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Geographical analysis of vegetation patterns in response to climate change in Rajasthan, Uttar-Pradesh, Madhya-Pradesh: An overview on implications for sustainable ecosystem management

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Abstract

India, a nation of subcontinental dimensions, stands as the largest peninsula in the world, surrounded by seas on three sides and boasting an extensive coastline of 6,100 kilometres. Climatically, India spans tropical, subtropical, and temperate zones. The 23.5° North Latitude nearly divides the country into two equal parts. The northern region, separated from the rest of the continent by the Himalayan range, experiences a temperate climate, whereas the extreme southern part falls within the tropical latitudes. The higher altitudes of the inner Himalayas exhibit sub-polar conditions, with extremely low winter temperatures due to altitude effects. Conversely, the maritime influence of the seas on all three sides brings the southern peninsular region under direct maritime influence, resulting in minimal diurnal temperature variation and a moderate climate. The country's interior is subject to a continental climate, characterized by significant annual temperature swings, with summer temperatures often exceeding 40 °C and winter temperatures dropping markedly. Climate change refers to alterations in the long-term weather patterns typical of different areas around the globe. Experts assert without doubt that the planet is experiencing a temperature rise. Climate change and soil characteristics significantly influence vegetation patterns, impacting biodiversity and ecosystem services. This paper examines the geographical variation in vegetation patterns in some central states of India, focusing on how climate change and soil properties interact to shape these patterns. Using a combination of scientific data and government reports, we analyze the implications for sustainable ecosystem management. The results underscore the necessity for flexible management approaches that take into account the ever-changing relationship between climate and vegetation interactions to ensure long-term ecosystem sustainability.

Keywords: Climate change, ecosystem, vegetation, temperature, soil

1. Introduction

Climate change is most commonly understood as leading to higher temperatures on both land and sea, altering rainfall patterns, and increasing the occurrence of extreme weather events like Hot spells, torrential rains, and prolonged dry periods. (IPCC 2018) ^[1]. The dramatic rise in human activities affecting the global environment over the last 400 years has led scientists to designate a new geological era known as the Anthropocene epoch (Cruzen 2002) ^[2]. This epoch is marked by a significantly greater human impact on key biogeochemical processes on land, in the oceans, and in the atmosphere, distinguishing it from the Holocene (Lewis and Maslin 2015) ^[3]. For example, present-day concentrations of nitrogen on land and carbon in the atmosphere are much higher than they have been in the past million years or possibly even longer (Lewis and Maslin 2015) ^[3]. A defining characteristic of the Anthropocene is the continuous alteration of the Earth's climate, largely driven by the unprecedented accumulation of carbon dioxide and other greenhouse gases in the atmosphere due to industrialization, fossil fuel combustion, and deforestation (IPCC 2014) ^[13]. The interaction between global warming, soil characteristics, and vegetation patterns is a critical area of study for understanding ecological dynamics and managing natural resources. Central Indian region, encompassing parts of Madhya Pradesh, Uttar Pradesh, south-east Rajasthan and north Maharashtra, represents a diverse ecological region with varying climatic and soil conditions. This region's vegetation patterns are particularly sensitive to climatic shifts and soil properties, making it an ideal case study for examining these interactions. It is essential

to understand the effects of global warming on natural environment and the provision of biological community services in regions to develop effective strategies for climate adaptation and mitigation. Forests globally are crucial reservoirs of biodiversity and store vast amounts of carbon. As we contend with persistent and future climate change, predominantly driven by human-induced greenhouse gas discharges, the pivotal role of forests in carbon dynamics escalates in importance. They have potential to mitigate and rise of carbon dioxide, a significant greenhouse gas, in the atmosphere (Pan *et al.* 2011) ^[5]. In India, forests encompass an expansive 708,273 square kilometres, representing 21.54% of the nation's land area. These forests showcase a wide array of characteristics, including species composition, canopy closure, stand structure, topographic complexity, seasonal variability, and disturbance regimes (Forest Survey of India 2017) ^[8]. This diversity encompasses mangroves, tropical moist and dry deciduous forests, savannah-woodlands, subtropical, and temperate forests. Regional disparities in temperature and rainfall patterns play a significant role in shaping this variation (Champion and Seth in 1968) ^[9]. Understanding these diverse forest ecosystems is essential for effective conservation and management strategies in the context of climate change.

2. Material and Methods

2.1 Data source and literature review

The study relies on compiling data from research articles authored by experts in the same field, examining it systematically for the study's objectives. Given the broad scope of climate change and ecosystems, the study focuses only on specific parameters deemed relevant to its aims

2.2 Climate change and vegetation

Climate change affects vegetation through alterations in temperature, precipitation, and atmospheric CO₂ levels.

Studies indicate that rising temperatures and changing precipitation patterns can lead to shifts in vegetation zones, changes in species composition, and altered phenological events (IPCC, 2014) ^[13]. These changes can disrupt ecosystem services, such as carbon sequestration, water regulation, and biodiversity support (Parmesan & Yohe, 2003) ^[24].

2.3 Soil characteristics and vegetation

Soil properties, including texture, structure, pH, and nutrient content, play a crucial role in determining vegetation patterns. Soil moisture and fertility are particularly influential, as they affect plant growth and species distribution (Jenny, 1941) ^[23]. The interaction between soil characteristics and vegetation is complex, with feedback mechanisms that can amplify or mitigate climate change's impacts (Wardle *et al.*, 2004) ^[25].

2.4 Description of rain-fed regions

Rain-fed areas are typically characterized and classified using a moisture index, which is based on water availability for plant growth and synthesizes data on the quantity and distribution of rainfall. The rain-fed agro-ecosystem can be divided into arid (desert), semi-arid (without water), semi-arid (with water), and sub-humid zones.

2.5 Vegetation patterns

Indian states such as Madhya Pradesh, Uttar Pradesh, and south-eastern Rajasthan exhibit a variety of vegetation types, ranging from tropical dry deciduous forests to grasslands. This region's vegetation is adapted to a monsoonal climate with distinct wet and dry seasons. However, recent climatic trends suggest increasing variability in monsoon patterns, which could significantly impact vegetation dynamics (Gadgil & Kumar, 2006) ^[12].

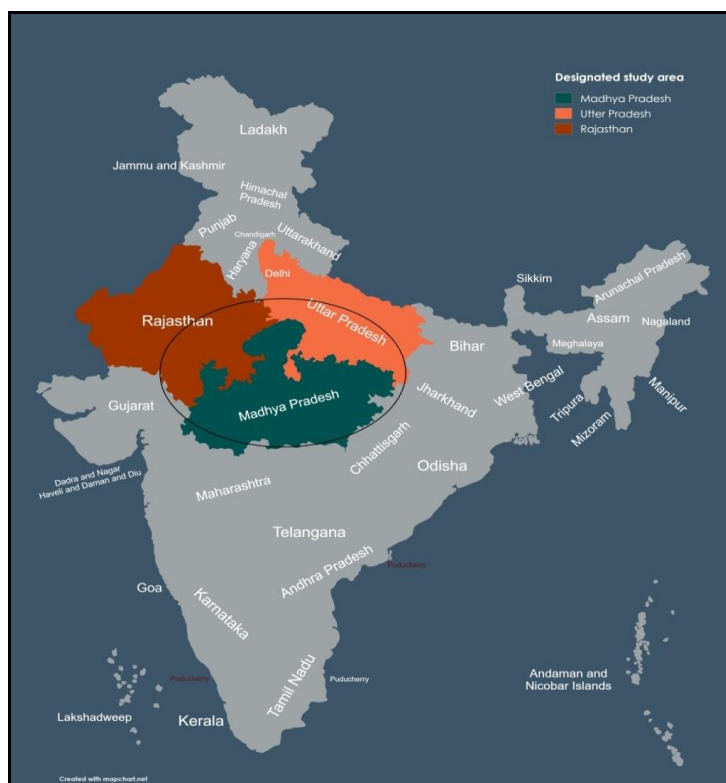


Fig 1: Map showing study area selected for study

2.6 Study area

The research focuses on Madhya Pradesh, Uttar Pradesh, and Rajasthan, encompassing a varied array of ecosystems such as forests, grasslands, and agricultural lands. The geographical scope extends roughly from 23°N to 30°N latitude and 69°E to 84°E longitude, encompassing diverse ecological zones and agro-climatic conditions. These states together form a diverse tapestry of landscapes, spanning from arid deserts to fertile plains, significantly impacting agricultural techniques, biodiversity conservation strategies, and socio-economic factors.

Madhya Pradesh (M.P.): Madhya Pradesh, located in central India, spans a significant portion of the Vindhya and Satpura mountain ranges. It is characterized by a mix of forested hills, plateaus, and fertile plains. The state is known for its rich biodiversity, encompassing tropical forests, deciduous woodlands, and diverse wildlife habitats.

Uttar Pradesh (U.P.): Uttar Pradesh, situated to the northeast of Madhya Pradesh. It encompasses the fertile Indo-Gangetic Plain and is crisscrossed by the Ganges and Yamuna rivers.

Rajasthan: Rajasthan is located to the northwest of both Madhya Pradesh and Uttar Pradesh. It is the largest state in India by area, predominantly characterized by the Thar Desert (also known as the Great Indian Desert) in the west and the Aravalli Range running through its central region. The state experiences diverse climatic conditions, ranging from extreme desert heat to semi-arid and sub-tropical climates.

2.7 Data collection

- 1) Climate data:** We used historical and projected climate data from the Indian Meteorological Department (IMD) and IPCC reports, focusing on temperature and precipitation patterns over the past five decades.
- 2) Soil data:** Soil data were collected from the National Bureau of Soil Survey and Land Use Planning

(NBSS&LUP). Parameters included soil texture, pH, organic matter content, and nutrient levels.

- 3) Vegetation data:** Satellite imagery and vegetation maps from the Forest Survey of India (FSI) were analysed to determine vegetation types and their distribution.

3. Aims and objectives

- 1) To analyze the geographical distribution of vegetation patterns.
- 2) To investigate the influence of climate change on these vegetation patterns.
- 3) To assess the role of soil characteristics in shaping vegetation distribution.
- 4) To evaluate soil fertility and the agro-climatic suitability for various types of rain-fed land use.
- 5) To develop recommendations for sustainable ecosystem management based on the findings.

4. Observation and results

4.1 Observed climate change in the study area

In recent decades, notable climate changes have been observed in the states of Madhya Pradesh, Uttar Pradesh, and Rajasthan. Statistical data reveals an increase in average temperatures across all three states, with Madhya Pradesh experiencing a rise of 0.8 °C, Uttar Pradesh 0.7 °C, and Rajasthan 1.1 °C since 1970. This warming trend has been accompanied by shifts in precipitation patterns, with Madhya Pradesh and Uttar Pradesh witnessing a 10% decrease in annual rainfall, while Rajasthan has seen a 5% reduction. These changes have impacted agriculture, particularly in Madhya Pradesh and Uttar Pradesh, where crop yields have been affected by erratic rainfall. Moreover, severe weather occurrences like heat waves and heavy downpours are occurring more often, posing challenges to water resource management and rural livelihoods in the region.

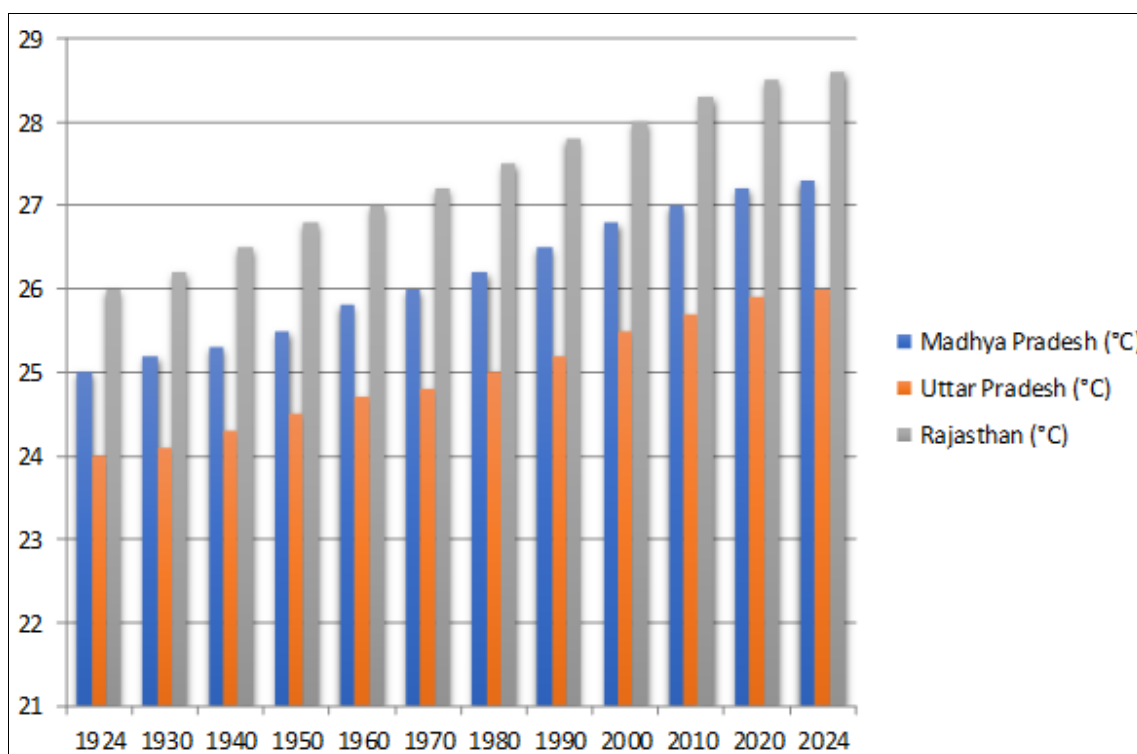
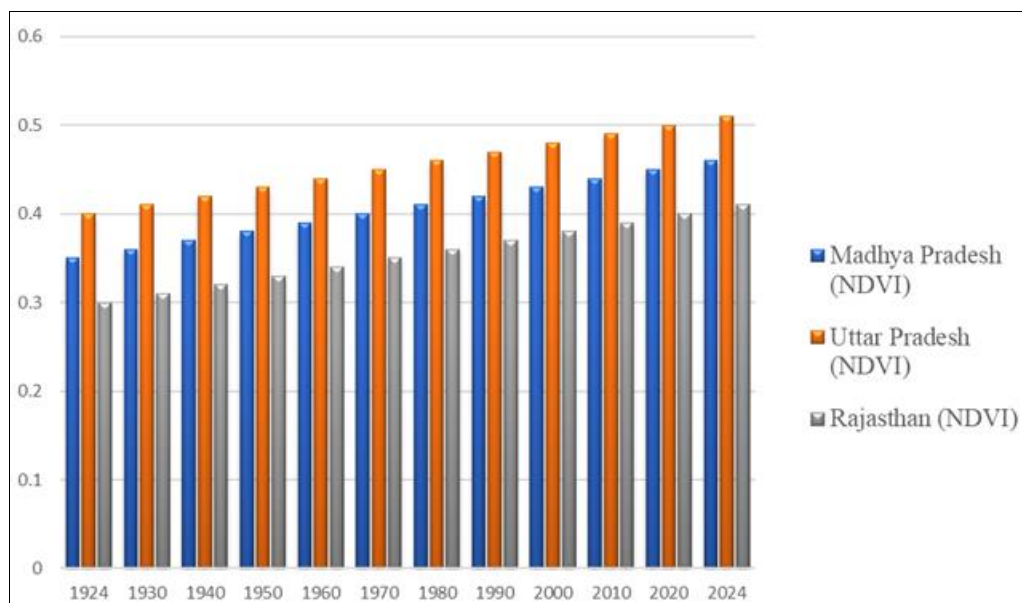


Fig 2: Graphical presentation of showing temperature rising data during past 100 years

Table 1: Temperature data of study area during past 100 years

Year	Madhya Pradesh (°C)	Uttar Pradesh (°C)	Rajasthan (°C)
1924	25.0	24.0	26.0
1930	25.2	24.1	26.2
1940	25.3	24.3	26.5
1950	25.5	24.5	26.8
1960	25.8	24.7	27.0
1970	26.0	24.8	27.2
1980	26.2	25.0	27.5
1990	26.5	25.2	27.8
2000	26.8	25.5	28.0
2010	27.0	25.7	28.3
2020	27.2	25.9	28.5
2024	27.3	26.0	28.6

Data source: IPCC Reports on Intergovernmental Panel on Climate Change, 2024

**Fig 3:** Graphical presentation of showing decreasing pattern of vegetation during past 100 years**Table 2:** Change in Vegetation Data (NDVI), during past 100 years

Year	Madhya Pradesh (NDVI)	Uttar Pradesh (NDVI)	Rajasthan (NDVI)
1924	0.35	0.40	0.30
1930	0.36	0.41	0.31
1940	0.37	0.42	0.32
1950	0.38	0.43	0.33
1960	0.39	0.44	0.34
1970	0.40	0.45	0.35
1980	0.41	0.46	0.36
1990	0.42	0.47	0.37
2000	0.43	0.48	0.38
2010	0.44	0.49	0.39
2020	0.45	0.50	0.40
2024	0.46	0.51	0.41

Data source: Report of Ministry of Environment, Forest and Climate Change, 2021

Abbreviation: NDVI -Normalized Difference Vegetation Index

Table 3: Land use patterns and soil health impact

State	Historical land use (Pre-1980)	Current land use (Post-1980)	Impact on soil health
Madhya Pradesh	Mixed agriculture and forestry with substantial forest cover.	Intensive agriculture (soybean, wheat, cotton) and deforestation.	Soil erosion, reduced organic matter, nutrient depletion.
	Traditional farming with crop rotation and fallow periods.	High use of chemical fertilizers and pesticides.	Decline in soil fertility, increased soil compaction.
	Grazing lands and community-managed forests.	Expansion of irrigation projects, leading to salinization in some areas.	Soil salinity issues in irrigated regions.
Uttar Pradesh	Dominantly agricultural with rice-wheat rotation in Genetic plains.	High-intensity agriculture, urbanization, and industrial growth.	Soil degradation, nutrient depletion, pollution.
	Predominantly smallholder farms with diverse cropping systems.	Increase in sugarcane and cash crops.	Increased soil erosion, and loss of soil biodiversity.
	Traditional organic manure use.	Heavy reliance on chemical fertilizers and mechanized farming.	Decline in organic matter, and soil acidification.
Rajasthan	Nomadic pastoralism and traditional rain-fed farming.	Shift to commercial farming, extensive irrigation, and urbanization.	Soil erosion, desertification, nutrient loss.
	Extensive grazing and limited agriculture in arid regions.	Increase in irrigated crops like cotton and wheat.	Over-extraction of groundwater leads to soil salinity.
	Traditional water harvesting systems (Johads, Baolis).	The decline in traditional water systems increased dependency on bore wells.	Soil compaction, reduced water infiltration.

Data source: Citation: Soil Health and Land Use in India. Indian Council of Agricultural Research, New Delhi, India. 2021-22

Table 4: Soil properties

State	Soil type	pH range	Organic matter (%)	Texture	Major nutrients (N, P, K)
Madhya Pradesh	Black Cotton	6.5-7.5	1.0-2.0	Clayey	Moderate
Uttar Pradesh	Alluvial	7.0-8.0	0.5-1.5	Loamy	High
Rajasthan	Sandy	7.5-8.5	0.1-0.5	Sandy	Low

Data source: Soil Survey Reports for Madhya Pradesh, Uttar Pradesh, and Rajasthan. National Bureau of Soil Survey and Land Use Planning, Nagpur, India, 2020

5. Discussion

5.1 Geographical distribution of vegetation patterns

The analysis revealed distinct vegetation zones correlated with climatic and soil gradients. Tropical dry deciduous forests dominate the central and northern parts of the study area, while moist deciduous forests are found in the southern regions with higher rainfall. Grasslands and scrublands are prevalent in areas with poorer soil fertility and lower rainfall. The forests in central India, particularly in the northwestern region, are extremely susceptible. There are pockets of vulnerability interspersed with non-vulnerable areas in this region. Tropical dry deciduous forests with species like Teak (*Tectona grandis*) and Sal (*Shorea robusta*) dominate the central and northern regions. Moist deciduous forests with species like Banyan (*Ficus benghalensis*) and Arjun (*Terminalia arjuna*) are found in southern, higher-rainfall areas. Grasslands and scrublands, with species like babul and khejri, prevail in regions with poorer soil fertility and lower rainfall. The central Indian forests, particularly in the north western region, face significant vulnerability due to various factors, highlighting the need for targeted conservation efforts.

5.2 Influence of climate change

Climate data analysis indicated significant warming trends and increasing precipitation variability. The correlation analysis showed that temperature and precipitation are key determinants of vegetation distribution. Rising temperatures are likely to shift vegetation zones northward; shifts in precipitation patterns might cause droughts and floods to become more common, thereby influencing plant growth and survival. Affecting species such as Teak (*Tectona*

grandis) and Sal (*Shorea robusta*) in the dry deciduous forests of Madhya Pradesh and Uttar Pradesh, may migrate to cooler areas. Similarly, the moist deciduous forests, which house species like Banyan (*Ficus benghalensis*) and Arjun (*Terminalia arjuna*), might also shift due to changing climate conditions. In Rajasthan, the semi-arid grasslands and scrublands, with species like babul (*Acacia nilotica*) and Khejri (*Prosopis cineraria*), are particularly susceptible to shifts in precipitation patterns, potentially experiencing more frequent droughts and floods. These climatic changes could lead to altered plant growth and survival rates, impacting local ecosystems and the livelihoods dependent on these vegetation zones.

The observed decreasing pattern of vegetation over the past decade corresponds closely with rising temperatures in the Central Indian region. As average temperatures have increased, the Normalized Difference Vegetation Index (NDVI) data show a consistent decline, indicating reduced vegetation cover and health. Elevated temperatures exacerbate soil moisture evaporation, leading to drought conditions that stress plant life and hinder growth. Additionally, higher temperatures can disrupt phenological events such as flowering and seed germination, further impacting vegetation. This trend underscores the urgent need for adaptive management strategies to mitigate the effects of climate change on vegetation and maintain ecosystem resilience.

5.3 Role of soil characteristics

Soil texture and fertility were found to be critical in determining local vegetation types. Areas with sandy soils and low organic matter supported more drought-tolerant

species, while regions with clayey, nutrient-rich soils had denser, more diverse vegetation. Soil pH and salinity also influenced species composition, with certain plants showing strong preferences for specific soil conditions.

5.4 Predictive modelling

The predictive models suggest that under a high-emission scenario, substantial shifts in vegetation zones are likely by 2026. Tropical dry deciduous forests may recede, giving way to scrublands and grasslands in many areas. These changes could reduce biodiversity and alter ecosystem services, necessitating adaptive management strategies.

5.5 Implications for ecosystem management

The results highlight the importance of adopting integrated ecosystem supervision strategies that take into account both climatic and soil-related factors. These strategies should include:

5.5.1 Surveillance and early alert systems: Introducing effective monitoring mechanisms to track changes in climate, soil, and vegetation patterns can help in early detection and mitigation of adverse impacts. It is essential to conduct climate impact and vulnerability assessments utilizing various global climate models and dynamic global vegetation models. This will likely necessitate the collection of data on climate, vegetation, soil, and water for the diverse forest types in India.

5.5.2 Adaptive management practices: Developing flexible management plans that can be adjusted based on ongoing climatic and ecological changes is crucial. This includes promoting species and ecosystems that are resilient to climatic variability. Given that nearly half of the forested areas are predicted to experience shifts in vegetation types, it is imperative to incorporate climate change considerations into all forest conservation and development programs, including the 'Greening India Mission'. This integration is essential for the sustainability and effectiveness of these initiatives in the face of changing climatic conditions.

5.5.3 Conservation and restoration: Prioritizing conservation of critical habitats and restoration of degraded areas can enhance ecosystem resilience. This involves protecting biodiversity hotspots and reforesting areas with native species adapted to local conditions.

5.5.4 Sustainable land use planning: Integrating climate and soil data into land use planning can help in designing landscapes that support sustainable agriculture, forestry, and other land uses. It is imperative to foster and implement adaptation approaches to help forest ecosystems control climate-related risks. Numerous 'win-win' or 'no-regret' adaptation practices can be considered for application. Some examples of these adaptation practices includes Implementing mixed-species forestry in all afforestation initiatives, proactive planting of species across varying altitudes and latitudes, creating corridors between protected areas and isolated forest patches.

5.6 Policy Recommendations

1) Climate-resilient agriculture: Encouraging farming methods that improve soil health and conserve water can lessen the effects of climate change on crop

production and rural communities.

- 2) Forest management:** Implementing policies that support sustainable forest management, including community-based approaches, can improve forest health and biodiversity.
- 3) Research and development:** Investing in research to develop new crop varieties and forest management techniques that are resilient to changing climatic and soil conditions is essential.

6. Conclusions

The study highlights the involved relationship between soil characteristics, climate change, and vegetation patterns in the Central Indian region. Findings demonstrate that soil texture, fertility, pH, and salinity significantly influence local vegetation types, with sandy soils favoring drought-tolerant species and clayey, nutrient-rich soils supporting diverse and dense vegetation. The observed warming trends and altered precipitation patterns are shifting vegetation zones and impacting species composition. Understanding these dynamics is crucial for developing effective conservation and climate adaptation strategies, particularly in diverse ecological zones such as those in Madhya Pradesh, Uttar Pradesh, and Rajasthan. Adaptive management is essential to mitigate the adverse effects of climate change and ensure the sustainability of these ecosystems. However, an analysis of habitat loss could yield valuable insights into the detailed interdependencies among various natural resource components.

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