra National Park, with the greatest effects in the buffer and transition zones (Sidaoui, 2017). Several fluctuations and sudden environmental changes are also very threatening to biodiversity conservation in the long run.

Lal Sohanra National Park's observations of a spatial relationship between LULC change and ecosystem response are in line with those of other protected ecosystems in arid and semi-arid regions, where core conservation areas typically experience less severe habitat degradation than buffer and transition zones. Vegetation continuity is reduced, and habitat fragmentation is increased in these environments due to agricultural development, grazing pressure, fuelwood extraction, and settlement expansions. Core zones have more ecological resilience due to their typically steady vegetative conditions, in contrast to the more vulnerable buffer and transition zones, which are more affected by human activities. The spatial results indicate that Lal Sohanra National Park's biodiversity conservation efforts should target restoration, restricted resource use, and community-based management in the surrounding zones, in addition to the core protected region.

Research on protected areas has shown that biodiversity is typically under the greatest stress in areas where people rely on them for their livelihoods, and this finding aligns with the spatial pattern of ecosystem responses in the core, buffer, and transition zones. Ecological resilience is stronger in the core zone of Lal Sohanra National Park, where vegetation is relatively stable; in contrast, habitat fragmentation and soil exposure are increased by agricultural development and urban growth in the buffer and transition zones. In dryland protected areas, researchers have found the same thing: that disruption of the buffer zone lowers habitat connectivity and increases edge effects. As a result, conservation planning should focus on buffer and transition zones, where human-ecosystem interactions are strongest, according to the combined spatial and socio-economic data.

5.9. Climatic variability changes analysis of the climatic variables in Lal Sohanra National Park

The change-point analysis revealed major structural changes in surface soil moisture, precipitation, temperature, and wind speed in the Lal Sohanra National Park. The differences between pre-change (m_1) and post-change (m_2) mean values indicate changes in the hydro-climatic regimes that affect ecosystem processes throughout the biosphere reserve. Possible evidence of rising aridity is a decrease in soil moisture and precipitation following observed break years that may limit vegetation productivity and habitat suitability. Conversely, local rainfall and moisture accumulation suggest spatial heterogeneity in ecosystem response (Fig. 7). Increasing maximum and minimum temperatures are signs of the warming that can increase evapotranspiration, alter phenology, and shift species distribution patterns (Fig. 8). Variation in wind speed also affects moisture loss, seed dispersion, and dune formation, especially in desert areas (Fig. 9). Comprehensively, the detected climatic changes emphasise the dynamics of interaction between environmental forces and biodiversity trends, and the necessity of adaptive management of the park's ecosystem (Fig. 10).

Year of change point in the time series of surface soil moisture for all seasons (μ_1 and μ_2 represent the mean values of surface soil moisture before and after the change point, respectively).

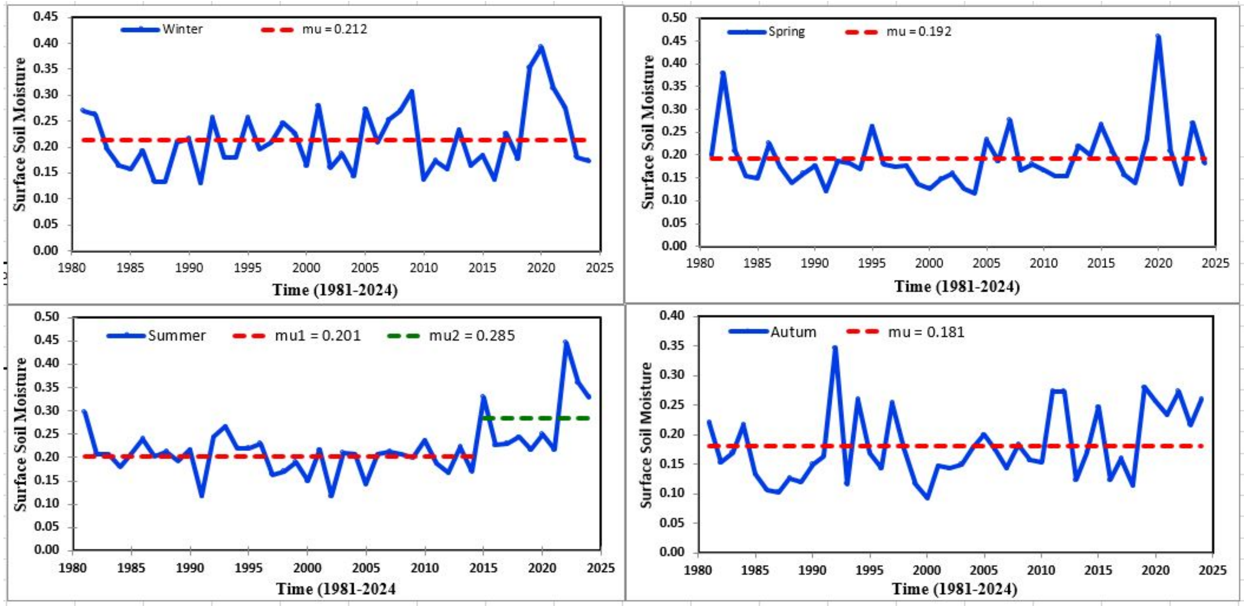

Figure 7. Pettitt's change-point results for precipitation in Lal Sohanra National Park/Biosphere Reserve. The figure shows the year of structural change in the precipitation time series, where μ_1 and μ_2 denote the means before and after the detected change point, respectively.

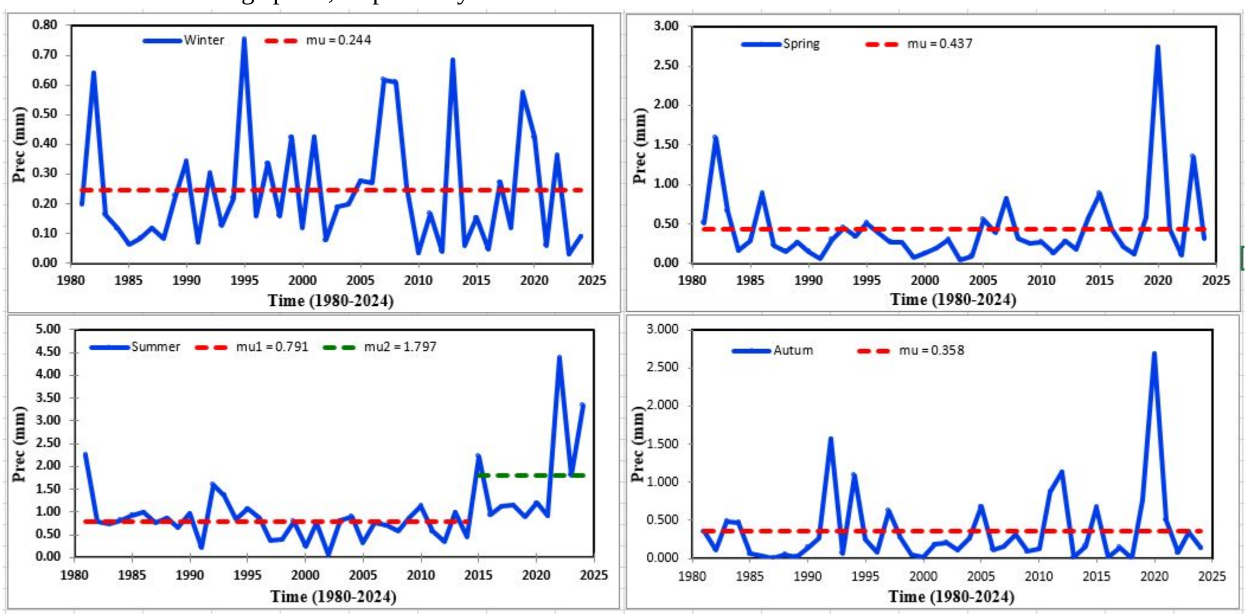

Figure 8. Pettitt's change-point results for seasonal maximum temperature in Lal Sohanra National Park/Biosphere Reserve. The figure shows the detected change-point year and the mean seasonal maximum temperature before and after the change point.

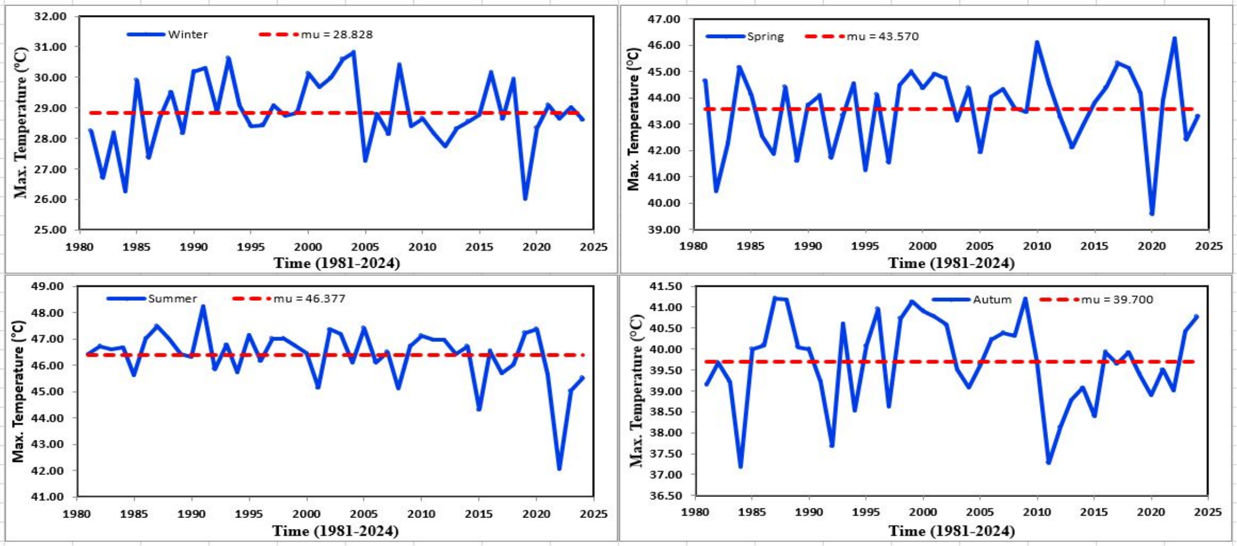

Figure 9. Pettitt's change-point results for seasonal minimum temperature in Lal Sohanra National Park/Biosphere Reserve. The figure shows the detected change-point year and the mean seasonal minimum temperature before and after the change point.

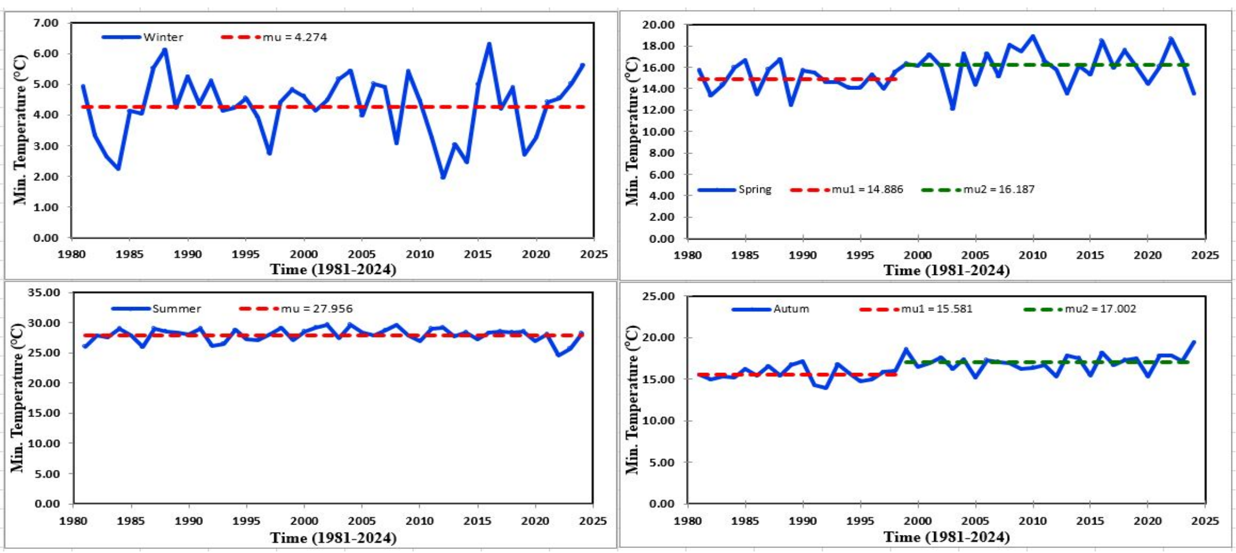

Figure 10. Pettitt's change-point results for wind speed in Lal Sohanra National Park/Biosphere Reserve. The figure shows the detected change-point year and the mean seasonal wind speed before and after the change point.

5.10. Biodiversity and Livelihood Effects

Primary field-based analysis is the most effective way to understand the complex interdependence between biodiversity and human socio-economic activities. This section presents the findings of an ecological and socio-economic survey conducted in and around the Lal Sohanra National Park. The data obtained provide information on local communities' reliance on natural resources and the consequences for biodiversity. It is analyzed based on quantitative and qualitative data collected from 100 households living around the park. The demographic outcomes show that 30 percent of respondents are aged 36-50 years, and that males constitute 85 percent of the sample, which is considered the majority in outdoor livelihoods. Checks for internal consistency, field observations, and comparisons with regional patterns of resource pressure seen in LULC and vegetation-index data were all used to confirm the socio-economic data. In towns and buffer-zone areas, we compared land-cover conditions with responses regarding fuelwood extraction, animal grazing, vegetation degradation, and reliance on resources. Interactions between livelihood activities and perceived biodiversity pressure were analyzed alongside spatial data, and descriptive statistics were used to characterize household characteristics and resource-use patterns. The socio-economic interpretation was strengthened, and a connection between household reliance on resources and observable ecological degradation was established through this integrated approach. The number of respondents who have resided in the area for less than 10 years is approximately 70%, indicating that the settlement has been expanding recently. Agriculture (38%) and livestock herding (32%) were the major livelihood activities, both highly dependent on natural resources.

The study of spatial proximity revealed that 64 percent of respondents are within 5 km of the park boundary, indicating that they are in direct contact with the conserved ecosystem. Wildlife observations indicate that 35 percent of respondents observed 10-15 species in the last year. Still, an equal number reported losing more than 10 species over the past five years, demonstrating that biodiversity is increasingly losing value. The trend analysis indicated that 57 percent of households collect firewood weekly, and 22 percent reported cutting more than 100 trees in the recent past around their settlements. Further, 63 percent of the respondents reported a decrease in vegetation and forest cover, with 29 percent estimating a decrease of 26-50 percent. Livestock grazing pressure was high, with 30 percent of households owning 11-20 animals. The income dependency analysis showed that 36 percent of households receive 11-25 percent of their income from park-related resources, and 15 percent rely on the park to earn over 50 percent of their income. On the whole, 61 percent of respondents assessed the anthropogenic effect on biodiversity as high to severe.

In line with the geographical findings, the socioeconomic data demonstrate that households' reliance on park resources (such as fuelwood, grazing land, and water) puts pressure on habitat quality and vegetation. Where conservation outcomes are heavily influenced by livelihood demands, such as in rural, resource-dependent communities, this pattern is commonly observed in protected areas near these communities. Protection measures are insufficient to conserve biodiversity in Lal Sohanra National Park due to the high proportion of households using park resources. To mitigate the direct impact on park ecosystems, we need community-based management, regulated grazing, fuelwood substitutes, livelihood opportunities, and education campaigns. Therefore, ecosystem dynamics can be better understood by combining LULC, climatic, and socioeconomic data rather than relying on just one dataset.

The socio-economic results corroborate the climatic and geographical ones by demonstrating the tight relationship between ecosystem strain and the reliance on local livelihoods. When people in dryland protected areas have few other livelihood options, activities such as grazing, gathering fuelwood, and extracting resources can hasten the loss of plants, expose soil, and disrupt habitat. The substantial reliance of families on park resources in Lal Sohanra National Park makes buffer and transition zones more susceptible to erosion. These results show that biodiversity loss is a problem for both the environment and the management of people's means of subsistence. As a result, more community involvement in park management, environmental consciousness, diversified livelihoods, restricted grazing, and alternate fuel sources are all necessary for effective conservation.

6. Conclusion

Between 1990 and 2023, Lal Sohanra National Park experienced significant changes in land use and land cover due to both natural and human-caused climate fluctuations and pressures. Vegetation loss, partial forest recovery, fluctuations in shrubland, and expansion of barren land are evident in the LULC data, with alternating periods. Indicators such as the normalized difference vegetation index (NDVI), normalized difference water index (NDWI), and bioslope stability index (BSI) patterns corroborate these shifts, showing that vegetation has recovered in some places. In contrast, in others, soil exposure and degradation remain threats. Moreover, change-point data demonstrate fundamental environmental adjustments in the late '90s and early '00s, and climatic trend analysis reveals substantial changes in wind speed and soil moisture. Taken as a whole, these results show that human activity, along with spatial and climatic factors, is the primary driver of ecosystem dynamics in the park.

Research on dry, protected ecosystems has shown that land-cover conversion, water availability, grazing intensity, and reliance on local resources significantly impact habitat stability and biodiversity. These conclusions align with this research. Habitat quality, animal mobility, and ecosystem resilience are all affected by even little changes in soil moisture, soil exposure, and vegetation in these habitats. Thus, this study's findings apply to protected regions and dryland biosphere reserves threatened by human populations and climate change.

The outcomes highlight the importance of a holistic, flexible management structure that reconciles biodiversity conservation with the practical considerations of local livelihoods. Restoring damaged buffer and transition zones, regulating grazing and fuelwood extraction, improving water-resource management, and promoting alternative livelihood options for neighboring communities should be the priorities of conservation initiatives. Households rely heavily on park resources, according to socioeconomic data; hence, community involvement is crucial. To enhance evidence-based conservation planning, future studies should use high-resolution satellite imagery, assess habitats at the species level, monitor socioeconomic conditions over the long term, and conduct field-based biodiversity monitoring. By taking these steps, we can help the environment become more resilient and ensure that Lal Sohanra Biosphere Reserve is managed sustainably.

List of Abbreviations and Symbols

Abbreviation / Symbol	Meaning
LSNP	Lal Sohanra National Park
BR	Biosphere Reserve
LULC	Land Use/Land Cover
RS	Remote Sensing
GIS	Geographic Information System
USGS	United States Geological Survey
TM	Thematic Mapper
OLI	Operational Land Imager
TIRS	Thermal Infrared Sensor
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
BSI	Bare Soil Index
MK test	Mann–Kendall trend test
SSE	Sen’s slope estimator
RMSE	Root-mean-square error
ha	Hectare
km^2	Square kilometer

°C	Degree Celsius
m s^{-1}	Meter per second
μ_1	Mean value before change point
μ_2	Mean value after change point
LuA_i	Land-use area of a class in the earlier year
LuA_{i+n}	Land-use area of the same class in the later year
n	Time interval in years

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