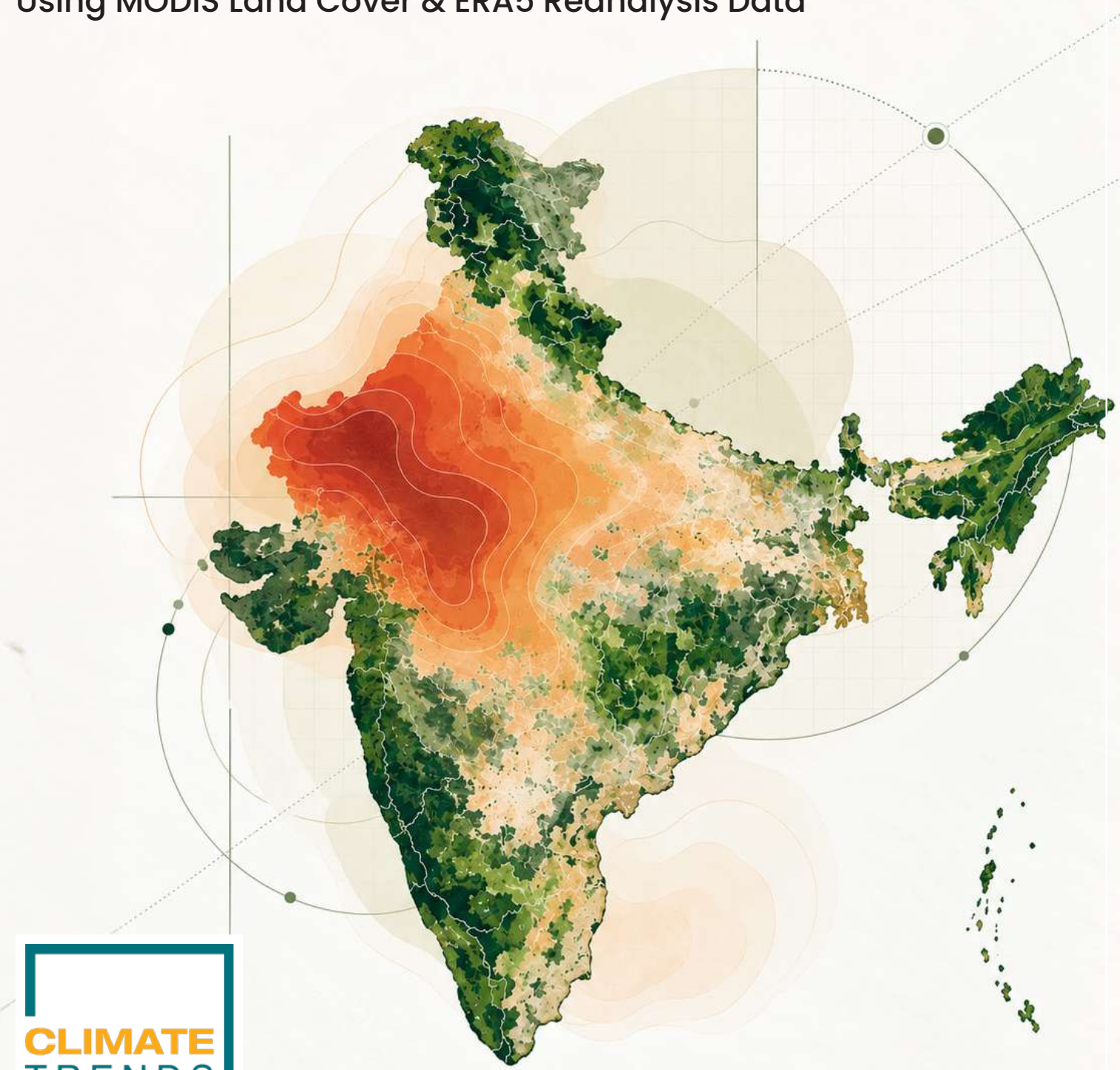
Assessment of Green Cover Dynamics and Their Influence on Summer Temperature *across India*

Using MODIS Land Cover & ERA5 Reanalysis Data



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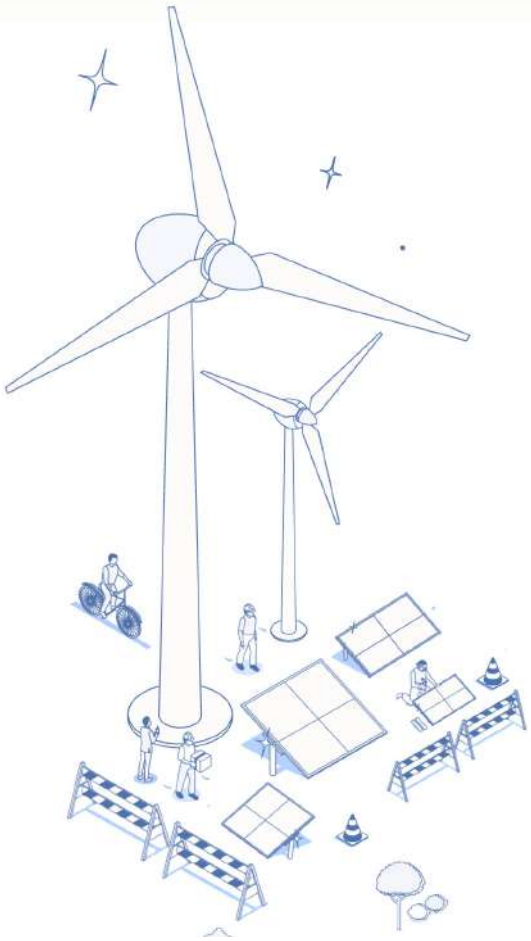

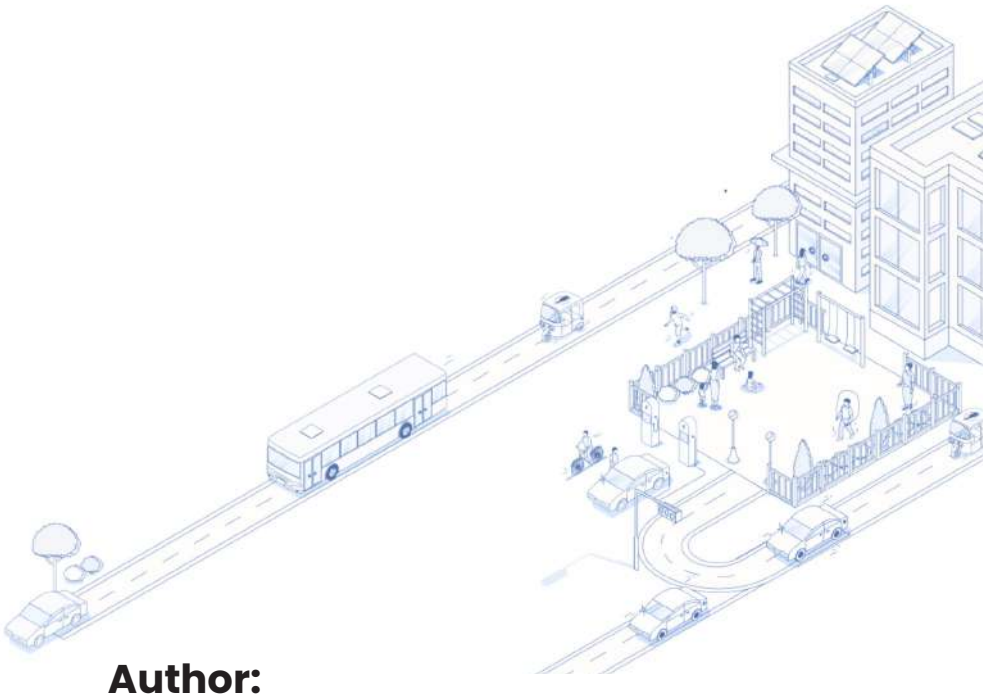

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Key Highlights

- Quantified long-term green-cover dynamics across India using MODIS MCD12Q1 land-cover data for 2001–2025.
- India lost 5.6 percentage points of green cover over two decades, accompanied by a corresponding expansion of non-green landscapes.
- Integrated ERA5 2-m air temperature data with satellite-derived land cover to evaluate the influence of vegetation on summer (March–May) temperature.
- Green-covered regions remained consistently 1–2.5 °C cooler than non-green landscapes, demonstrating the significant cooling effect of vegetation.
- Non-green landscapes consistently exhibited higher summer temperatures than vegetated areas.
- Regions experiencing green-cover loss generally coincided with stronger summer warming, although regional climate forcing also influenced temperature trends.
- Land-cover transition analysis revealed distinct thermal responses, emphasizing the importance of conserving and restoring vegetation for climate adaptation and sustainable land management.
- Vegetation conservation mitigates local warming but cannot fully offset regional climate change.





01

Background

01: Background

Climate change has emerged as one of the most pressing environmental challenges of the twenty-first century, with increasing global temperatures profoundly affecting ecosystems, human health, water resources, agriculture, and biodiversity. According to the Intergovernmental Panel on Climate Change (IPCC), the Earth's average surface temperature has risen significantly since the pre-industrial era due to increasing greenhouse gas emissions, resulting in more frequent and intense heatwaves, prolonged droughts, changing precipitation patterns, and widespread ecological disturbances. Developing countries such as India are particularly vulnerable because of their large population, rapid urbanization, dependence on climate-sensitive sectors, and diverse climatic conditions.

Among the various drivers of regional climate change, land-use and land-cover (LULC) change plays a crucial role in regulating the Earth's surface energy balance. Vegetation acts as a natural climate regulator by controlling evapotranspiration, enhancing soil moisture, increasing carbon sequestration, and reducing surface heating through shading effects. Consequently, the conversion of forests, grasslands, and other vegetated landscapes into croplands, urban settlements, or barren land alters land-atmosphere interactions and contributes to regional warming. These effects are particularly evident during the summer season, when high incoming solar radiation amplifies the influence of vegetation on near-surface temperature.



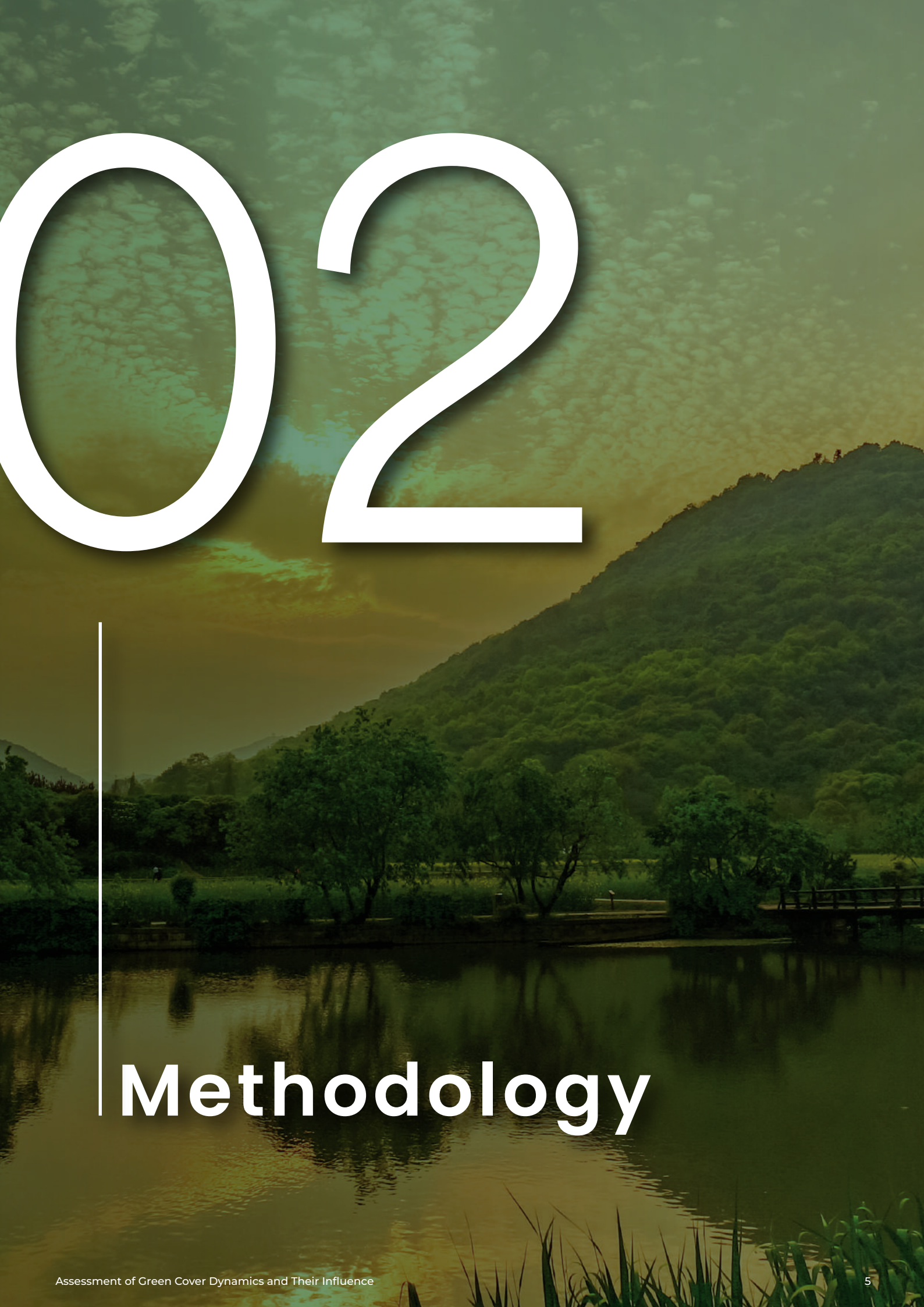
India has experienced substantial land-cover changes over the past two decades owing to rapid population growth, urban expansion, agricultural intensification, infrastructure development, and climate variability. While afforestation programmes have increased vegetation in some regions, deforestation, land degradation, and expansion of built-up areas have simultaneously reduced green cover in many parts of the country. Such contrasting land-cover dynamics influence local and regional climate differently, making it essential to evaluate how changes in vegetation affect temperature patterns across diverse geographical regions.

Several previous studies have investigated either long-term land-cover dynamics or temperature variability independently. However, relatively few studies have quantitatively examined how changes in green cover influence regional summer temperature across India using consistent satellite-derived land-cover observations and high-resolution climate reanalysis data. Understanding this relationship is important for evaluating the climatic benefits of vegetation conservation and for supporting sustainable land management, climate adaptation, urban planning, and ecosystem restoration strategies.

Remote sensing provides an effective framework for monitoring long-term land-cover dynamics over large geographical regions. The Moderate Resolution Imaging Spectroradiometer (MODIS) MCD12Q1 land-cover product offers consistent annual observations of global land cover, while the ERA5 reanalysis dataset provides spatially continuous meteorological information with high temporal resolution. The integration of these datasets enables a comprehensive assessment of vegetation dynamics and their influence on regional temperature over extended time periods.

In this study, we investigate the spatiotemporal changes in green cover across India between 2001 and 2025 using the MODIS MCD12Q1 land-cover dataset and evaluate their influence on summer (March–May) 2-m air temperature derived from the ERA5 reanalysis. Green and non-green land-cover categories are compared to quantify differences in mean summer temperature, while land-cover transition analysis is employed to assess the thermal response associated with vegetation loss and gain. By combining satellite observations with long-term climate data, this study provides new insights into the role of vegetation in regulating regional climate and offers scientific evidence that can support climate mitigation, ecological conservation, and sustainable land-use planning in India.





02

Methodology

02: Methodology

2.1: Study Area

The present study was conducted over the Indian subcontinent, extending approximately from 68°E to 98°E longitude and 6°N to 38°N latitude. India encompasses diverse climatic regimes, ranging from the Himalayan alpine region in the north to tropical forests in the northeast and southern peninsula, arid deserts in the northwest, fertile Indo-Gangetic plains, and extensive coastal regions. Such geographical diversity results in substantial variations in vegetation cover, land-use practices, and thermal characteristics, making India an ideal region for

investigating the influence of long-term green-cover dynamics on regional temperature. Administrative state boundaries were used for spatial visualization and interpretation of the results.



2.2: Land Cover Dataset

Annual land-use and land-cover (LULC) information was obtained from the MODIS MCD12Q1 Version 6.1 product, which provides global land-cover classification based on the International Geosphere–Biosphere Programme (IGBP) classification scheme. The dataset has a spatial resolution of approximately 500 m and classifies the Earth's surface into 17 land-cover categories using annual MODIS Terra and Aqua observations.

To investigate long-term land-cover dynamics, six representative years (2001, 2005, 2010, 2015, 2020, and 2025) were selected. The original IGBP land-cover classes were reclassified into two broader categories, namely green cover and non-green cover, to facilitate the assessment of vegetation-related temperature variations. The green-cover category comprised natural and semi-natural vegetated ecosystems, including forests, shrublands, savannas, grasslands, and permanent wetlands.

These land-cover types are characterized by active vegetation, higher biomass, evapotranspiration, and greater carbon sequestration capacity, thereby playing an important role in regulating regional climate and mitigating surface warming.

The non-green category included croplands, urban and built-up lands, cropland/natural vegetation mosaics, permanent snow and ice, barren lands, and water bodies. These classes generally exhibit lower or highly variable vegetation density, altered surface energy balance, and different thermal characteristics compared to natural vegetation. Croplands were grouped within the non-green category because seasonal agricultural vegetation differs substantially from permanent natural vegetation in terms of phenology, canopy structure, and evapotranspiration, making their thermal behaviour distinct from forests and other natural ecosystems. Binary masks representing green (value = 1) and non-green (value = 0) pixels were generated for each study year. The total area occupied by each category was estimated by multiplying the number of classified pixels by the corresponding pixel area, and the percentage coverage was calculated with respect to the total valid land pixels.

Table 1. Reclassification of MODIS MCD12Q1 IGBP land-cover classes into Green and Non-Green categories.

IGBP Class	MODIS Land-Cover Description	Category Used in This Study
1	Evergreen Needleleaf Forest	Green
2	Evergreen Broadleaf Forest	Green
3	Deciduous Needleleaf Forest	Green
4	Deciduous Broadleaf Forest	Green
5	Mixed Forest	Green
6	Closed Shrublands	Green
7	Open Shrublands	Green
8	Woody Savannas	Green
9	Savannas	Green
10	Grasslands	Green
11	Permanent Wetlands	Non-Green
12	Croplands	Non-Green
13	Urban and Built-up Lands	Non-Green
14	Cropland/Natural Vegetation Mosaic	Green
15	Permanent Snow and Ice	Non-Green
16	Barren	Non-Green
17	Water Bodies	Non-Green

Note: The original MODIS MCD12Q1 IGBP product also includes an Unclassified category (code = 255), which was excluded from all analyses. Pixels with invalid or missing values were treated as NaN and were not included in area or temperature calculations.

2.3: Temperature Dataset

Near-surface air temperature was obtained from the ERA5 reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Hourly 2-m air temperature data corresponding to the selected study years were extracted and converted from Kelvin to degrees Celsius.

The hourly observations were aggregated into daily mean temperatures by averaging the 24-hourly values for each day. Subsequently, seasonal mean temperature was calculated for the March–May (MAM) period, representing the summer season over India. This season was selected because vegetation exerts its strongest influence on the surface energy balance and thermal environment during the pre-monsoon months. Temperature values below 0°C were excluded from the analysis to avoid unrealistic seasonal averages associated with snow-covered Himalayan regions.



2.4: Green Cover Dynamics

The temporal evolution of vegetation was analysed using the binary green-cover masks generated from the MODIS land-cover product. For each selected year, the total green-cover

area, non-green area, and their respective percentage contributions were estimated. Changes between 2001 and 2025 were further quantified to identify regions experiencing vegetation loss or gain.

The percentage of green cover was calculated as

$$Green\ Cover\ (\%) = \frac{A_{green}}{A_{total}} \times 100$$

where A_{green} represents the total green-cover area and A_{total} denotes the total valid land area.

2.5: Green and Non-Green Temperature Analysis

The binary land-cover masks were overlaid on the seasonal ERA5 temperature fields to extract temperature values corresponding to green and non-green pixels separately. Mean summer temperature was calculated independently for both categories for each study year.

The temperature difference between green and non-green regions was estimated as

$$\Delta T = T_{non-green} - T_{green}$$

where T_{green} and $T_{non-green}$ represent the mean summer temperatures over green and non-green land-cover classes, respectively.

To further investigate the distribution of temperature within each category, boxplot analysis was performed, allowing comparison of the median, interquartile range, and variability between vegetated and non-vegetated landscapes.



2.6: Land Cover Transition Analysis

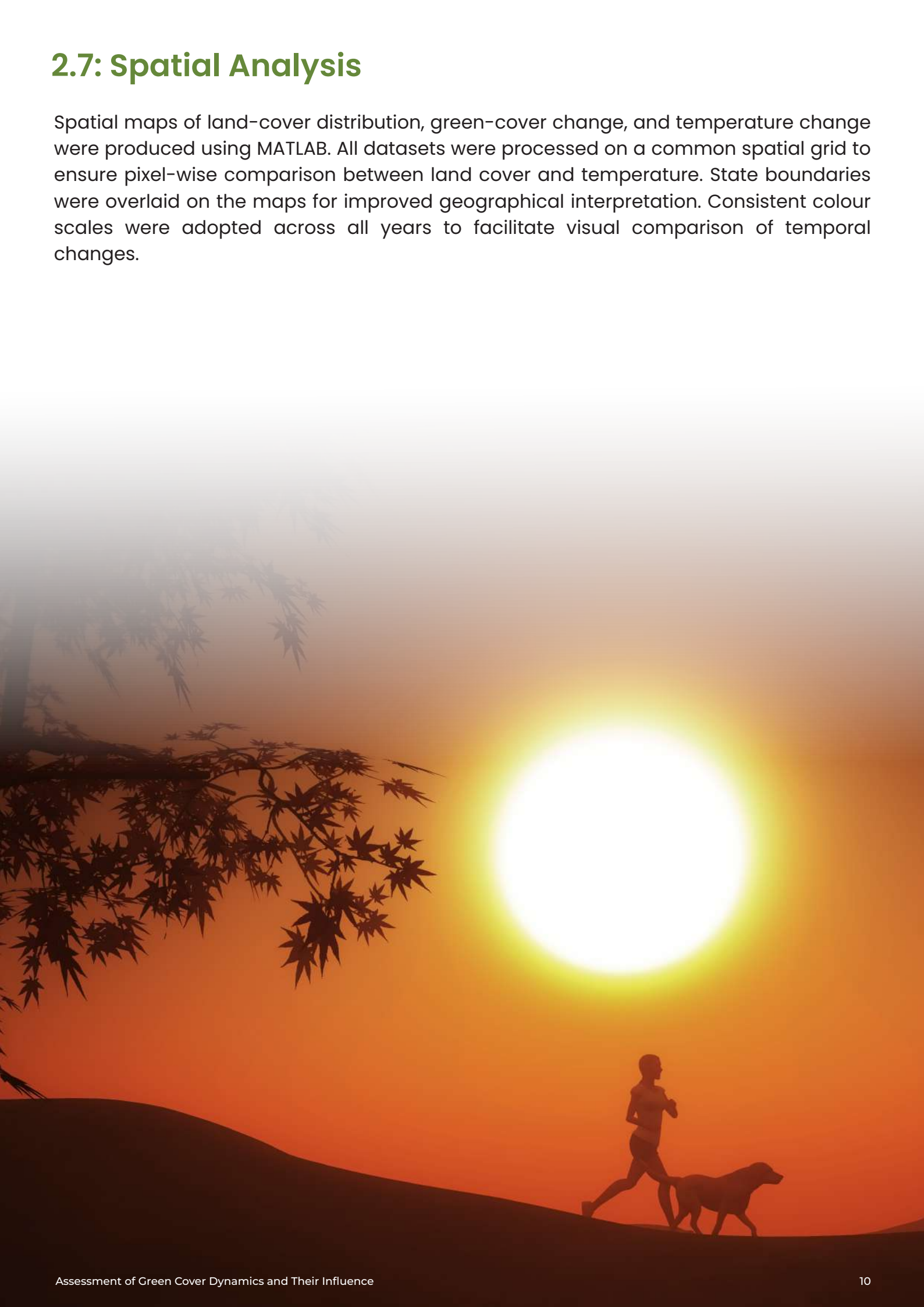
To investigate the thermal response associated with land-cover change, transition maps were generated between 2001 and 2025. Each pixel was classified into one of four transition categories:

- Stable Green (Green → Green)
- Green Loss (Green → Non-Green)
- Green Gain (Non-Green → Green)
- Stable Non-Green (Non-Green → Non-Green)

Seasonal temperature change was calculated for each pixel as where and denote the summer mean temperatures for 2025 and 2001, respectively.
The spatial distribution of temperature change was analysed separately for each transition class, and the corresponding mean temperature change and areal proportion were computed.

2.7: Spatial Analysis

Spatial maps of land-cover distribution, green-cover change, and temperature change were produced using MATLAB. All datasets were processed on a common spatial grid to ensure pixel-wise comparison between land cover and temperature. State boundaries were overlaid on the maps for improved geographical interpretation. Consistent colour scales were adopted across all years to facilitate visual comparison of temporal changes.





03

Results

03: Results

3.1: Spatiotemporal Dynamics of Land Use and Land Cover in India (2001–2025)

Figure 1 presents the spatial distribution of land use and land cover (LULC) across India for the years 2001, 2005, 2010, 2015, 2020, and 2025 based on the MODIS MCD12Q1 IGBP classification. Croplands remained the dominant land-cover type throughout the study period, occupying a large proportion of the Indo-Gangetic Plain, central India, and peninsular regions. Dense forest classes, including evergreen and deciduous forests, were primarily concentrated in the northeastern states, the Western Ghats, the Himalayan foothills, and parts of central India. Barren land was mainly distributed across the northwestern arid regions and the high-altitude Himalayan terrain, whereas urban and built-up areas appeared as scattered clusters around major metropolitan regions.

A visual comparison of the six study years indicates that the overall spatial distribution of major land-cover classes remained relatively stable during the study period. However, noticeable local-scale changes were observed in several regions. Expansion of urban land is evident around major cities, while changes in cropland and natural vegetation are visible across parts of central and southern India. Forest-dominated regions in the northeastern states and the Western Ghats remained comparatively persistent, although localized changes in vegetation patterns can be identified over the two-decade period.

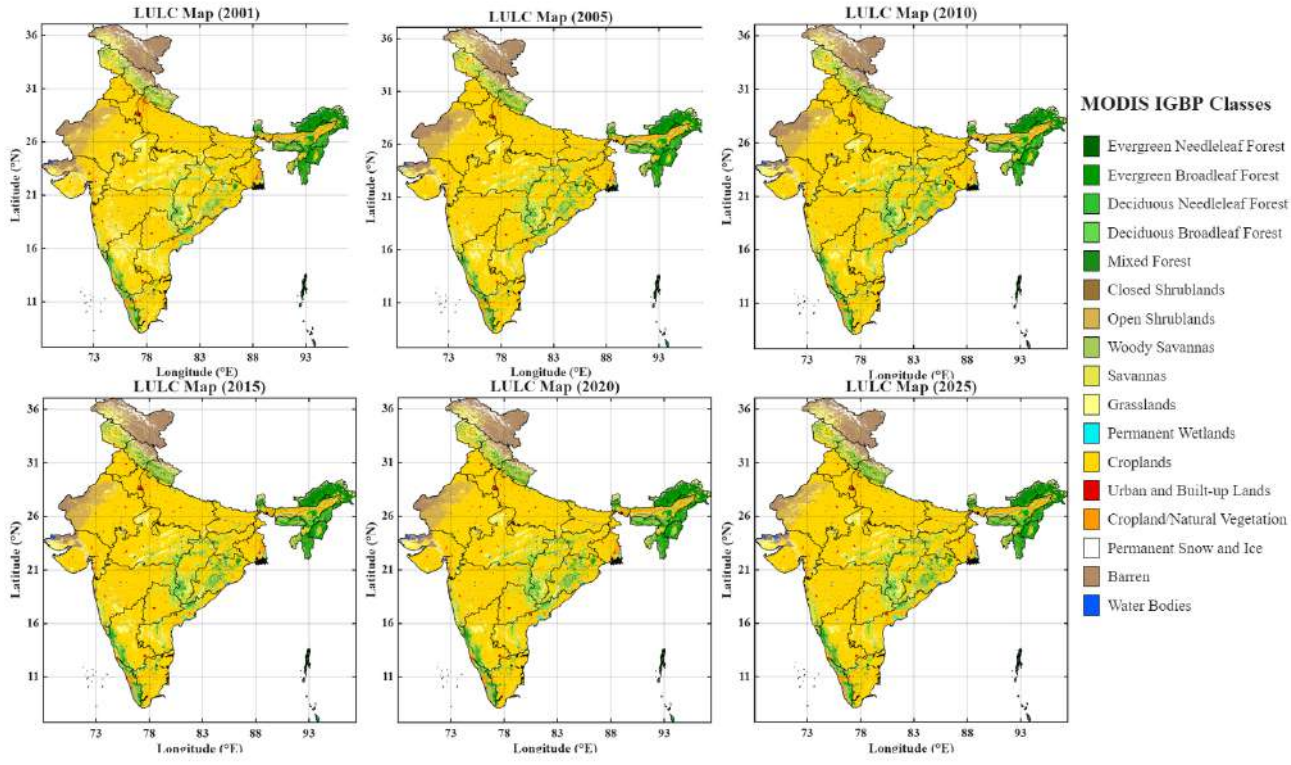


Figure 1. Spatial distribution of land use and land cover (LULC) across India for 2001, 2005, 2010, 2015, 2020, and 2025 derived from the MODIS MCD12Q1 Version 6.1 product using the International Geosphere–Biosphere Programme (IGBP) classification scheme. The same colour scale is used for all years to facilitate interannual comparison.

The reclassified green-cover classes, consisting of forests, shrublands, savannas, grasslands, and wetlands, continued to occupy ecologically important regions, whereas non-green classes, including croplands, urban land, barren land, permanent snow and ice, and water bodies, dominated much of the remaining landscape. These spatial variations provide the basis for evaluating the influence of vegetation dynamics on summer temperature presented in the subsequent sections.

3.2: Temporal Changes in Green & Non-Green Cover

The temporal variation in green and non-green land cover across India during 2001–2025 is presented in Figure 2, while the corresponding area statistics are summarized in Table 2. The results indicate a substantial decline in green cover during the early part of the study period, followed by relatively minor fluctuations in subsequent years.

In 2001, green cover occupied approximately 1.21 × 10^6 km^2, representing 36.95% of the total land area, whereas non-green land covered 2.07 × 10^6 km^2 (63.05%). Between 2001 and 2005, green cover decreased markedly to 1.05 × 10^6 km^2 (31.95%), corresponding to a reduction of approximately 0.16 × 10^6 km^2 (about 13.5% relative to the 2001 green-cover area). During the same period, the proportion of non-green land increased from 63.05% to 68.05%, indicating a substantial expansion of non-vegetated landscapes.

Table 2. Temporal variation in green and non-green land cover across India.

Year	Green Area (×10^6 km^2)	Non-Green Area (×10^6 km^2)	Green Cover (%)	Non-Green Cover (%)
2001	1.21	2.07	36.95	63.05
2005	1.05	2.23	31.95	68.05
2010	1.01	2.27	30.84	69.16
2015	1.05	2.23	31.98	68.02
2020	1.03	2.25	31.48	68.52
2025	1.03	2.25	31.35	68.65

After 2005, the overall green-cover extent remained comparatively stable, fluctuating between 30.84% and 31.98% throughout the remaining study period. A slight recovery was observed in 2015, when green cover increased to 31.98%, followed by a gradual decline to 31.35% in 2025. Conversely, non-green land consistently occupied approximately two-thirds of the study area after 2005, reaching 68.66% in 2025.

Overall, the analysis demonstrates that the most pronounced land-cover transition occurred between 2001 and 2005, whereas changes after 2005 were relatively modest. The persistent dominance of non-green land across India suggests long-term modifications in land-cover composition, which may have important implications for regional thermal conditions explored in the subsequent sections.

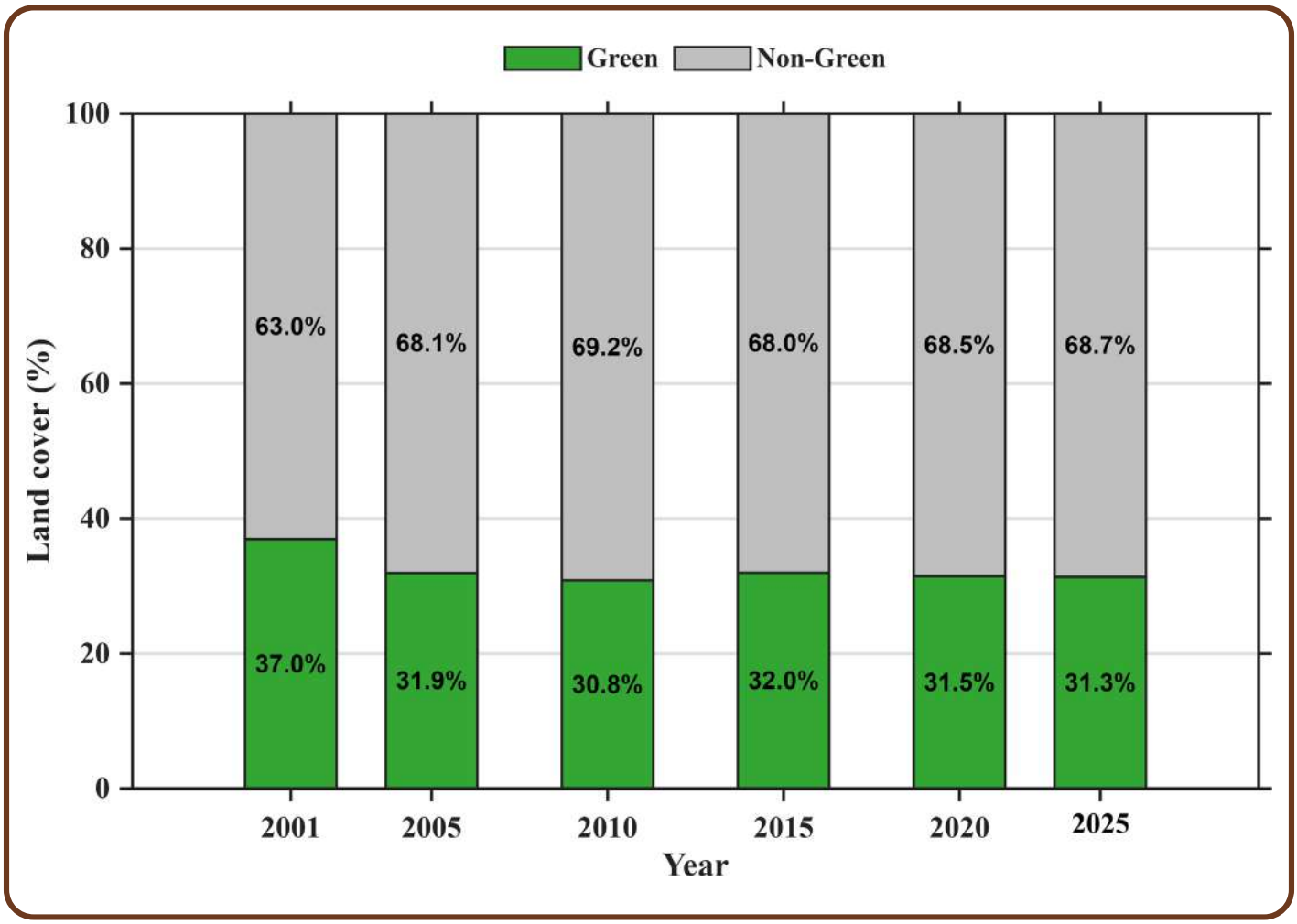


Figure 2. Temporal variation in green and non-green land-cover area across India during 2001–2025. The stacked bar chart illustrates the percentage contribution of green and non-green land-cover classes, highlighting the decline in green cover between 2001 and 2005 and the relatively stable land-cover composition during the subsequent years.

3.3: Comparison of Summer Temperature over Green and Non-Green Areas

Figure 3 compares the mean summer (March–May) temperature over green and non-green land-cover categories during the study period (2001–2025). Throughout all study years, non-green areas consistently exhibited higher summer temperatures than green-covered regions, highlighting the important role of vegetation in moderating the regional thermal environment.

In 2001, the mean summer temperature over green areas were 24.76 °C, whereas non-green areas recorded a higher mean temperature of 25.81 °C, resulting in a temperature difference of 1.05 °C. This difference increased substantially in the following decade, reaching 2.07 °C in 2005 and peaking at 2.49 °C in 2010. A similarly high difference (2.30 °C) was observed in 2015, indicating a pronounced thermal contrast between vegetated and non-vegetated landscapes during this period.

Although both land-cover categories exhibited interannual variability, the overall temperature difference remained consistently above 2 °C after 2010, except in 2020, when the difference decreased slightly to 2.34 °C. In 2025, the mean summer temperatures over green and non-green areas were 24.23 °C and 26.45 °C, respectively, corresponding to a temperature difference of 2.22 °C.

Overall, the results demonstrate that green-covered regions remained consistently cooler than non-green landscapes throughout the study period. The persistent temperature difference of approximately 1–2.5 °C suggests that vegetation plays a significant role in reducing summer warming through processes such as evapotranspiration, canopy shading, and enhanced surface moisture, whereas non-green landscapes are more susceptible to heat accumulation.

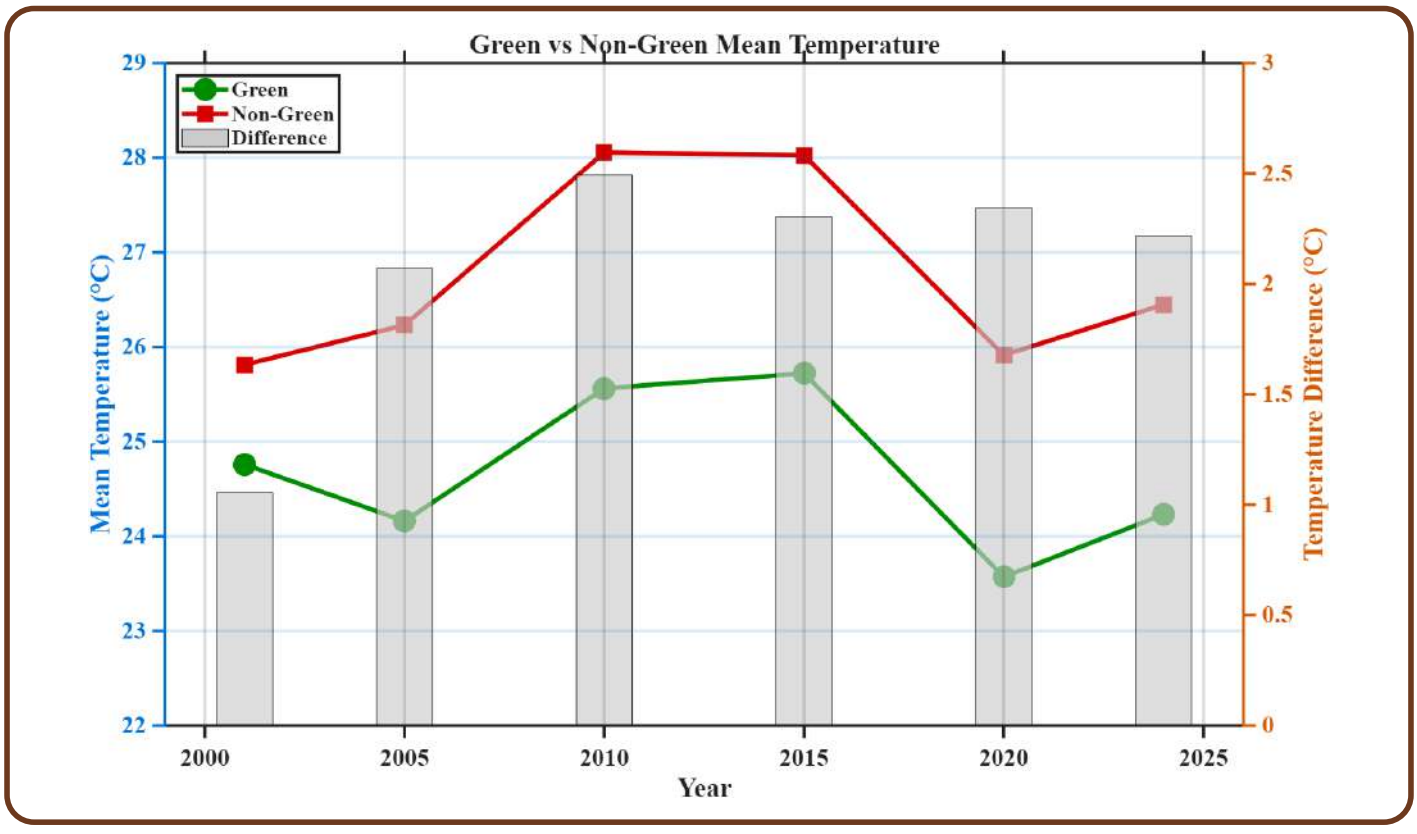


Figure 3. Temporal variation in mean summer (March–May) temperature over green and non-green land-cover categories across India during 2001–2025. The green and red lines represent the mean temperatures of green and non-green areas, respectively, while the grey bars indicate the corresponding temperature difference between the two land-cover categories.



3.4: Distribution of Summer Temperature over Green and Non-Green Land Cover

Figure 4 illustrates the distribution of summer (March–May) temperatures over green and non-green land-cover categories using boxplots for the selected study years (2001–2025). In all years, the temperature distribution over non-green areas is consistently shifted towards higher values compared with green-covered regions, confirming that non-green landscapes experience warmer summer conditions.

The median summer temperature over green-covered areas ranged from approximately 28–30°C, whereas the median temperature over non-green areas remained consistently higher, varying between 29 and 32 °C. The interquartile range (IQR) of green-cover temperatures is wider than that of non-green areas, indicating greater spatial variability associated with different vegetation types and climatic zones across India. In contrast, non-green areas exhibit a comparatively narrower temperature distribution but consistently higher median values.

The highest summer temperatures were observed during 2010 and 2015, when both green and non-green regions experienced elevated thermal conditions. Nevertheless, the median temperature over green-covered areas remained lower than that of non-green areas in every study year. During 2020, both categories exhibited relatively lower temperatures, although the thermal contrast between vegetated and non-vegetated landscapes persisted. Similar behaviour was observed in 2025, where green-covered regions maintained lower temperatures despite widespread warming.

Overall, the boxplot analysis confirms that vegetation not only reduces the average summer temperature but also influences the overall temperature distribution across India. The persistent separation between the two boxplots demonstrates that green-covered landscapes consistently provide a cooling effect relative to non-green surfaces throughout the study period.

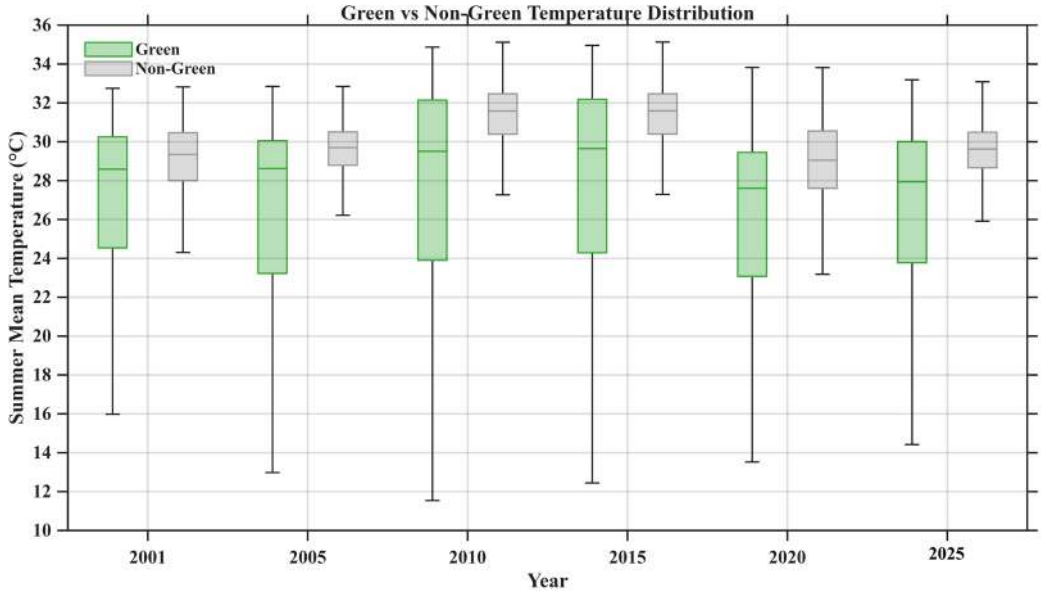


Figure 4. Distribution of summer (March–May) mean temperatures over green and non-green land-cover categories across India during 2001–2025. The boxplots represent the median, interquartile range, and overall variability of pixel-wise temperatures for each land-cover category, demonstrating consistently cooler thermal conditions over vegetated landscapes.

3.5: Spatial Patterns of Green Cover Change and Temperature Change

Figure 5 illustrates the spatial distribution of green-cover change across India between 2001 and 2025, while Figure 6 presents the corresponding change in mean summer (March–May) temperature over the same period. Together, these figures provide an overview of the long-term evolution of vegetation and its associated thermal response.

The green-cover change map (Figure 5) reveals that land-cover transitions were spatially heterogeneous across the country. Green-cover loss was predominantly observed across western India, the Indo-Gangetic Plain, parts of central India, and several regions of peninsular India. In contrast, localized green-cover gains were identified in portions of the northeastern states, the Himalayan foothills, and scattered areas of southern and eastern India. Large regions also exhibited little or no detectable change in green cover over the study period, indicating relatively stable vegetation conditions.

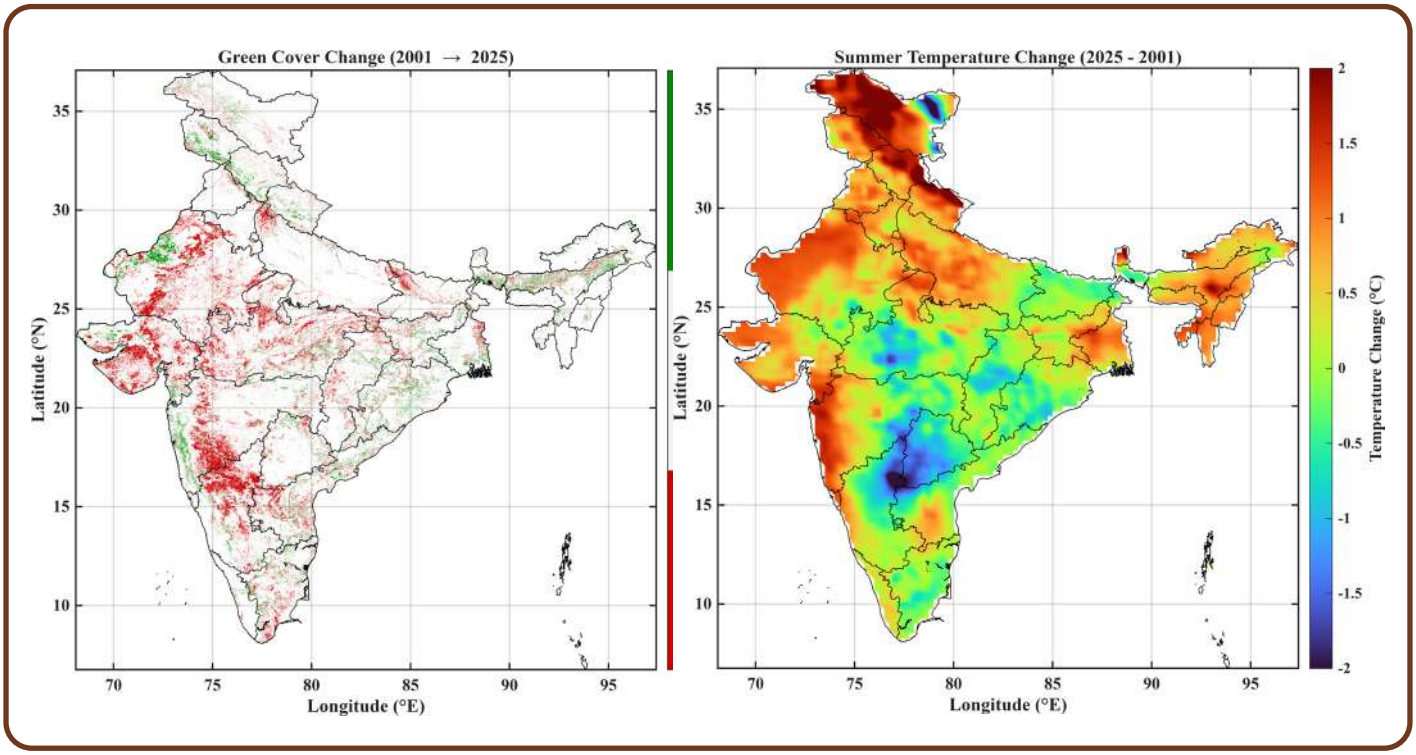


Figure 5 & 6. Spatial changes in green cover and summer temperature across India between 2001 and 2025. (Left panel; Figure 5) Spatial distribution of green-cover change, where green indicates green-cover gain, red represents green-cover loss, and white denotes areas with no detectable change. (Right panel; Figure 6) Spatial distribution of changes in mean summer (March–May) temperature relative to the 2001 baseline, where positive values indicate warming and negative values indicate cooling.

The summer temperature change map (Figure 6) shows considerable spatial variability in thermal trends between 2001 and 2025. Pronounced warming (generally exceeding 1–2 °C) is evident across northwestern India, the western Himalayan region, and parts of northeastern India. In contrast, several areas of central and southern India exhibit comparatively smaller temperature increases, with localized cooling or weak negative temperature anomalies observed in some regions.

A comparison of Figures 5 and 6 suggests that areas experiencing substantial green-cover loss often coincide with regions exhibiting positive summer temperature changes. However, this relationship is not spatially uniform across India. Several regions with relatively stable vegetation also experienced noticeable warming, whereas localized cooling occurred despite limited land-cover change.

These observations indicate that, although vegetation dynamics contribute to regional temperature variability, the observed thermal patterns are also influenced by additional climatic and physiographic factors, including elevation, regional circulation, and land–atmosphere interactions.

3.6: Influence of Land-Cover Transitions (2001 to 2025) on Summer Temperature Change

To quantify the thermal response associated with land-cover transitions, the study classified all pixels into four transition categories between 2001 and 2025: green loss, green gain, stable green, and stable non-green (Figure 7). Stable non-green land constituted the largest fraction of the study area (63.76%), followed by stable green (29.70%), green loss (9.95%), and green gain (4.03%).

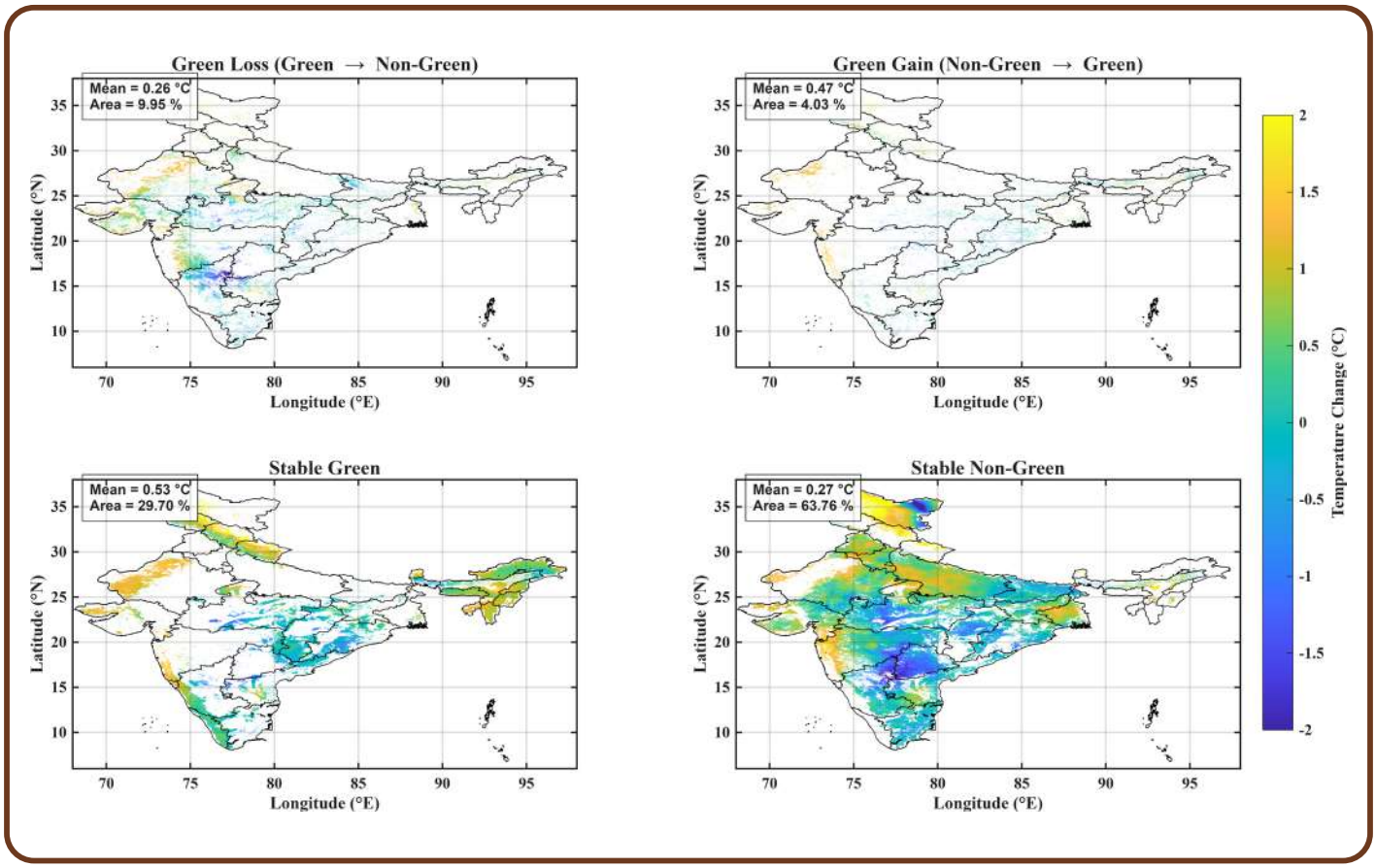


Figure 7. Spatial distribution of summer (March–May) temperature change associated with major land-cover transitions between 2001 and 2025 across India. The four panels represent (a) Green Loss (green → non-green), (b) Green Gain (non-green → green), (c) Stable Green, and (d) Stable Non-Green areas. Colours indicate the magnitude of temperature change relative to the 2001 baseline, with positive values representing warming and negative values indicating cooling. Insets report the mean temperature change and the percentage area occupied by each transition category.

Areas experiencing green-cover loss exhibited a mean summer temperature increase of 0.26°C, indicating that conversion of vegetated land to non-green surfaces was generally associated with warming. Although green-gain regions occupied a relatively small proportion of the study area, they recorded an average temperature change of 0.47 °C, suggesting that recently restored vegetation has not yet fully offset the influence of regional climatic warming.

The stable green category showed the highest mean temperature increase (0.53 °C), while stable non-green areas exhibited a comparatively lower average increase (0.27 °C). Spatially, warming within stable green regions was mainly concentrated over the northwestern Himalayas and parts of northeastern India, whereas localized cooling was evident across portions of central and southern India. Stable non-green regions displayed widespread warming across northern and western India, with cooler conditions observed over sections of the Deccan Plateau.

Overall, the transition analysis demonstrates that the observed changes in summer temperature are influenced not only by land-cover conversion but also by broader regional climatic processes. Nevertheless, areas undergoing vegetation change exhibit distinct thermal responses, highlighting the importance of preserving and restoring green cover to mitigate long-term surface warming.



3.7: Temperature Response Across Land-Cover Transition Categories

Figure 8 compares the distribution of summer (March–May) mean temperatures in 2001 and 2025 for four land-cover transition categories: Green Loss (Green → Non-Green), Green Gain (Non-Green → Green), Stable Green, and Stable Non-Green. Overall, all four categories exhibit an upward shift in temperature between 2001 and 2025, indicating a general warming trend across India irrespective of land-cover transition.

Areas that experienced green-cover loss showed an increase in the median summer temperature from approximately 29.4°C in 2001 to 29.6°C in 2025, corresponding to a mean warming of about 0.23°C. The warming observed in these regions is consistent with the reduction in vegetative cover, which decreases evapotranspiration and increases sensible heat flux, thereby enhancing local surface temperatures.

Pixels classified as green gain also exhibited a measurable increase in temperature, with the mean rising from 27.45°C to 27.86°C (ΔT ≈ 0.41°C). Although vegetation expanded in these areas, the increase in temperature suggests that regional climate warming during the study period exceeded the local cooling benefits provided by newly established vegetation. Many of these gains also occurred in regions that were already undergoing broader climatic warming, indicating that land-cover change alone does not fully explain the observed thermal response.

Among all categories, stable green areas displayed the largest increase in mean temperature, increasing from 24.95°C to 25.41°C (ΔT ≈ 0.46°C). Despite remaining vegetated throughout the study period, these regions experienced continued warming, implying that persistent vegetation moderates but does not eliminate the influence of large-scale climate change. The wider interquartile range observed for stable green areas further reflects the substantial climatic diversity across India's forested and naturally vegetated landscapes.

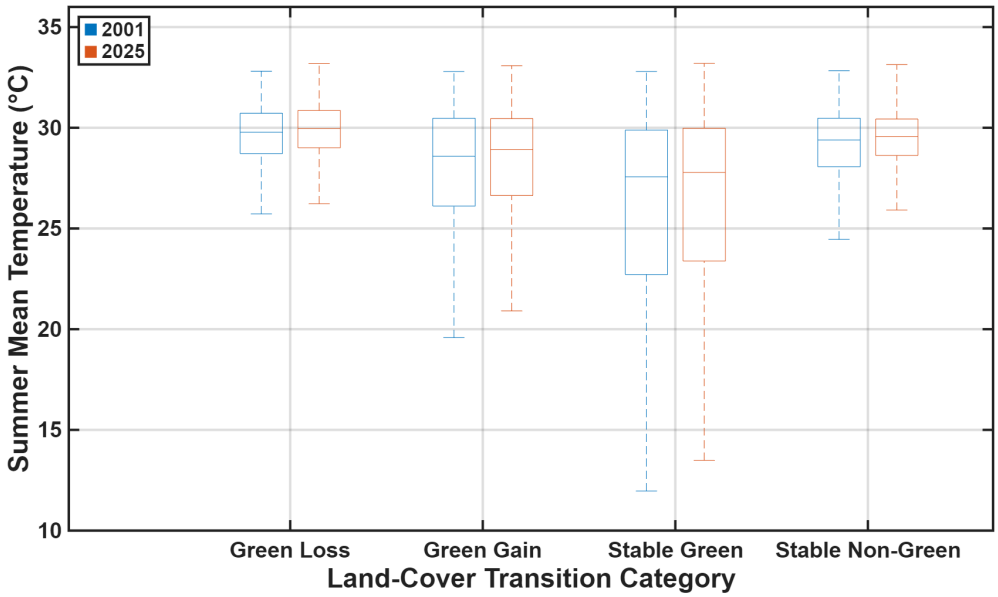


Figure 8. Comparison of the distribution of summer mean temperatures for four land-cover transition categories in 2001 and 2025. Side-by-side boxplots illustrate the shift in temperature distributions associated with green-cover loss, green-cover gain, stable green, and stable non-green areas. The central line indicates the median, boxes represent the interquartile range (IQR), and whiskers denote 1.5 × IQR. Statistical differences among groups were evaluated using the Kruskal–Walli's test ($p < 0.001$).

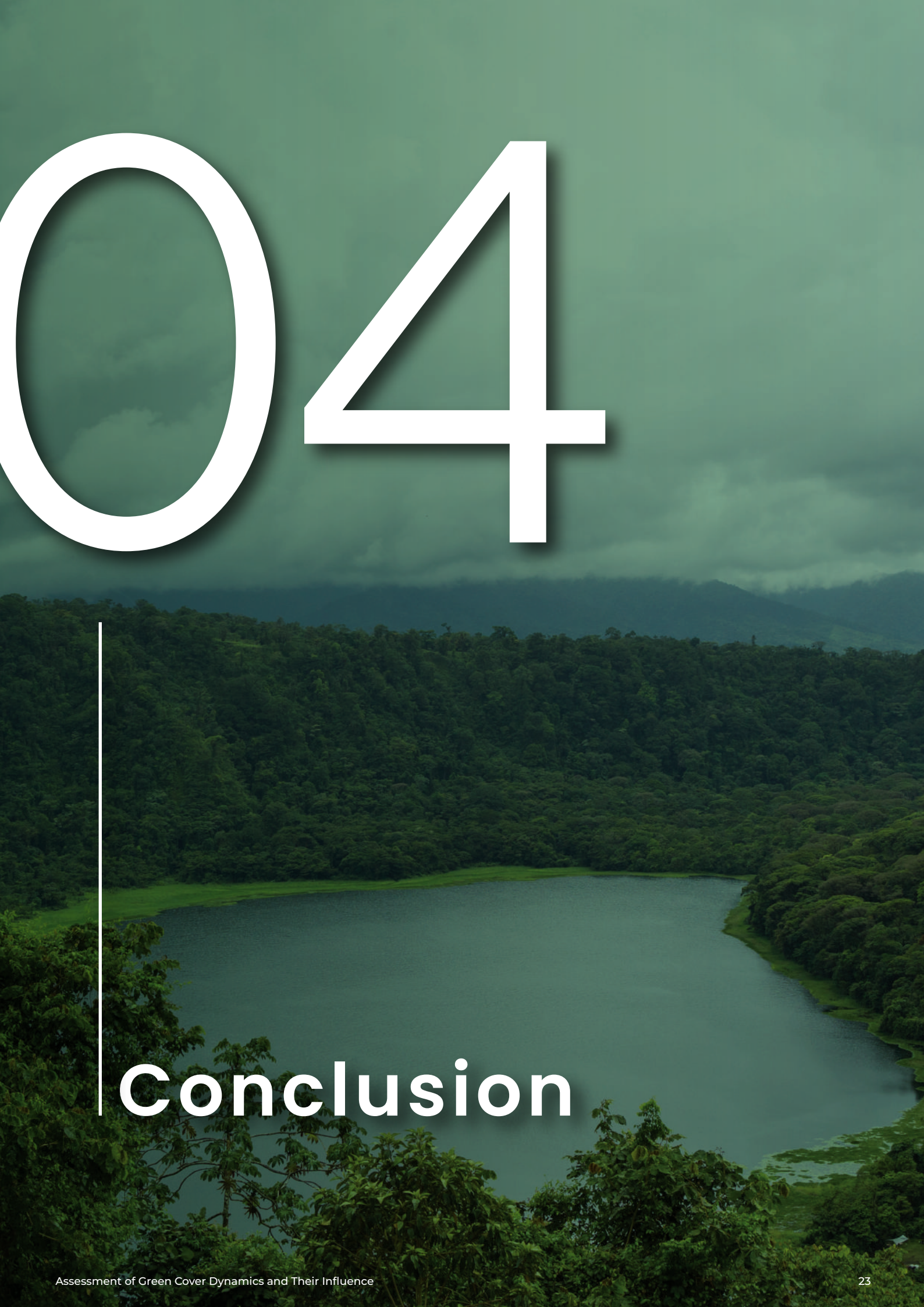
In contrast, stable non-green areas exhibited the smallest temperature increase, with the mean changing from 29.18°C to 29.37°C (ΔT ≈ 0.19°C). These regions were consistently characterized by croplands, built-up areas, barren land, water bodies, or other non-green land-cover classes throughout the study period and generally maintained relatively high baseline temperatures.

The overall differences among the four transition categories were found to be statistically significant according to the Kruskal–Walli's test ($p < 0.001$), indicating that land-cover transition categories exhibit distinct thermal characteristics. Nevertheless, the relatively modest warming observed in areas of green-cover loss compared with stable green regions suggests that the observed temperature changes are governed by the combined influence of regional climate warming and local land-cover dynamics rather than by land-cover transition alone. These findings highlight that vegetation change modifies local thermal conditions but operates within the broader context of ongoing climate change across India.

Table 3. Summary statistics of summer (March–May) mean temperature for different land-cover transition categories between 2001 and 2025.

Land-cover transition	Mean Temp. (2001, °C)	Mean Temp. (2025, °C)	ΔT (°C)	Median (2025,°C)	Standard Deviation (2025, °C)	Interpretation
Green Loss (Green → Non-Green)	29.40	29.63	0.23	29.96	2.37	Moderate warming following conversion of vegetated land to non-green surfaces.
Green Gain (Non-Green → Green)	27.45	27.86	0.41	28.93	4.40	Temperature increased despite vegetation gain, suggesting dominance of regional climate warming.
Stable Green	24.95	25.41	0.46	27.78	6.72	Largest warming observed in persistent, vegetated areas, reflecting broad-scale climate warming across forests and natural vegetation.
Stable Non-Green	29.18	29.37	0.19	29.57	1.83	Smallest increase in temperature among all transition categories.





04

Conclusion

04: Conclusion

This study provides a comprehensive assessment of the relationship between long-term land-use/land-cover (LULC) dynamics and summer surface temperature over India using MODIS land-cover products and ERA5-Land temperature data for the period 2001–2025. By integrating multi-temporal LULC information with seasonal (MAM) temperature observations, the study quantifies changes in green-cover extent and evaluates their influence on spatial patterns of summer warming.

The results reveal a substantial decline in green cover during the study period. Green-cover area decreased from approximately 1.21×10^6 km^2 (36.95%) in 2001 to 1.03×10^6 km^2 (31.35%) in 2025, representing a net reduction of nearly 5.6 percentage points. Correspondingly, non-green land increased from 63.05% to 68.65%, indicating continuous expansion of anthropogenic and sparsely vegetated surfaces across large parts of the country. Temperature analyses consistently demonstrated that non-green surfaces remained warmer than green-covered areas throughout the study period. The average summer temperature difference

between the two land-cover categories ranged from approximately 1-2.5 °C, highlighting the important role of vegetation in regulating land-surface thermal conditions through evapotranspiration, shading, and enhanced surface moisture availability. Although both land-cover categories exhibited warming over time, green-covered regions consistently maintained lower temperatures than surrounding non-green landscapes.



Spatial analyses further revealed pronounced regional variability in summer temperature change. Warming was particularly evident across northwestern and northern India, while localized cooling occurred over parts of central and southern India. The spatial correspondence between vegetation change and temperature patterns suggests that areas experiencing persistent vegetation degradation generally exhibited stronger warming, whereas regions with relatively stable vegetation showed comparatively moderated thermal responses.

The land-cover transition analysis provided additional insight into the thermal consequences of landscape change. Stable non-green land occupied the largest proportion of the study area, followed by stable green land, whereas green-loss and green-gain regions accounted for comparatively smaller fractions. Distinct temperature responses among these transition classes indicate that land-cover change modifies local thermal environments, although regional climatic forcing also contributes substantially to observed temperature trends. The coexistence of warming within stable green areas emphasizes that vegetation alone cannot completely offset the influence of large-scale climate change, but it remains an important natural mechanism for reducing local thermal stress.

Overall, the findings demonstrate that long-term decline in green cover, together with the expansion of non-green landscapes, has contributed to increasing summer temperatures across India. Maintaining existing vegetation, preventing unnecessary green-cover loss, and promoting ecological restoration should therefore be considered integral components of climate adaptation and sustainable land-management strategies. The framework developed in this study provides a scalable approach for assessing interactions between land-cover dynamics and thermal environments and can support future investigations on urban expansion, ecosystem resilience, and climate-change mitigation at regional and national scales.





05

Recommendations

05: Recommendations

A. Prioritize protection of existing green cover, particularly in green-loss hotspots

The priority should be preventing further conversion of existing natural and semi-natural vegetation, rather than relying only on new plantation or restoration. The analysis shows that green-cover loss was concentrated in western India, the Indo-Gangetic Plain, parts of central India and peninsular India.

From a climate-adaptation perspective, mature vegetation provides an established combination of canopy shading, evapotranspiration, soil-moisture regulation and carbon storage. Therefore, land-use planning should adopt a "protection before restoration" principle. Conversion of forests, shrublands, grasslands and wetlands should require stronger ecological and thermal-impact assessment, particularly in regions where green-cover loss overlaps with increasing summer temperature.

Scientific basis: The study found that green-loss areas experienced an average summer temperature increase of approximately 0.26°C, and the spatial comparison showed that many regions with vegetation loss also experienced warming.



B. Develop region-specific ecological restoration programmes in areas showing simultaneous vegetation loss and warming

Afforestation or ecological restoration should not be implemented uniformly across India. The study demonstrates strong spatial heterogeneity in both vegetation change and temperature trends, with warming exceeding 1–2°C in several northwestern, Himalayan and northeastern regions.

A spatial-priority framework should therefore be developed by overlaying:

- green-cover loss,
- summer temperature increase,
- frequency/intensity of heat exposure,
- population density,
- water availability,
- ecosystem vulnerability, and
- existing protected/natural vegetation.

Areas with simultaneous green-cover loss and strong summer warming should receive the highest restoration priority.

Restoration should also use native, climate-adapted species and locally appropriate ecosystems rather than simply maximizing tree numbers. In dry regions, for example, restoration of native grassland, shrubland or dry-forest ecosystems may be more ecologically appropriate than dense tree plantations.

Why this is important: The report found that green-gain regions still experienced approximately 0.41–0.47°C warming, indicating that vegetation restoration alone cannot immediately reverse the influence of broader climatic warming.



C. Integrate vegetation-based cooling into urban and peri-urban heat-management planning

The expansion of built-up land should be treated not only as a land-use issue but also as a thermal-risk issue. The report identifies urban expansion as an important component of observed land-cover change and demonstrates that non-green landscapes consistently experience higher summer temperatures.

Urban planning should therefore incorporate minimum green-cover and canopy requirements, especially in rapidly expanding cities and peri-urban regions. Measures could include:

- preservation of existing urban forests and large tree patches;
- development of connected green corridors;
- roadside and neighbourhood tree canopy;
- protection/restoration of urban wetlands;
- parks strategically located in heat-vulnerable neighbourhoods;
- integration of green spaces with drainage and water-retention systems.

The emphasis should be on spatial configuration and canopy quality, not simply total green area. Connected vegetation can potentially provide greater local cooling and ecological connectivity than small, isolated patches of equivalent area.



D. Adopt a "green infrastructure + water management" approach for summer cooling

Vegetation cooling is strongly dependent on evapotranspiration and water availability. The report identifies evapotranspiration, shading and surface moisture as important mechanisms through which vegetation moderates summer temperature.

Therefore, vegetation restoration should be coupled with water-sensitive land management, particularly in water-limited regions. Policies should promote:

- rainwater harvesting;
- restoration of ponds, wetlands and riparian vegetation;
- soil-moisture conservation;
- permeable surfaces;
- groundwater recharge;
- protection of natural drainage systems.

This is particularly important because simply planting vegetation in water-stressed environments may produce limited long-term cooling if vegetation cannot maintain sufficient evapotranspiration during the pre-monsoon period.
A scientifically robust strategy should therefore evaluate vegetation cover together with soil moisture, precipitation and evaporative demand, rather than treating green cover as an independent cooling mechanism.



E. Establish a national satellite-based Green Cover–Heat Monitoring and Early-Warning framework

The results demonstrate the value of combining annual land-cover information with seasonal temperature observations. This framework can be developed into a continuous national monitoring system. Satellite and reanalysis datasets should be used to monitor, at annual or seasonal intervals:

- green-cover loss and gain;
- vegetation condition/NDVI;
- land-surface temperature;
- 2-m air temperature;
- soil moisture;
- urban expansion;
- surface albedo;
- heatwave occurrence;
- changes in wetlands and forest cover.

A Green Cover–Heat Risk Index could then identify districts where simultaneous vegetation degradation and increasing thermal stress are occurring.

Such a system would allow policymakers to move from a reactive approach responding after vegetation loss or heatwaves occur to a preventive land-management strategy. The study already provides a scalable framework for this type of assessment.

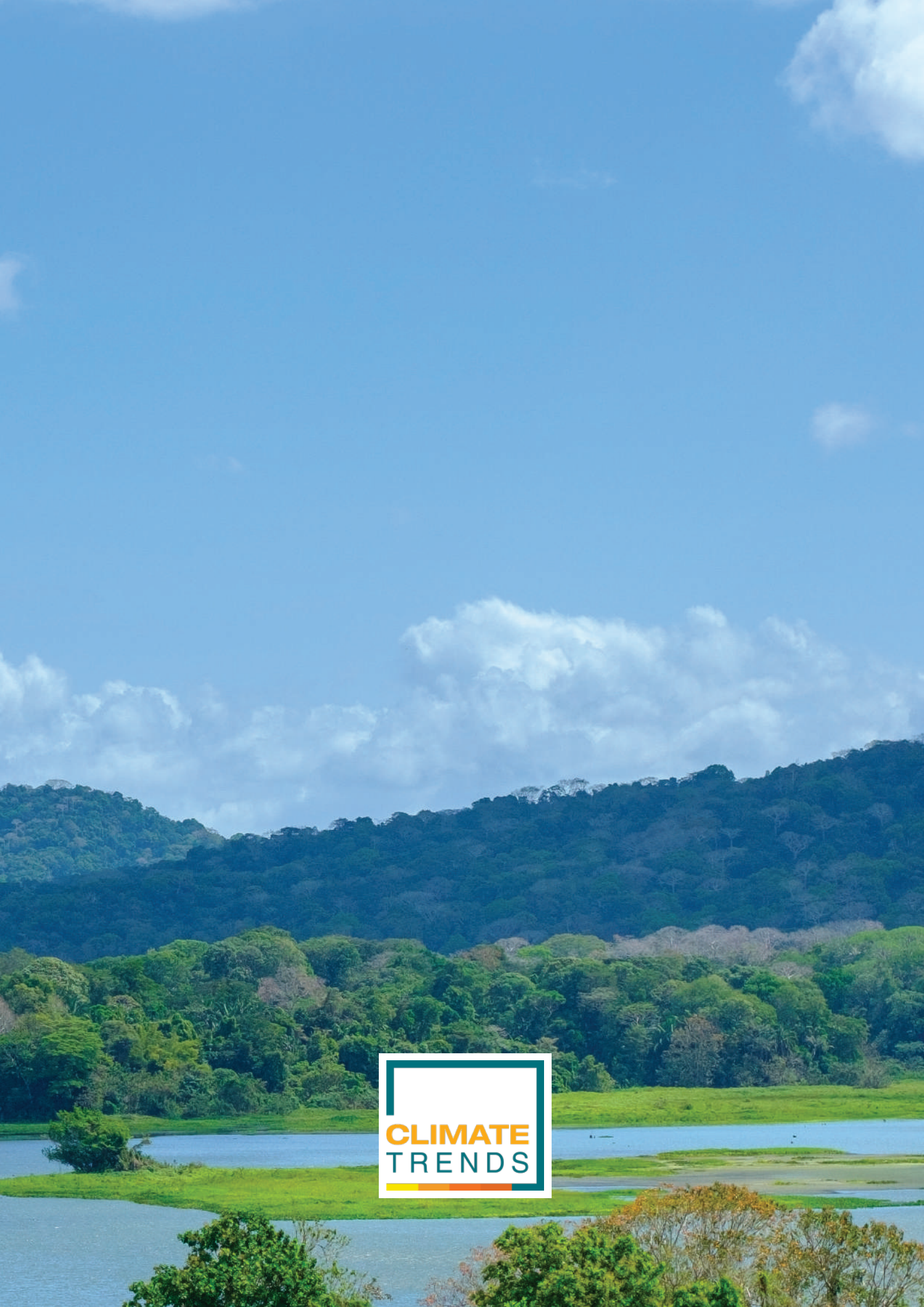


F. Incorporate vegetation conservation into climate adaptation and land-use policy, but avoid treating vegetation as the sole solution

The study provides strong evidence that vegetation contributes to thermal regulation, but it also demonstrates an important scientific limitation: vegetation cannot completely counteract large-scale climate warming. Stable green areas experienced approximately 0.46°C warming, despite remaining vegetated throughout the study period.

Therefore, climate policy should use vegetation conservation as one component of a broader adaptation strategy, alongside heat-health action plans, water management, urban design, improved building efficiency and reduction of greenhouse-gas emissions.

Future assessments should also explicitly control for elevation, precipitation, soil moisture, atmospheric circulation, urbanization, albedo and other climatic drivers. This is important because the study itself finds that temperature changes are influenced by both land-cover dynamics and broader regional climatic processes.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