

Case Study

Optimizing land use for climate mitigation using nature based solution (NBS) strategy: a study on afforestation potential and carbon sequestration in Rajasthan, India

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Received: 31 May 2024 / Accepted: 16 July 2024

Published online: 23 July 2024

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Abstract

Rajasthan faces significant environmental challenges, including the pressing need for effective climate change mitigation strategies. Recognizing afforestation as a vital tool in this endeavor, this study leverages the latest in remote sensing and geospatial analysis to map out the state's afforestation potential. The goal is to assess land suitability across Rajasthan for afforestation projects and evaluate the potential carbon sequestration capabilities of different tree species. This aims to inform sustainable land management strategies that can contribute to climate change mitigation. By integrating satellite imagery, land cover data, terrain analysis, and vegetation indices, the study evaluates environmental factors such as slope, soil moisture, and vegetation health to identify areas optimal for tree planting. A carbon sequestration model was also developed to estimate sequestration rates based on species-specific growth patterns. Findings indicate that approximately 40% of Rajasthan is suitable for afforestation, with potential carbon sequestration rates ranging from 2 to 8 tons per hectare per year. Species such as *Azadirachta indica* (Neem) and *Prosopis cineraria* (Khejri) are identified as particularly effective for short-term sequestration, while *Phyllanthus emblica* (Amla) and *Ziziphus mauritiana* (Ber) are better suited for long-term carbon capture. This research highlights the importance of targeted afforestation using suitable tree species as a nature-based solution (NBS) for climate change mitigation in Rajasthan. The study offers a data-driven approach to enhancing ecosystem resilience and supports decision-making for climate adaptation in arid regions, highlighting the significant potential of Rajasthan's land for carbon sequestration through afforestation.

Keywords Carbon sequestration · Afforestation suitability · Geospatial analysis · Remote sensing · Environmental dynamics · Land cover classification · NDVI assessment

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1 Introduction

Carbon capture within the biosphere has emerged as a critical strategy to mitigate the increasing atmospheric carbon dioxide (CO₂) [1]. Rajasthan, a large state in India, faces compounded challenges of desertification and environmental deterioration, exacerbated by climate change and unsustainable land use practices [2, 3]. These issues threaten the state's diverse ecosystems and biodiversity, endanger agricultural output, and reduce water availability, impacting its population's well-being and economic stability. Both anthropogenic and natural factors have shaped Rajasthan's environment over the centuries [4]. The state's Recorded Forest Area (RFA) covers approximately 32,863 km², which is 9.60% of its total land area. This includes Reserved Forests (37.0% of the RFA), Protected Forests (56.4%), and Unclassed Forests (6.5%) [5]. According to the Forest Survey of India's 2021 report, Rajasthan's forest cover stands at 16,654.96 km², or 4.87% of the state's geographical area, categorized into Very Dense Forest, Moderately Dense Forest, and Open Forest [6]. Additionally, the state has two national parks and 25 wildlife sanctuaries, covering 421.23 and 8739.98 km², respectively, and hosts two Tiger Projects with a combined tiger population of 70 [7].

Recognizing afforestation as a vital tool for climate change mitigation, this study leverages remote sensing and geospatial analysis to map out Rajasthan's afforestation potential. The study assesses land suitability across Rajasthan for afforestation projects and evaluates different tree species' potential carbon sequestration capabilities. By integrating satellite imagery, land cover data, terrain analysis, and vegetation indices, the study evaluates environmental factors such as slope, soil moisture, and vegetation health to identify optimal areas for tree planting. A carbon sequestration model was developed to estimate sequestration rates based on species-specific growth patterns. Findings indicate that approximately 40% of Rajasthan is suitable for afforestation, with potential carbon sequestration rates ranging from 2 to 8 tons per hectare per year. Species such as *Azadirachta indica* (Neem) and *Prosopis cineraria* (Khejri) are identified as particularly effective for short-term sequestration. At the same time, *Phyllanthus emblica* (Amla) and *Ziziphus mauritiana* (Ber) are better suited for long-term carbon capture. The study offers a data-driven approach to enhancing ecosystem resilience. It supports decision-making for climate adaptation in arid regions, emphasizing the significant potential of Rajasthan's land for carbon sequestration through afforestation.

Climate change poses severe threats to arid regions like Rajasthan, where water scarcity, extreme temperatures, and soil degradation are already critical issues. These challenges will likely intensify, leading to more frequent and severe droughts, reduced agricultural productivity, and further biodiversity loss. Effective mitigation strategies are essential to sustaining the livelihoods of the millions who depend on these fragile ecosystems. Afforestation, the process of planting trees in previously non-forested areas, is globally recognized as a vital strategy for carbon sequestration. By capturing and storing atmospheric CO₂, afforestation contributes significantly to reducing greenhouse gases and mitigating climate change impacts. Strategic tree planting enhances carbon sinks, which is crucial in achieving international climate goals such as those outlined in the Paris Agreement. In addition to carbon sequestration, afforestation in arid regions like Rajasthan offers numerous ancillary benefits. It stabilizes soil, reducing erosion and desertification, which are major concerns in these areas. Improved water retention is another significant advantage, as trees help maintain soil moisture and replenish groundwater, which is essential for sustaining agriculture and local water supplies. Enhanced biodiversity is a further benefit, with afforestation providing habitats for various species, thus contributing to ecosystem resilience and sustainability.

Afforestation is globally recognized as a pivotal strategy for carbon sequestration, crucial for reducing atmospheric CO₂ levels and mitigating climate change impacts. Strategic tree planting supports international climate goals, such as those outlined in the Paris Agreement, and offers additional benefits in arid regions. It stabilizes soil, prevents erosion, and enhances water retention, vital for sustaining agriculture and local communities. Moreover, afforestation fosters biodiversity by creating habitats for diverse species, thereby bolstering ecosystem resilience. In regions like Rajasthan, targeted afforestation efforts with suitable tree species can restore degraded lands, improve agricultural productivity, and uplift rural livelihoods. The manuscript highlights the urgent need for mature, scientifically robust discussions and implementations of afforestation to effectively address environmental challenges and socio-economic development. In the context of Rajasthan, targeted afforestation using carefully selected tree species represents a multifaceted approach with significant potential. Beyond its role in carbon sequestration to mitigate climate change, afforestation plays a pivotal role in restoring degraded lands, thereby improving soil quality and preventing erosion. This restoration effort supports local biodiversity by providing habitats for various species and enhancing ecosystem resilience against environmental stresses such as droughts and heat waves. Furthermore, the

socio-economic impacts of afforestation are profound. By revitalizing degraded landscapes, these initiatives create new opportunities for rural communities dependent on natural resources. Improved land productivity resulting from afforestation can boost agricultural yields and secure water resources, essential for sustaining livelihoods in arid regions. Additionally, strategic tree planting fosters local employment in forestry and related sectors, contributing to economic stability and poverty alleviation efforts. These combined benefits underscore the urgent need to integrate afforestation into comprehensive climate action plans, highlighting its potential to address environmental challenges while promoting sustainable socio-economic development globally in Rajasthan and similar regions. There is a growing discourse on environmental conservation in Rajasthan, focusing on climate change mitigation and ecosystem protection [8]. Kundu et al. conducted a study on desertification in western Rajasthan, India, using remote sensing to analyze vegetation cover decline as an indicator of land degradation. The research utilized rain-use efficiency (RUE) and the residual trend method to assess the relationship between NDVI (Normalized Difference Vegetation Index), rainfall patterns, and desertification trends from 1983 to 2013. Their findings reveal significant vegetation depletion due to climatic variability and human activities, with approximately 35% of the region experiencing severe human-induced desertification. This underscores the urgent need for sustainable land management practices to address desertification in arid regions [9]. Rivera-Marin et al. reviewed the expanding use of remote sensing in desertification research, tracing its application since 1991 and noting a surge in studies from 2015 to 2020, primarily in Asia with a focus on China. They utilized Landsat imagery for classification and change detection to analyze variables like land cover and NDVI, highlighting the lack of standardized thresholds as a critical gap in accurately assessing desertification risks [10]. Lezaic et al. emphasized the importance of afforestation in combating the annual loss of 18.7 million acres of forest due to various pressures. Their research, supported by GIS and satellite data, assessed land suitability for afforestation in Bor, Serbia, focusing on Black pine. The study identified 7.56% of the area as highly suitable through fieldwork and NDVI analysis, contributing to sustainability goals under the Forest and Climate project backed by the Ministry of Environmental Protection [11]. Zomer et al. conducted a global analysis to identify land suitable for Clean Development Mechanism afforestation and reforestation (CDM-AR) projects under the Kyoto Protocol's criteria. They found 749 million hectares eligible, primarily in South America (46%) and Sub-Saharan Africa (27%), with Asia having smaller areas of low-intensity agricultural land. The study cautioned against potential implications for food security and local livelihoods with the expansion of CDM-AR projects, emphasizing the need to consider socio-economic and ecological impacts [12].

The study conducted by Tanwar et al. from ICAR-Central Arid Zone Research Institute in Jodhpur, India, evaluated the carbon sequestration potential of various land-use systems in arid western Rajasthan. Their research compared eight recommended systems and found substantial variations in biomass and soil carbon stocks among them. Farm forestry using *Acacia tortilis* exhibited the highest biomass carbon stock at $31.4 \text{ Mg C ha}^{-1}$ and the highest soil carbon stock at $47.6 \text{ Mg C ha}^{-1}$, resulting in a total carbon sequestration of $49.80 \text{ Mg C ha}^{-1}$ over nineteen years. Silvoarable systems with *Prosopis cineraria* and *Hardwickia binata* showed biomass carbon stocks ranging from 8.8 to $10.6 \text{ Mg C ha}^{-1}$ and soil carbon stocks of 32.5 to $33.9 \text{ Mg C ha}^{-1}$, sequestering 11.0 to $13.3 \text{ Mg C ha}^{-1}$ in total. Other systems like hortipasture, agri-horti, silvopasture, and sole pasture also demonstrated varying levels of carbon sequestration potential, highlighting the benefits of integrating trees into agricultural and pastoral landscapes in Rajasthan's arid regions. These findings provide critical insights into sustainable land-use practices that can mitigate climate change impacts, enhance soil fertility, and support rural livelihoods, informing policies aimed at promoting resilient agricultural systems in similar arid environments across India [13].

Babbar et al. investigates carbon sequestration dynamics in the Sariska Tiger Reserve, India, using Markov chain and InVEST models. It underscores the critical role of forests in mitigating climate change through biomass carbon storage and highlights significant carbon losses observed from 2000 to 2018, amounting to 1.351 Tg, primarily attributed to illegal fuelwood extraction. Projections suggest a further loss of 0.107 Tg by 2035, mitigated by forest management practices like strategic plantations. The economic impact reveals substantial carbon losses valued at \$214.57 million from 2000 to 2018, contrasting with a projected \$17.19 million worth of carbon sequestration in 2035. This underscores the economic and environmental benefits of reforestation and sustainable management practices, advocating for enhanced conservation efforts and cleaner energy initiatives to curb carbon emissions in sensitive ecosystems like the Sariska Tiger Reserve [14].

Afforestation and carbon sequestration through Nature-based Solutions (NbS) are increasingly recognized as pivotal strategies for mitigating climate change impacts, particularly in regions like Rajasthan, India. Studies highlight NbS applications relevant to afforestation initiatives, such as the chapter "Climate Change and Nature-Based

Solutions: Harnessing Nature's Potential for Adaptation and Mitigation," which explores integrating NbS into climate policies to enhance sustainability, resilience, and coexistence with nature while addressing climate challenges (Optimizing Land Use for...). Another study, "Modeling place-based nature-based solutions to promote urban carbon sequestration," provides insights into NbS frameworks that maximize local-scale benefits, offering applicable lessons despite its urban focus (Optimizing Land Use for...). Additionally, the study "Nature-based solutions potential for flood risk reduction in urban areas" discusses NbS's role in mitigating flood risks, highlighting its relevance to Rajasthan's flood-prone regions and underscoring NbS's no-regrets approach to climate adaptation (Optimizing Land Use for...). Furthermore, "A Critical Review of Nature-Based Systems (NbS) to Treat Stormwater Pollutants" assesses NbS effectiveness in managing stormwater, offering insights that can inform similar environmental challenges in Rajasthan, despite its broader focus (Optimizing Land Use for).

The studies reviewed underscore the critical role of Nature-based Solutions (NbS) in global and regional climate strategies, emphasizing afforestation's significance in addressing desertification, carbon sequestration, and climate change impacts. Remote sensing has become pivotal in monitoring these processes and evaluating land suitability for tree planting. Global and regional assessments have mapped afforestation and reforestation potentials, identifying effective methodologies and key areas for implementation. Integrating Geographic Information Systems (GIS) enhances environmental management by refining land suitability analyses. This research introduces innovative methodologies for assessing afforestation suitability in Rajasthan, combining advanced remote sensing with detailed environmental analysis. A key feature is species-specific carbon sequestration simulation, enhancing precision in identifying suitable tree species and evaluating afforestation's potential benefits for carbon sequestration and climate change mitigation.

This study aims to conduct a comprehensive geospatial analysis to assess land suitability for afforestation in Rajasthan, focusing on enhancing carbon sequestration capabilities. By integrating remote sensing data with critical environmental factors such as soil attributes, climatic conditions, and vegetation health, the research aims to identify optimal areas and suitable tree species for afforestation initiatives. This approach strategically aims to mitigate climate change impacts and bolster ecosystem resilience. Additionally, the study will comprehensively analyze tree cover distribution and assess the effects of desertification by examining spatial data on tree cover dynamics, temperature fluctuations, and wind patterns. The study aims to provide scientifically supported recommendations for sustainable land management and effective afforestation strategies in Rajasthan and beyond. These insights aim to assist policymakers, environmental advocates, and local communities in implementing targeted environmental conservation efforts, advancing climate resilience, and promoting sustainable resource utilization practices.

2 Materials and methods

2.1 Study area

Rajasthan is a state in India that is known for its beautiful landscapes and diverse ecology [15] Fig. 1. Rajasthan is nestled within the Thar Desert. The state serves as a miniature representation of environmental challenges [16]. These challenges are faced not just in India but also in the world at large. Rajasthan has a population surpassing 77 million individuals. The state has a diverse economy spanning from agriculture to tourism. Rajasthan's developmental path is closely tied to its natural resources. These natural resources include land and water. Conversely, rapid urbanization has put an enormous strain on Rajasthan's delicate ecosystems. Unsustainable land use methods have also put strain on the ecosystems. Climate variability has put strain on the ecosystems too. This strain has intensified problems such as soil erosion. Water shortage is another intensified problem. Biodiversity decline is also an intensified problem. Additionally, the state is experiencing significant desertification [17]. The state is also experiencing forest cover loss.

The study focuses on Rajasthan, India, a state renowned for its striking landscapes and rich cultural heritage, encapsulating a vast expanse of the Thar Desert, arid regions, and relatively greener patches in the south and east. Covering an area of approximately 342,239 km², Rajasthan is the largest state in India by land area, accounting for about 10.4% of the country's total geographical area. The international border with Pakistan bounds it to the west

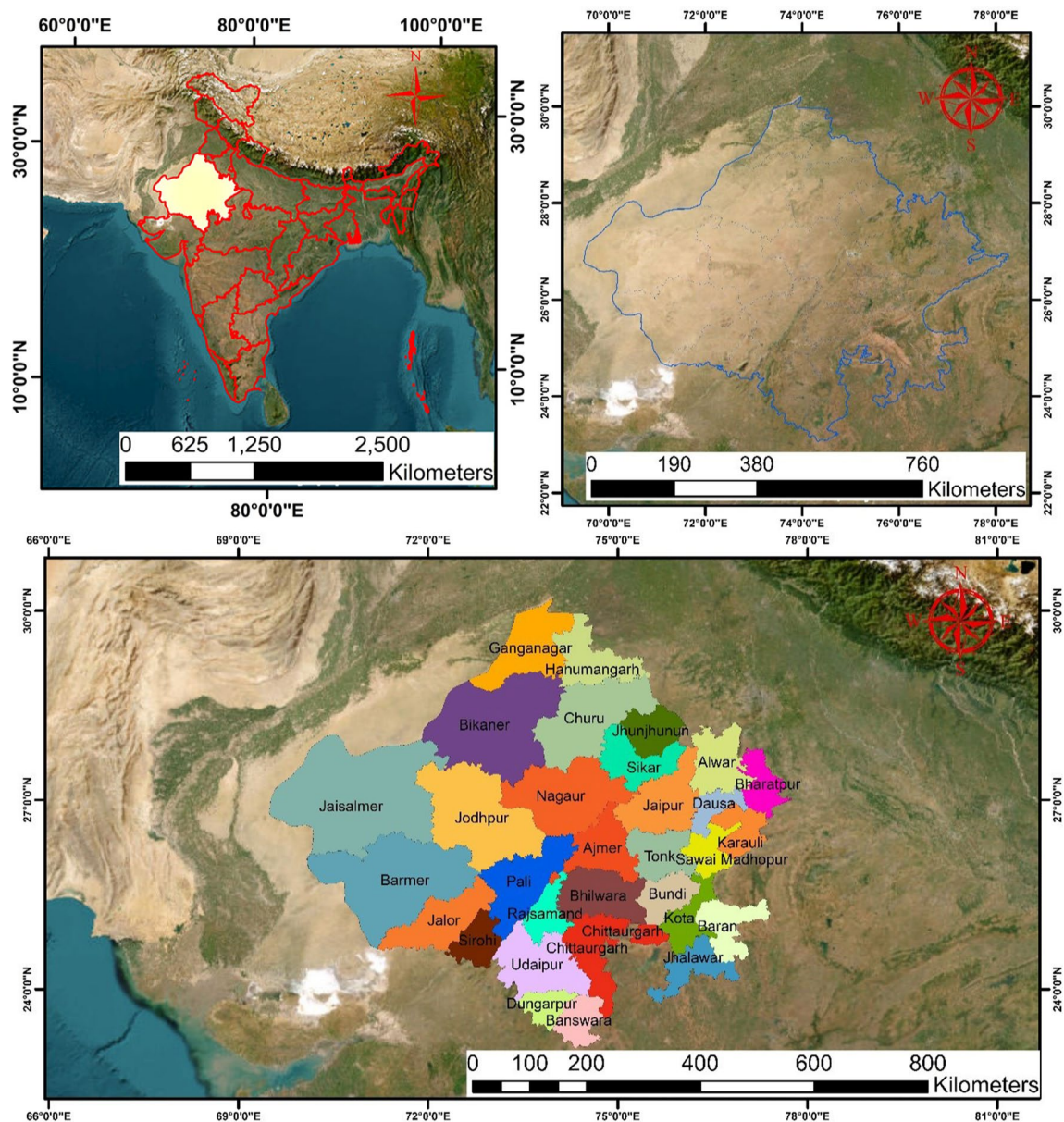


Fig. 1 Location of the study area

and northwest and by five Indian states: Punjab, Haryana, Uttar Pradesh, Madhya Pradesh, and Gujarat. Geographically, Rajasthan is characterized by diverse landscapes, including the arid sandy stretches of the Thar Desert, rocky terrain, hilly regions in the south and southeast (part of the Vindhya and Aravalli mountain ranges), and the fertile plains of the east. This variation in topography contributes to a wide range of climatic conditions across the state, from extreme aridity in the west to semi-arid and subtropical humid conditions in the east and south.

2.2 Data collection

The data collection process involves acquiring a series of high-resolution optical images from the Sentinel-2 satellite, a part of the Copernicus Programme orchestrated by the European Space Agency (ESA) [18]. These images are critical for providing up-to-date and precise information about the Earth's surface. To ensure the accuracy and applicability of the data, the images are meticulously filtered based on the date they were captured and the presence of cloud cover. This filtering process is essential to guarantee that only the most recent and unobstructed images are used for analysis, thereby providing a clear and reliable depiction of the current state of the land surface.

Step	Date	Purpose	Satellite images	Software used	Equations involved	Analysis process
Data Collection	2021 mean	Acquire high-resolution images	Sentinel-2	Google Earth Engine	N/A	Filter images based on date and cloud cover to ensure accuracy and applicability
Region of Interest Definition	February	Define study area	N/A	GAUL dataset (FAO)	N/A	Use GAUL dataset to demarcate Rajasthan's boundaries
Image Processing	February	Refine images for the study area	Sentinel-2	QGIS, ArcGIS	N/A	Clip images to fit Rajasthan's boundaries
Land Cover Classification	March	Classify land cover	Glob Cover (ESA)	QGIS, ArcGIS	N/A	Remove irrelevant sections and reclassify to focus on afforestation areas
Slope Calculation	April	Calculate terrain slope	SRTM (USGS)	QGIS, ArcGIS	N/A	Calculate slope and exclude areas with slope > 15 degrees
Soil Moisture Calculation	May	Determine soil moisture levels	Sentinel-2	QGIS, ArcGIS	Soil Moisture = $(\text{Band11} + \text{Band12}) / (\text{Band11} - \text{Band12})$	Calculate soil moisture and exclude areas with moisture < 0.1
NDVI Calculation	June	Assess vegetation health	Sentinel-2	QGIS, ArcGIS	NDVI = $(\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$	Calculate NDVI and exclude areas with NDVI < 0.3
Suitability Assessment	July	Assess land suitability for afforestation	Sentinel-2, SRTM, Glob Cover	QGIS, ArcGIS	Multi-Criteria Evaluation (MCE)	Assign scores based on land cover, slope, soil moisture, and NDVI to map suitable areas for afforestation
Carbon Sequestration Rate Definition	August	Define carbon sequestration rate	NA	Google Earth engine	Based on Suitability class	Use a baseline rate of 10 tons/ha/year and adjust by species-specific growth rates
Carbon Credits Calculation	September	Calculate carbon credits	N/A	QGIS, ArcGIS	1 carbon credit = 1 metric tCO ₂ e	Convert sequestration potential into CO ₂ equivalents and visualize using GeoTIFF files

2.3 Region of interest definition

To delineate the study's specific geographic focus, the region of interest is precisely defined as the state boundaries of Rajasthan, India. This critical step ensures that the analysis is confined to the targeted area. The demarcation of Rajasthan's boundaries is conducted using the Global Administrative Unit Layers (GAUL) dataset maintained by the Food and Agriculture Organization of the United Nations (FAO). The GAUL dataset is known for its high level of accuracy and detail regarding administrative boundaries [19], providing a reliable framework for various spatial analyses. By utilizing this dataset, the research can accurately align the satellite imagery and other geospatial data with the official extents of Rajasthan, thereby ensuring that the subsequent analyses, such as land cover classification and carbon sequestration potential, are specific to the region in question.

2.4 Image processing

The image processing phase involves a careful refinement of the collected satellite imagery to align with the region of interest, which, in this case, is the state boundary of Rajasthan. The process starts with clipping, where each image in the collection is trimmed to fit precisely within the predefined geographic boundaries of Rajasthan. This ensures that only relevant data is retained for analysis.

2.5 Land cover classification

The land cover classification step involves utilizing the Glob Cover dataset from the European Space Agency to obtain a global land cover map [20, 21]. This map is then tailored to the specific region of Rajasthan by removing irrelevant sections [22]. The map is further refined by reclassifying it to omit areas such as bodies of water, urban developments, croplands, and barren lands, focusing the analysis on potential areas for afforestation.

2.6 Slope calculation

Using the high-resolution elevation data from the Shuttle Radar Topography Mission (SRTM) dataset by the USGS the slope of the terrain is calculated [23, 24]. Areas with a slope greater than 15 degrees are then excluded to focus on regions more suitable for afforestation.

2.7 Soil moisture calculation

Soil moisture levels are determined by analyzing Sentinel-2 satellite imagery, specifically utilizing the optical depth method applied to the bands [25]. This method calculates soil moisture by employing the formula:

$$\frac{Band11 + Band12}{Band11 - Band12}$$

Following the calculation, areas are reclassified, with those having a soil moisture threshold below 0.1 being excluded to identify regions potentially unsuitable for afforestation due to insufficient moisture levels.

2.8 NDVI calculation

The Normalized Difference Vegetation Index (NDVI) is computed using data from Sentinel-2 satellite bands. NDVI, a widely utilized indicator for evaluating vegetation health and density, is derived from the difference between the near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs) divided by the sum of these two measures [26, 27]. For this analysis, areas with an NDVI value below 0.3 are reclassified and excluded to focus on regions with healthier and denser vegetation suitable for afforestation efforts.

2.9 Suitability assessment

For the suitability assessment, a Multi-Criteria Evaluation (MCE) technique is employed, integrating various factors such as land cover, slope, soil moisture, and NDVI [28, 29]. Each pixel within the study area is assigned a score based on these criteria, effectively combining them to map out areas suitable for afforestation. This method allows for a comprehensive analysis of the land's potential, pinpointing the most viable locations for tree planting by assessing their overall suitability across the mentioned environmental parameters [30].

2.10 Carbon sequestration rate definition

A theoretical rate of 10 tCO₂e/ha/year is often used as a baseline for estimating carbon sequestration potential. This figure is supported by various research studies and reports which suggest that, on average, reforested or afforested areas can sequester this amount of carbon dioxide equivalent annually. Specific tree species, however, have different carbon sequestration capabilities, influenced by factors such as growth rates and environmental conditions.

MedCrave Online: Discusses various aspects of carbon sequestration and provides insights into average sequestration rates for different tree species MedCrave Online.

For instance, species-specific sequestration rates include:

- Neem: 5 tCO₂e/ha/year
- Khejri: 10 tCO₂e/ha/year
- Rohida: 15 tCO₂e/ha/year
- Ber: 20 tCO₂e/ha/year
- Amla: 25 tCO₂e/ha/year.

These rates consider each species' unique growth characteristics and carbon absorption capacities. These variations are crucial to consider for accurate estimation and planning in afforestation projects. A study published in Carbon Balance and Management discusses carbon sequestration rates from forest landscape restoration activities. This study found that removal factors for different forest types ranged from 4.5 to 40.7 tCO₂e per hectare per year, with planted forests typically showing the highest removal rates; it also discusses the amount of carbon sequestration by particular trees (BioMed Central). Research from Forest Research details the net annual carbon sequestration in UK woodlands, showing various rates of CO₂ equivalent sequestration depending on forest type and management practices. This research helps understand the variability and potential of different tree species in sequestering carbon. To calculate the overall carbon sequestration potential, this study multiplies the suitability scores derived from previous steps by the pixel area and the assigned carbon rate [31]. The result is then adjusted for hectare measurements by dividing by 10,000, converting the figures from square meters to hectares.

$$C_{seq} = \sum (S_i \times A_i \times R)$$

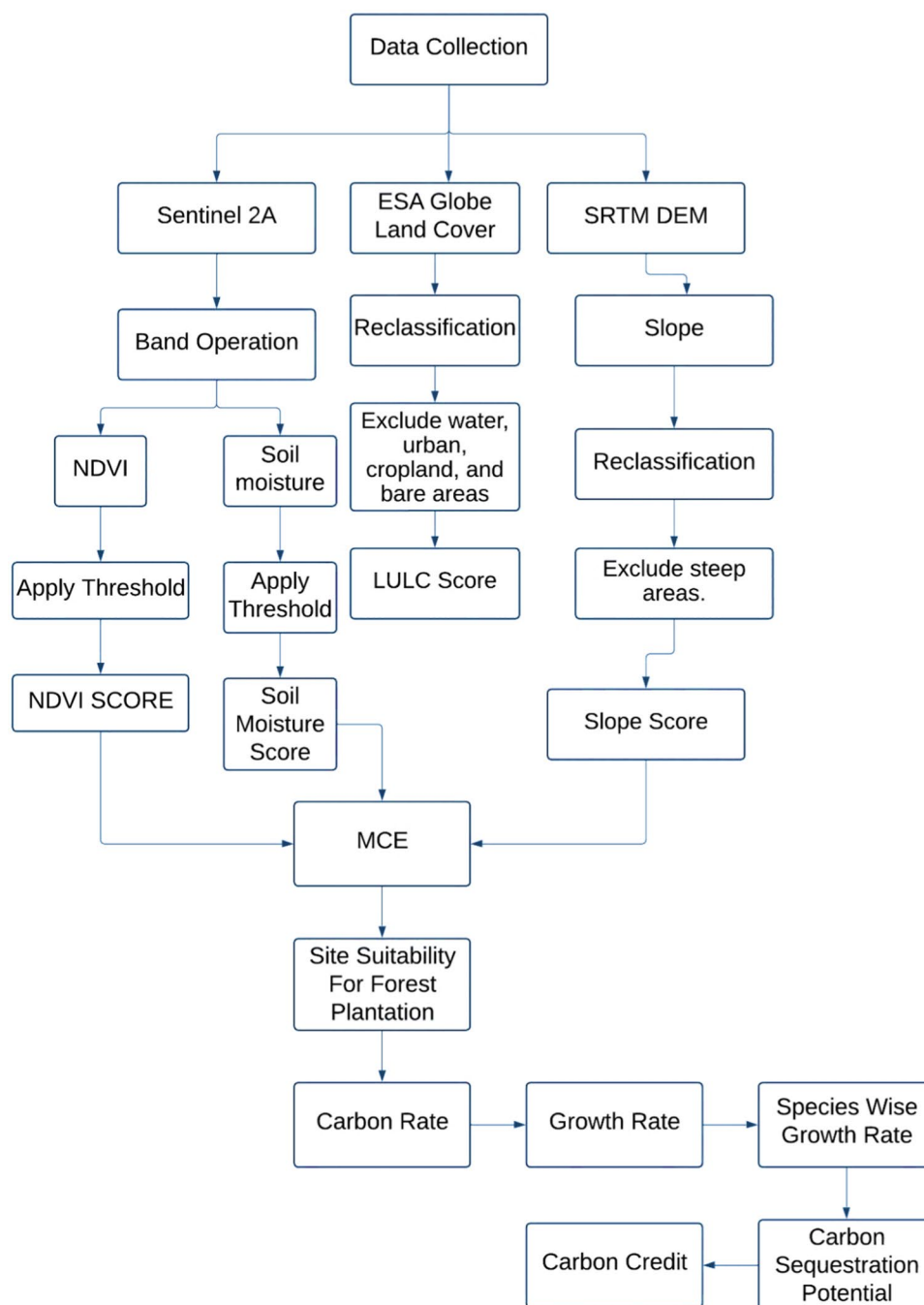
- C_{seq} is the total carbon sequestration potential (tCO₂e Y⁻¹).
- S_i is the suitability score of pixels i
- A_i is the area of pixel i (in hectares).
- R is the carbon sequestration rate (tCO₂e ha⁻¹ Y⁻¹ per year).

For species-specific calculations, the equation can be adjusted to:

$$C_{seq, species} = \sum (S_i \times A_i \times R_{species})$$

where $R_{species}$ is the sequestration rate for the specific tree species.

Fig. 2 A schematic overview of the study's methodological approach



2.11 Carbon credits calculation

The carbon credits calculation transforms the carbon sequestration potential of different areas and tree species into carbon dioxide equivalents. This process standardizes the potential into a universal metric, where each carbon credit represents one metric ton of CO₂ sequestration. This standardization facilitates the understanding and comparison of the sequestration capabilities across various species and locations (Fig. 2).

$$1 \text{ carbon credit} = 1 \text{ metric tCO}_2\text{e}$$

Fig. 3 Graphical representation of tree cover percentages across Rajasthan

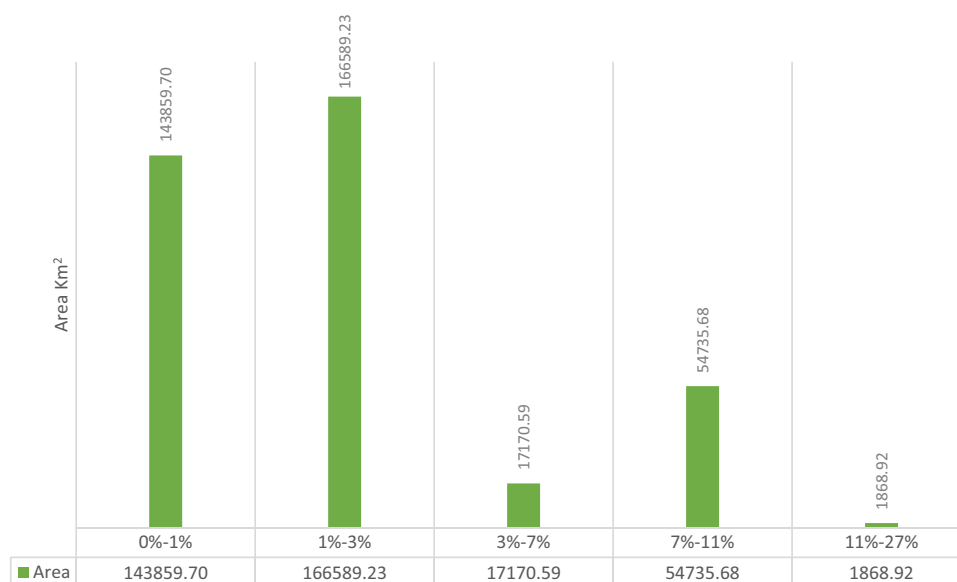


Table 1 The max temperature anomaly 1988–2010 mean vs 2020 mean (Annual)

Temperature (°C)	Area (km ²)
–0.017 to 0	148,176
0 to 0.1	235,648

3 Results and discussion

3.1 Tree cover

The data given represents the tree cover in Rajasthan as per the MODIS continuous vegetation field data (Fig. 4). The spatial distribution of tree cover is given (Fig. 3). 0–1% Tree Cover: An area of 143,859.70 km² in Rajasthan has a tree cover between 0 and 1%. This could be largely desert or barren land with very few trees. 1–3% Tree Cover: An area of 166,589.23 km² has a tree cover between 1 and 3%. This could represent areas with sparse vegetation. 3–7% Tree Cover: An area of 17,170.59 km² has a tree cover between 3 and 7%. These areas have moderate tree cover. 7–11% Tree Cover: An area of 54,735.68 km² has a tree cover between 7 and 11%. These areas could be considered as having moderate tree cover. 11–27% Tree Cover: An area of 1868.92 km² has a tree cover between 11 and 27%. These areas have the highest tree cover in the given data and could represent forests or areas with dense vegetation. This data provides a snapshot of the distribution of tree cover across Rajasthan.

3.2 Desertification impact on Rajasthan

From the data above provided (Table 1), it appears that the area experiencing a slight increase in temperature (0 to 0.1 °C deviation from the average) is larger (235,648 km²) than the area experiencing a slight decrease in temperature (–0.017 to 0 °C deviation from the average) which is 148,176 km² (Fig. 4). This could suggest that desertification might lead to an overall temperature increase in Rajasthan, as the area with a positive temperature deviation is larger.

The data shows that the area in Rajasthan experienced certain wind anomalies (Table 2). Wind anomaly refers to the deviation of wind speed from the average. An area of 76,672 km² experienced a wind anomaly between –1.7 and 0. This means the wind speed was below the average in this area. An area of 70,528 km² experienced a wind anomaly between 0.01 and 0.033, indicating a slight increase in wind speed from the average. An area of 76,080 km² had a wind anomaly

Fig. 4 Spatial distribution of tree cover in various district in Rajasthan

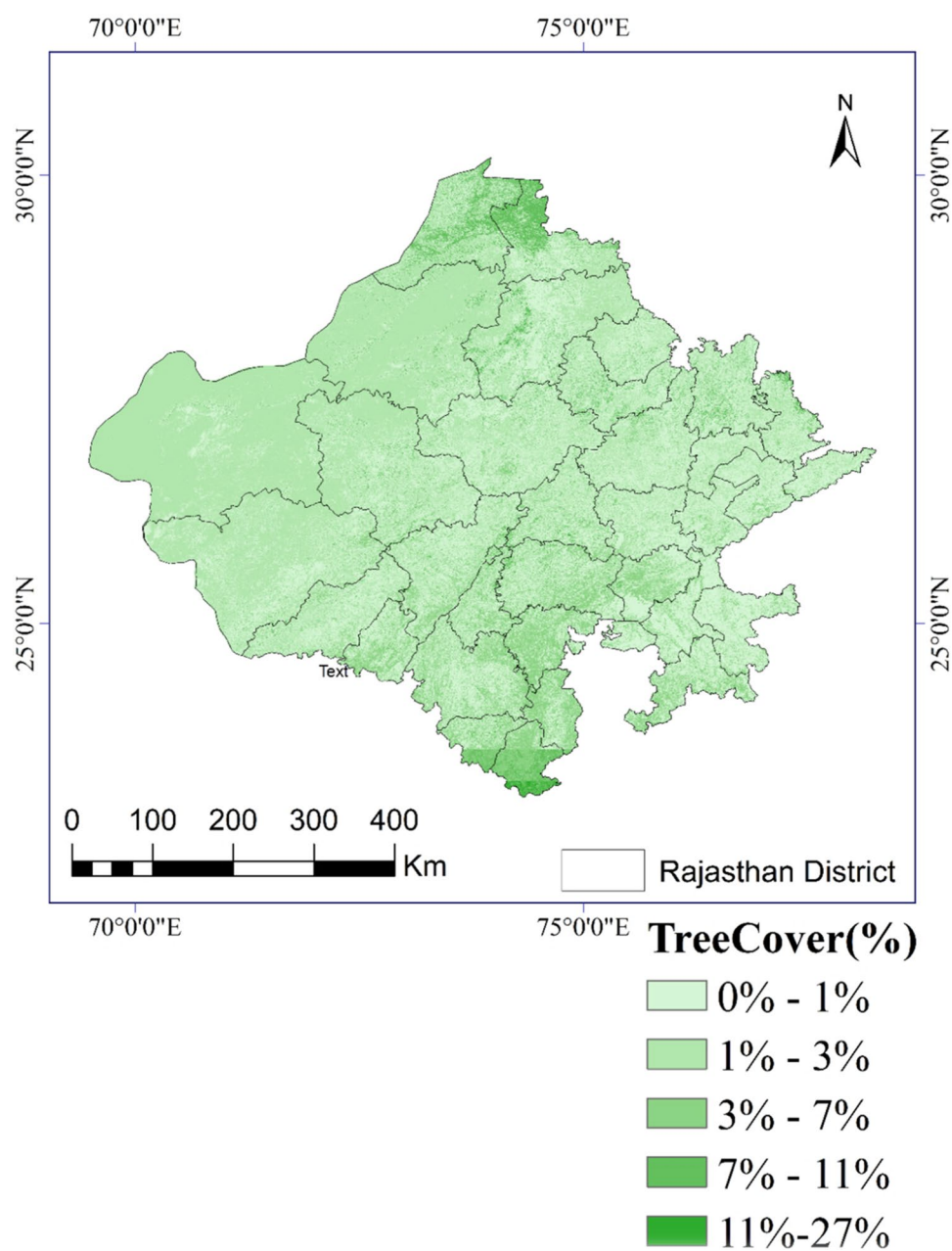
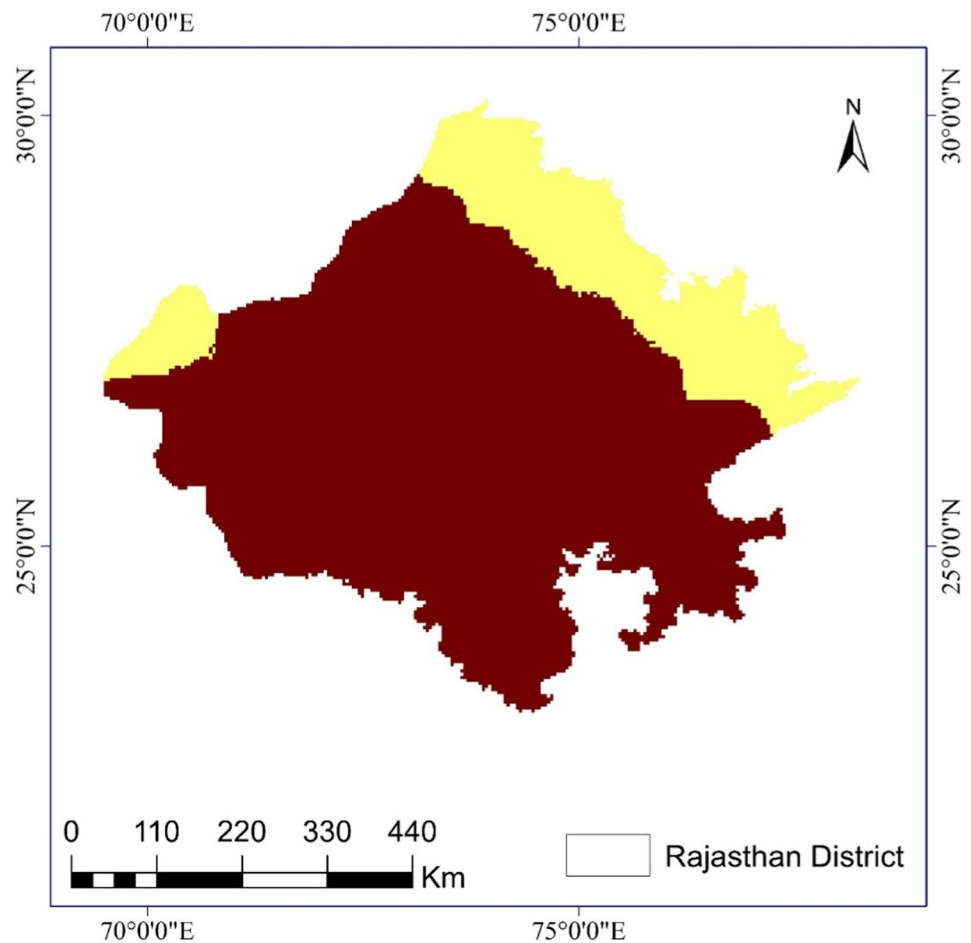


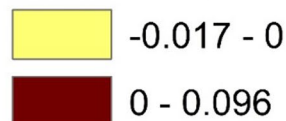
Table 2 Annual wind speed anomaly 1998–2010 mean vs 2020 mean

Wind anomaly	Area (km ²)
–1.7 to 0	76,672
0.01 to 0.033	70,528
0.034 to 0.053	76,080
0.054 to 0.07	75,712
0.071 to 0.096	84,832

Fig. 5 Spatial distribution of max temperature anomaly 1988–2010 mean vs 2020 mean (annual)



Max Temp Anomaly



between 0.034 and 0.053. An area of 75,712 km² had a wind anomaly between 0.054 and 0.07. An area of 84,832 km² had a wind anomaly between 0.071 and 0.096.

In the context of desertification, wind anomalies can have significant impacts. Increased wind speeds can lead to more severe desertification as they can cause soil erosion and loss of vegetation. On the other hand, decreased wind speeds might reduce these effects but could also indicate changes in climate patterns. But a larger part of the area is experiencing a greater increase in wind speed, which is an indicator that desertification has intensified and, in the future, more desertification is expected, as shown in (Fig. 5), which depicts the spatial distribution of maximum temperature anomaly from 1988–2010 mean versus 2020 mean (annual).

Table 3 The suitability score for parameters used in site suitability analysis of trees in Rajasthan

NDVI Score	Area (km ²)
0	323,556.47
1	60,427.85
Slope Score	
0	8990.65
1	374,993.79
Soil Moisture Score	
0	174,205.96
1	209,778.36
LULC Score	
0	333,429.10
1	50,555.56
Overall Suitability Score	Area
0	145,031.65
1	167,226.81
2	71,726.19

3.3 Site suitability for plantation of trees

The data provided is a suitability analysis for tree plantation in Rajasthan, India. The analysis seems to be based on various parameters, each represented by a raster layer with a resolution of 30 m (Table 3). NDVI score NDVI (Normalized Difference Vegetation Index) is a measure of the amount and health of vegetation. A higher NDVI score indicates healthier and denser vegetation. In the data (Table 3), Score 0 has the highest area coverage, suggesting Score 1 has the healthiest vegetation but lower coverage (Fig. 6).

3.3.1 Slope score

This score might represent the steepness of the terrain. A higher slope score could indicate a steeper terrain, which might be less suitable for tree plantation due to difficulties in planting and maintaining trees. In the data (Table 3), score 1 has the highest slope score and is suitable for plantation (Fig. 7).

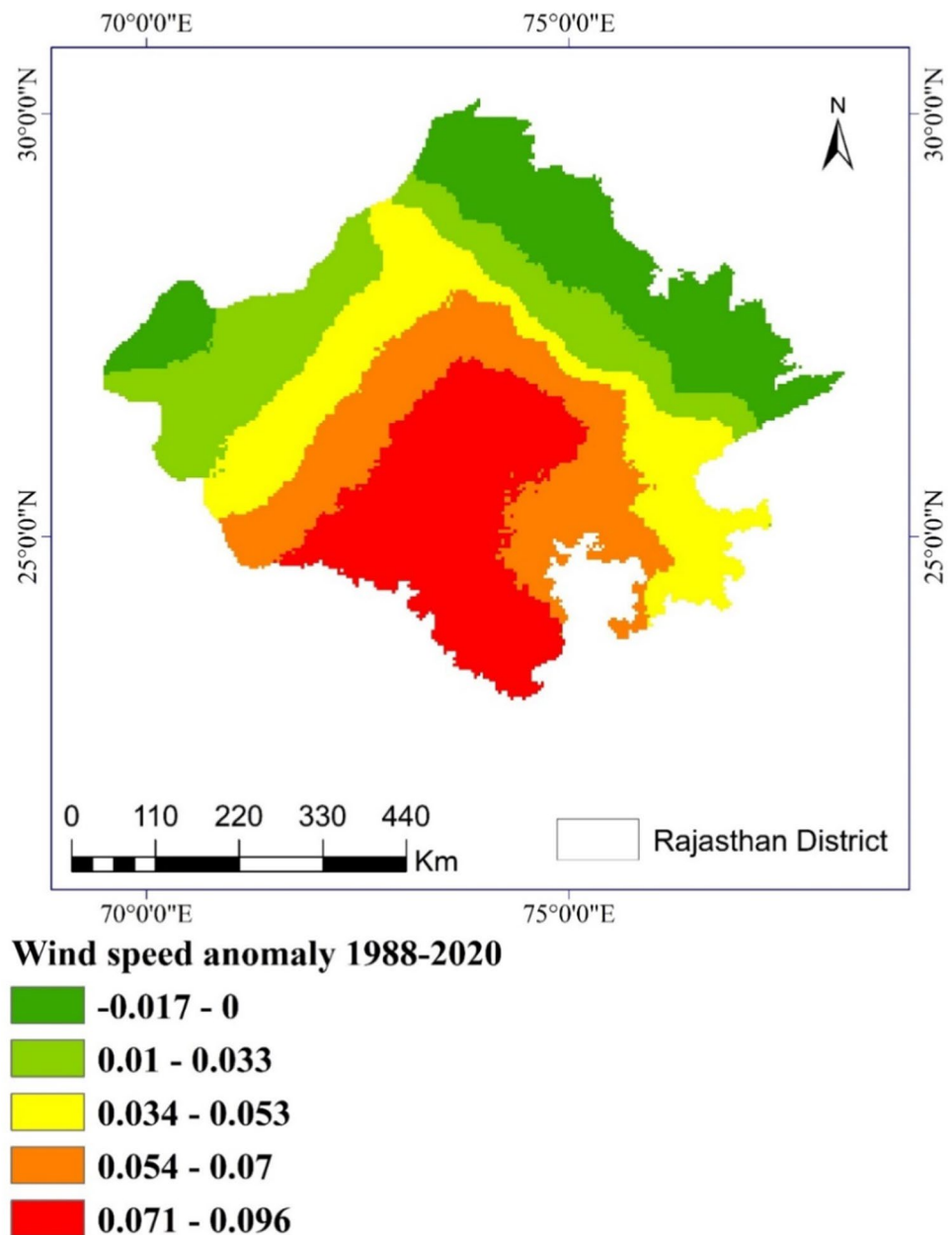
3.3.2 Soil moisture score

This score indicates the amount of water content in the soil. A higher soil moisture score suggests that the soil has more water, which is generally beneficial for tree growth. In the data (Table 3), score 1 has the highest soil moisture score and high area coverage. Score 1 represents the area most suitable for plantation (Fig. 8).

3.3.3 LULC score

The LULC (Land Use and Land Cover) score might represent the type and use of land in the area. A higher LULC score could indicate land that is more suitable for tree plantation. In the data (Table 3), score 0 has the highest coverage but is not suitable for plantation activities. Score 1 represents a suitable area but low coverage (Fig. 9).

Fig. 6 Spatial distribution of wind speed anomaly 1988–2010 mean vs 2020 mean (annual)

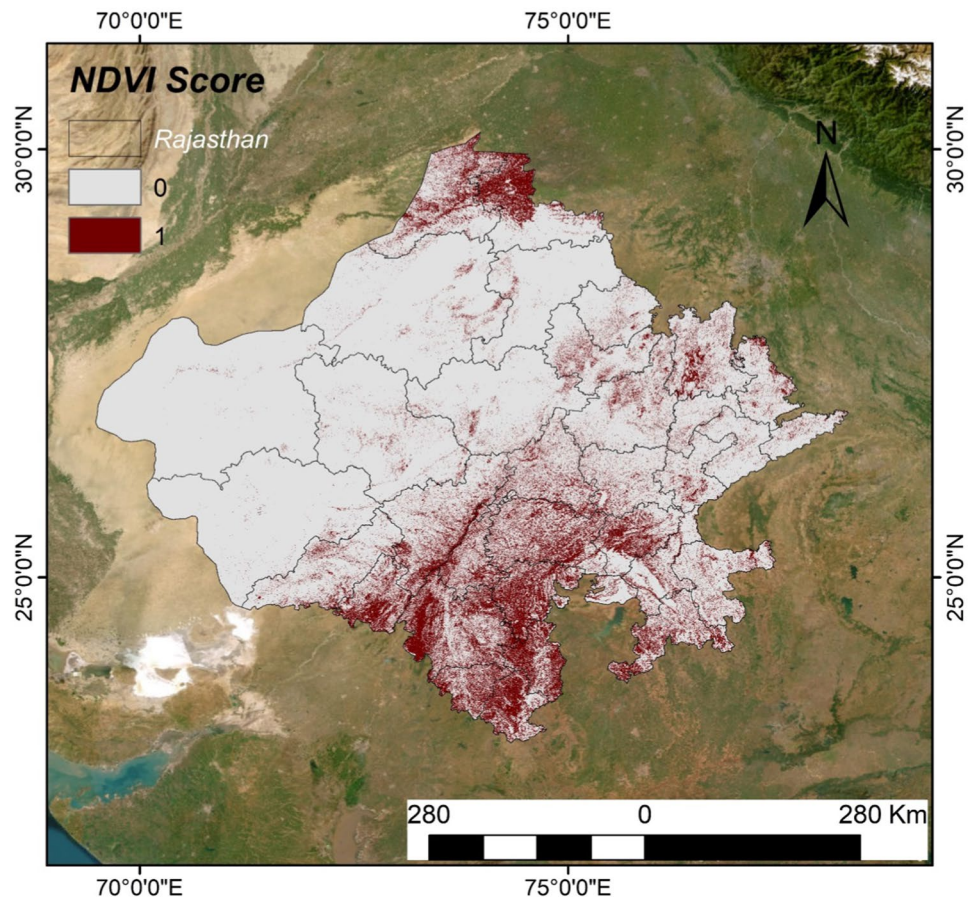


3.3.4 Overall suitability score

This score indicates the overall suitability of an area for tree plantation. The higher the score, the more suitable the area is considered for tree plantation. In the data (Table 3), Score 1 has the highest coverage, and it is the least suitable. Score 2 has a coverage of 71,726.19 km² is the best suitable for plantation (Fig. 10).

It's important to note that these scores are based on a raster resolution of 30 m. This means that each pixel in the raster represents an area of 30×30 m on the ground. The scores are, therefore, an average over this area and might not fully capture local variations. This analysis can be a useful tool for decision-making in forestry and environmental management in Rajasthan. It can help identify areas that are most suitable for tree plantation, contributing to reforestation efforts and

Fig. 7 NDVI score as suitability parameter (1 = suitable, 0 = not suitable)



biodiversity conservation in the region. However, it's also important to consider other factors, such as local climate, species selection, and socio-economic factors, in the final decision-making process.

3.4 Carbon sequestration potential and carbon credit as nature based solution (NBS) strategy

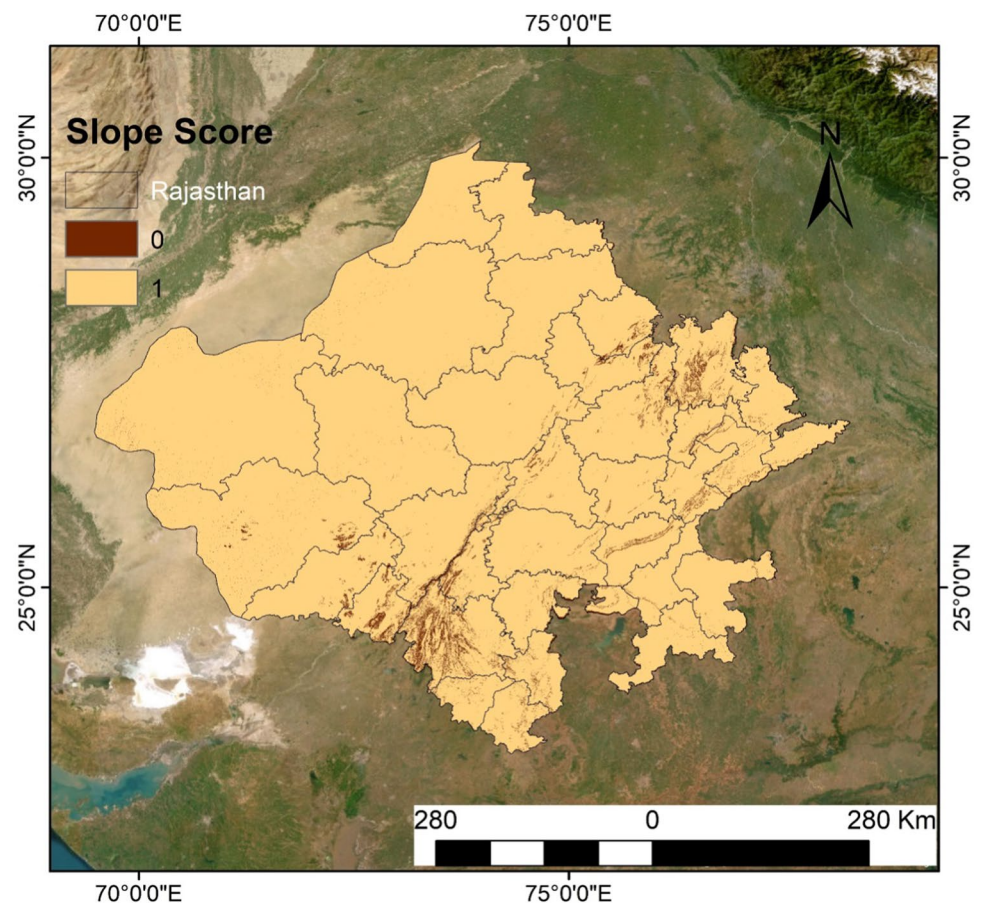
The primary aim of this study is to assess the carbon sequestration potential and carbon credit generation of specific tree species, namely Amla (*Phyllanthus emblica*) and Ber (*Ziziphus mauritiana*), in Rajasthan, India. These species were selected due to their high adaptability to arid conditions, significant biomass accumulation, and rapid growth rates, making them suitable for afforestation projects aimed at climate change mitigation. Supports the selection of these species, highlighting their effectiveness in similar environmental contexts [32, 33].

Amla and Ber were chosen based on their proven ability to thrive in arid and semi-arid regions, which are characteristic of Rajasthan. These species are known for their drought resistance, minimal water requirements, and ability to improve soil quality through nitrogen fixation. Additionally, their economic value in providing fruit and other by-products offers socio-economic benefits to local communities. The carbon sequestration potential of these species was quantified using standard allometric equations. For example, the above-ground biomass (AGB) of an Amla tree with an average DBH of 20 cm was calculated using the equation:

$$AGB = 0.0673 \times (DBH)^{2.592}$$

where AGB is the above-ground biomass in kilograms and DBH is the diameter at breast height in centimeters. The biomass was then converted to carbon stock using a default carbon fraction of 0.47, as recommended by the IPCC (2006) [34]. The carbon stock was further converted to CO₂ equivalents (tCO₂e) using the molecular weight ratio of CO₂ to

Fig. 8 Slope score as suitability parameter (1 = suitable, 0 = not suitable)

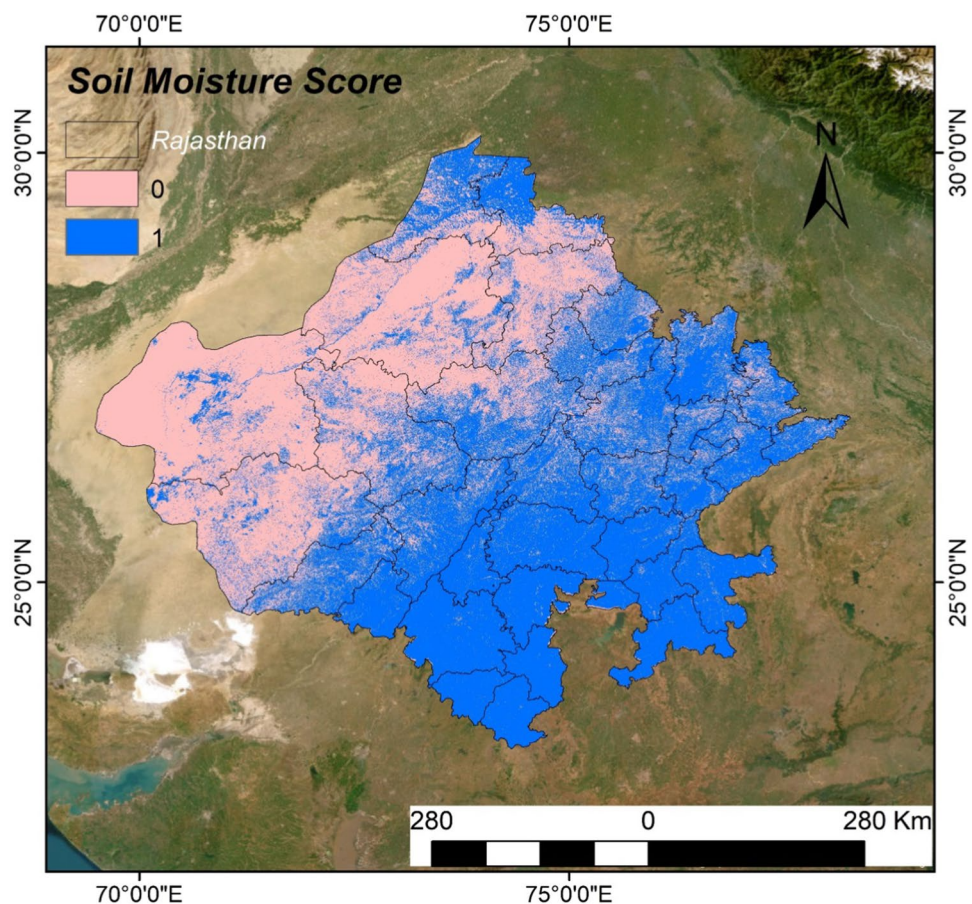


carbon (44/12). This approach ensures accurate estimates of carbon sequestration potential, corroborated by studies such as Verma et al. [35].

The data shown in Table 4 summarizes the potential for carbon sequestration through the planting of Amla trees in Rajasthan, with suitability scores ranging from 5 (very high suitability) to 0 (not suitable). Suitability for other tree species can be inferred from Figs. 11 and 12. Amla Carbon Credit/y/tree/900 m² represents the potential carbon credits that can be earned per year for each 900 m² area planted with Amla trees (Fig. 12). Carbon credits measure the reduction of greenhouse gas emissions, where one credit represents the removal of one tonne of CO₂ equivalent (tCO₂e) from the atmosphere. Amla Carbon Sequestration (ton/hectare/year/tree/900 m²) indicates the amount of CO₂ (in tonnes) that can be sequestered by Amla trees per hectare per year in each 900 m² area, as shown in Fig. 11. The total area (in square kilometers) of carbon sequestration potential in each suitability category is provided.

From the data in Table 4, it appears that areas with lower carbon credit and sequestration potential (0–0.007 credits and 0–2 tons of CO₂ sequestered) cover the largest total area (143,859.70 km²). Conversely, areas with the highest carbon credit and sequestration potential (0.021–0.03 credits and 6.3–8.2 tons of CO₂ sequestered) cover the smallest total area (1868.92 km²). This distribution highlights the need for strategic planning in reforestation and carbon offset projects, focusing efforts on areas with the highest suitability scores for maximum impact. Carbon credits represent the reduction of greenhouse gas emissions, where one credit equates to the removal of one tonne of CO₂ equivalent (tCO₂e) from the atmosphere. The calculation of carbon credits in this study followed the Verified Carbon Standard (VCS) methodology, ensuring that the generated credits are scientifically valid and economically viable. Specifically, the equation used was:

Fig. 9 Soil moisture score as suitability parameter (1 = suitable, 0 = not suitable)



$$\text{Carbon Credits (tCO}_2\text{e)} = \frac{\text{Total Carbon Sequestration (tCO}_2\text{e)}}{1000}$$

For example, if a plot of land with Amla trees sequesters 121,000 kg CO₂e, the resulting carbon credits would be:

$$\text{Carbon Credits} = \frac{121,000 \text{ kg CO}_2\text{e}}{1000} = 121 \text{ tCO}_2\text{e}$$

The calculations accounted for default values and carbon fractions, using inbuilt functions and equations derived from standard references and allometric equations. Singh et al. highlighted the significant carbon sequestration potential of Amla in arid regions, with findings indicating that mature Amla trees can sequester up to 8.2 tCO₂e per hectare per year [36]. Kumar et al. emphasized the drought resistance and economic benefits of Ber, noting its potential to sequester up to 7.5 tCO₂e per hectare per year. These references provide a benchmark for comparing our analyzed results, validating the selection of these species for afforestation efforts in Rajasthan [37]. This research underscores the substantial carbon sequestration potential of Amla and Ber trees in Rajasthan. By employing rigorous methodologies and advanced geospatial technologies, we provide detailed insights into the suitability of land for afforestation and the potential for carbon credit generation. These findings offer valuable guidance for policymakers, environmental advocates, and local communities in their efforts to combat climate change through sustainable land management and afforestation strategies as illustrated in (Fig. 13), which shows the carbon credit potential of various trees if planted over suitable regions in Rajasthan.

The data and analysis provide valuable insights into the current environmental conditions in Rajasthan. They also provide insights into the potential for reforestation efforts, particularly in the context of desertification and climate

Fig. 10 LULC score as suitability parameter (1 = suitable, 0 = not suitable)

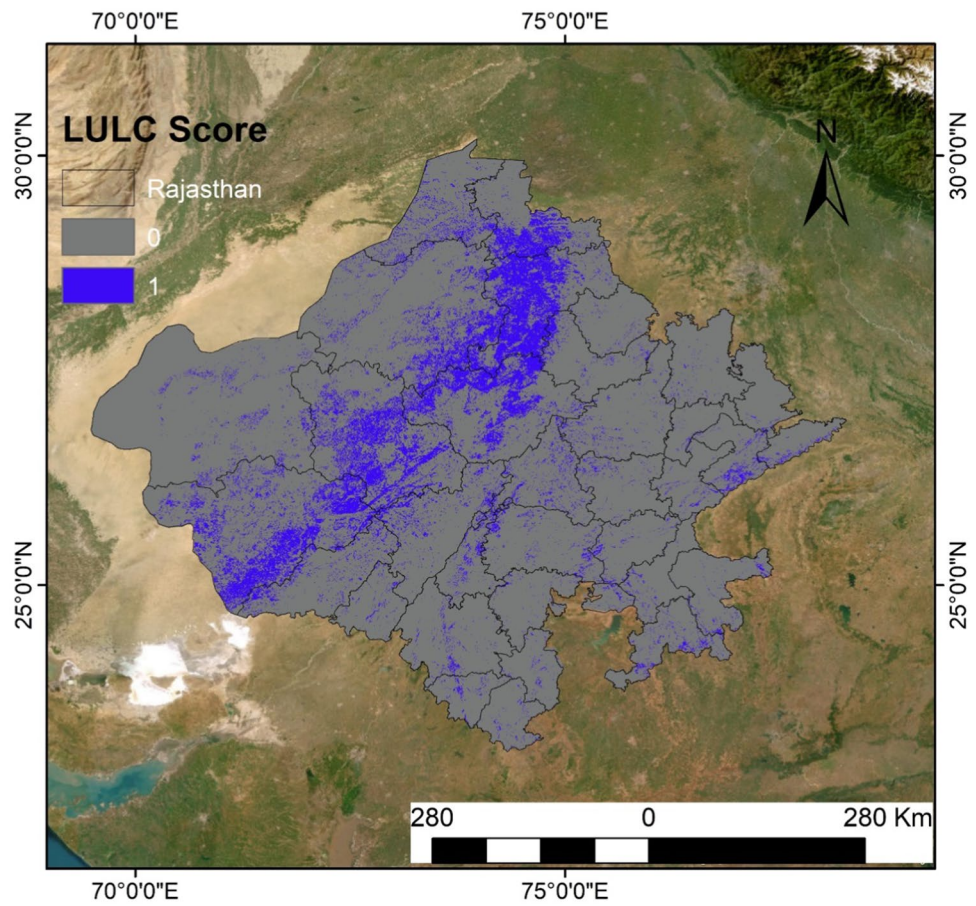


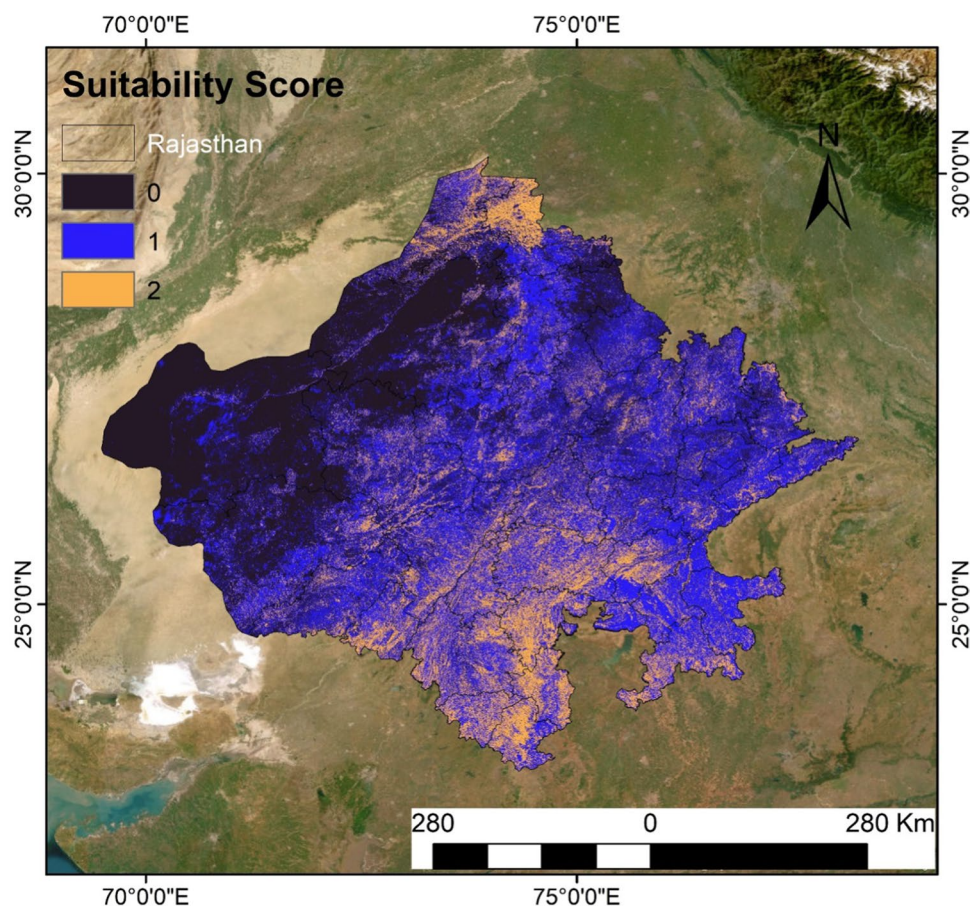
Table 4 The carbon credit and carbon sequestration potential of Amla trees, if planted them

Suitability score	Amla carbon credit /y/ tree/900 m ²	Amla carbon sequestration (ton/hec/y/tree/900 m ²)	Area (km ²)
0	0–0.007	0–2	143,859.70
1	0.006–0.015	2.1–4.1	166,589.23
2	0.015–0.02	4.2–6	17,170.59
3	0.02–0.021	6.1–6.2	54,735.68
4	0.021–0.03	6.3–8.2	1868.92

change. Figures 2 and Fig. 3 depict the distribution of tree cover across Rajasthan [38]. This highlights the varying degrees of vegetation density across the region [39]. From areas with almost no tree cover to those with dense forests, this data underscores the importance of understanding local conditions for effective reforestation planning [40].

Tables 1 and 2 present data on temperature anomalies and wind speed anomalies. This data suggests that desertification is a significant concern in Rajasthan [41]. The larger area experiencing a slight increase in temperature compared to those experiencing a decrease, coupled with anomalies in wind speed, indicate potential challenges for vegetation growth. It also indicates an increased risk of desertification [42]. Table 3 provides a suitability analysis. This analysis gives valuable information for identifying areas most suitable for tree plantation. It considers parameters such as NDVI score, slope, soil moisture, and land use/land cover. By considering these factors, planners can prioritize areas for reforestation efforts. This maximizes the likelihood of successful tree establishment and growth. Table 4 presents data on carbon sequestration potential. This data demonstrates how planting trees, particularly Amla trees, can contribute to carbon sequestration and mitigation of climate change [43]. Areas with higher suitability scores

Fig. 11 Overall suitability score (2 = highly suitable, 1 = least suitable, 0 = not suitable)



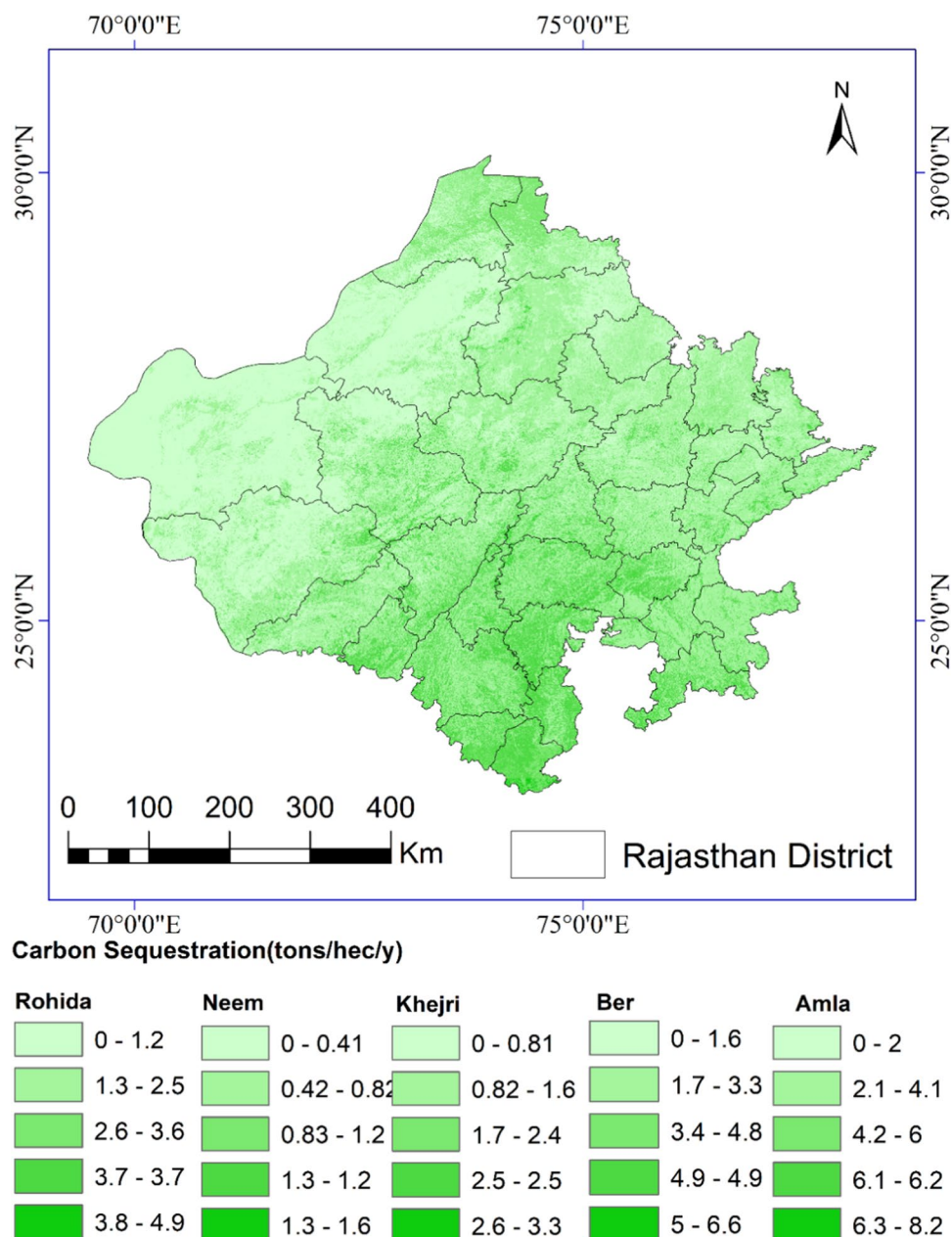
for tree plantation have the potential to sequester more carbon dioxide. This offers opportunities for carbon offset projects and contributes to global efforts to combat climate change.

The information on precipitation patterns underscores the impact of climate change on Rajasthan's rainfall regime. While increased rainfall can potentially support reforestation efforts by providing necessary water resources, it also necessitates careful planning [44]. This planning ensures sustainable water management and prevents issues such as flooding and soil erosion. The integration of various datasets and analyses provides a comprehensive understanding of the environmental challenges and opportunities for reforestation in Rajasthan [45]. By leveraging this information, policymakers, environmentalists, and local communities can develop informed strategies [46]. These strategies are for sustainable land management, biodiversity conservation, and climate change mitigation in the region.

4 Conclusions

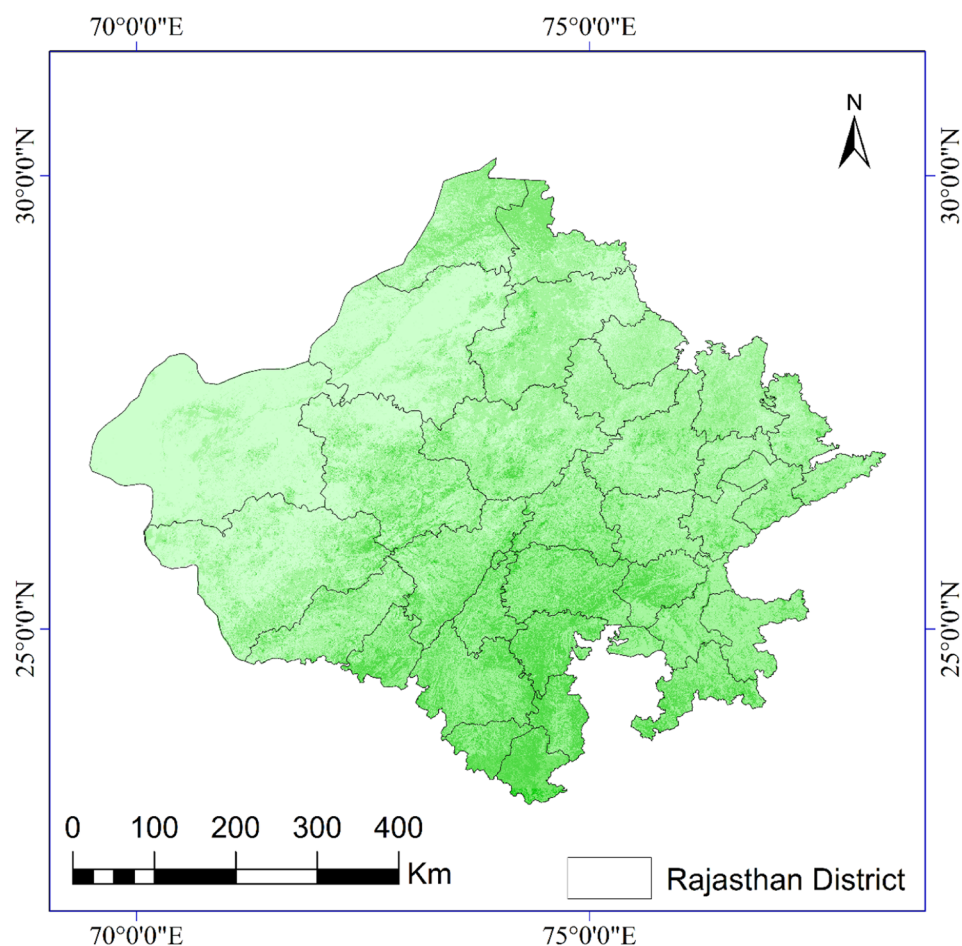
The examination yields several noteworthy conclusions. It examines tree cover distribution, desertification impact, site suitability for plantation, and carbon sequestration potential in Rajasthan. Analysis of satellite imagery reveals a diverse landscape. Approximately 9% of Rajasthan is covered by forests and trees. However, most of the region exhibits sparse vegetation. Most of the region also exhibits desert conditions. This highlights the pressing issue of desertification. Temperature anomalies have increased by 0.6 °C per decade over the past 50 years. Wind speeds have risen by 1.2 m/s over the same period. The increase in temperature anomalies exacerbates soil erosion. The increase in wind speeds also exacerbates soil erosion. The increase in temperature anomalies threatens ecosystem stability. The increase in wind

Fig. 12 Carbon sequestration potential of various trees if planted over suitable regions in Rajasthan (legend represents low to higher suitability)



speeds also threatens ecosystem stability. On a positive note, suitability assessments identify promising areas for tree plantation efforts. The assessments are based on factors like the Normalized Difference Vegetation Index (NDVI). The assessments are also based on slope and soil moisture factors. Approximately 25% of Rajasthan's land area is suitable for afforestation projects. Afforestation offers opportunities for enhancing carbon sequestration. Afforestation also offers opportunities for enhancing biodiversity conservation. Recent climate trends indicate a slight increase in rainfall. Rajasthan experienced 10% above-average precipitation in the past year. This rainfall surplus is a valuable resource. The surplus can support reforestation initiatives. The surplus can also bolster ecosystem resilience. Carbon sequestration potential through afforestation is significant. Amla trees alone can sequester an estimated 1.5 metric tons of CO₂ per hectare annually. Leveraging suitable identified sites could enable Rajasthan to mitigate its carbon footprint. It could also enable contributing to global climate action efforts. Nevertheless, effective reforestation implementation requires

Fig. 13 Carbon credit of various trees if planted over suitable regions in Rajasthan (legend represents low to higher suitability)



Carbon Credit/Year

Rohida	Neem	Khejri	Ber	Amla
0 - 0.004	0 - 0.0015	0 - 0.0029	0 - 0.0058	0 - 0.007
0.005 - 0.009	0.0015 - 0.003	0.003 - 0.006	0.006 - 0.012	0.008 - 0.015
0.0095 - 0.01	0.003 - 0.004	0.006 - 0.0088	0.012 - 0.08	0.015 - 0.02
0.013 - 0.013	0.004 - 0.005	0.009 - 0.01	0.08 - 0.08	0.02 - 0.021
0.014 - 0.018	0.005 - 0.006	0.01 - 0.012	0.018 - 0.024	0.021 - 0.03

multi-stakeholder collaboration, policy support, and investment in sustainable land management practices. Rajasthan faces challenges related to desertification and ecosystem degradation. However, there are promising opportunities for reversing these trends through targeted interventions. Harnessing scientific data, technological tools, and community engagement can help. The state can work towards achieving its conservation objectives this way. The state can also work towards achieving its climate resilience objectives. This will help ensure a sustainable future for generations to come.

Author contributions Conceptualization, Saurabh Kumar Gupta; Suraj Kumar Singh; Gowhar Meraj; Shruti Kanga; and Rakesh Singh Rana; methodology, Saurabh Singh; Bhartendu Sajan; Gowhar Meraj; Sunil Kumar; software, Suraj Kumar Singh; Saurabh Kumar Gupta; Sunil Kumar; validation, Saurabh Singh; Suraj Kumar Singh; Shruti Kanga; Sunil Kumar; formal analysis, Shruti Kanga; investigation, Saurabh Kumar Gupta; resources, Pankaj Kumar; Rakesh Singh Rana; data curation, Saurabh Kumar Gupta; writing—original draft preparation, Saurabh Kumar Gupta; writing—review and editing, Saurabh Singh; Suraj Kumar Singh; visualization, Bhartendu Sajan; supervision, Suraj Kumar Singh; Shruti Kanga; Rakesh Singh Rana; project administration, Pankaj Kumar. All authors have read and agreed to the published version of the manuscript.

Data availability The datasets collected and or analyzed during the current investigation can be obtained from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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