Remote sensing of seasonal variation of LAI and fAPAR in Pakistan under changing climate using machine learning

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Abstract

Climate change represents an intense threat to terrestrial ecosystems, influencing vegetation dynamics that are essential for ecosystem functionality and agricultural yields. Hence, an accurate monitoring of such phenomenon is quite essential for an agricultural country like Pakistan. Our study evaluates the effects of climatic variability on vegetation in Pakistan through the utilization of two critical biophysical indicators of vegetation vitality and productivity, Leaf Area Index (LAI) and the Fraction of Absorbed Photosynthetically Active Radiation (fAPAR). Using remote sensing data from the Copernicus(GLS)SPOT/PROBA-V satellite and employing machine learning method, Random Forest (RF) algorithm, we analyzed the spatial and temporal distributions of LAI and fAPAR across the diverse climatic regions of Pakistan.LAI and fAPAR spatial plots illuminated significant regional discrepancies. Higher values were predominantly recorded in the fertile Indus River basin and northern mountainous areas, suggested a moderate to strong vegetation productivity. On the other hand, the arid regions of Balochistan and southern Sindh expressed low values, which indicates low vegetation and heightened vulnerabilities to desertification, diminished agricultural productivity, and ecological deterioration. Temporal analysis specified clear seasonal variabilities, with peaks during the monsoon interval and downplay throughout the dry months. The RF model demonstrated substantial predictive efficacy, attaining R^2 equals to 0.92 and 0.91 for LAI and fAPAR, respectively. We believe that these outcomes will provide a robust foundation for policymakers to address climate-induced stresses on vegetation and boost resilience in vulnerable areas of Pakistan

Keywords: Climate change, Vegetation growth, Fraction of absorbed photosynthetically active radiation, Leaf area index, Random forest.

1. Introduction

Climate change is arguably one of the most important issues of the 21st century with serious implications for ecosystems, agricultural systems, and human life worldwide. Increasing variability in temperatures, precipitation, and extremes events disrupts ecosystems, and changes in land cover, in particular vegetation cover, is one of the most responsive signals of such environmental changes [1]. Within this context, remote sensing metrics like the Leaf Area Index (LAI) and the Fraction of Absorbed Photosynthetically Active Radiation (fAPAR) have become established as key biophysical indicators of vegetation status and phenology and their response to climatic variations [2].

fAPAR has been defined as the fraction of incident radiation within the spectral range of 400-700 nm that is absorbed by the canopy under specific known lighting conditions and is an important parameter of light-use efficiency models [3]. fAPAR is amongst the key parameters that can describe the condition of vegetation growth and the influence of biological and physical processes on vegetation as photosynthesis, respiration, transpiration, and the carbon cycle [4]. Leaf Area Index is defined as half of the total area occupied by green elements, per unit area of horizontal ground [5]. It controls the fluxes of energy, water and greenhouse gases between the land surfaces and the atmosphere [6]. Both LAI and fAPAR are key variables in most of the ecosystem productivity models, and global models of climate, hydrology, biogeochemistry and ecology [7].

LAI quantifies the amount of leaf surface area potentially available for photosynthesis and is a necessary parameter for climate and hydrological models [8]. This index is directly related to the health and productivity and area of vegetation, and is thus critical to understanding the impact of changing climate on terrestrial ecosystems [9]. Likewise, fAPAR measures the fraction of solar radiation absorbed by green vegetation and is an important measure of vegetation productivity and potential yield in a variety of environmental conditions [10]. Taken together, these parameters are essential for the thorough assessments of ecosystem functioning [2], particularly in regions such as Pakistan, among those most vulnerable to climate change.

Pakistan's diverse landscape, from dry deserts to high forested slopes, adds complexity to the understanding of how vegetation responds to climate change and makes it crucial to this study. Recent studies have highlighted changes in temperature and precipitation patterns [11] these things have caused important impacts in the agricultural productivity and natural ecosystems of the country [12]. , The use of LAI and fAPAR in these types of studies provides a good framework for understanding the patterns of space and time in vegetative growth and productivity. For instance various studies have high lightened the inherent link existing between climate and vegetation, such as vegetation's response to current weather [2, 10].

However, to derive precise insights, the applications of advanced machine learning methodologies become vital. They are quite effective in data scarce regions like Pakistan [13]. The Random Forest (RF) as an algorithm has shown great performance when it comes to modelling complex nonlinear relationships between vegetative indices and climatic variables ensuring accurate predictions and a solid model performance overall [14]. Here we aim to use RF technique to understand complexities of how vegetative indices relate to climate fluctuations so that necessary information regarding climate change impacts on heterogeneous ecosystems of Pakistan can be obtained.

2. Materials and Methods

2.1 Data sources

Our study utilizes the SPOT/PROBA VEGETATION dataset (version 3) for LAI and fAPAR analysis, accessible by the European Copernicus Global Land Service (CGLS). This dataset has a spatial resolution of approximately 1 km and has been providing global LAI and fAPAR products since 1999 to present day [15]. These LAI and fAPAR values are produced using algorithms from satellite sensors like VEGETATION, which guarantees the availability of reliable and uniform data over large areas, over time [16].

The SPOT/PROBA-V FAPAR dataset combines the data coming from the SPOT VEGETATION program that ran from 1998 to 2014, and from the Project for On-Board Autonomy-Vegetation program launched in 2013 and ongoing, which allows for extensive time series studies. This retrieval process is based on the application of an algorithm that employs neural networks to merge and improve MODIS and CYCLOPES FAPAR products to provide a "best estimate" of fAPAR. The approach relies on top-of-canopy directional normalized reflectance from satellite data as input. The data set has a very good temporal resolution, available every ten days and is provided on a grid of 1/112°, making it suitable to capture vegetation dynamics in all biomes. This dataset has been shown to be reliable and accurate for tracking vegetation in several biomes [18].

2.2 Methods

We used Random Forest (RF) for these analyses because it is particularly well suited to analyze large data sets and can model complex nonlinear relationships between predictor and response variables [19]. Random Forest ensures high prediction accuracy and robustness, and is particularly applicable in the study of complex ecological data like vegetation index and climate data [20, 14].

Remote sensing images were then processed and analyzed within ArcGIS to show patterns over space and time. Remote sensing allows for the creation of high quality spatial maps, offering particularly useful information on patterns of variation in LAI and fAPAR over large areas of Pakistan. The use of RF algorithm in combination with ArcGIS allows for a more thorough understanding of shifts in vegetation response under varying climate conditions [21]. Therefore, providing a method to holistically assess the impacts of climate change on vegetation.

3. Results and discussion

3.1 Spatial Plot of LAI

The spatial plot of the LAI revealed considerable variability throughout Pakistan, with higher LAI values predominantly located in the Indus River basin and northern territories, revealing moderate to dense vegetation as described by table 1. While arid and semi-arid regions in the southern and western parts displayed diminished values resulting in a trend of low productivity refer to table 1. The observed spatial differences can be attributed to the presence of diverse climatic zones, ranging from varied temperate conditions in the north to arid zones in the south, alongside differing land-use practices [22]. Areas with elevated LAI mostly the agricultural areas of Pakistan, such as Punjab and certain areas of Khyber Pakhtunkhwa, benefitted from irrigation infrastructure and favorable climatic conditions with high agricultural yields, whereas regions characterized by low LAI face limitations due to water scarcity and soil degradation [23].

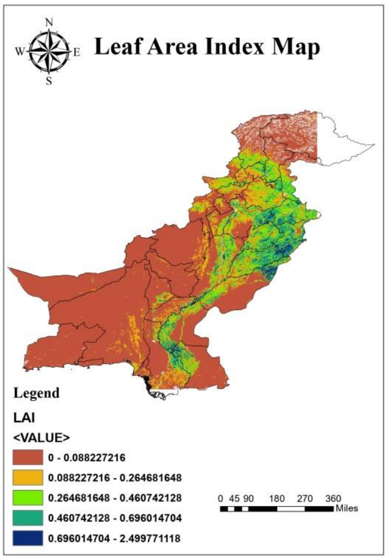

Figure 1 Leaf Area Index Map for Pakistan.

Table 1 Threshold for Leaf Area Index [6].

LAI	Description
< 1	Sparse vegetation or barren land. Low productivity.
1-3	Grasslands, croplands, or shrublands. Moderate productivity.
3-5	Forest under stress or moderate density vegetation. Moderate-to-high productivity.
5-8	Dense forest or highly productive vegetation. High productivity.
>8	Extremely dense forest or lush tropical vegetation. Very high productivity.

This spatial variation draws attention to the challenges associated with climate change, including intensified aridity, disrupted precipitation patterns, and increasing temperatures, all of which may intensify vegetation stress in susceptible regions [24]. For instance, southern Pakistan is particularly vulnerable to desertification [25], while northern territories may confront alterations in vegetation growth cycles as a result of changing precipitation patterns [26].Understanding the spatial underlying conditions of LAI will help policymakers prioritize adaptation strategies, including the promotion of drought-resistant crops and improved water resource management in low-LAI regions.

3.2 Spatial plot of fAPAR

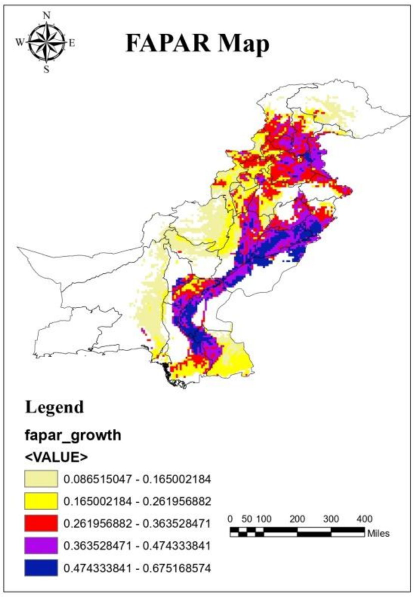

Figure 2 Fraction of absorbed photosynthetically active radiation map

Table 2 Threshold for fAPAR values [3].

fAPAR Values	Description
Low fAPAR values (< 0.2)	Barren or stressed vegetation.
Moderate fAPAR values (0.35–0.5)	Moderate vegetation growth.
High fAPAR values (> 0.5)	Healthy and productive vegetation.

The spatial distribution of the fAPAR throughout Pakistan, as illustrated in the figure 2, revealed considerable regional variability shaped by climatic zones and the extent of vegetation cover. In this plot the higher fAPAR values refer to table 2 are primarily recorded within the fertile Indus River basin and the northern mountainous areas, indicative of substantial vegetation productivity and the effective utilization of photosynthetically active radiation. In contrast, the arid regions of Balochistan and southern Sindh have displayed diminished fAPAR values as described by table 2, which are reflective of sparse vegetation and low productivity. These observations are consistent with the spatial distribution patterns of vegetation, as mentioned by [26] and are influenced by factors such as water availability, soil fertility, and land-use practices [24].

The identified spatial trends highlighted the susceptibility of low-fAPAR regions to the adverse effects of climate change [27], including extended droughts and diminished precipitation [28, 11]. The observed decline in fAPAR within these areas put forward a situation of reduced photosynthetic efficiency, potentially resulting in desertification [25] and a degradation of ecosystem services. Conversely, regions characterized by high fAPAR values have played a vital role in sustaining agricultural productivity and fostering biodiversity [3]. Nonetheless, these areas are also vulnerable to climate-induced pressures, such as heat waves [29] and flooding events [30], which may disrupt photosynthetic processes and adversely affect crop development [31].

3.3 Time series for Leaf Area Index by using Random Forest technique

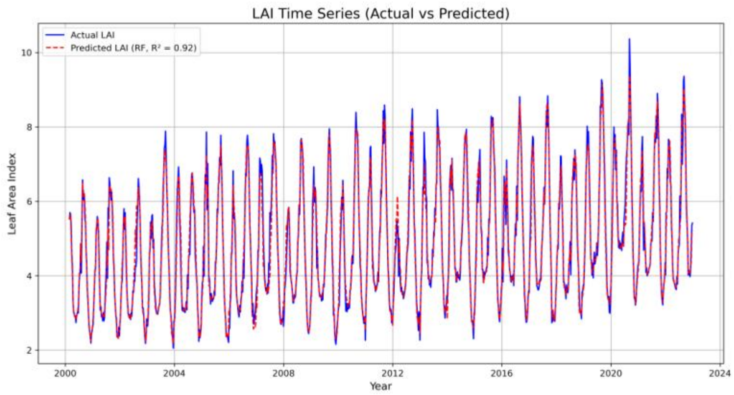

Figure 3 Comparison of actual and predicted Leaf Area Index from 2000 to 2023.

The time series analysis presented a noticeable seasonal recurring in LAI values, which corresponds with the phenological growth cycles of vegetation in Pakistan [23]. Peaks in LAI are observed during the monsoon season, when abundant amount of rainfall promotes vegetative growth, whereas decline in values are noted during arid periods, indicating a decline in photosynthetic activity [32]. The close correlation between observed and predicted LAI values, evidenced by an R^2 of 0.92, underscores the efficacy of the RF model in accurately capturing these ecological dynamics[14]. However, a noticeable trend of increasing inter-annual variability in LAI may reflect the consequences of climate change [33]on both vegetation and productivity [23].

Intensifying temperatures and erratic precipitation patterns [11], particularly during crucial growing seasons [34], present significant threats to Pakistan's agriculture-dependent economy. Deviations in LAI trends may represent early indicators of vegetation stress, reduced agricultural outputs, or alterations in growing seasons, all of which carry profound implications for food security and the livelihoods of rural populations [35]. Addressing these pressing challenges necessitates the integration of remote sensing data with ground-based observations [1] to facilitate continuous monitoring of vegetation health and to implement targeted measures for climate adaptation.

3.4 Time series results of fAPAR by using Random Forest technique

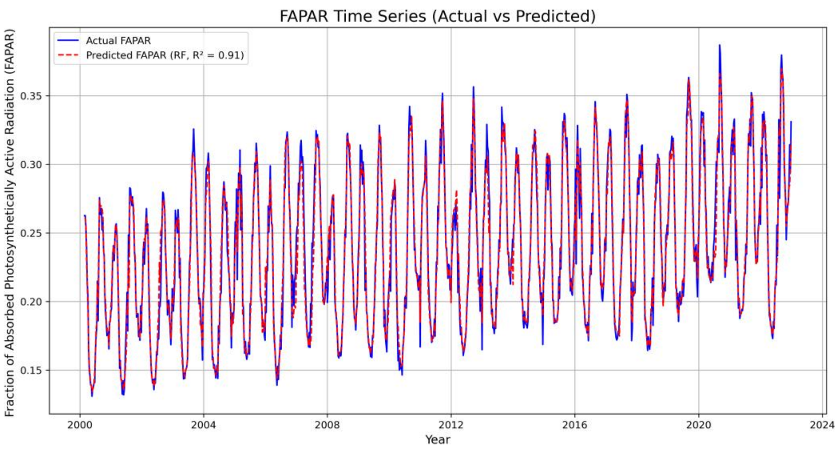

Figure 4 Comparison of actual and predicted fraction of absorbed photosynthetically active radiation from 2000 to 2023.

This time series of fAPAR has revealed distinct seasonal repetitive events, characterized by maxima corresponding to intervals of peak vegetation productivity [23] during the monsoon season and minima during periods of aridity [22]. The predicted fAPAR demonstrated a considerable resemblance with empirical observations, attaining an R^2 coefficient of 0.91, thereby substantiating the precision of the random forest modelling approach [14]. Even so, the dataset also uncovers inter-annual fluctuations in fAPAR, which may signify the complications of evolving climatic conditions, including the variability in monsoonal precipitation and escalating temperatures [11].

The discriminated trends in fAPAR underscored significant challenges for sustainable agricultural practices and ecosystem integrity in Pakistan. The increasing variability of fAPAR might thus indicate a higher vulnerability of vegetation to climate extremes in the region, including its late/non- onset of monsoon [36]. Such variability poses a potential food security risk as reduced photosynthesis will have a direct impact on crop production [37]. On top of that, the time series analysis allows for future operational adaptive management interventions, which may include planting drought-resilient cultivated crops and improving irrigation practices to alleviate negative consequences of climate change on vegetation productivity [32].

5. Conclusions

By using remote sensing techniques and machine learning algorithms, our research systematically explored the impacts of climate variability on the dynamics of vegetation cover within Pakistan. By analyzing LAI and fAPAR, our work contributes valuable information about the spatio-temporal variation in vegetation productivity in different climatic zones of Pakistan.

There were significant regional discrepancies in the results, with higher values of LAI and fAPAR concentrated in hydrologically and plough-able fertile areas within the Indus River basin and northern areas, whereas lower levels of vegetative productivity measured the influence of monsoon rains and irregularity of rainfall events in arid zones. The Random Forest proved to be an outstanding model to predict LAI and fAPAR values, showing its capability of deciphering complex vegetation-climate interactions. Areas of low values of LAI and fAPAR, such is the case in southern and western Pakistan have greater risk of desertification and decrease of productivity, hence necessitating focused interventions. To address these challenges, our study advocates for the implementation of climate-responsive strategies, including the promotion of drought-resistant crop varieties, the optimization of water resource management, and the incorporation of remote sensing data for real-time monitoring of vegetation.

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Abbreviations

The following abbreviations are used in this manuscript:

fAPAR	fraction of absorbed photosynthetically active radiation
LAI	Leaf Area Index
SPOT	Satellite pour l'Observation de la Terre

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