Thesis Subject: Examining the impact of climate change in the Apennine Mountains: A Remote Sensing-based Data Analysis

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Abstract

Mountain ecosystems are particularly sensitive to climate change, and the implications for vegetation dynamics and ecosystem stability are far reaching. As the Apennine Mountains constitute an environment that is particularly vulnerable to climate change, this study aims to explore the impact of climate change on vegetation greening in this region, by utilizing remote sensing technologies and geospatial analysis. Using MODIS NDVI datasets (2001–2023) and climatic variables from ERA5-Land and CHIRPS, this study analyses spatiotemporal greening trends at different elevations and the effect of primary climate drivers—temperature and precipitation—in the study area.

Results show vegetation green up has increased significantly, especially in lower- and mid-elevation (2000m), likely due to climatic constraints such as temperature extremes in these areas and reduced soil productivity. Temperature appears to be the primary driver of greening, as warmer winters (obtained from nearby weather stations) and earlier snowmelt date all favor larger patches of vegetation. Nonetheless, the trend in precipitation is negative, indicating possible future water shortages.

This study highlights the importance of remote sensing and using cloud-based platforms such as Google Earth Engine (GEE) for long-term vegetation monitoring. This study offers important information on climate-driven vegetation shifts within Mediterranean mountain biomes that may help facilitate ecological management, biodiversity conservation, and climate adaptation initiatives.

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1 Introduction

1.1 Problem statement and research significance

Climate change is one of the most severe 21st-century challenges, which is drastically altering natural systems and their ecological processes, especially in mountainous regions, which are some of the most sensitive to global warming. Studies suggest that mountain regions may experience warming at significantly higher rates than the global average (Pepin et al., 2015; Tao et al., 2017; Kumari et al., 2021). These environments are vital, not only for the people living in these areas but also for other people, as they provide essential resources such as water, biodiversity, and climate regulations (Huang et al., 2022). This has prompted scientists to take a keen interest in studying the impacts of climate change on these fragile environments.

Vegetation plays an important role in regulating the cycles of water and energy in ecosystems on land (Almalki et al., 2022; Liu et al., 2022). It influences runoff control and enhances regional evapotranspiration, contributing to declining air temperature and surface albedo (Zhu & Zeng, 2015). Thus, vegetation is considered a critical indicator for understanding the state of environmental conditions (Piao et al., 2019). Scientists and policymakers are paying close attention to the increasing spread of green plants for clear reasons: they help absorb carbon dioxide, thereby mitigating global temperature rises (Zhu et al., 2016; Kumari et al., 2021).Scientists and policymakers are paying close attention to the increasing spread of green plants for clear reasons: they help absorb carbon dioxide, thereby mitigating global temperature rises (Zhu et al., 2016; Kumari et al., 2021).

Remote sensing (RS) technologies have transformed existing vegetation dynamics studies by allowing extensive coverage and high-spatial resolution observations of environmental changes on time scales from hours to decades. More recently, cloud computing platforms have allowed to run such studies in ways that broaden the type of applications (Velastegui-Montoya & Montalván-Burbano 2023), where one of the examples is the integration of RS data within Google Earth Engine (GEE), both aiming to improve efficiency in ecological investigations. There are many contemporary studies implementing RS data processed through GEE for environmental monitoring, especially for plants (Parracciani et al., 2024).

GEE's cloud-based processing environment allows users to generate near-real-time data and monitor large dataset information, for example, MODIS and Landsat imagery, thus permitting more detailed assessments of vegetation trends, extents, and potentials within complex and varied terrains such as those in the Apennines.

As with latitude, elevation has exerted a major physical influence on vegetation since the time of Alexander von Humboldt in the nineteenth century (Rahbek et al., 2019; Liu et al., 2021). Hopkins' Bioclimatic Law explains how leaf-out happens later at higher elevations. Vitasse et al. (2018) later explored this idea in the context of global warming, showing how climate change is affecting this natural pattern. Elevation has emerged as a significant factor in environmental studies, most notably evidenced by research conducted in high-altitude areas such as the Tibetan Plateau, the Andes, and the Alps (Körner, 2007; Beniston et al., 1997). Nevertheless, the influence of elevation on vegetation greening in mountainous regions has been scarcely addressed. Therefore, it would be valuable to investigate the potential correlation between greening trends and elevation.

The Apennine Mountains, running the length of northern and southern Italy, host an extensive range of habitats, from temperate forests to Mediterranean shrublands. This heterogeneity, coupled with the regionwide high sensitivity to climate change, makes the Apennines of great interest for studying vegetation responses to climate change. It is an ideal region to study the effect of climate change on vegetation greening because of its rich biodiversity, complex topography, and diverse climatic conditions. These dynamics are critical for informing effective management strategies to conserve biodiversity and ecosystem services.

1.2 Research Background

Vegetation greening is an important indicator of ecological responses to climate change and human activity (Chen et al. 2020 and Piao et al. 2020) explored the linkages between climate, human activities, and vegetation greening across multiple regions and environments, including Central Asia, China, Mongolia, and High Mountain Asia. Their analysis demonstrated how different biophysical pressure factors impact the effects of climate variability on vegetation cover. The findings indicated that although climate—particularly changes in precipitation and temperature—remains the predominant driver of vegetation trends, human interventions such as afforestation and irrigation play increasingly significant roles.

In semi-arid Central Asia, analyses over a longer time scale (1985–2020) confirmed the ultimate control of soil moisture by climatic conditions (Amantai et al.,2024). The results showed that

NDVI (Normalized Difference Vegetation Index) and LAI (Leaf Area Index) have positively impacted vegetation activity. This simultaneous greening and drying phenomenon are notably observed in regions such as Kazakhstan and Xinjiang, where greening is accompanied by a sharp drop in soil moisture. This inference highlights that precipitation patterns, rather than vegetation growth, are fundamentally responsible for driving soil moisture dynamics in dryland regions, thereby adding an important consideration for climate-centric water resource management approaches (Amantai et al.,2024).

Besides climate factors, ecological restoration in China has played an important role in vegetation greening (Chen et al., 2020; Cheng et al., 2021). From 1982 to 2020, 55% of China's land exhibited greening trends, with the most significant improvements occurring in the Loess Plateau, Northeast Plain, and southern regions. Climate accounted for 72% of the observed greening, while intensive afforestation programs, such as the Three-North Shelterbelt Program and the Grain for Green Program, were instrumental in counteracting land degradation (Gan et al., 2021). However, studies caution that 60% of areas experiencing greening today are susceptible to vegetation collapse if adaptation strategies are not sustained in the long term (Amantai et al., 2023).

These disparities between satellite observations and tree-ring records are evident when examining long-term vegetation trends in western Mongolia. While NDVI data starting in the 1980s demonstrate expanding greenness over time, tree-ring investigations (1940–2010) report no sustained greening trend (Zhang et al., 2023). More recently, greening has been linked to transitory climate variability, such as the wetter period of the 1990s, rather than a long-term response to climate change. Additionally, higher temperatures have stressed forested areas, reduced biomass and increasing vulnerability to drought (Song et al., 2023). These results highlight the limitations of satellite-derived vegetation indices, which may reflect only short-term ecological changes. Consequently, the authors advocate for multi-proxy and multi-decadal approaches to accurately interpret vegetation dynamics (Yang et al., 2024; MacDonald, G. M., et al. 2008).

Nationwide trends in greening and browning observed in China from 2000 to 2020 suggest that only 25% of vegetated lands were greening, while 11% experienced browning. In other words, the majority of vegetated areas did not exhibit significant change (Yi et al., 2023). The success of greening programs has been mixed, varying across regions and influenced by the restoration techniques employed. For example, the Beijing-Tianjin Sand Source Control Project has achieved notable success, whereas the Returning Grazing Land to Grassland Program has yielded mixed outcomes. Additionally, urbanized and industrialized regions, such as the Yangtze River Delta, display divergent greening and browning trends (Bai et al., 2024). These disparities suggest that the relationships among urbanization, climate change, and ecosystem recovery are complex. Both trees and grass exhibit limited recovery potential, indicating that climate stressors and urban expansion drivers may outweigh vegetation recovery responses. This underscores the need for integrated climate adaptation and land-use planning strategies (Zhang et al., 2024).

The climatic and anthropogenic drivers of substantial vegetation greening trends across High Mountain Asia (HMA) were identified in studies conducted between 1999 and 2014 (Zhong et al., 2019). Three key factors were highlighted: increased precipitation, warming-induced snowmelt, and intensive irrigation. Precipitation remains the predominant factor influencing seasonal vegetation dynamics in both evergreen and mixed forests of the Irrawaddy Basin, across high, mid, and low-elevation areas. In cold, dry regions such as the Tibetan Plateau, reduced snow cover enhances soil moisture availability, thereby extending the growing season and stimulating vegetation growth. Simultaneously, irrigation has fundamentally altered the soil moisture balance in many of the world's major agricultural regions, including the Ganges-Brahmaputra and Indus Basins. Furthermore, these studies highlight the feedback loops between vegetation and climate, where greening supports localized cooling through evapotranspiration. These findings underscore the importance of integrated water and land management strategies to sustain vegetation growth under varying climate conditions.

1.3 Research objectives

Based on REMOTE SENSING (RS) data processed on cloud computing platforms, this study investigates the elevation-dependent response of vegetation greening to climate change in the Apennine Mountains. Using decades of satellite imagery and vegetation indices, we seek to reveal spatiotemporal patterns of vegetation change and their relationships with relevant climatic variables along the warmth gradient, temperature and precipitation. This research specifically aims for three main goals:

- To measure the trend of vegetation greening throughout the Apennines.
- To examine how climatic factors drive observed vegetation patterns.
- To investigate the role of elevation in modulating vegetation responses to climate change.

1.4 Scientific Questions

This study examines long-term satellite observations of vegetation greening in response to climate change at various elevations and explores their relationships with long-term climatic patterns. The current study generally aims to resolve the following scientific questions:

- What are the trends (space-time) of vegetation greening in the Apennine mountains in the 21st century?
- What is the effect of key climatic variables (i.e., temperature and precipitation) on the greening patterns in the Apennines?
- To what extent does elevation affect vegetation responses to climate change, and are there distinct elevation-dependent trends in vegetation greening?

2 Data and Material

2.1 Study Area

The Apennine Mountains, which are located all along the Italian peninsula, form an ecological and cultural backbone to Italy. This mountain belt extends about 1,200 kilometers and features peaks of 2,912-meter elevation. The region encompasses various ecosystems, such as forests, grasslands, and shrublands, and is home to many endemic species, with, among others, the Apennine wolf and Marsican brown bear. The region also plays a critical role in hydrological cycles, serving as a water source for numerous rivers and streams. As shown in Figure 1, the Apennine Mountains can be divided into three parts: Northern, Central, and Southern. This research employs the hierarchical mountain inventory version 2, developed under the auspices of the Global Mountain Biodiversity Assessment (GMBA) (Zhang & An, 2024), to determine the area of the Apennine Mountains. This inventory offers a detailed classification of the global mountainous areas, facilitating worldwide comparative studies in mountain science.

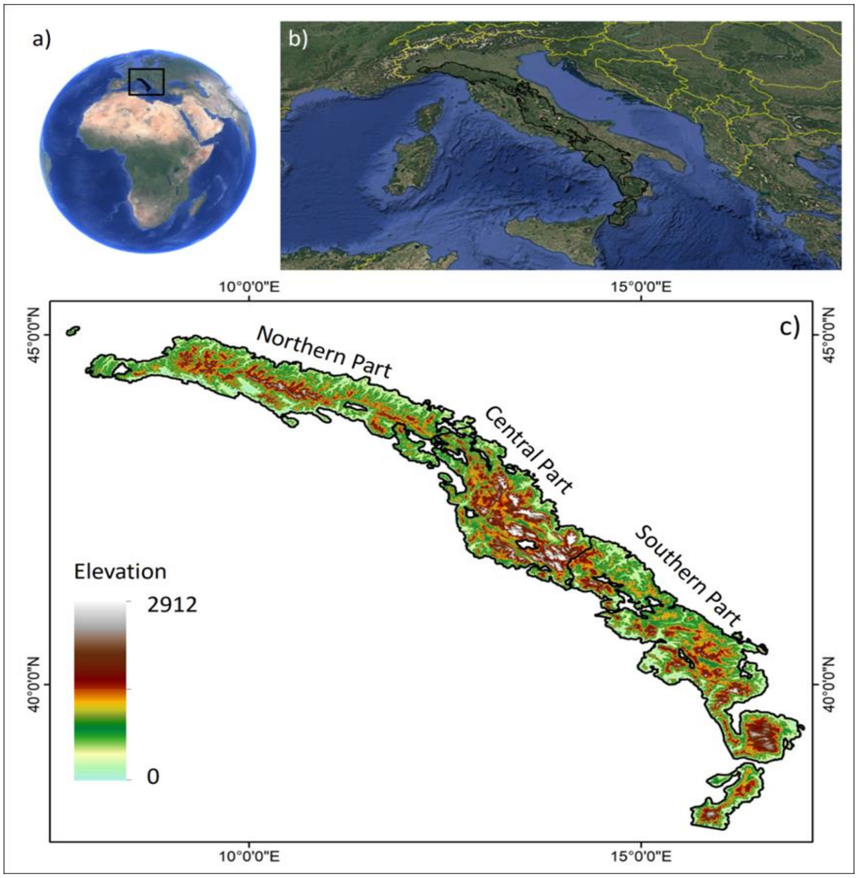


Figure 1. Location of the Apennine Mountains in world (a) and Italy (b). C) The elevation map of the Apennine Mountains

2.1.1 Remote Sensing data

RS is a powerful scientific technique used for monitoring and studying Earth's surface using satellite based, airborne and ground-based sensors. By monitoring data across various spectral bands, RS offers critical information on land use, vegetation changes, hydrologic connectivity and climate conditions. The ability to collect spatially continuous and temporally consistent data makes remote sensing essential for studying environmental changes on both local and global scales. Given the efficiency of RS data, this study made use of four publicly available RS data: MCD12Q1.061, MOD13A1.061 and ERA5-land, and Climate Hazards Center InfraRed Precipitation with Station data (CHIRPS).

2.1.2 Land cover data

The MCD12Q1 is a MODIS Land Cover Type data product from the Terra and Aqua satellites which provides global land cover types at annually intervals. MCD12Q1 Version 6.1: Derived from supervised classifications of MODIS Terra and Aqua surface reflectance data. Types of land cover are based on International Geosphere-Biosphere Programme (IGBP), University of Maryland (UMD), Leaf Area Index (LAI), BIOME-Biogeochemical Cycles (BGC), and Plant Functional Types (PFT) classification systems. The supervised classifications were then subjected to an additional post-processing step that uses prior knowledge and ancillary information to refine select classes. The Food and Agriculture Organization (FAO) Land Cover Classification System includes other layers of assessment of land cover properties such as land cover, land use, and surface hydrology.

2.1.3 Normalized Difference Vegetation Index

The MOD13A1 V6.1 product gives the Vegetation Index (VI) value per pixel. Two main vegetation layers co-exist:

The first is NDVI, as the continuity index to the existing National Oceanic and Atmospheric Administration-Advanced Very High-Resolution Radiometer (NOAA-AVHRR) based NDVI.

The second vegetation layer is the Enhanced Vegetation Index (EVI), which reduces canopy background variations and enhances sensitivity over high biomass regions. Finally, the EVI uses the blue band to remove some residual atmospheric contamination from smoke and sub-pixel thin cloud contaminants.

The MODIS NDVI and EVI products are computed from atmospherically corrected bi-directional surface reflectances that have been masked for water, clouds, heavy aerosols, and cloud shadows.

2.1.4 ERA5-Land

For this project, we used ERA5-land Daily Aggregated to sense temperature trend across case study area. ERA5 is the most recent global atmospheric reanalysis product offered by the European Centre for Medium Range Weather Forecasts (ECMWF). It combines observational data to a comprehensive globally consistent dynamical models to deliver a complete and up-to-date dataset, and replaces its previous version: ERA-Interim. ERA5 monthly aggregates climate data on a monthly basis and provides key information on atmospheric properties. The ERA5 data range from 1940 up to ~ 3 months before near real-time. This data set is critical for understanding longer-term climate patterns, testing climate models, and carrying out environmental impact assessments.

2.1.5 CHIRPS data

To analysis precipitation trend, we used CHRIPS product in this study. CHRIPS is a global precipitation data set developed by the Climate Hazards Center (CHC) at the University of California, Santa Barbara. It provides long-term precipitation estimates since 1981. CHIRPS incorporates satellite imagery with in-situ station data to create gridded rainfall time series. With its high resolution (5566 meter) and long historical record, CHIRPS is widely used by meteorologists, researchers, and policymakers to improve climate resilience and disaster response strategies.

2.2 Google Earth Engine Platform:

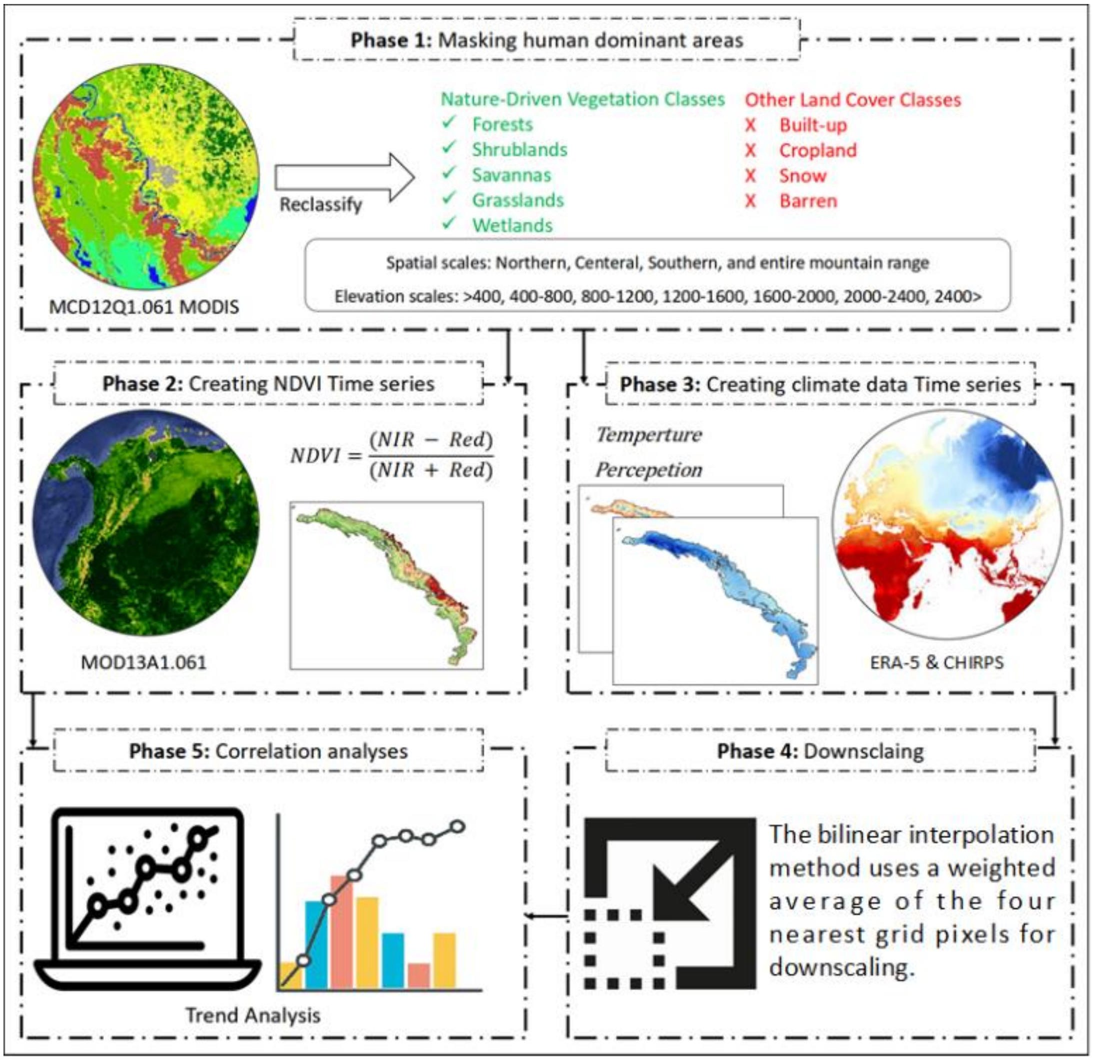
With the rapid increase of RS data, there is a demand for efficient processing and analysis platforms. Google Earth Engine (GEE) is a cloud-based platform for planetary-scale geospatial analysis. Such massive environmental monitoring can be performed without a huge use of local computational resources thanks to GEEs potential computing infrastructure. The benefits are numerous, however, for mountain greening studies, GEE offers access to long-term vegetation data sets such as MODIS imagery, offering researchers the ability to quantify trends over decades. With its built-in machine learning algorithms, vegetation indices, and time-series analysis capabilities, the platform is particularly well-suited for evaluating vegetation change over broad and complex mountainous landscapes. Table 1 displays dataset(s) used in the study and their Google Earth Engine code.

Data set	**Variable**	**GEE ID**
ERA5-Land	Temperature	ECMWF/ERA5_LAND/DAILY_AGGR
CHIRPS	Precipitation	UCSB-CHG/CHIRPS/DAILY
MCD12Q1 Version 6.1	Land cover type	MODIS/061/MCD12Q1
MOD13A1 Version 6.1	NDVI	MODIS/061/MOD13A1

Table 1. Data used in this study

3 Methodology:

To investigate the relation between climate data (precipitation and temperature) and mountain greening in Apennine Mountains, we have designed a simple yet efficient workflow based on remote sensing data and GEE cloud computing platform. The entire process is shown in Figure 2 which comprises five primary steps: masking human dominant areas, generating NDVI time series, creating climate data time series, downscaling of climate data, and correlation analysis. Considering the variability of climate data (precipitation and temperature) across different elevation scales, we classified the entire region into eight classes: 0-400, 400-800, 800-1200, 1200-1600, 1600-2000, 2000-2400, 2400-2912 meters. Additionally, we conducted a region-specific analysis due to the extensive nature of Appennine mountains. As a result, we performed our analysis at four levels: northern Apennine, central Apennine, southern Apennine, and entire Apennine.



The bilinear interpolation method uses a weighted average of the four nearest grid pixels for downscaling.

Figure 2. An overview of the applied methodology

3.1 Masking human dominant areas

To constrain our analysis exclusively to areas with natural vegetation and its response to climate variability, we masked human-dominant areas using the MCD12Q1 Version 6.1 land cover data layer. Global land cover classification with 17 different land cover classes. As our study aims to analyze the effects of climate change on greening of Apennine mountains, we reclassified the land cover product to obtain binary values:

- Vegetation based on nature (value 1): Forests, Shrublands, Savannas, Grasslands and Wetlands
- Other land cover types (0): Urban areas, croplands, barren land, water bodies, and other man-made surfaces.

This classification enables the analysis to exclude anthropogenic activities like agriculture and urbanization, leading to a more accurate assessment of climate-driven vegetation dynamics. This binary mask was then applied to all data sets in later workflow steps (Figure 3).

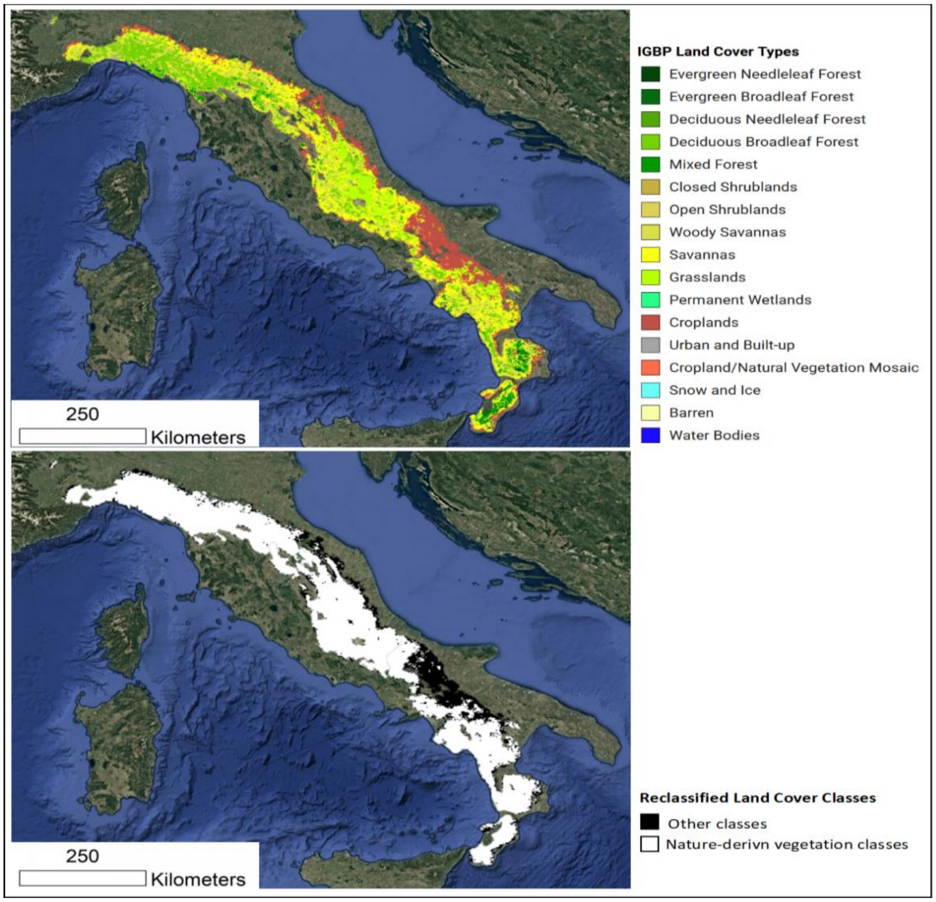


Figure 3. An example of masking nature-driven land cover classes of MCD12Q1 Version 6.1 product for 2020.

3.2 Creating NDVI time-series

To examine vegetation dynamics in response to climate variability, we used the MOD13A1 Version 6.1 data set, which consists of a 16-day composite NDVI data at 500-m spatial resolution. The consistent temporal coverage and atmospheric correction make this data set ideal for long-term monitoring of vegetation. For this study, NDVI data from 2021 to 2023 were processed, with 16-day composites being summed up to create seasonal and annual time series. Seasonal NDVI values were calculated as the average of the data for the respective season (spring, summer, autumn, and winter), and the annual NDVI values were based on the average of all observations within each year (Figure 4). The yearly scale aggregation in terms of matched pixel will capture both the intra- and inter-annual trends of vegetation, which will enable us to probe into a discussed but still ambiguous mountain greening phenomenon in response of climate factors.

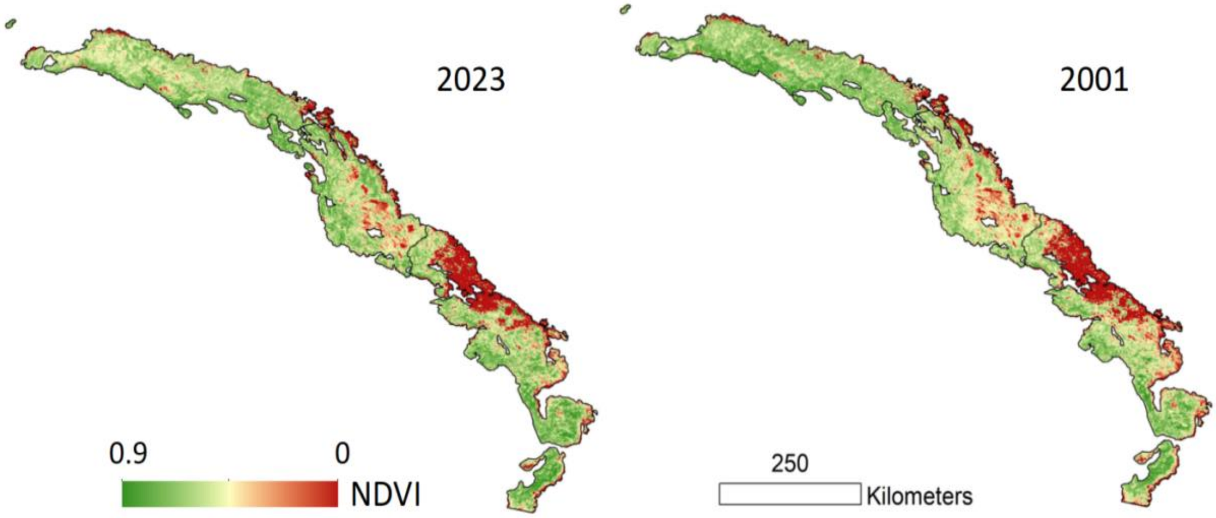


Figure 4. Examples of generated annual NDVI maps for the entire Apennine mountains for 2001 and 2023 using MOD13A1 Version 6.1 product for 2020.

3.3 Creating climate data time-series

To analyze the link between climate variability and mountain greening we derived time series based on two main climatic factors, i.e. precipitation and temperature. We extracted precipitation (P) and Temperature (T) data at high temporal and spatial resolution from the CHIRPS and ERA5-land products to conduct accurate climate trend analysis. For each climatic variable, like NDVI time-series, we extracted values for the study region, and aggregated them into time series on seasonal and annual scales for the period 2021–2023. Seasonal values were calculated by averaging values over each season (spring, summer, autumn, and winter) and annual values from the mean of values during all years.

3.4 Downscaling of Climate Data

A well-known and common downscaling process was implemented to acquire consistent spatial units among CHIRPS and ERA5 data with spatial resolution of 5566 and 11132 meters, respectively, and MOD13A1 NDVI data (500-meter resolution). The bilinear interpolation, which estimates the values of climate variables for a finer spatial resolution by taking a weighted average of the values of four nearby grid points, was used in this study. The effectiveness of this method has been confirmed in prior research for mountain greening studies (Mukhtar et al., 2025). The resulted 500 m resolution of climate variables (i.e., P, Tmax and Tmin) along with NDVI data allowed for more precise correlation analyses between climate variables and vegetation dynamics.

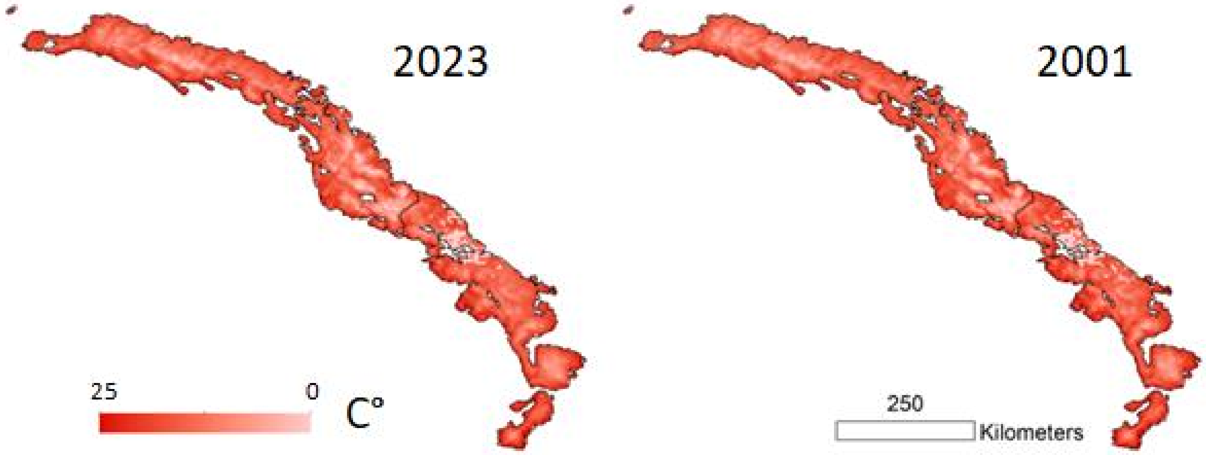


Figure 5. Examples of downscaled ERA-5 temperature product for years 2001 and 2023.

3.5 Trend and Correlation Analysis

To evaluate the role of climate variability in mountain greening, we performed a trend analysis and a correlation analysis between NDVI trends and elevation classes and between NDVI trends and different geographic regions of the Apennines. As climatic data can differ among eight elevation classes and regions, we used the Mann-Kendall test to identify significant trends for NDVI, precipitation, and temperature gradients from 2001 to 2023. We also calculated Sen's slope to estimate the magnitude of these trends. We calculated the Pearson correlation coefficient (r) between NDVI and precipitation/temperature at the seasonal and annual scale for each elevation class and geographic region to examine their relationship. Our methodology offers localized and integrated elevation and regional-tailored analyses, thus filling a knowledge gap concerning the role played by climate drivers for mountain greening in the context of the Apennine Mountains, disentangling relevant from background climate drivers.

4 Results:

This section first presents a comprehensive analysis of greening, temperature, and precipitation trends from 2001 to 2023 across the Apennine Mountains at three distinct levels: regional, seasonal, and elevation-based. It then examines the correlation between greening patterns and climate variables in this mountain range.

4.1 Greening trend in Apennine Mountains

4.1.1 Region-specific analysis

NDVI trends from 2001 to 2023 over the three different regions of Apennine mountains are shown in figure 6. The classified NDVI data is further divided into southern, central and northern regions along with representing the annual NDVI trend providing insight into regional vegetation greenness over time. The NDVI values also increased in all regions, suggesting an overall greening trend, but the rates of change differ between regions. The southern region experienced the most substantial growth in NDVI starting at 0.63 in 2001 and rising to around 0.69 in 2023, compared to the other two locations. A R^2 value equal to 0.5402 corresponds a moderate to strong greening trend reflected by an increase in vegetation cover over the time. Similarly, NDVI values in the central region were positive, with an increase from 0.59 in 2001 to 0.65 in 2023. The relatively R^2 value of 0.4439 suggests that while a similar significant trend is here, it is less pronounced than the southern region. In contrast, the northern section of the Apennines exhibited the lowest NDVI increase, ranging from 0.65 to 0.69 during the entire study period. Though there is a slight upward trend, the R^2 value (0.1554) demonstrates little long-term change, reflecting that vegetation greenness in this region has remained stable over the years.

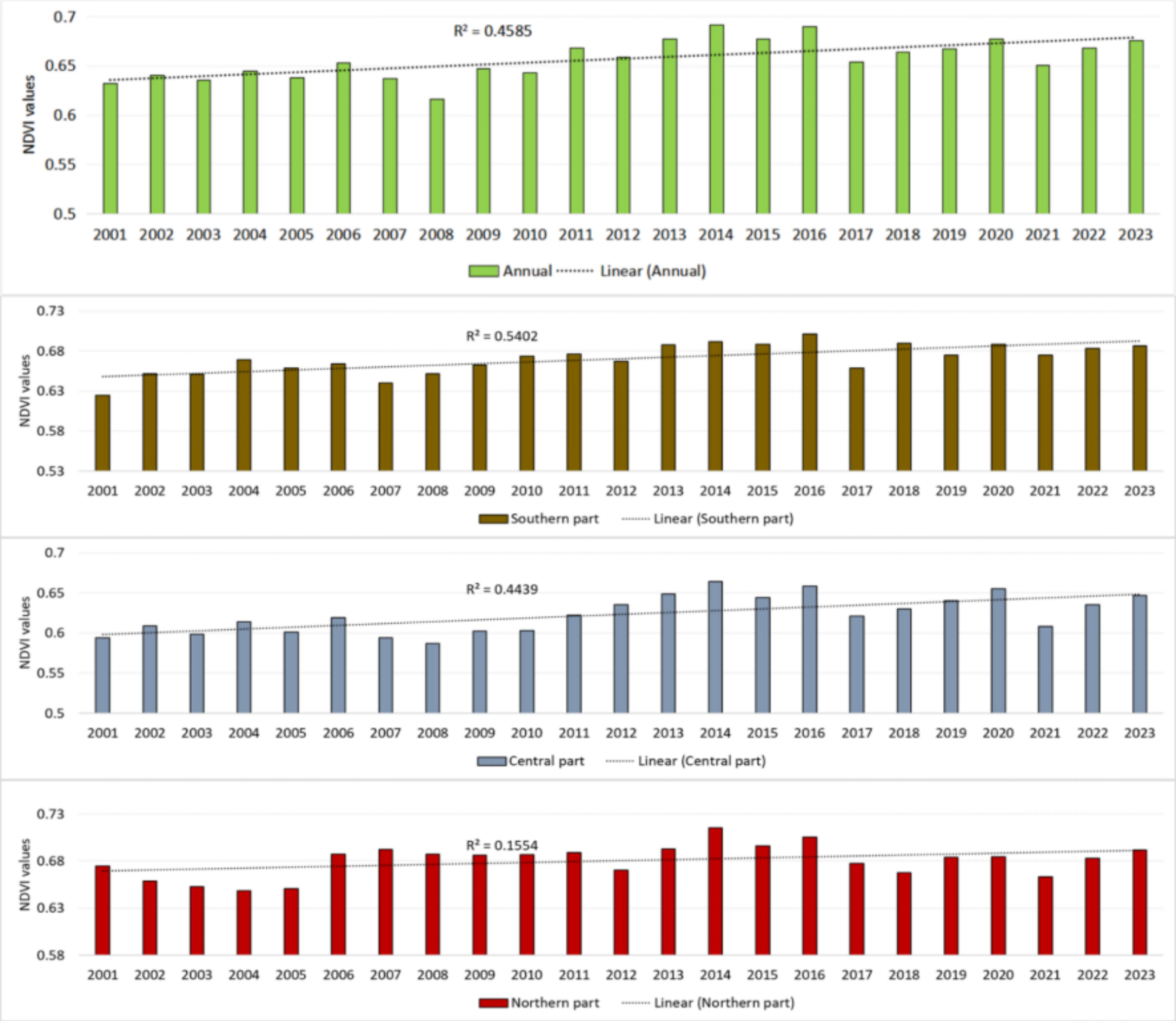


Figure 6. Annual NDVI trends in different parts of Apennine Mountains from 2001 to 2023.

4.1.2 Annual and seasonal analysis

As shown in Figure 7, NDVI values of the Apennine mountains across all seasons exhibited an upward trend, indicating a consistent increase in vegetation greenness over time. Summer NDVI values had the highest throughout the 2001-2023 period, whereas winter values remained the lowest. More specifically, the increase in winter NDVI values was the strongest (R^2=0.4423), with the vegetation greenness steadily rising in the cold season. Fall NDVI values also exhibited a clear increasing trend (R^2 = 0.3523) with some variations with time, which suggested a better state of vegetation during the post-summer period. Summer NDVI acebriefs, however, had a relatively moderate (R^2 = 0.2526), indicating a slow but consistent increase in the coverage of vegetation in warm season. However, NDVI values in the spring displayed the weakest positive trend (R^2 = 0.0981). Thus, no significant long-term trends were detected.

Figure 7. Annual and seasonal trend of NDVI values across the Apennine mountains from 2001 to 2023.

4.1.3 Elevation-based analysis

The NDVI trends in the Apennine Mountains from 2001 to 2023 across different elevation ranes. Across all elevations, NDVI values tended to show an increase as we go towards the year, suggesting that vegetation greenness gradually increased. However, the rate of change from NDVI is elevation-dependent, with lower elevations showing robust NDVI increases, and only small and extremely variable increases at higher elevations. For the lowest elevation, 0-400 meter band, NDVI shows a generally increasing trend from approximately 0.58 in 2001 to 0.64 in 2023 (fig. 8). The greening effect of the 400–800m range showed a similar tendency with an increase of 0.61 to 0.67 (R^2 of 0.5577, mild but consistent greening). The 800–1200 meter category showed some fluctuation but also overall increased during the study period from 0.63 to 0.68.

At mid-elevations, the greening trend was somewhat weaker. NDVI in the 1200-1600 metered increased gradually from 0.59 to 0.63 and in the 1600-2000 metered category it followed a similar pattern where in 2023 the value was reached to 0.51. At the same time, high elevations (2000-2400m and 2400-2900m) showed little increase in NDVI, with 2000-2400m increasing from 0.24 to 0.30 across the period. From 2010 to 2020, however, this range showed fairly strong fluctuations. Lowest NDVI values were in the highest elevation band (2400 - 2900m) with weak oscillations values between 0.08 and 0.13 and showing a very weak upward trend (R^2= 0.0072).

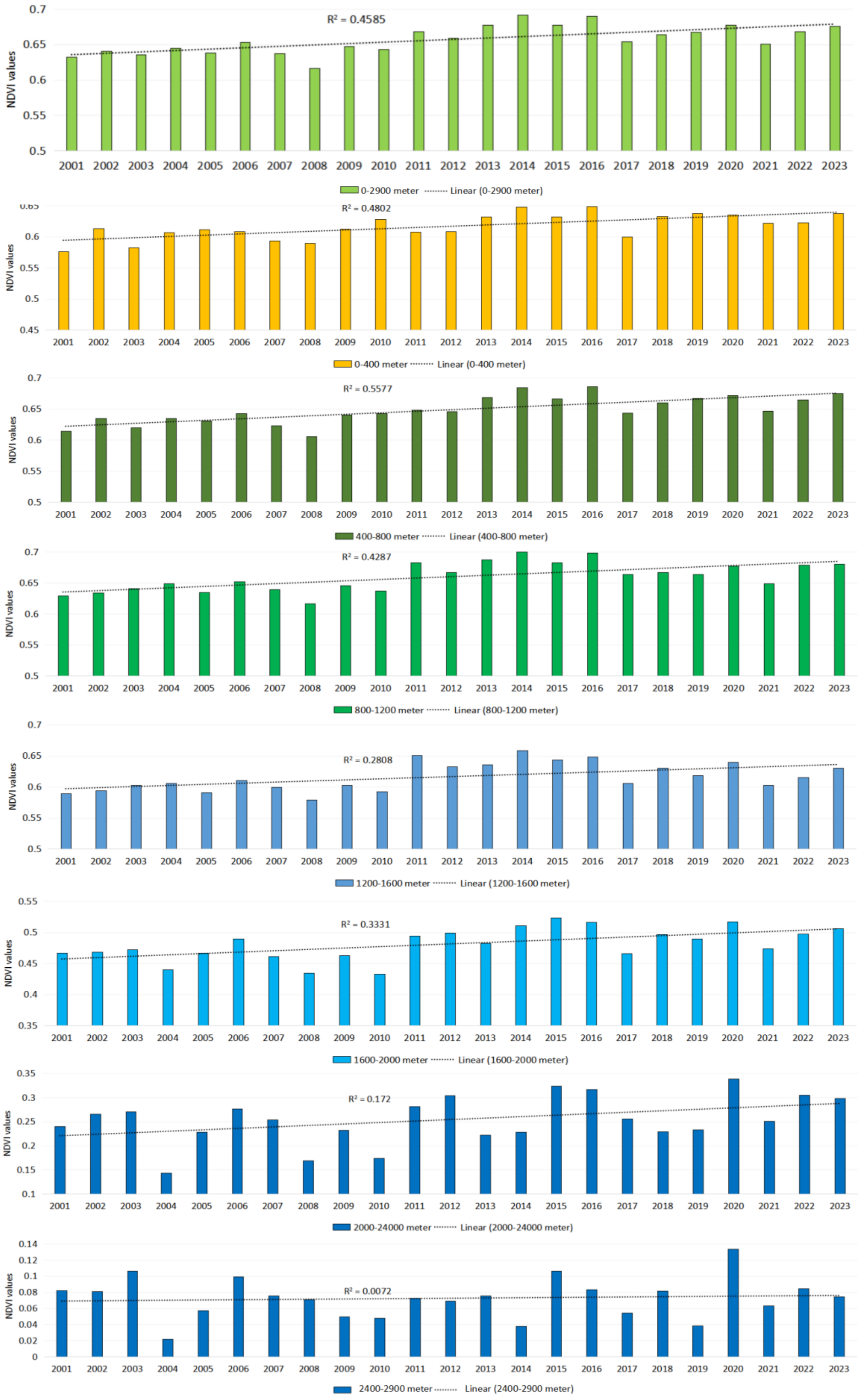


Figure 8. NDVI values across different elevation ranges of the Apennine mountains from 2001 to 2023.

4.2 Temperature trend in Apennine Mountains

4.2.1 Region-specific analysis

The variations in temperature over the Apennine Mountains specific to the region for 2001–2023 are reported in Figure 9. Seasonal temperature trends showed a small positive correlation ($R^2 = 0.0987$), indicating a slight net increase in temperature for the Apennines. Although the temperature shifts vary by region, a slight warming trend is evident in all three areas. 2018 was the warmest year overall, particularly in the central and southern regions, while 2003 saw the coldest temperatures in the northern region. With $R^2 = 0.0987$, the northern region showed a relatively higher temperature rise than the other two regions. Temperature in the northern area was increased from 11.64°C in 2001 to 11.83°C in 2023. The southern region started from 13.53 °C in 2001 and had a value of 13.12 °C in 2023, having undergone a slight increase ($R^2 = 0.083$) despite the fluctuations. The central region showed the least rise (R2 = 0.066) stage of three regions, starting from 11.22°C in 2001 and dropping to 10.61°C in 2023.

Figure 9. Annual temperature trends in different parts of the Apennine Mountains from 2001 to 2023.

4.2.2 Annual and seasonal analysis

As shown in Figure 10, the warming trend in the Apennine Mountains region is not uniform across all seasons, with some experiencing more pronounced changes than others. In some more detail, Winter displayed the most significant warming trend ($R^2 = 0.4711$), indicating a steady increase in winter temperatures. Temperatures rose from approximately 1.96°C in 2001 to 6.57°C in 2023, suggesting milder winters over time. Summer illustrated a moderate positive trend ($R^2 = 0.2193$), with temperatures increasing from 21.12°C in 2001 to around 22.12°C in 2023. Unlike winter and summer, Fall and spring season had weak increase. Fall exhibited a weak increasing trend ($R^2 = 0.0843$), suggesting some variability in autumn temperatures. Spring had the weakest correlation ($R^2 = 0.0282$), indicating minimal long-term changes.

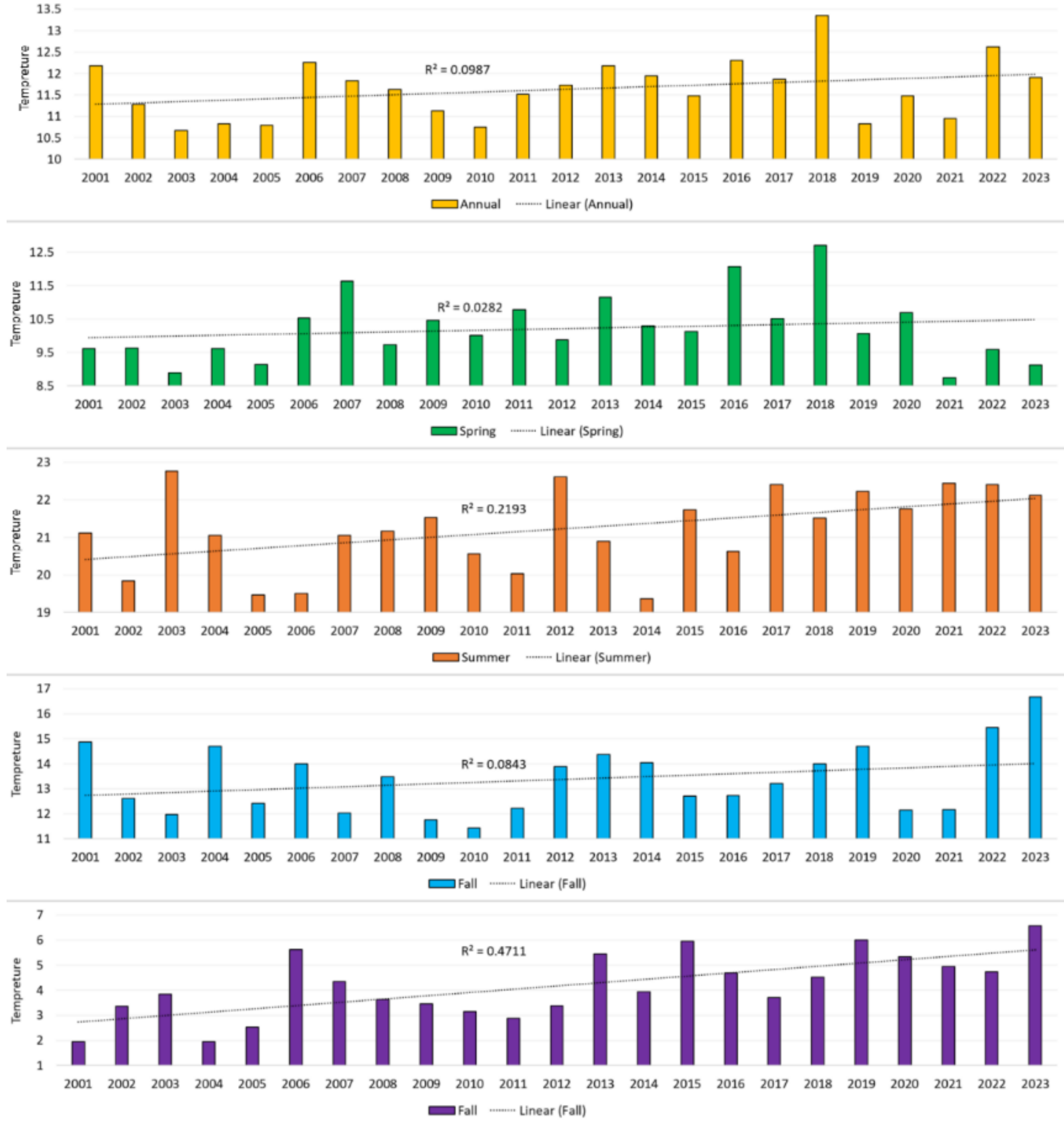


Figure 10. Annual and seasonal temperature values across the Apennine mountains from 2001 to 2023.

4.2.3 Elevation-based analysis

Figure 11 shows the annual temperature trends in the Apennine Mountains between 2001 and 2023 for different elevation ranges. Overall, the Figure 11 indicates a general trend of warming across elevations, with lower elevations experiencing greater variability in temperature. Higher elevations are still cooler, but they are not immune to the warming trend, part of what is known as climate change in the mountains. In specific years, however, we see some considerable variation like in 2005 when temperatures fell in every elevation band. On the other hand, 2018 and 2019 has spikes on temperature which could also reflect extreme climatic event.

The temperatures of the lowest elevation (0-400m) area are about 13.8°C in 2001 and they vary slightly then increase at the end of the year by 13.6°C in 2023. We see a similar pattern in the case of 400-800m, in which the initial temperature is 12.6°C and the final temperature is 12.3°C. Both elevation bands show some fluctuation, but over all they continue to trend upward.

In contrast, temperatures at mid-range elevations (800–1200 m, 1200–1600 m, and 1600–2000 m) exhibit a parallel pattern; however, these values are less strict than those at higher elevations. Temperatures at 800–1200 m have decreased from 11.7 °C in 2001 to 11.3 °C in 2023.At 1200–1600 m, the values decreased from 10.7 °C to 10.2 °C in 2023.From 1600–2000 m, the elevation band that provides records shows a decrease in the temperature throughout the period with temperatures below 10 °C.

At higher elevations (2000-2400m and 2400-2900m), temperatures remain much cooler. The 2000–2400m class begins in 2001 with 9.2°C, decreasing to 8.4°C in 2023. Similarly, the higher class (2400–2900m) starts with 9.5°C and decreases to 8.5°C at the end. These patterns indicate that temperate and warming are happening overall, but the rate of warming is relatively muted at extreme elevations.

Figure 11. Annual temperature values across different elevation ranges of the Apennine mountains from 2001 to 2023.

4.3 Precipitation trend in Apennine Mountains

4.3.1 Region-specific analysis

The Figure 12 illustrates precipitation trends across different regions in the Apennine Mountains from 2001 to 2023. The annual precipitation levels exhibited fluctuations rather than a consistent increase or decrease. However, a general downward trend is noticeable (R^2 = - 0.11), especially after 2013. Precipitation trend had almost similar trend in all three regions, with the northern Apennine receiving the highest decreasing trend (R^2 = -0.1433), followed by the Central region (R^2 = -0.089), while the southern part recorded the lowest decrease (R^2 = 0.0453). The years 2006-2010 were those with higher precipitation, and some fluctuations and declines appear in the following years.

Indeed, the cumulative rainfall between 2006 and 2010 increased in all regions and peaked in 2010 for Central (1096 mm) and South regions (1108 mm).The highest values in the Northern part were recorded in 2014 (1207.03 mm).But after 2014, precipitation began to fluctuate widely, alternating between growth and decline instead of moving in one direction.

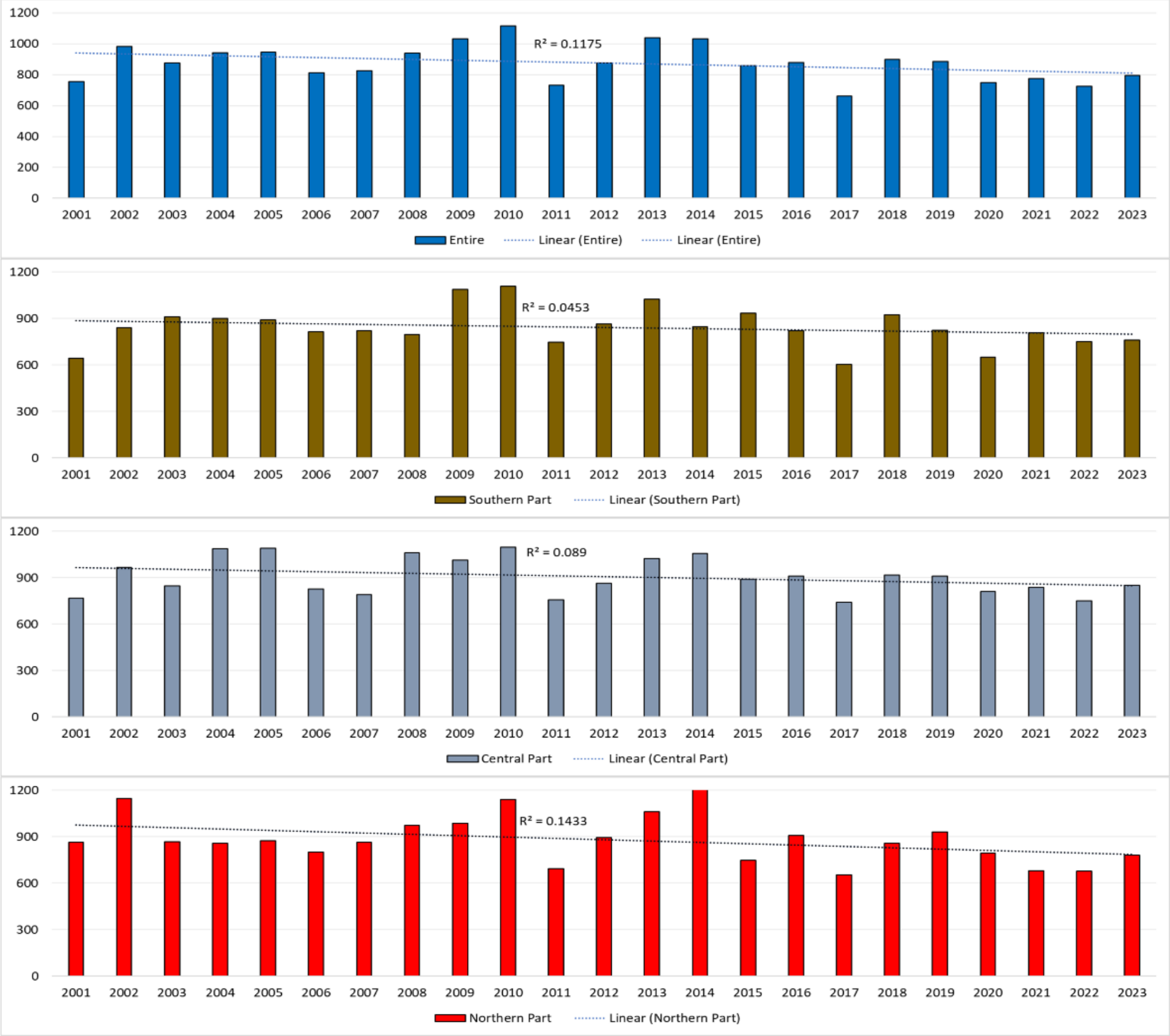


Figure 12. Annual temperature trends in different parts of the Apennine Mountains from 2001 to 2023.

4.3.2 Annual and seasonal analysis

As can be seen in Figure 13, precipitation levels exhibit significant interannual variability, with no strong upward or downward trend. Among the seasons, fall consistently records the highest precipitation, peaking at 383.7 mm in 2010 before decreasing to 209.7 mm in 2023.Summer was the driest season, varying from 72.4 mm in 2001 to 137.5 mm in 2023.

In terms of the highest precipitation years, 2009 and 2010 stood out, especially winter and fall precipitation:

Winter peak recorded at 393.6 mm for 2009, Fall peak corresponding to 383.7 mm for 2010.

On the other hand, the winter precipitation in 2019 and 2020 was significantly lower than in previous years, especially in 2020, which measured only 129.6 mm, making it one of the years with the least precipitation levels. In terms of the precipitation trends:

Winter showed the greatest decrease, going from 255.8 mm in 2001 to 236.5 mm in 2023 (R^2 = 0.0743).

Spring precipitation was relatively constant (232.2 mm in 2001 vs. 252.8 mm in 2023; R^2 = 0.018), with a muted long-term trend.

Autumn also demonstrated a slight negative trend (R^2 = 0.0159).Summer demonstrated the least negative trend in precipitation levels (R^2 = 0.0121).

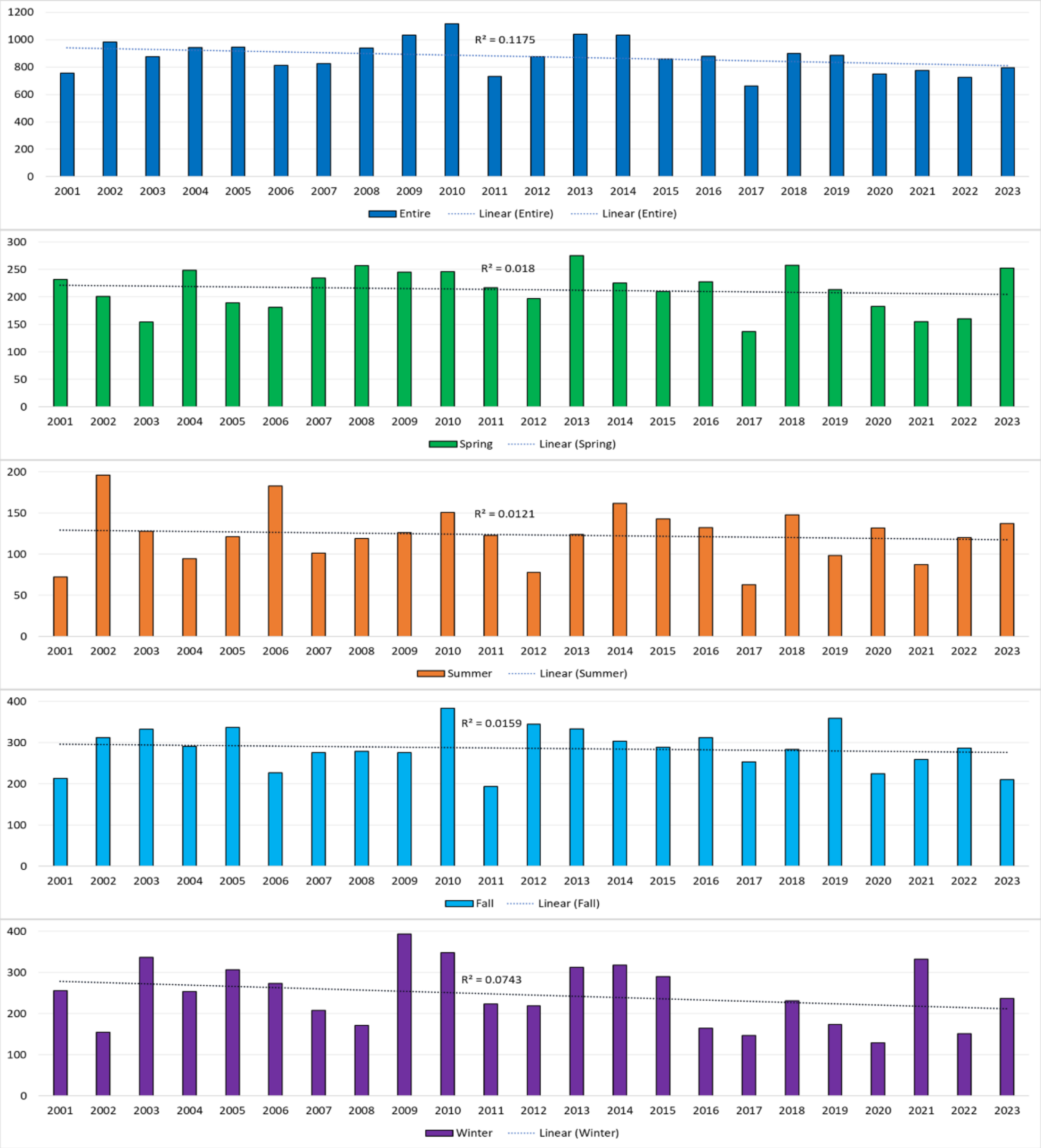


Figure 13. Annual and seasonal temperature values across the Apennine mountains from 2001 to 2023.

4.3.3 Elevation-based analysis

Figure 14 shows precipitation trends from 2001 to 2023 by elevation bands in the Apennine Mountains. Rainfall patterns varied with elevation, in general, high-altitude areas were associated with higher precipitation. That is, like with regional and seasonal analysis, there was no compelling increasing or decreasing trend over time among the elevation bands.

Lower Elevations (0-400m, 400-800m) showed moderate levels of precipitation, with overall levels usually between 628 mm and 1080 mm. Maximum precipitation 2010 (1080.8 mm at 0-400m, 1068.46 mm at 400-800m). Both categories considerably decreased in 2017, with values of 628.38 mm at 0-400m and 635.38 mm at 400-800m, which were the lowest values recorded. The 800–1200m, 1200–1600m, and 1600–2000m mid-altitudes followed a similar pattern with peak occurrences of 2010 (1108.88 mm at 800–1200m, and 1133.40 mm at 1200–1600m). Since 2017 was a special year in which precipitation dropped sharply to 665.16 mm, 691.05 mm respectively. Mid-elevations get more precipitation overall than lower elevations, but their trends are very variable, and did not show a clear increase or decrease. The year 2010 (1093.65 mm in 2000-2400m and 1029.43 mm in 2400-2900m) was the wettest for the Higher Elevations (2000-2400m, 2400-2900m). Despite having peaks during certain years, annual precipitation at 2000–2400m and 2400–2900m had considerable variability rather than being linear, dropping down to 735.79 mm and 674.60 mm, respectively in 2017.

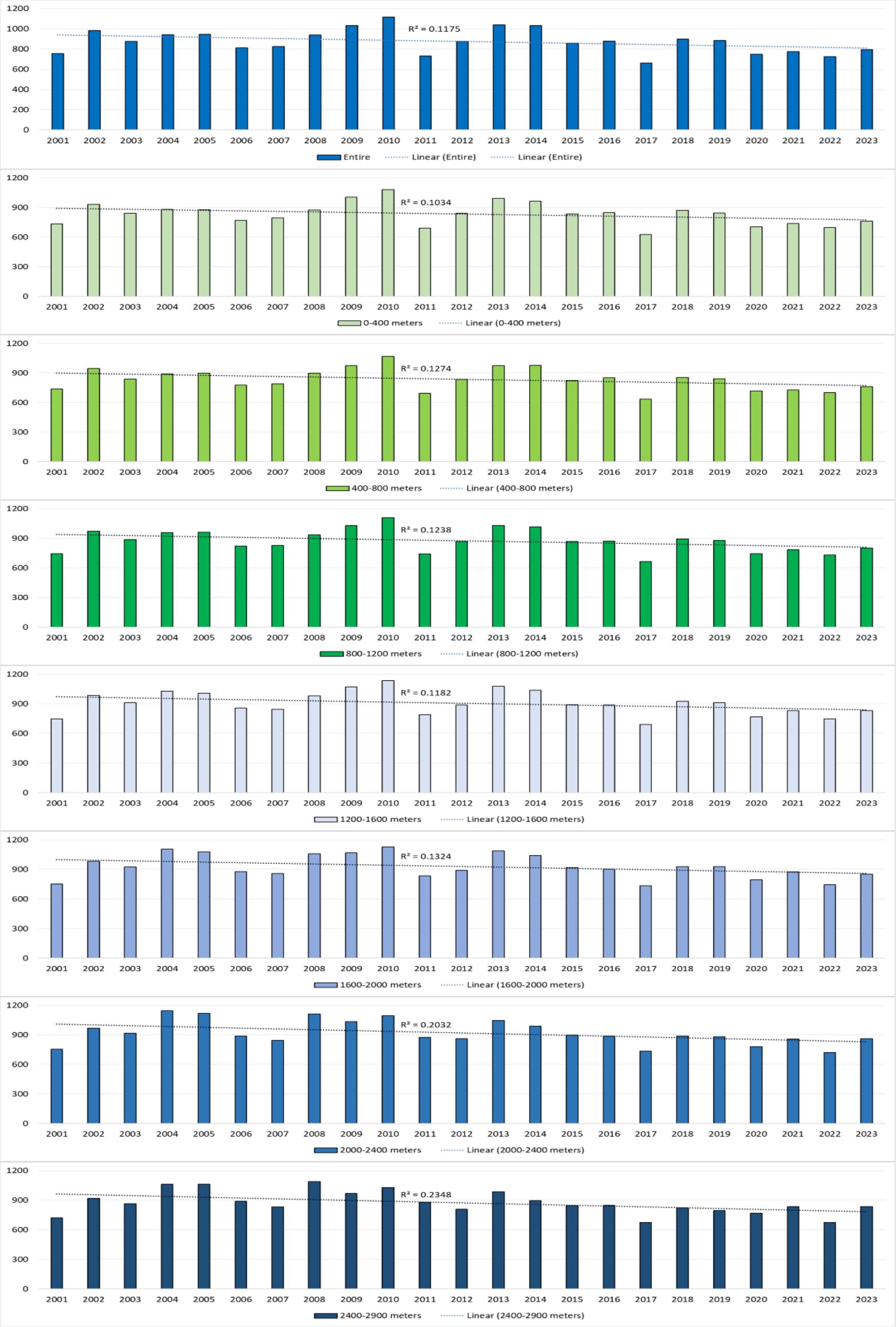


Figure 14. Annual precipitation values across different elevation ranges of the Apennine mountains from 2001 to 2023.

4.4 Correlation analysis

4.4.1 Regional-based analysis

Figure 15 - Image based on the effect of two meteorological variables (temperature and precipitation) on the phenomenon of the greening of mountain slopes in different regions of the Apennines (entire, northern, central, and southern part).

Temperature is the main responsible variable for greening in the study area, and its influence is more positive in the northern area compared with the southern area. This indicates that temperature explains a moderate portion (overall $R^2 = 0.1397$) of the observed greening trends across the study area.The low R^2 indicates that there is only a weak correlation, with the highest correlation recorded in the northern part ($R^2 = 0.224$). For the central and southern parts, the R^2 values were lower (0.1033 and 0.0793 respectively), showing a weaker total temperature influence.

On the contrary, precipitation plays a negligible role in greening in all the regions. The regional variation also indicates that temperature may be more important in mountainous regions, where even small amounts of warming can stimulate vegetation growth.

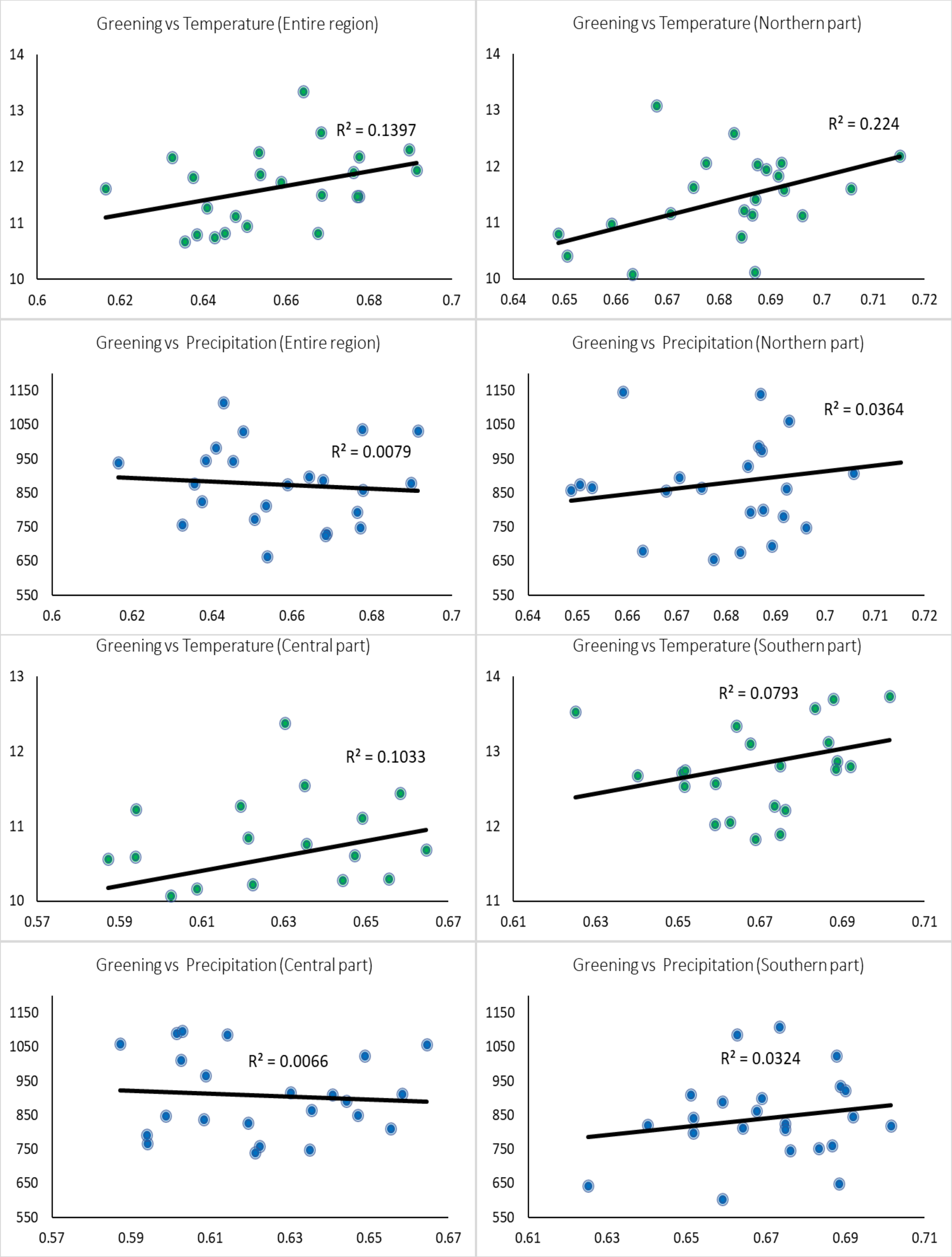


Figure 15. Correlation results between mountain greening and two climate variables (temperature and precipitation) across different regions of the Apennine mountains

4.4.2 Seasonal analysis

Our analysis of greening and climate factors across seasons (Figure 16) found that temperature was the strongest determinant of greening, particularly in winter (R² = 0.7478) and during springtime (R² = 0.3385). Because of the strong association of greening and temperature in winter, it can also suggest that winter temperature is a significant driver of vegetation, possibly due to higher temperatures reducing snow depth and allowing some vegetation to grow.

Water availability is probably the most important factor limiting growth in summer, considering that precipitation was the most relevant in this season (R² = 0.32). In fall, both temperature (R² = 0.1077) and precipitation (R² = 0.0136) had weak effects.

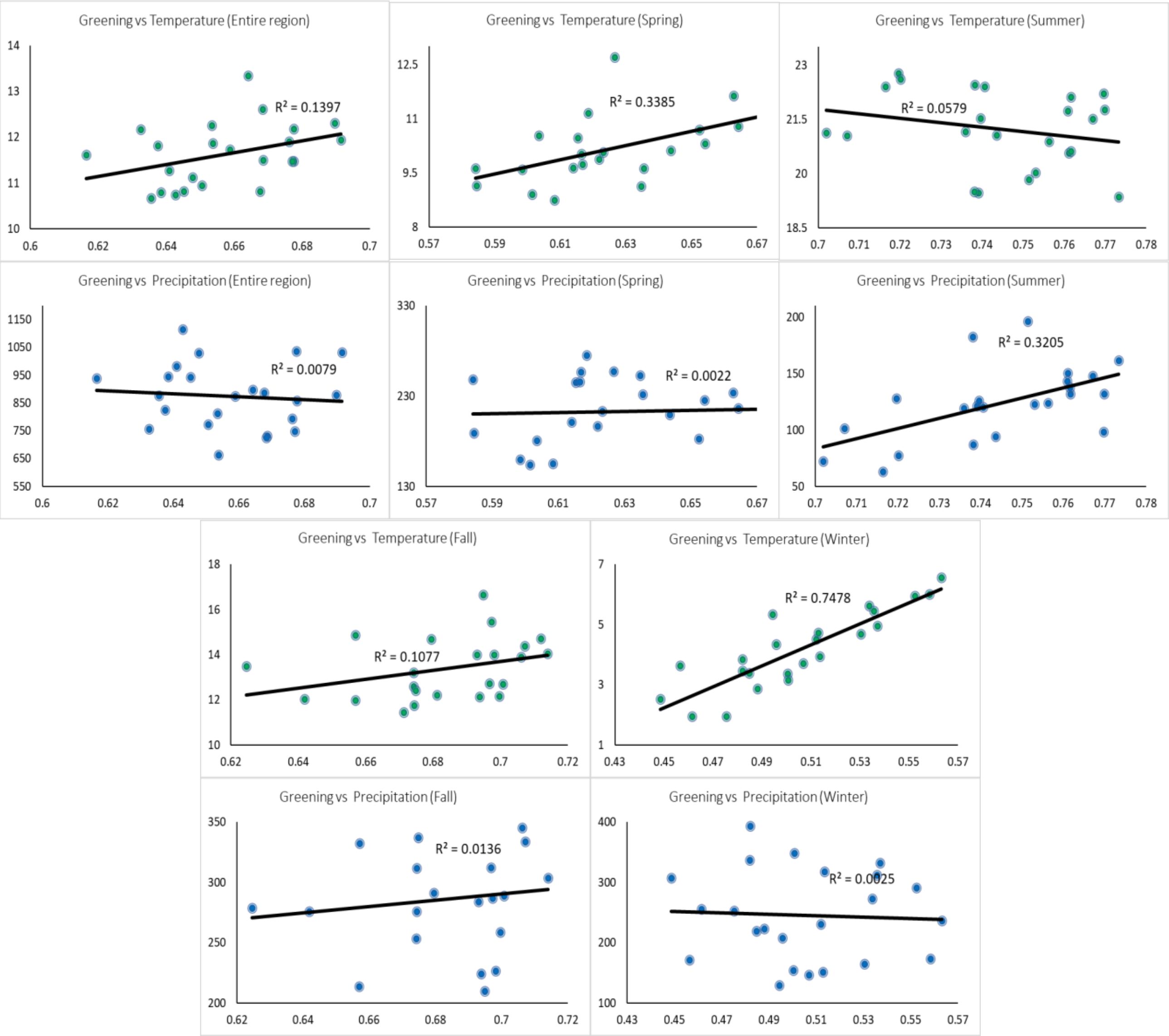


Figure 16. Correlation results between mountain greening and two climate variables (temperature and precipitation) in different seasons across the Apennine mountains.

4.4.3 Elevation-based analysis

Figure 17 shows the correlation between greening and either temperature or precipitation across separate elevation ranges of the Apennine Mountains.

Temperature

Temperature showed initially weak correlations at lower elevations ($R^2 = 0.0361$ for 0–400m and $R^2 = 0.1036$ for 400–800m) but then moderate correlations at mid-elevations (800–2000m) with greening ($R^2 = 0.1078$ for 1200–1600m and $R^2 = 0.1734$ for 1600–2000m). However, above 2000m, the correlation went weak again ($R^2 \simeq 0.0869$ for 2000–2400m and $R^2 \simeq 0.0983$ for 2400–2900m), indicating that other environmental factors may have a greater influence on vegetation dynamics at extreme altitudes.

Precipitation

At lower elevations, the contribution from precipitation to greening was weak or negligible ($R^2 = 0.0621$ for 0–400m and $R^2 = 0.0001$ for 400–800m; Fig). Precipitation was only a marginally influencing factor at mid-elevations (800–2000m) with $R^2 = 0.0289$ for 800–1200m and $R^2 = 0.0163$ for 1200–1600m. Yet, at higher altitudes (1600–2400m), it had a positive impact, which was the most stable impact at 2000–2400m ($R^2 = 0.5102$). The correlation decreased once more at distances greater than 2400m ($R^2 = 0.1369$ for 2400–2900m).

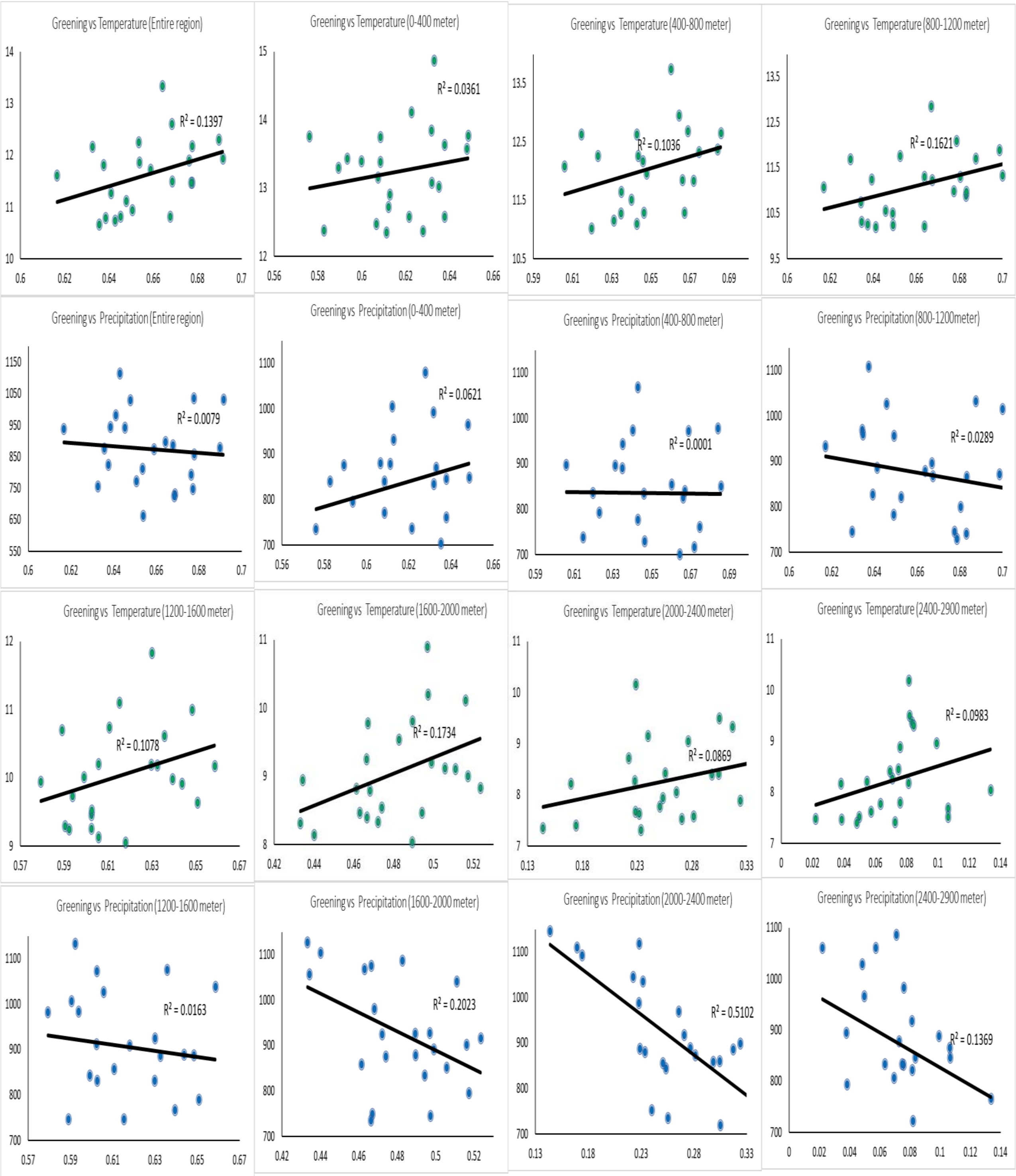


Figure 17. Correlation results between mountain greening and two climate variables (temperature and precipitation) in different elevation ranges of the Apennine mountains.

5 Discussion & Conclusion:

5.1 Discussion

5.1.1 Application of Remote Sensing in Mountain Monitoring

Mountain ecosystems are some of the most ecologically important and fragile landscapes on our planet, offering vital services such as biodiversity conservation, water delivery, and climate moderation. In recognition of their significance, the United Nations declared 2002 the International Year of Mountains and called for sustainable development in the mountain contexts as well as better environmental monitoring (UN, 2002).Mountainous regions play a vital role, but are especially susceptible to climate change, suffering from the impacts of rising temperatures, changing patterns in precipitation, and the loss of biodiversity.

Remote sensing (RS) has become an essential means for mountain monitoring because of the ability of this technique to provide large-scale high-resolution data for long periods. Field-based ecological studies in lowland areas are feasible, yet mountains are very difficult to access due to steep slopes, extreme weather, and distant locations. Fieldwork tends to be labour-intensive, time-consuming, and space-constrained in these situations, so RS offers a timely and practical solution (Gorelick et al., 2017).RS technology, when associated with cloud computing, particularly GEE, allows monitoring, in almost real time, of key variables such as vegetation dynamics, climate, and land cover change over large mountainous areas (Velastegui-Montoya & Montalván-Burbano, 2023).

Advantages of RS in mountain monitoring are:

- Extensive Spatial Coverage: RS offers consistent and spatially-coherent data collection over entire mountain ranges, which overcomes the limitations of sparse point-based field measurements.
- High temporal resolution Satellite images are long time series that allow long-term change trends.
- Analysis in both the multi-spectral and multi-temporal domains: With multiple spectral bands capturing details essential for vegetation and climate analysis, and with the ability to continually update measurements, remote sensing tools provide the potential for ongoing monitoring.

the remote sensing approach is considered the best for this study as it allows for a broad evaluation of vegetation greening trends over the Apennine Mountains. By combining satellite-based NDVI datasets, temperature and precipitation records with geospatial analysis in a GEE environment, we provide a methodological framework for understanding climate-vegetation interactions in complex mountainous environments.

5.1.2 Vegetation Greening Trend

The analysis of terrestrial vegetation greening trends helps us understand climate change impacts on terrestrial ecosystems. Greening trends are valuable indicators of ecosystem responses to climatic change and reflect changes to plant productivity, phenology, and ecosystem stability. Long-term NDVI variations could reflect variability in whether climate change is promoting vegetation expansion or degradation across the globe (Zhu et al., 2016).

Our results indicate that from 2001 to 2023 the degree of vegetation greening over the Apennine Mountains has significantly increased, demonstrated that warming temperatures and extended growing seasons positively affect the vegetation thriving, In comparison to other mountain ranges, like the Tibetan Plateau and the European Alps, shows reported greening trends that vary considerably (Zhong et al., 2019; Vitasse et al., 2018), the Apennines present a more consistent upward trend. This may be due to moderate climatic situations and enough moisture that helps the plants spread out.

Trends towards greening have been widely reported in other high-elevation ecosystems such as High Mountain Asia and the Swiss Alps, where increasing warmth enhances vegetation productivity (Chen et al., 2020; Bai et al., 2024). Greening trends are often water-limited in semi-arid mountain regions such as Central Asia, and certain regions have continued to demonstrate browning trends as a result of soil moisture depletion (Amantai et al., 2024). Such concomitant divergence expresses the necessity of the regional bias of climate conditions for vegetation reactions to climate change.

Overall, this persistent greening in the Apennines highlights climate change effects on mountain vegetation change processes. Long-term trends in NDVI values over the time course reflect changes in ecological dynamics with possible long-term implications for biodiversity, carbon sequestration, and ecosystem resilience in Mediterranean mountain ecosystems.

5.1.3 Climate Change and Its Impact on Mountainous Regions

Climate change has widespread implications for mountain ecosystems, including more extreme weather events, glacial melt, and shifts in temperature regimes. A key challenge arising from intensified precipitation patterns and extreme weather variability is their impact on vegetation dynamics and hydrological processes, which in turn influence ecosystem stability in mountainous regions.

Previous findings suggest climate change is responsible for more frequent and intense floods, especially in mountainous and lowland areas where rapid snowmelt and heavy rainfall events are prevalent (Huggel et al., 2019).In particular, the frequency of ice-related floods has been associated with changing precipitation regimes and glacial meltwater surges in the European Alps and the Himalayas (Kääb et al., 2021).

Another significant impact of global warming is the melting of glaciers, which disrupts hydrological cycles and endangers water supplies. Glaciers in the Alps, Andes, and Himalayas have all been receding rapidly over recent decades, driving long-term water deficits and perturbing distal ecosystems (Zemp et al., 2019). Similar trends can also be found in the Apennine Mountains, where a small number of remaining glaciers are declining and affecting regional hydrology and biodiversity.

5.1.4 Impact of Climate Change on Mountain Greening

Elevation is a key factor in vegetation responses to climate change. We find that lower and mid-elevation zones (0-1600m) of the Apennines display stronger greening trends driven by longer vegetative periods and increased temperature while even higher elevations (above 2000m) display weaker or more variable trends suggesting climatic limitations may restrict vegetation at extreme altitudes. Other elevation-dependent trends have been reported for the Tibetan Plateau and the Andes, where the mid-elevation areas are significantly greening, and a very high-altitude area (above 4000m) is also constrained due to harsh climatic conditions (Zhong et al., 2019; Körner, 2007).

5.1.5 Limitations and Future Work

Although this study gives us additional insights on vegetation greening in response to changes in climate, it should be better streamlined in certain areas. A potential issue may be related to spatial resolution differences between datasets, i.e. MODIS NDVI (500m) vs Climate data sets. Although these datasets are standard in climate-vegetation analysis and are well suited for long-term observations, higher-resolution data may be beneficial for localized studies. In order to explore vegetation dynamics at yet smaller scales, future research may utilize higher-resolution climate datasets, such as Sentinel-2 imagery, especially within complex mountainous terrains where our modeling framework could not represent vegetation dynamics in detail. Nevertheless, the methodology used in this research isolates large patterns and phenomena, laying the groundwork for more advanced studies.

Moreover, the present study did not distinguish climate drivers other than temperature and precipitation. Nevertheless, Land Surface Temperature (LST) is another climatic factor that directly impacts vegetation dynamics. LST can shed light on surface energy exchange and microclimatic conditions in greater detail. Future studies should combine the LST data to evaluate its effect on the trends of vegetation greenness, especially in high-altitude regions where temperature extremes can limit the growth and stress resilience of plants.

By tackling limitations of climate-vegetation interactions, future research may lead to improved compositions for more accurate ecological modeling in mountainous regions.

5.2 Conclusion

The study investigates the climatic effects on vegetation greening in the Apennine Mountains by means of remote sensing technologies and shows a notable increase in greening from 2001 to 2023, mostly at low and mid-elevations (0–1600m) where regions have become warmer and the growing season has extended, enhancing the productivity of plants. Higher altitudes (>2000m) exhibit weak and spatially heterogeneous greening, with likely driving climate constraints (i.e., temperature extremes and impoverished soil productivity). Almost all the greening could be explained by temperature—the trend toward milder winters and a longer growing season—and declining precipitation trends in some of the places they examined suggest that water availability could become a limiting factor at some stage. Our results hew with similar observations from the Alps, Tibetan Plateau and the High Mountain Asia, further affirming the influence of elevation on vegetation responses to climate change. Although NDVI (500m) and precipitation datasets (11 km) deliver fine-scale climate-vegetation interactions, fine scale dynamics may be impacted, yet the methodology effectively captures large-scaled patterns and trends.More refined vegetation-climate relations in mountain terrains could be built up using high resolution datasets as Sentinel-2 imagery and other climatic factors such as Land Surface Temperature (LST). Overall, this study highlights the substantial effects of climate change on Mediterranean mountain ecosystems, and it shows the importance of remote sensing for long-term environmental monitoring. This research provides vital information relevant to ecologists, policymakers and conservationists, with potential application to strategies that reduce climate impacts and help conserve biodiversity in mountain regions.

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