Results in Engineering 21 (2024) 101811

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Study of mountain ecosystem accounting in lower Himalaya range in Uttarkhand, India using geospatial technology

Manoj Kumar Patley [a], Ashutosh Tiwari [a], Kireet Kumar [a], Thangavelu Arumugam [a,b,*], Sapna Kinattinkara [c], Manimaran Arumugam [d]

[a] G.B. Pant National Institute of Himalayan Environment, Almora, Uttarkhand, 263643, India
[b] Department of Environmental Studies, Kannur University, Kannur, Kerala, 670567, India
[c] Department of Environmental Sciences, PSG College of Arts and Science, Coimbatore, TamilNadu, 641014, India
[d] Department of Mathematics, Kongu Engineering College, Erode, TamilNadu, 638060, India

ARTICLE INFO

Keywords:
Himalaya
Land use land cover
Mountain ecosystem
Remote sensing
Uttarkhand

ABSTRACT

The study was focused on the systematic investigation of forest cover mapping and the maximum normalized difference vegetation index (NDVImax) pattern. The study was to support the conservation and sustainable management of vital ecosystems by integrating remote sensing and geographic information systems techniques into mountain ecosystem accounting. The study used remote sensing technologies and satellite imagery data, which provides a valuable means to monitor and assess the status and changes in mountain ecosystems. The NDVImax cover study area declined from 44.90 % in 2015 to 43.75 % in 2019, which resulted in a 1.15-square-kilometer reduction in the area with green cover. The percentage of areas such as flood-bare land (0.46 %), scrub land (21.64 %), crop land (4.28 %), built-up areas (1.33 %), bare land (14.7 %), water (1.05 %), wet area (0.05 %), and snow/glacier and snow cover (14.12 %) were used to categorize the land use land cover (LULC) pattern. According to the initial analysis of the MODIS annual mean temperature, in 2015, the satellite sensors recorded a minimum land surface temperature (LST) of −15.3 °C and a maximum value of 33.1 °C. In the additional analysis of the MODIS annual mean temperature in 2019, the sensors recorded a minimum and a maximum LST value of −14.3 °C and 33.4 °C, respectively. The maximum annual mean temperature increased by 0.4 °C between 2015 and 2019 in terms of the annual mean LST. The study revealed the potential to inform policies and strategies for safeguarding mountain ecosystems in the face of ongoing environmental challenges and provide decision-makers with valuable insight.

1. Introduction

The Himalaya is considered one of the most sensitive and diverse ecosystems on earth. A variety of crucial commodities and services are provided by mountain ecosystems [1–3]. Ecosystem accounting is essential for eco-environment system and natural cycle research. Mountain ecosystems are unique and ecologically valuable landscapes that provide numerous ecosystem services and support the livelihoods of millions of people and economic sustainability in the Himalayan region [4]. Forest is one of the most important pillars for sustainable development and natural conservation [5,6].

The Himalayas are a very large landmass and the source of human prosperity due to natural resources [7]. It extends as an almost unbroken arc for about 3000 km from west to east and occupies more than ten degrees from North latitude (27°-38° N) to Eastern longitude (72° −97°E). The altitude of this mountain range varies considerably, from about <300 m to >8000 m. Owing to its vertical and horizontal extent, the climatic conditions in the region are very diverse [8,9]. The extent and diversity of the Himalayas are well known. It has thousands of rivers that supply water to a large land cover and more than 60 million people throughout the year in the Indian Himalayan range (IHR).

The temporal and spatial variations in physical condition and the diversity of ecosystems and habitats in the region have resulted in markedly diversified forest stocks, characterized by a high degree of endemism, richness, and uniqueness of biodiversity elements [10]. According to Schirpke et al. [11]; forests are crucial for regulating the climate and storing carbon. One of the last natural forests in the state of Uttarkhand is the temperate forest, which provides the local population

* Corresponding author. Department of Environmental Studies, Kannur University, Kannur, Kerala, 670567, India.
E-mail address: thangavelgis@gmail.com (T. Arumugam).

https://doi.org/10.1016/j.rineng.2024.101811

Available online 19 January 2024

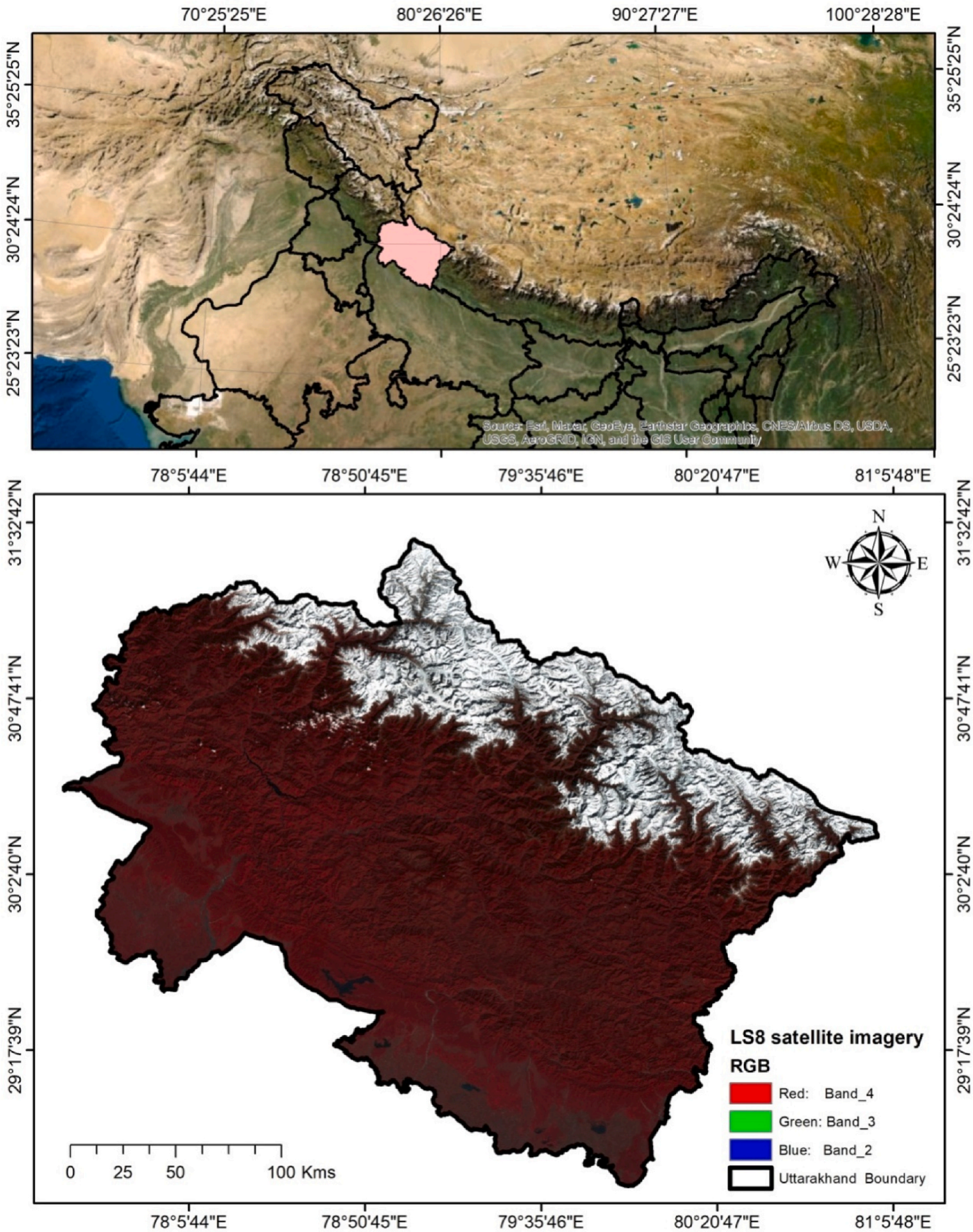

Fig. 1. Location map of the study area of Uttarakhand state.

Table 1
Data products to achieve research objective.

Datasets	Resolution	Year of acquisition	Purpose
Landsat 8	30 m	2015, 2019	NDVImax
ALOS PALSAR DEM	12.5 m	2008	Terrain, slope and drainage network
MOD11A1 V6	–	2015, 2019	MODIS LST
MODIS AOD	$10 \times 10\,km^2$	2000	–

with building materials, energy, and furniture. The benefits that ecosystems provide to people's well-being are known as ecosystem services (TEEB Foundations, 2010).

IHR is widely recognized for its distinctive, representative, ecological, and socio-economically significant flora and fauna. The unparalleled vertical extent of this mountain range forms the most apparent and sharp environmental gradient that controls the patterns of diversity in ecosystem elements [12,13]. Various pieces of evidence have indicated that the forests of the Himalaya are significantly different from both

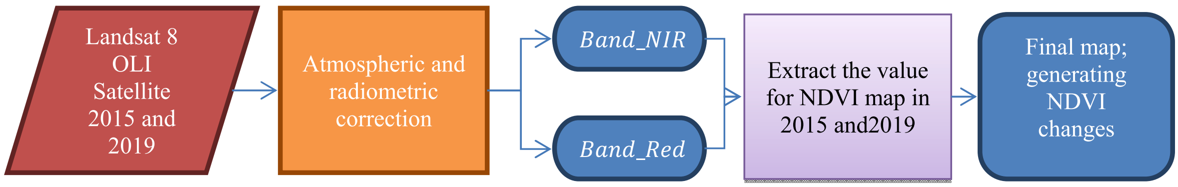

Fig. 2. Flowchart of methodology for NDVImax classification.

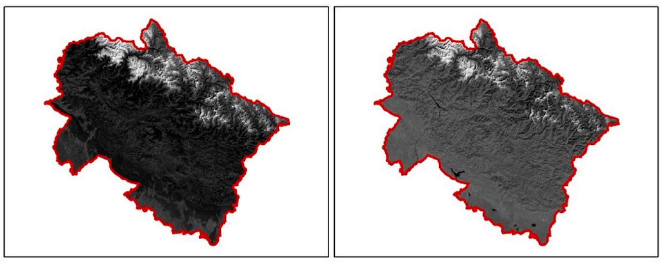

Fig. 3. Spectral band red and band NIR (Landsat 8 OLI imagery).

tropical and temperate forests around the world [14,15]. Further, intensive ecological research on Himalayan forests has highlighted the significance of available voluminous data sets at the global scale. The IHR in Uttarkhand, with over 63.42 % of land under forests, largely represents a forested landscape. Due to its enchanting, picturesque landscape, this region has attracted ecologists, naturalists, and pilgrims since time immemorial, and it has remained a G.B.Pant National Institute of Himalayan Environment (GBPNIHE).

The richness, representativeness, uniqueness, and fragility considerations, accompanied by the wide-ranging life support values, put the Himalayan vegetation on top priority both in an Indian and global context. The Himalayan forests most often exhibit great diversity in their ecosystem patterns owing to altitudinal variation and changes in rainfall patterns [16]. The types of vegetation change with changes in altitude [17–19]. Sediment in dams and reservoirs causes erosion downstream and changes the dynamics of sediment movement [20,21]. This affects the morphology of rivers, aquatic environments, and sedi ment-dependent ecosystems. Effective sediment management techniques must be put into place in order to protect ecological integrity and energy production [22] In recent decades, the consequences of global climate change for forest diversity along altitudinal gradients have become increasingly important [23]. There is evidence that suggests that increasing temperatures will lead to upward migration and changes in species in mountain systems [24,25]. For ecosystem services assessment, relate NDVI values to ecosystem services unique to the Lower Himalaya Range, such as watershed protection, biodiversity conservation, and tourism [26].

The Normalized Difference Vegetation Index (NDVI) with GIS is used in the Himalayan ecosystem accounting paradigm, which entails evaluating and tracking the ecosystem's changes and overall health [27,28]. An important indicator of vegetation activity and the health of the ecosystem is the NDVI, which is a commonly used remote sensing index [29]. Therefore, the present research focuses on the systematic investigation of forest cover mapping and the maximum NDVI pattern. Forest cover is a key element in ecosystem maintaining and functioning, and its mapping can help us better understand mountain ecosystem accounting.

The study appears to focus on mountain ecosystem accounting in the Uttarkhand region of India [30]. The ecosystem accounting framework typically involves assessing the contribution of ecosystems to the economy and human well-being [31]. This framework measures and values ecosystem services, including provisioning services (like food and water), regulating services (such as climate and flood control), cultural services (recreation, spiritual, etc.), and supporting services via soil formation [32]. They contribute to regional water cycles, serve as habitats for unique flora and fauna, and offer cultural services to indigenous communities [33]. Assessing their contribution through an ecosystem accounting framework helps understand their resilience and vulnerability to changes in land use, climate, and other stressors [34]. It is ability to capture variations in vegetation density and health within forested areas, and its compatibility with satellite imagery data sources that are widely available for mountainous regions. Mapping long-term land use and land cover change in the central Himalayan region using a tree-based ensemble classification approach [35]. These analyses help to understand the distribution pattern of land surface resources in ecosystem resource accounting and service applications. However, further research is needed to validate the accuracy of this approach and to determine its applicability to different types of mountain ecosystems with varying vegetation densities and distribution patterns. The study aims to investigate forest cover mapping and the maximum Normalized Difference Vegetation Index (NDVI) pattern in order to better understand the mountain ecosystem and its functioning.

2. Study area

The study area is presented as mountain regions in the lesser Himalayan ranges in the Uttarkhand state of India, which is also a state situated in the north of the country. Uttarkhand state lies between 28°44' N to 31°28' N latitude and 77°35' E to 81°01' E longitude and covers an area of approximately 53,483 sq. km., of which approximately 85 % is mountainous region and 63.42 % is covered by forest, as shown in Fig. 1. The state is surrounded by mountains in the north, east, and west, and the opening south is much plainer than the north. Mountain ranges are rising in the Himalaya, a fresh and dynamic orogenic belt. Each geological block in the Himalaya, including the Higher Himalaya, the Lesser Himalaya, and the Outer Himalaya, exhibits a variety of geomorphic behaviors that give them their own unique characteristics. It is located in the Himalayas, and their geological structure is related to the Main Central Thrust or Tethyan Himalayan Sequence. Most of the people engaged in primary activities such as shifting cultivation, animal husbandry, and the sale of medicinal plants. Seasonal migration frequently takes place in the upper hills. The Himalayas' high elevation

Table 2
NDVImax classification and change detection in Uttarkhand.

Method	Class	Changes class	Area (sq. km.)	Area in %	Changes in area	Year
NDVI	NDVImax (cover)	–	23529	44.90	0	2015
			22926	43.75	1.15	2019
	NDVImax	NDVImax (Forest to Forest)	19985.88	87.18	0	2015–2019
	NDVImax	NDVImax (Forest to non-forest)	3012.2	13.14	–	2015–2019
	NDVImax	NDVImax (Non-forest to Forest)	2962.4	12.92	–	2015–2019

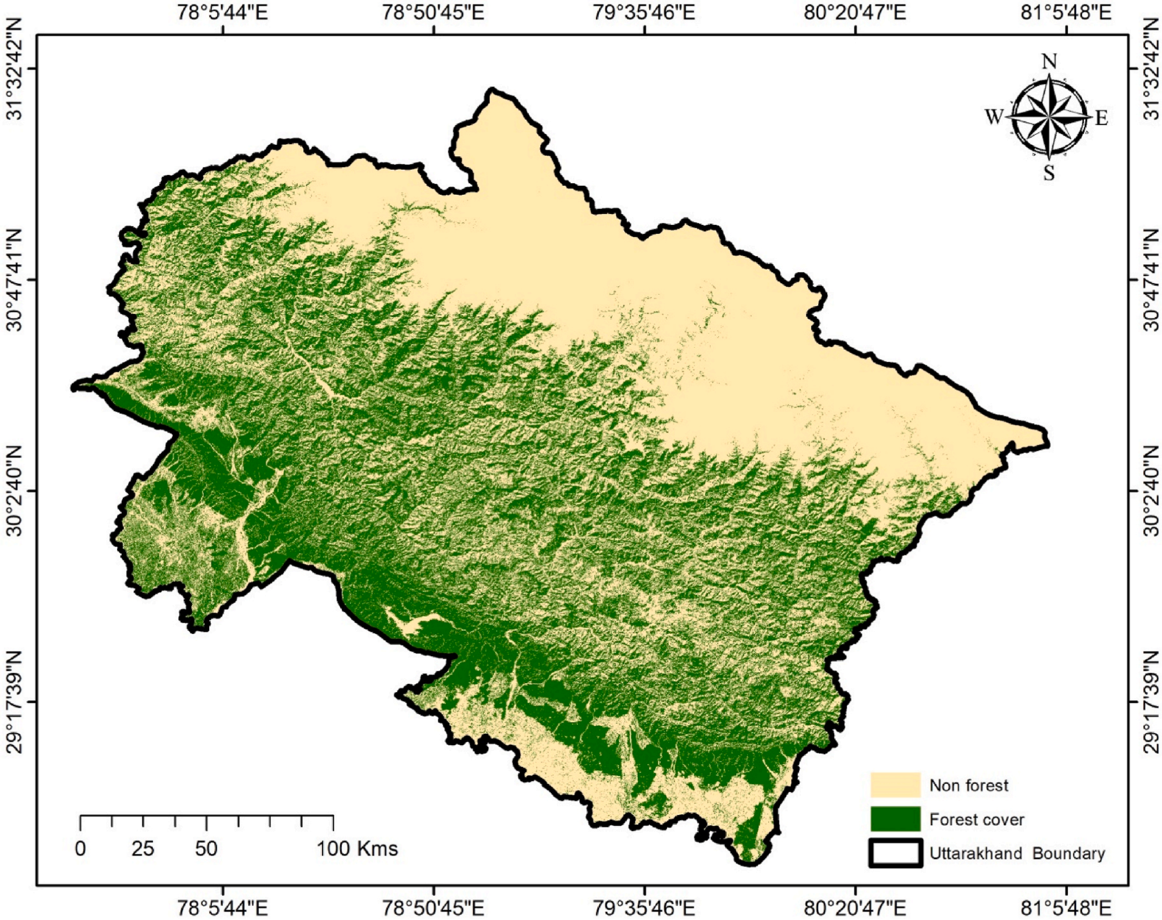

Fig. 4. Derived NDVImax for the study area from Landsat 8 OLI 2015.

and unique geography contribute to the formation and flow of these important rivers, and the Himalayan mountain range is the source of the majority of the rivers. The sustainability of these rivers is under threat due to various factors such as climate change, pollution, dam construction, and over-extraction of water resources. The melting of glaciers due to climate change is causing a decrease in river flows during dry seasons, leading to water scarcity in downstream areas.

3. Method and materials

Satellites with freely available cloud-free datasets were used, such as satellite data from Landsat 8 for NDVImax and LULC and Digital Elevation Model (DEM) data from Advanced Land Observing Satellite (ALOS) Palsar with 12.5 m for the year 2008 for terrain mapping. The watershed delineation for the study area was done using high-resolution DEM datasets. The DEM datasets were downloaded from the Alaska Vertex web portal (https://search.asf.alaska.edu/#/), which is an open source dataset for across the globe with 12.5 m spatial resolution and a vertical accuracy of 4.1 m and above depending on the contingent nature of terrain. The multispectral dataset was downloaded from the site (https://earthexplorer.usgs.gov/) with a 30 m spatial resolution. These datasets have been found to be suitable with varying vertical elevation accuracy depending on the surface topography or terrain of the earth (Mukul et al., 2017; [36]. The elevation model is more useful for topographic landscapes and hydrological aspects. MODIS images were downloaded freely through NASA Earth Observation via https://neo.gsfc.nasa.gov/and "https://earthengine.google.com/".

The brief details of the data used in the study are shown in Table 1. The data acquisition time plays an important role in selecting the data for natural resource mapping. During the winter period, exact mapping of permanent and maximum forest cover should be done because this period is suitable for mountain forest cover mapping. NDVI was at its maximum at the time of the peak forest period. To avoid this problem, some precautions were taken in the selection of the data. The actual forest and NDVI were fully exposed during the acquisition of satellite imagery. The level of accuracy of the user's methods, expertise, and optical capacity to identify and detect the many signatures among the various patterns in the satellite images determines how accurately the NDVI categorization is performed in Fig. 2. Each pixel is assigned a classification based on the spectral data encoded in the one spectral band index. The spatial data integration and the creation of thematic maps were both accomplished using the ArcGIS 10@ version. For this study, before completing thematic maps, adequate field checks to visualize the role of terrain analysis, a slope and elevation map was created using ALOS Palsar DEM data.

3.1. *Normalized difference vegetation index*

The normalized difference vegetation index (NDVI) is a widely used technique to detect forest cover change, especially changes in green area and its pattern. It was produced by combining the red and near-infrared wave bands. It is widely used for mapping and forest monitoring. NDVI used a cloud masking technique to remove cloudy pixels from the images and ensure that only clear-sky pixels were included in the analysis. This method implicated identifying pixels with cloud cover using a threshold value based on brightness and texture characteristics and then replacing these pixels with values from adjacent clear-sky pixels. This technique involved calculating the NDVI values for each pixel at different eleva-

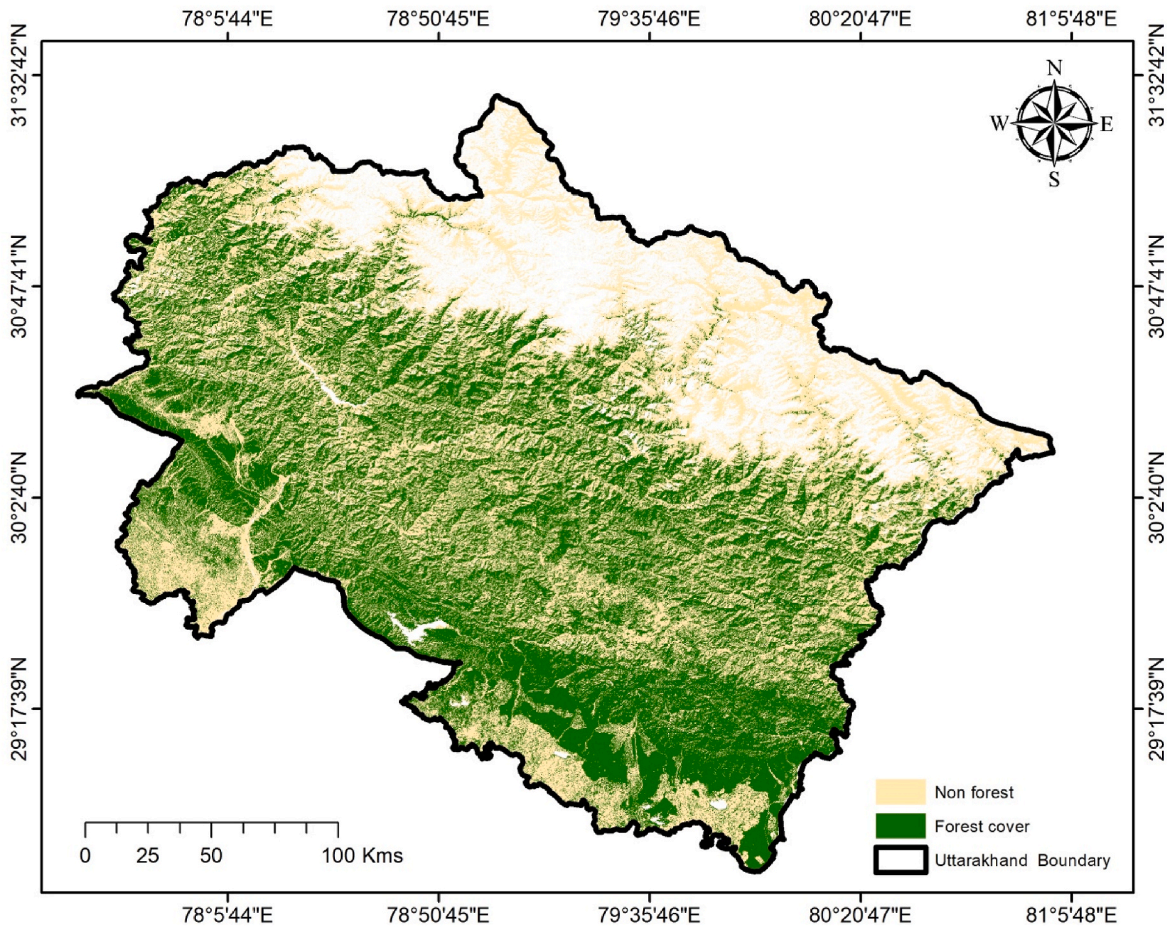

Fig. 5. Derived NDVImax for the study area from Landsat 8 OLI 2019.

Fig. 6. Photographs of forest cover of Uttarakhand; (a) forest cover of Darma valley at 3450 m msl and (b) forest cover of lesser Himalaya at 1580 m from msl

tions and slopes and then averaging these values to generate a final NDVI map that was more accurate and representative of the study area, as determined by formula 1:

$$\mathrm{NDVI} = \frac{\mathrm{Band\_NIR} - \mathrm{Band\ Red}}{\mathrm{Band\ NIR} + \mathrm{Band\ Red}} \tag{1}$$

3.2. Land surface temperature

Land Surface Temperature (LST) is a complicated variable with several influences; it is compelled to change both spatially and temporally quickly. LST information for Uttarkhand was taken from the MODIS LST annual mean L3 Global MOD11A1 V6 product. The MOD11A2 V6 product provides an annual mean land surface temperature (LST) on a 0.5-km grid. Each pixel value in MOD11A2 is a simple average of all the corresponding MOD11A1 LST pixels collected within that 8-day period. The MODIS reprojection tool ArcMap was used to reproject from the original sinusoidal (SIN) to the Universal Transverse Mercator projection (UTM Zone 44 N, WGS84 ellipsoid).

The following formula (2) is used to determine the MODIS land surface temperature:

$$\mathrm{LST} = \mathrm{k1} * (\mathrm{T1} * \mathrm{T2})\hat{\ }0.5 + \mathrm{k2} \tag{2}$$

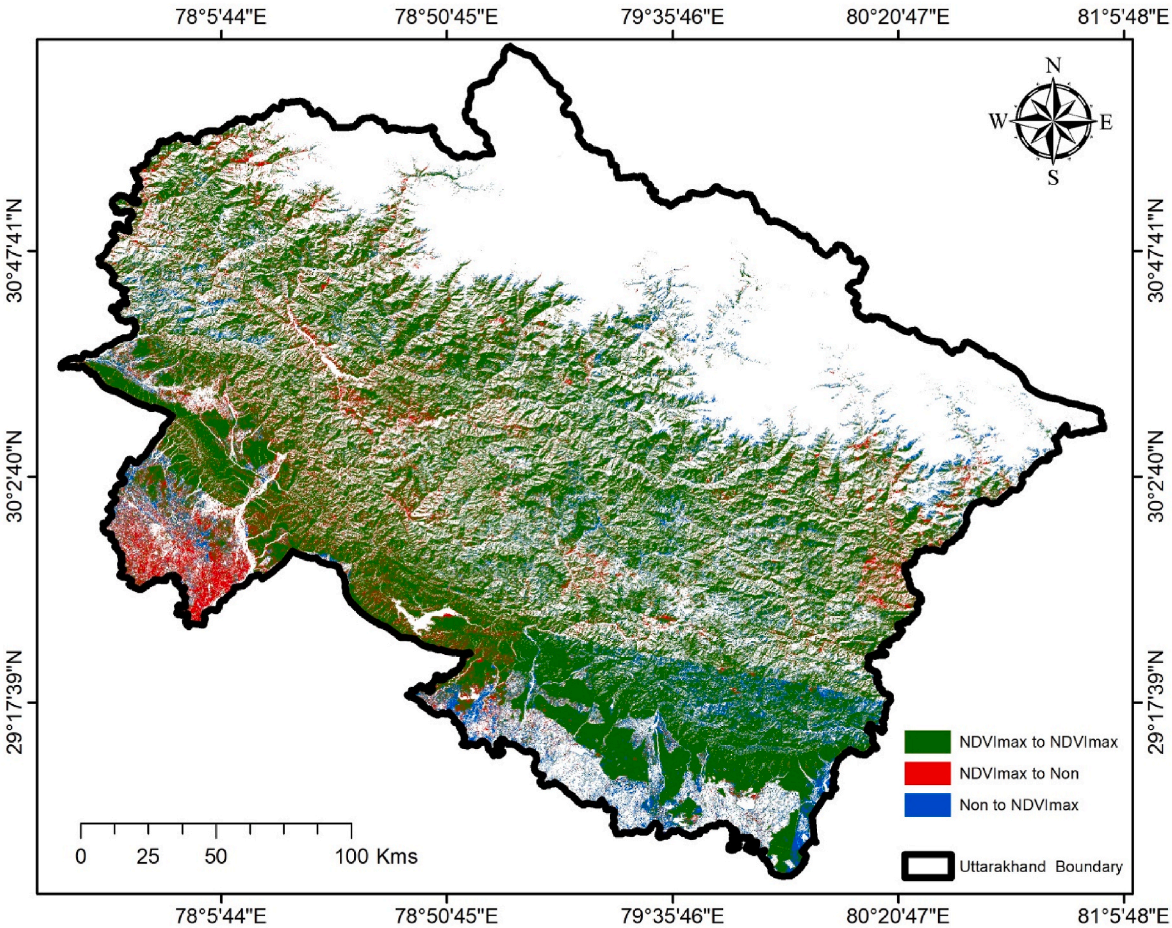

Fig. 7. Temporal changes of NDVImax cover in 2015 and 2019.

Fig. 8. Photograph of land temperature zone of study area; (a) maximum temperature zone in lower elevation area of state and (b) minimum temperature zone in higher elevation area.

where.

The land surface temperature (LST) is expressed in Celsius degrees.

The brightness temperatures T1 and T2, which are expressed in Kelvin, are derived from two different MODIS bands, often 31 and 32.

k1 and k2 are coefficients that depend on the specific MODIS product being used.

For this, calibration and validation procedures are used to determine these coefficients. Based on the hypothesis that two MODIS bands with varying degrees of sensitivity to different atmospheric paths can be used to estimate the LST, a formula is developed. The formula proposes to reduce the impact of atmospheric interference and provide an accurate estimation of the LST by combining these two temperatures.

3.3. Digital elevation model

The Digital Elevation Model (DEM) data of ALOS Palsar, which has 12.5 m for the year 2008 for the terrain mapping product, was used to determine the elevation data for Uttarkhand. The data for the study region was downloaded from the website and then re-projected to the Universal Transverse Mercator (UTM) coordinate system as presented in Fig. 3. The state of Uttarkhand is divided into two major eco-biogeographic areas. The highlands are a region that stretches from north to south and is characterized by varieties of mountains that rise up to 750 m above mean sea level.

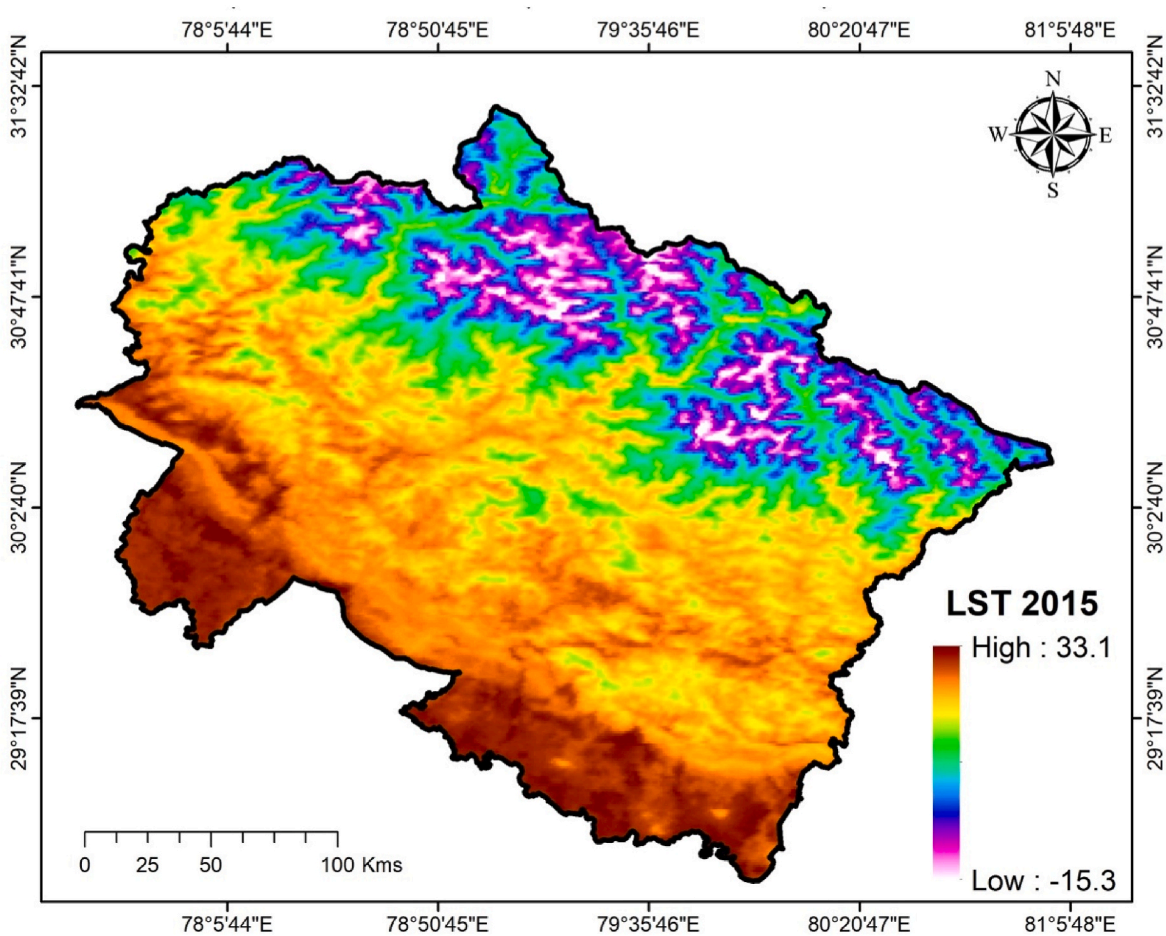

Fig. 9. Land surface temperature of the study area (MODIS image) in 2015.

3.4. Change detection techniques

For this study, multi-temporal datasets were used in the change detection process to identify locations where the land cover has changed since the imaging dates. The analysis of multi-temporal datasets is a common practice in remote sensing applications. It has the ability to recognize various NDVImax modifications at any given time. Multi-temporal Landsat 8 data and MODIS were collected to detect changes in forest ecosystems between the years 2015 and 2019. Post-classification change detection comparative techniques were used to analyze forest change, as presented in formula 2.

$$r = \frac{1}{t_2 - t_1} \times \ln\left(\frac{A_{t_2}}{A_{t_1}}\right) \tag{2a}$$

where,

r-the land cover changes and.

A_{t_1} and A_{t_2} are the forest covers at time t_1 and t_2 respectively in the logarithm.

The formula used for the calculation of rate of the rate of change has been derived from the formula [37].

3.5. Land use land cover pattern (LULCP) techniques

The model of land use land cover pattern (LULCP) indicates the way land is managed and distributed spatially for a variety of uses, including forestry, urbanization, agriculture, and conservation. It entails identifying and categorizing various forms of land cover, such as vegetation, bodies of water, populated areas, and bare ground [38]. For the purpose of developing strategies for the sustainable management of land resources, LULCP is an essential tool in the field of sustainable land management. It involves the identification and classification of different land cover types, data collection, analysis, modelling, and decision-making using field surveys, remote sensing data, and GIS [39].

The main device used in this work to categorize LULCP was the Maximum Likelihood Classifier in study area. The maximum likelihood classification approach makes the assumption that the statistics for each class in each band are normally distributed in order to calculate the likelihood that a particular pixel belongs to a given class. One popular method is the maximum likelihood classifier, which assigns a pixel to the class with the highest likelihood value [40]. The likelihood Lk, also known as the probability density function, is the posterior probability of a pixel belonging to class k given its feature vector, and it is based on the feature vector X and the prior probability P(k). Under common assumptions, such as equal prior probabilities and a common prior-likelihood product for all classes, Lk only depends on P(X/k). Formula 3 can be used to express Lk in the context of normal distributions, which are frequently utilized for mathematical purposes.

$$\mathrm{Lk}(X) = P(k) * (2\pi)^{-\frac{n}{2}} * |\Sigma_k|^{-\frac{1}{2}} * \exp\left(- \frac{(X - \mu_k)^{T\Sigma_k^{-1}(X-\mu_k)}}{2} \right) \tag{3}$$

where n is the number of bands, X is the image data of n bands, k is the mean vector of class k, Σ_k is the variance-covariance matrix of class k, and exp() represents the exponential function. This formula shows that Lk is a function of both the mean vector and variance-covariance matrix of each class. By maximizing Lk for each pixel, we can obtain the most probable class assignment for that pixel, P(X/k): conditional probability to observe X from class k, or probability density function.

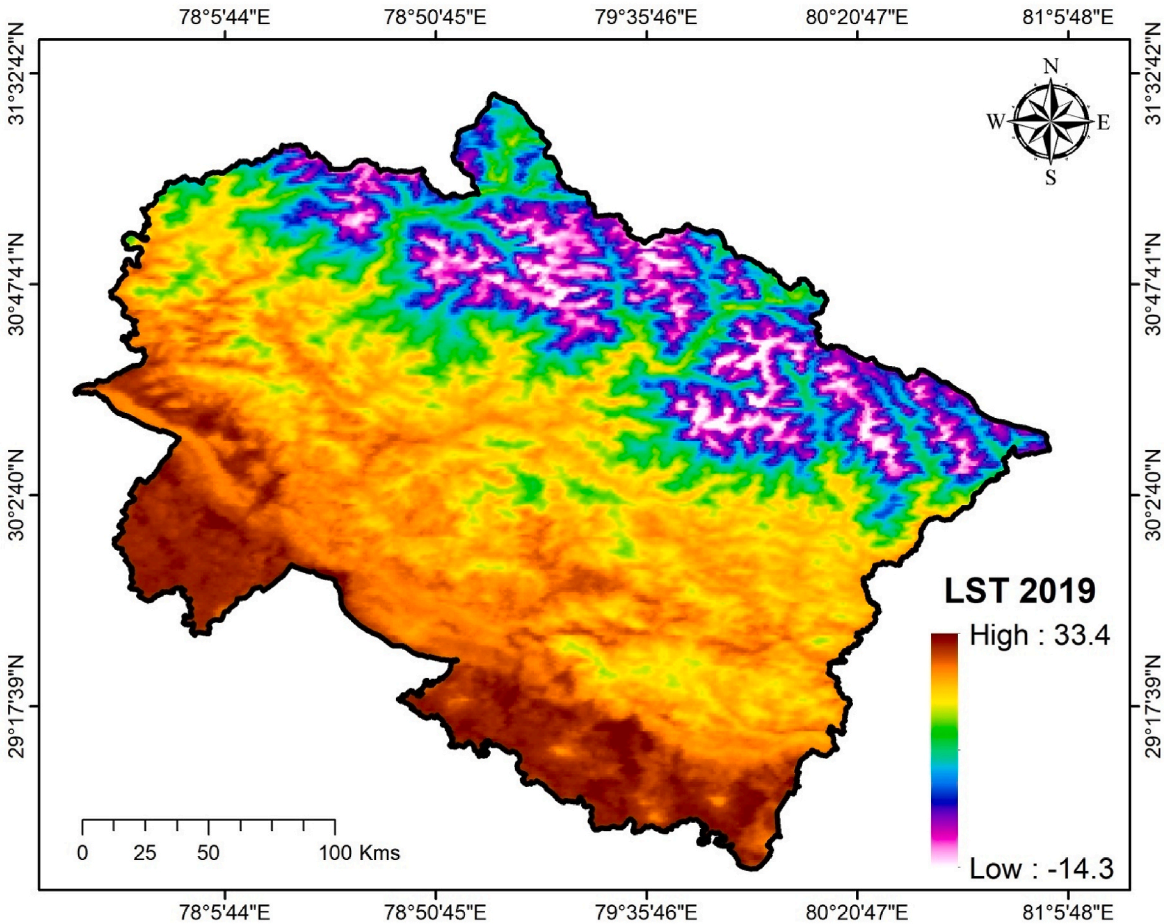

Fig. 10. Land surface temperature of the study area (MODIS image) in 2019.

4. Results and discussion

4.1. Normalized difference vegetation index calculations (NDVImax)

The normalized difference vegetation index has been employed in the study to examine the connection between changes in plant growth rates and spectral variability. It is also useful for determining the output of detecting vegetation changes along with green vegetation, and the results are included in Table 2. The bands represent the combination, extracted from the satellite image of Uttarkhand State. A pixel's vegetation density and "greenness" are significantly correlated with the NDVI values (which range from −1 to 1), with higher values being associated with denser forest cover or more vegetation. It enables simple classifications like those that cover only non-forest and forest. In this study, pixels with an NDVI of 0.7 or higher were distinguished from pixels with an NDVI of 0.6 or below because it was considered that pixels with an NDVI of 0.7 or higher were probably to contain forest or vegetation, as shown in Figs. 4 and 5.

The result of this study confirms that the NDVI maximum covered can be accurately estimated using NDVI and satellite data. It has been found that the satellite imagery gives the best result for forest cover at the NDVI value, as presented in Figs. 6 and 7. The normalized difference vegetation index is extended to 23529 km^2 in 2015 and 22926 km^2 in 2019, which is a total area of 44.90 % and 43.75 %, respectively. For this study of 2015 and 2019, changes in NDVImax cover have been observed in 1.15 % of the area. More than 87 % of the NDVImax cover area is stable, while more than 13 % of the NDVImax cover is changing to a non-NDVImax cover, and 12 % of the area is joining the new NDVImax cover.

The maximum of the NDVImax cover is changing around the places where there are settlements, roads, and agricultural land. This change can be seen in all the places where they are moving from non-forest cover to forest cover in the higher elevation zone, as well as in riverside and forest-covered areas. Findings of the NDVImax index may be used as an indicator for future trends in land cover change and to determine the variables influencing forest cover to help planners and decision-makers better understand this issue. The study found a decrease in forest cover but an increase in vegetation density and health within forested areas, which suggests that there may be trade-offs between green cover and forest cover in mountain ecosystems. As mountain ecosystems are particularly vulnerable to the impacts of climate change, understanding how these ecosystems are changing is crucial for developing adaptation and mitigation measures.

4.2. Land surface temperature (LST)

The results show that annual mean temperatures derived from MODIS LST data are generated by the Google Earth Engine (GEE). It is a quantitative analysis of the MODIS LST for differences between 2015 and 2019 data as observed in Fig. 8. The analysis of MODIS's annual mean temperature shows the maximum land surface temperature is 33.1 °C and the minimum land surface temperature detected by the sensors is −15.3 °C in 2015. The second analysis of MODIS's annual

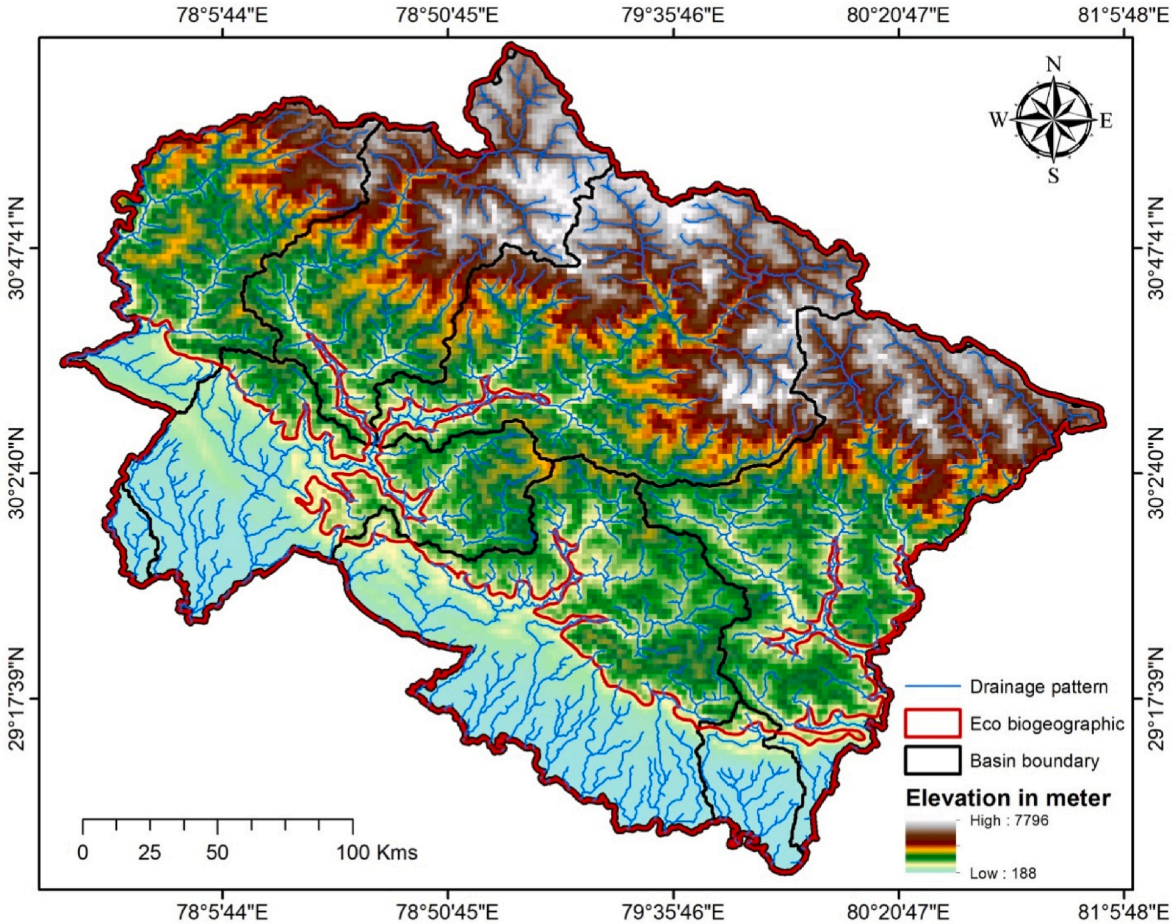

Fig. 11. Sub-basin of river and eco-biogeographic zone of site.

mean temperature found the maximum land surface temperature is 33.4 °C and the minimum land surface temperature detected by the sensors is −14.3 °C in 2019. The change in annual mean land surface temperature from 2015 to 2019 is 0.4 °C (increase) in maximum annual mean temperature and the minimum annual mean land surface temperature in 1 °C (change) from 2015 to 2019 as presented in Figs. 9 and 10.

The elevation of a particular location is a major factor that determines the temperature. It is topography also impacts temperature as it affects the amount of solar radiation received by a particular location. Areas with more exposed rock surfaces and less vegetation tend to have higher temperatures due to increased absorption of solar radiation, while areas with more vegetation and shaded surfaces tend to have lower temperatures due to reduced absorption of solar radiation. For this study, temperature is a critical role in determining the distribution and abundance of various plant and animal species, as well as their physiological processes such as photosynthesis and respiration. As temperatures continue to rise, many species may be forced to migrate to cooler areas or adapt to new environmental conditions, which could have significant ecological and evolutionary consequences [41].

LST has a very important function in sustaining mountain ecosystems and biodiversity. It was observed that LST increased in both the higher elevation zone and the lower elevation zone. For this reason, natural resources are shifting or changing due to increased land surface temperatures. The study attempted to use various methodologies and materials to assess and analyze different aspects of the mountain ecosystem. The study included the use of the NDVI for vegetation analysis, LST measurements, digital elevation models, and change detection techniques. The study exposed valuable insights into the mountain ecosystem of Uttarkhand. The calculations of NDVI max provided information on vegetation distribution and health, highlighting areas of high vegetation density and potential changes over time. The analysis of LST helped in understanding temperature patterns and variations across the study area. Furthermore, these study outcomes contribute to the broader scientific understanding of mountain ecosystems and their response to environmental changes. This information contributes to a comprehensive understanding of the landscape composition and guides land management and planning efforts.

4.3. River basin pattern

Digital elevation models (DEMs) are frequently explored for drainage analysis of river basins through the extraction of topographic parameters and stream networks, and their use presents several advantages over traditional topographic maps and allows for better mapping of natural resources. Variation in topography also affects forest patterns and the distribution of other resources. The DEM is a regular gridded matrix representation of the continuous variation of relief over space and a digital model of the form of the land surface. Uttarkhand State is one of the most important and significant rivers in India. Most of the rivers have their origins in glaciers, which are located in the upper elevation zone, as observed in Fig. 11. Watershed delineation means creating a boundary that represents the contributing area for a control point or outlet.

ArcMap software applications are available that provide automated watershed delineation tools. The watershed of this region encompasses an area of 53732.23 km^2, which comprises two major biogeographic zones of 13 districts under six major sub-basins and two small sub-

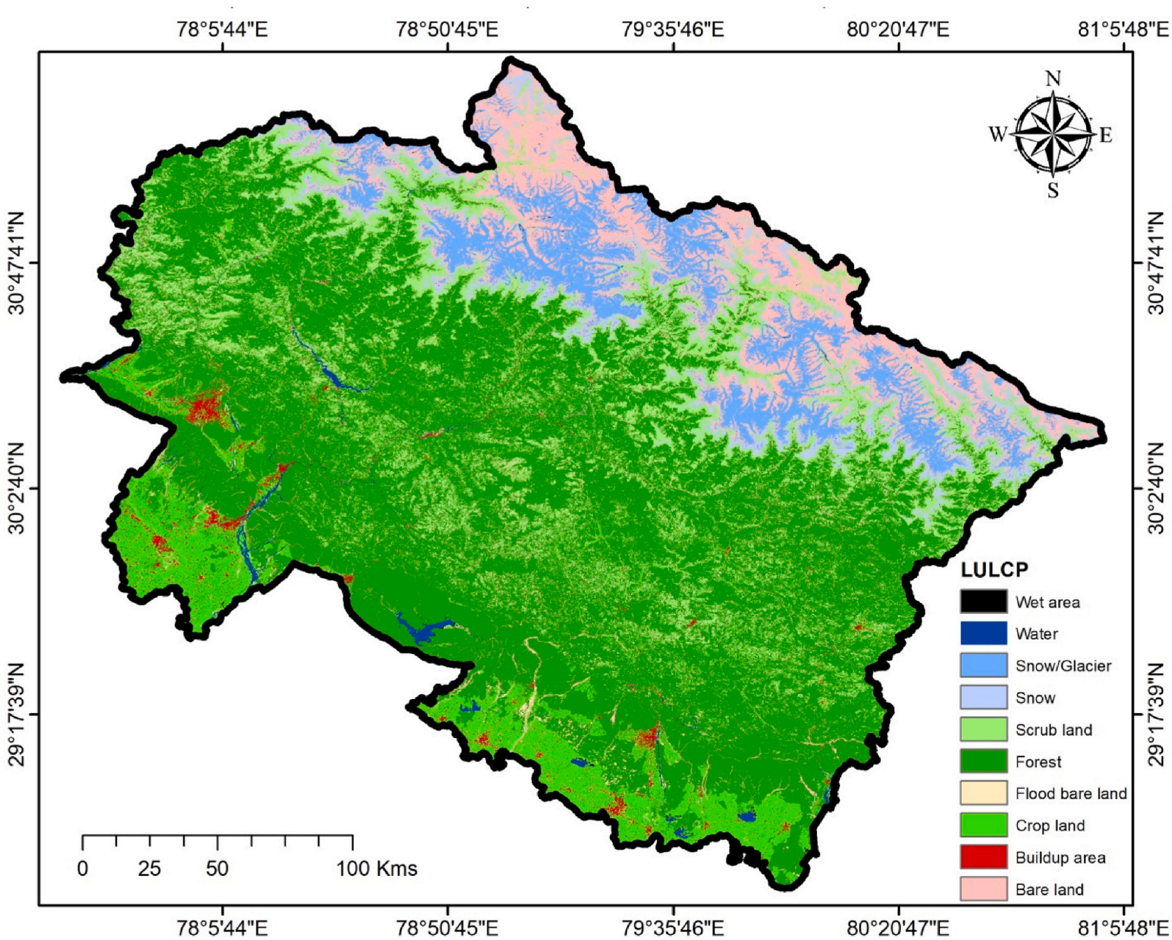

Fig. 12. LULCP of Uttarakhand state (2020).

basins. The lower biogeographic zone covers an area of 12769.8 km^2, which includes two major sub-river basins and two small river basin areas. The upper biogeographic area extended to 39633.2 km2 in the state of Uttarkhand, which covers four major sub-basin areas. The sustainability of these rivers is under threat due to various factors such as climate change, pollution, dam construction, and over-extraction of water resources. The melting of glaciers due to climate change is causing a decrease in river flows during dry seasons, leading to water scarcity in downstream areas.

The assessment of river basin patterns and LULCP provided a comprehensive understanding of the landscape and its utilization. The mountain ecosystems in the Himalayas are crucial for various ecological services and play a vital role in the well-being of both local communities and the broader environment. The data and insights generated through this project contribute to a better understanding of the mountain ecosystem's dynamics, including vegetation patterns, temperature variations, and land use. For this study, the identification of areas with high vegetation density and changes in vegetation cover can guide targeted conservation efforts and reforestation initiatives. Knowledge of temperature patterns can aid in assessing the vulnerability of different areas to climate change impacts and developing appropriate mitigation measures.

4.4. Land use land cover pattern (LULCP)

Land use land cover pattern indicators are usually used as existing patterns for ecosystem service assessment. In this view, the assessment of ecosystem services includes an important quantitative component that depends on suitable indicators. To accurately and comprehensively assess the various facets of ecosystem supply, a whole set of indicators has been assigned to the major classes of ecosystem services over time. For this study, with the help of remote sensing, the land has been classified into 10 classes categorized by the land cover pattern. The derived classification map exhibits a spatial distribution pattern of classes in accordance with the supervised classification of area. The LULCP area of each class in 2020 showed that forest cover land had maximum cover at 43 % of the total land cover, as shown in Fig. 12. The percentage of other areas as classified are: flood bare land (0.46 %), scrub land (21.64 %), crop land (4.28 %), built-up areas (1.33 %), bare land (14.7 %), water (1.05 %), wet area (0.05 %), and snow/glacier and with snow cover (14.12 %) as shown in Fig. 13. The performance of this classification method was assessed for LULC classification from geospatial datasets. These analyses help to understand the distribution pattern of land surface resources in ecosystem resource accounting and service applications. The results could inform policymakers and land managers about the importance of preserving and restoring the mountain ecosystem to ensure the provision of ecosystem services, such as water supply, climate regulation, and habitat preservation.

5. Conclusion

Normalized difference vegetation index (NDVI), land surface temperature (LST), river basin pattern, and land use land cover pattern (LULCP) were the four GIS databases that were integrated in this study to estimate the portion of the study region that fell into each of the mentioned mountain ecosystem groups. The lower Himalaya is vulnerable to climate change due to its ecological fragility and economic marginality. The study confirms its vulnerability, with analysis and

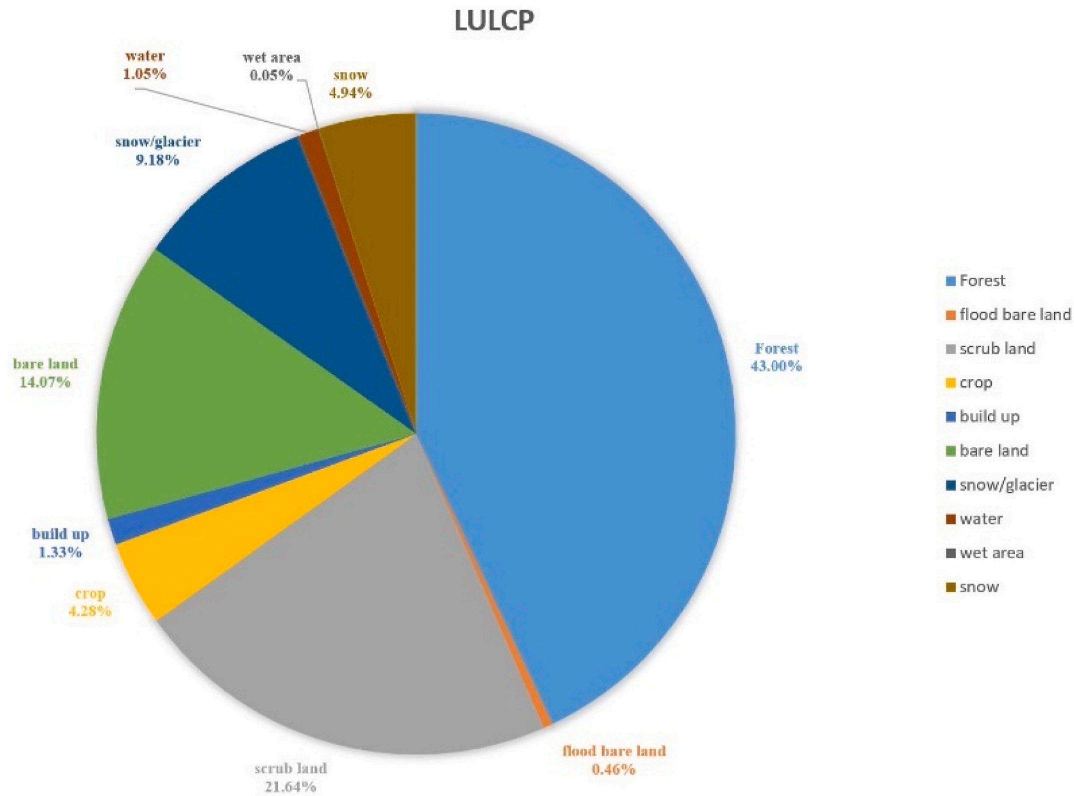

Fig. 13. LULCP percentage share of each class in Uttarakhand state (2020).

predictions showing an increasing magnitude of change with elevation, both in mean shifts in temperature and in greater stretching in precipitation variation. Climate change is poised to alter this status quo with far-reaching consequences for the condition of biodiversity and the quality of ecosystem flow downstream. While the ecological and human value of forests and water security is well understood in the literature, the extent to which they may be affected by agricultural expansion in the Himalayas is not known. Due to the very limited amount of quantifiable research on mountain ecosystem suitability in the study area, including GIS and remote sensing techniques. This study benefits from long-term projections for 5 to 10 decades so that policymakers can consider research evidence to come up with proactive solutions to the problem of conventional focus on land-sparing strategies. Specific research areas include the quantity and accessibility of land suitable for ecological use in the frontier regions, specifically to promote agroecological transitions in climate change-driven ecological frontiers.

Mountain states that are the principal providers of ecological services are often forced to curtail or restrict developmental activities owing to various environmental conservation policies and acts, thus forgoing various developmental benefits and still languishing as backward and poor states. For example, Uttarkhand (a mountain state in north India) has dedicated approximately 14 % of its geographical area to protected areas, which is among the highest in Indian states. Human disruption of the climate system is quickly destroying this ecological equilibrium in the movement of energies and matter as well as the systems of linkages and responses. The management options must be evaluated on an individual basis, and the priorities need to be distinct, attainable, and not exhaustive.

The study's contribution to the understanding of the diversity and patterns of Lower Himalayan forests, particularly in relation to altitudinal variation and changes in rainfall patterns. By systematically mapping forest cover and analyzing the maximum NDVI pattern, the study can provide insights into the distribution and dynamics of vegetation in the mountainous region. This information can be valuable for ecosystem management, conservation planning, and assessing the impact of climate change on forest diversity along altitudinal gradients. The data and analysis presented in the study can inform decision-making processes related to sustainable development, natural resource management, and climate change adaptation strategies in the Uttarkhand region and other similar mountainous areas. Furthermore, these study outcomes contribute to a broader scientific understanding of mountain ecosystems and their response to environmental changes. There is a need to guard against management inactivity in the face of the major uncertainties raised by climate change and to inform policy decisions.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Thangavelu Arumugam reports a relationship with Kannur University that includes: employment. Thangavelu Arumugam reports a relationship with Kannur University that includes: non-financial support. There is no conflict of Interest.

Data availability

The data that has been used is confidential.

Acknowledgments

This work was supported by the Director, National Institute of Himalayan Environment Almora Uttarakhand, India, and Ministry of Environment, Forest and Climate Change, India.

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Further reading

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