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Forest Type Mapping of Mandi District of Himachal Pradesh, India: Using Sentinel-2B Multispectral Satellite Data with Supervised Classification Techniques

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ABSTRACT: Accurate mapping of forest types is essential for their sustainable management, ecological studies, and climate change mitigation. Remote sensing techniques using high-resolution satellite imagery have emerged as a cost-effective and reliable tool for vegetation classification and biomass estimation studies. This study focuses on forest type mapping of Mandi district of Himachal Pradesh using Sentinel-2B multispectral satellite data having 10m resolution. In this supervised classification method with Maximum Likelihood Classifier (MLC) was adopted, which was further supported by ground truth data and ancillary resources like SOI toposheets. A total forest area of 1603.19 km^2(40.50% of the geographical area of the district) was classified into 13 major forest types. The most dominant forest types included Moist Deodar forest (24.17%) followed by Chir Pine forest (21.10%), Western Mixed Coniferous Forest (18.04%), and Ban Oak Forest (11.19%), while the remaining forest types occupied comparatively smaller proportions. The overall classification accuracy was 84.67% with a Kappa coefficient of 0.83 which reflects the strong reliability of the results. These findings highlight the dominance of temperate coniferous and broad leaved forests in the district due to its climatic and altitudinal variations. The study demonstrates the potential of Sentinel-2 data to produce detailed, accurate, and up-to-date forest type maps that can serve as critical inputs for biomass estimation, resource management, and climate change studies in Himalayan ecosystems.

Keywords: Forest type mapping, Sentinel-2B, Remote sensing, Supervised classification, Mandi district, Himachal Pradesh.

1. INTRODUCTION

Forests are one of the most important ecosystems, which provide many ecological, economic, and social services to the world. In the Himalayan region, they play a vital role in biodiversity conservation, carbon sequestration, soil and water conservation, climate regulation, and livelihood security. Accurate mapping of forest types is therefore fundamental for sustainable forest management, biomass estimation, and climate change studies. In India, customary methods of mapping forest types were carried out using forest surveys and visual interpretation of aerial photographs (Champion & Seth, 1968), which were labour-intensive, time-consuming, and had limited spatially coverage.

With remote sensing and the emergence of geospatial data, forest monitoring has become synoptic, affordable, and repeatable over large areas. Satellite data, combined with Geographic Information Systems (GIS), have been extensively applied to vegetation classification, forest inventory, and biomass estimation worldwide (Lu et al., 2005; Franklin & Wulder, 2002). In India, agencies like the Forest Survey of India (FSI) have used IRS and Landsat imagery for vegetation mapping at national and regional scales (FSI, 2019). Studies such as Roy et al. (2006) and

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Reddy et al. (2015) demonstrated the potential of multispectral satellite data for mapping diverse forest formations, while Bijalwan et al. (2010) and Bisht (2015) highlighted applications in Himalayan states, particularly for assessing species composition and above-ground biomass.

Recent advances in sensor technology have further improved classification accuracy. Multispectral data at 10-20 m (30 m globally) spatial resolution with a five-day repeat frequency are provided by the European Space Agency Sentinel-2 mission. This represents a major advance over previous satellite sensors. Research has shown its effectiveness in forest type discrimination, vegetation phenology studies, and biomass estimation (Immitzer et al., 2016; Waser et al., 2019). Sentinel-2 images have been used to classify vegetation in the Himalaya (Jain et al., 2021) and assess carbon stock (Pandey et al., 2022) .The Himalayas present a complex ecological mosaic where phenological cycles strongly influence forest type distribution. Recent studies, such as Singh et al. (2023), have demonstrated the utility of Sentinel-2-based NDVI (Normalised Difference Vegetation Index) time series in capturing seasonal forest dynamics across the Western Himalayas. In this study, we extend these approaches by applying Sentinel-2B imagery for forest type mapping in Mandi district. Such findings highlight the suitability of Sentinel-2 data for forest type mapping in heterogeneous and rugged terrains like Himachal Pradesh.

Mandi district, centrally located in Himachal Pradesh, represents a unique mosaic of forest ecosystems shaped by altitudinal and climatic gradients. The district ranges from subtropical low hills to alpine pastures, resulting in coniferous, broad-leafed, scrub, and alpine vegetation. Although forests occupy almost 28% of the area of the State and provide numerous ecosystem services along with important biodiversity, there is no thorough and up-to-date district scale forest type map available and generally, very little fine-scale heterogeneity information available. This creates a barrier for forest resource planning, biodiversity conservation and climate change mitigation.

The present study aimed to classify and delineate the major forest types of Mandi district using high-resolution Sentinel-2B multispectral imagery supported by ground truth data collected during field surveys. The study further evaluated the accuracy and reliability of the classification results through error matrix assessment and Kappa coefficient analysis. In addition, the spatial distribution of forest types was examined in relation to topographic and climatic variations across the district in order to understand the ecological patterns of Himalayan vegetation. By integrating remote sensing data with field validation techniques, the study sought to develop a reliable and updated database on forest types in Mandi district that could support sustainable forest management, biomass estimation, biodiversity conservation, and ecological research in Himalayan landscapes.

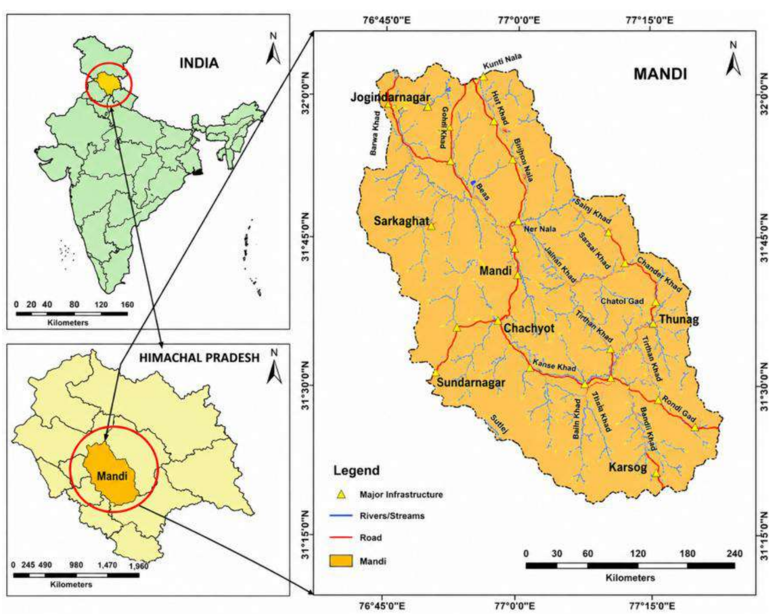

Figure 1. Location map of Mandi District, Himachal Pradesh

The study was based on the hypothesis that high-resolution Sentinel-2B multispectral data, combined with supervised classification techniques and field validation, can effectively discriminate and map the major forest types of Mandi district with high classification accuracy. It was further hypothesised that variations strongly influence the spatial distribution of forest types in the district in altitude, topography, and climatic conditions across the Himalayan terrain.

2. MATERIALS AND METHODS

2.1. Study Area

The study area, Mandi district, was located in central Himachal Pradesh (31°13′-32°05′ N; 76°37′-77°23′ E) in India and covers about 3,950 km² (Figure 1). The elevation ranges from 467 meters (1,532 ft) to 3,350 m (10,991 ft) and the climate ranges from subtropical in the lower region to temperate and alpine in the higher altitudes. Most of the region is drained by the Beas and its tributaries. The district supports diverse forest ecosystems, including chir pine, deodar, ban oak, blue pine, mixed-conifer, birch-rhododendron scrub and alpine pasture. The diversity of forest types makes Mandi ideal study area for satellite based forest mapping

2.2. Data Sources

Sentinel-2B level 1C multispectral data (10 m resolution) were acquired from the Copernicus Open Access Hub. Four bands—Blue (B2: 490 nm), Green (B3: 560 nm), Red (B4: 665 nm), and Near Infrared (NIR) (B8: 842 nm)-were used for vegetation classification (Table 1).

2.3. Image Pre-processing

Cloud-free Sentinel-2B images were corrected radiometrically and geometrically in ERDAS Imagine.

Table 1. Details of spectral bands of Sentinel-2B used in the study

Bands	Resolution	Central wavelength	Description
B2	10 m	490 nm	Blue
B3	10 m	560 nm	Green
B4	10 m	665 nm	Red
B8	10 m	842 nm	Near Infrared (NIR)

Ancillary datasets included conventional Survey of India (SOI) 1:50,000 topographic sheets (52D/12, 52D/16, 53A/9, 53A/13, 53E/1, 53A/10, 53A/14, 53E/2, 53E/6, 53A/15, 53E/3, 53E/7) for geo-referencing and ground validation.

Individual spectral bands were stacked to generate False Colour Composites (FCC) (Figure 2). Images were geo-referenced using SOI topographic sheets with RMS error < 0.3, and subsets were extracted based on district boundaries (Figure 3). Composite images and RGB band combinations are shown in Figure 4.

2.4. Forest Type Classification

Forest types were classified following the system of Champion and Seth (1968) using Supervised Classification with the Maximum Likelihood Classifier (MLC). Representative training samples for each forest type were selected based on field observations, visual image interpretation and their spectral reflectance characteristics. The Maximum Likelihood Classifier (MLC) assumed a normal distribution of class statistics. The probability that a pixel with feature vector x belonged to class i was estimated using Eq. 1.

$$p(x|i)= \frac{(2\pi)n}{2}|\Sigma i| \frac{1}{21 \exp[-21(x-\mu i)T\Sigma i-1(x-\mu i)]} \ldots(1)$$

Where, μi is the mean vector and Σi is the covariance matrix of class i. Each pixel was assigned to the class with

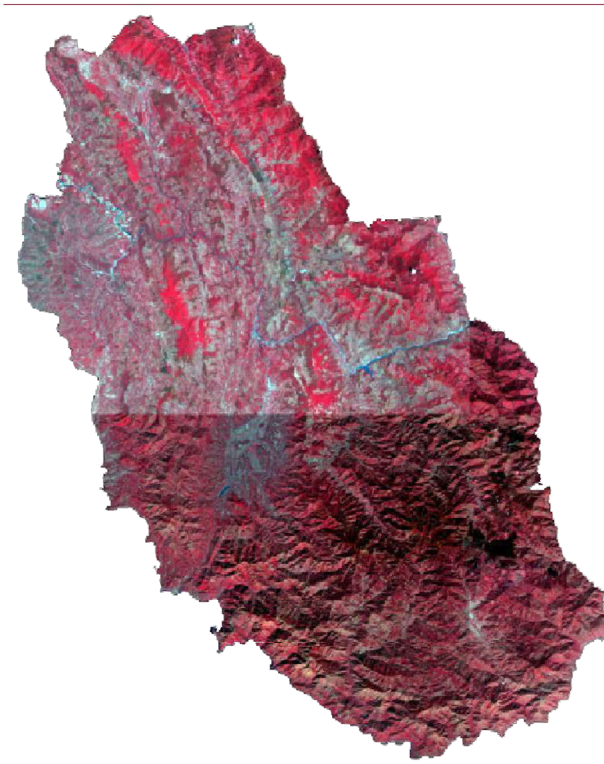

Figure 2. False colour composite (FCC) of the study area

the highest probability. Non-vegetated areas were masked using NDVI derived from Red (B4) and NIR (B8) bands.

2.5. Accuracy Assessment

Accuracy of classification was assessed using stratified random sampling with 150 ground truth points (Eq.2). An error/confusion matrix was generated by comparing reference data with classified outputs (Table 3). Overall classification accuracy and Kappa coefficient (κ) were computed following Congalton (1991). The Kappa coefficient was calculated using Eq. 3.

$$\text{Accuracy assessment percentage} = \left(\frac{\text{No.of ground truthing points classfied correctly}}{\text{Total number of ground truthing points checked}}\right) \times 100 \quad (2)$$

$$K_{hat} = \frac{N\sum_{i=1}^{r} X_{ii} - \sum_{i=1}^{r}(X_{i+} * X_{+i})}{N^2 - \sum_{i=1}^{r}(X_{i+} * X_{+i})} \quad \ldots\ldots(3)$$

where

- r = number of rows in the matrix,
- Xii = observations in row i and column i,
- $Xi+$ and $X+i$ = marginal totals of row i and column i,
- N = total number of observations.

2.6. Methodological Framework

The methodology for forest type classification is illustrated in Figure 5 and consists of five main components: data collection, data pre-processing, classification, ground validation, and accuracy assessment.

3. RESULTS AND DISCUSSION

Forest type mapping provides critical baseline information for biodiversity assessment, habitat evaluation, carbon stock estimation, and sustainable forest management

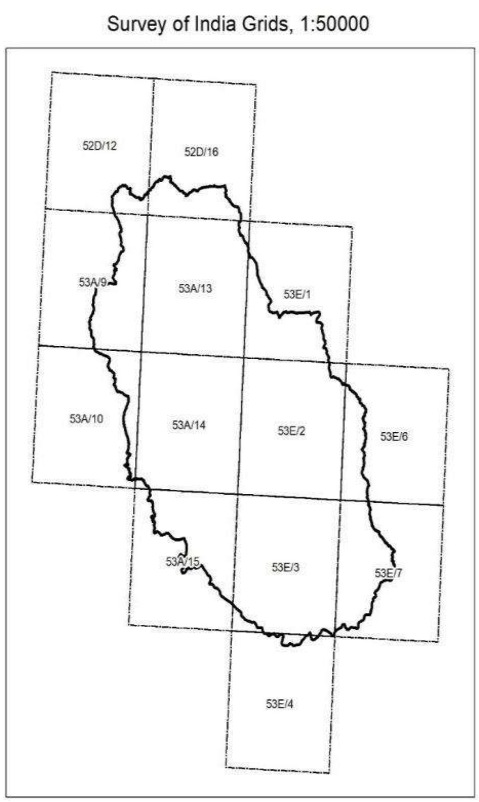

Figure 3. Survey of India (SOI) 1:50,000 scale toposheets covering Mandi district, Himachal Pradesh. The figure illustrates the SOI grid sheets overlapping the study area, which were used as base reference maps for image georeferencing, preparation of the study area boundary, and validation of the forest type map

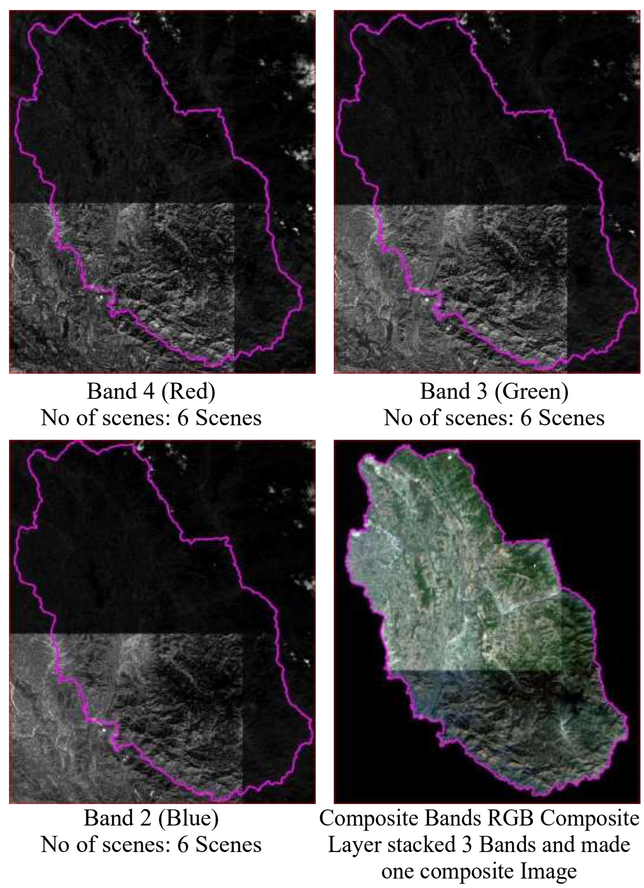

Figure 4. Sentinel-2B multispectral imagery used for image processing, showing the individual spectral bands—Band 4 (Red), Band 3 (Green), and Band 2 (Blue)—along with the RGB composite image generated by layer stacking

in mountainous ecosystems. In the present study, Sentinel-2B multispectral imagery, combined with supervised classification, successfully delineated 13 major forest types in Mandi district, Himachal Pradesh (Figure 6). The spatial distribution and area statistics of these forest types are presented in Table 2. These results show the applicability of Sentinel-2 data for classifying heterogeneous Himalayan vegetation across complex topographic gradients with high accuracy.

3.1. Forest Types of Mandi District

The classified map revealed that Moist Deodar Forest occupied the largest area (38,752.50 ha; 24.17%), followed by Chir Pine Forest (33,834.00 ha; 21.10%) and Western Mixed Coniferous Forest (28,925.90 ha; 18.04%). In contrast, Birch-Rhododendron Scrub occupied the smallest extent (57.37 ha; 0.04%). The dominance of coniferous forests in mid and higher elevations reflects the prevailing temperate climatic conditions and altitudinal zonation of vegetation in the Western Himalayas. Similar vegetation distribution patterns have been reported by Roy (1987), Bisht (2015), and Jain et al. (2021), who observed the predominance of chir pine and deodar forests in Himachal Pradesh under varying elevation regimes.

The observed forest distribution strongly influenced by topographic and climatic variability. Lower elevations were characterised by Northern Dry Mixed Deciduous Forests and Himalayan Subtropical Scrub, while Chir Pine Forests dominated warm subtropical slopes between 800 and 1800 m elevation. Mid-altitude zones supported Moist Deodar Forests, Ban Oak Forests, and Temperate Secondary Scrub, whereas Western Mixed Coniferous Forests, Kharsu Oak Forests, and alpine vegetation characterised higher elevations (>2500 m). Such ecological zonation is consistent with the findings of Singh et al. (2023), who demonstrated that Himalayan forest composition and spectral behaviour in Sentinel-2 imagery is strongly influenced by seasonal vegetation dynamics and altitudinal gradients.

The high spatial resolution and multispectral capability of Sentinel-2B proved highly effective in separating major forest classes with distinct canopy structures and phenological characteristics. Similar observations were

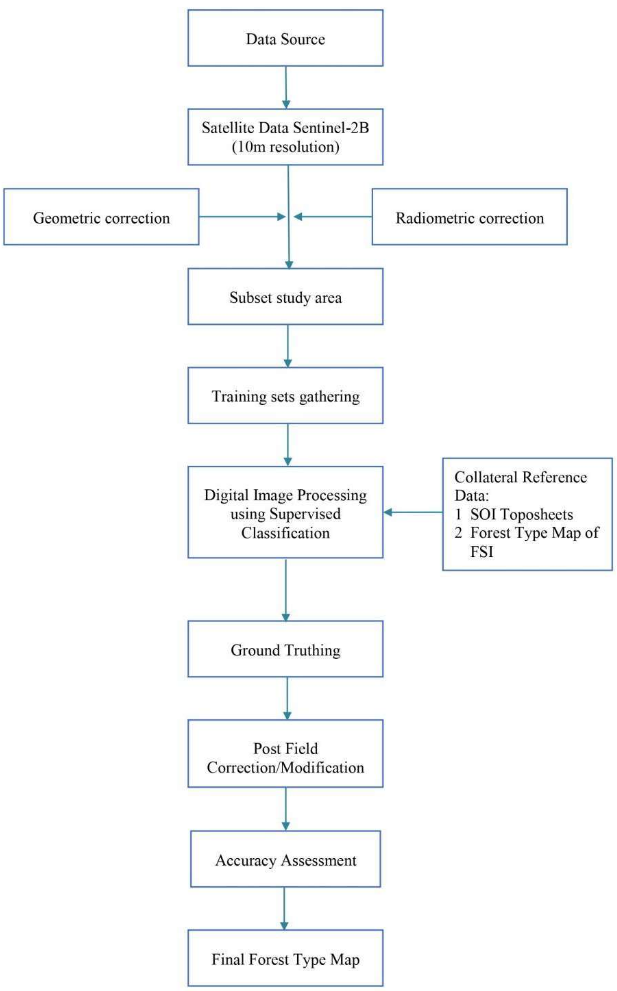

Figure 5. Methodological flow chart illustrating the sequence of steps followed for forest type mapping in Mandi district, Himachal Pradesh

Table 2. Area under different forest types of Mandi district

Forest type classes	Area (ha)	Area (%)
12/C1c Moist Deodar Forest	38752.50	24.17
9/C a&bChir Pine Forest	33834.00	21.10
12/C1d Western Mixed Coniferous Forest	28925.90	18.04
12/C1f Blue Pine Forest	8483.39	5.29
12/C1a Ban Oak Forest	17931.80	11.19
12/C1b Mohru Oak Forest	1062.81	0.66
5B/C2 Northern Dry Mixed Deciduous Forest	5984.50	3.73
12/C2a Kharsu Oak Forest	842.22	0.53
12/Ci/Ds2 Himalayan Temperate Secondary Scrub	6303.38	3.93
9Ci/DS1 Himalayan Subtropical Scrub	4482.73	2.80
12/C1/DS1 Oak Scrub	12316.96	7.68
15/C1 Birch-Rhododendron Scrub	57.37	0.04
12/DS3 Alpine Pastures	1341.55	0.84
Total	**160319.11**	**100**

reported by Immitzer et al. (2016) and Waser et al. (2019), who highlighted the superiority of Sentinel-2 data for tree species discrimination and forest diversity mapping. Furthermore, Vanguri, Laneve, and Hościło (2024) demonstrated that combining Sentinel-2 temporal features with the advanced spectral datasets could improve the discrimination of tree species and biodiversity in heterogeneous forests. Since this study was primarily conducted using Sentinel-2B multispectral bands and not hyperspectral datasets, the classification performance achieved indicates substantial potential for district-level ecological mapping in Himalayan terrain.

3.2. Accuracy Assessment

The classification accuracy assessment as given in Tables 3 and 4 yielded an overall accuracy of 84.67% with a Kappa coefficient (κ) of 0.83, indicating strong agreement between classified outputs and ground reference data. Producer's accuracy ranged from 71.43% for Birch-Rhododendron Scrub to 100% for Alpine Pastures and Non-Forest classes, while user's accuracy ranged from 72.73% for Blue Pine Forest to 100% for Mohru Oak Forest and Birch-Rhododendron Scrub. High classification accuracies obtained for Moist Deodar Forests, Chir Pine Forests, and Western Mixed Coniferous Forests is mainly due to their

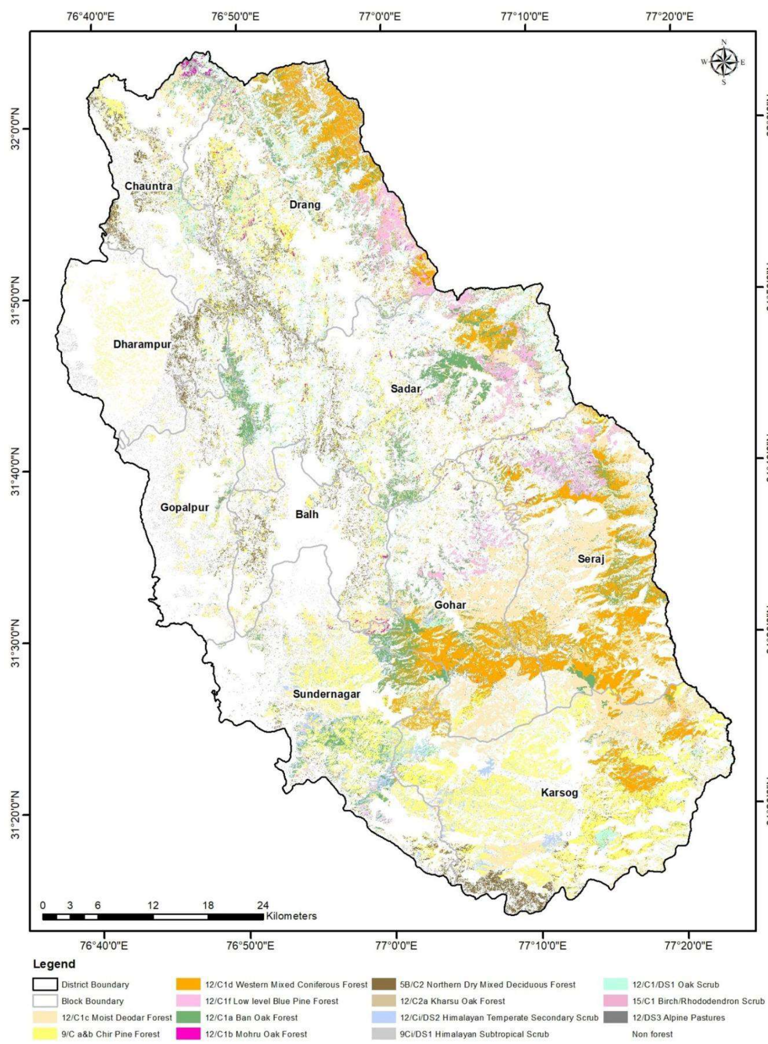

Figure 6. Forest Type map of Mandi District, Himachal Pradesh prepared using Sentinel-2B multispectral imagery and supervised classification. The figure depicts the spatial distribution of major forest types across the district

Table 3. Error matrix for the forest type classification

Classified data	Reference data														
	MDF	CPF	BPF	WMCF	HTSS	NDDF	BOF	HSS	KOF	AP	B/R-S	MOF	OS	NF	Classified total
MDF	16	1	0	0	0	0	0	0	0	0	0	0	0	0	17
CPF	1	17	1	0	0	0	0	0	0	0	0	0	0	0	19
BPF	0	1	8	1	1	0	0	0	0	0	0	0	0	0	11
WMCF	1	0	1	12	0	0	0	0	0	0	0	0	0	0	14
HTSS	0	0	0	0	8	0	0	1	0	0	0	0	1	0	10
NDDF	0	1	0	0	0	9	1	0	0	0	0	0	0	0	11
BOF	0	0	0	0	0	1	9	0	1	0	0	0	1	0	12
HSS	0	0	0	0	1	0	1	6	0	0	0	0	0	0	8
KOF	0	0	0	1	0	0	0	0	5	0	0	0	0	0	6
AP	0	1	0	0	0	0	0	0	0	6	1	0	0	0	8
B/R-S	0	0	0	0	0	0	0	0	0	0	5	0	0	0	5
MOF	0	0	0	0	0	0	0	0	0	0	0	6	0	0	6
OS	0	0	0	0	0	0	0	0	0	0	1	1	9	0	11
NF	0	1	0	0	0	0	0	0	0	0	0	0	0	11	12
Reference total	18	22	10	14	10	10	11	7	6	6	7	7	11	11	150

Overall Classification Accuracy= 84.67 %, Khat= 0.833
Abbreviations: MDF = Moist Deodar Forest; CPF = Chir Pine Forest; BPF = Blue Pine Forest; WMCF = Western Mixed Coniferous Forest; HTSS = Himalayan Temperate Secondary Scrub; NDDF = Northern Dry Mixed Deciduous Forest; BOF = Ban Oak Forest; HSS = Himalayan Subtropical Scrub Forest; KOF = Kharsu Oak Forest; AP = Alpine Pastures; B/R-S = Birch/Rhododendron Scrub; MOF = Mohru Oak Forest; OS = Oak Scrub; NF = Non-Forest

Table 4. Detailed accuracy statistics of image classification

Class name	Reference totals	Classified totals	Number correct	Producers accuracy %	Users accuracy %
Moist Deodar Forest	18	17	16	88.89	94.12
Chir Pine Forest	22	19	17	77.27	89.47
Blue Pine Forest	10	11	8	80.00	72.73
Western Mixed Coniferous Forest	14	14	12	85.71	85.71
Himalayan Temperate Secondary Scrub	10	10	8	80.00	80.00
Northern Dry Mixed Deciduous Forest	10	11	9	90.00	81.82
Ban Oak Forest	11	12	9	81.82	75.00
Himalayan Subtropical Scrub	7	8	6	85.71	75.00
Kharsu Oak Forest	6	6	5	83.33	83.33
Alpine Pastures	6	8	6	100.00	75.00
Birch-Rhododendron Scrub	8	5	5	71.43	100.00
Mohru Oak Forest	7	6	6	85.71	100.00
Oak Scrub Forest	10	11	9	81.82	81.82
Non Forest	11	12	11	100.00	91.67
Total	150	150	127		

relatively distinct spectral signatures and homogeneous canopy structures. In contrast, comparatively lower accuracies for Blue Pine and scrub categories may be attributed to spectral mixing, fragmented patches, shadow effects, and overlapping phenological characteristics in rugged terrain.

The overall classification accuracy obtained in this study is comparable with earlier Himalayan forest mapping studies. Jain et al. (2021) achieved similar accuracies using Sentinel-2 imagery for vegetation classification in the Indian Himalayas, while Srivastava et al. (2022) reported that in complex mountainous environments there is strong performance of machine learning approaches for Sentinel-based land use and vegetation mapping. Likewise, Vanguri et al. (2024) reported improved forest biodiversity mapping accuracy by using Sentinel-2 temporal datasets supported with hyperspectral information. These comparisons signifies that Sentinel-2 imagery remains a highly reliable and cost-effective dataset for ecological and forest type mapping in data-scarce Himalayan regions. Although minor differences were observed when compared with the Forest Survey of India (FSI) vegetation maps, these variations primarily resulted from differences in spatial resolution, image acquisition period, mapping scale, and classification methodology. The use of 10 m Sentinel-2 imagery enabled improved delineation of fragmented forest patches and finer discrimination of forest types compared with conventional vegetation maps. Furthermore, temporal differences between the datasets may reflect natural vegetation succession, anthropogenic disturbances, and ongoing forest management activities. Despite these limitations, the spatial distribution and composition of the major forest types were in good agreement with the regional vegetation characteristics reported by the Forest Survey of India, supporting the reliability of the forest-type map produced in this study.Ecologically, the predominance of deodar, oak, and mixed conifer forests highlights their significance in maintaining biodiversity, slope stability, watershed protection, and carbon sequestration in the Western Himalayas. Oak forests, despite occupying comparatively smaller areas, are particularly important for water conservation and ecosystem resilience. The occurrence of degraded scrub vegetation near human settlements suggests the influence of grazing, fuelwood extraction, forest fires, and land-use change on forest condition. These observations highlight the importance of sustainable forest management and ecological restoration in vulnerable Himalayan landscapes.

4. CONCLUSION

In this study, the forest types of the Mandi district of Himachal Pradesh were mapped and classified using the Sentinel-2B multispectral satellite imagery using a supervised classification method. This resulted in the identification of thirteen major forest types with an overall classification accuracy of 84.67% and Kappa coefficient of agreement 0.83. The major forest types were Moist Deodar Forest, Chir Pine Forest and Western Mixed Coniferous Forest, while minor vegetation types included alpine and scrub vegetation. These results indicate that the Sentinel-2B image can be satisfactorily used for forest-type mapping in the complex and diverse mountainous region of the north-western Himalaya.

The distribution of these different types of forest in the district was largely a function of altitude and climate. The majority of subtropical and deciduous forests occurred at lower altitudes, with temperate coniferous and oak forests occupying higher altitudes in the district. This distribution is consistent with the elements of ecosystem ecology in the Himalayas where precipitation and topography are the major driving forces for the distribution of forest types. The forest-type map may be used in the updating of forest inventories and ecological monitoring, as well as biomass and carbon stock estimation, and biodiversity and watershed management. In addition, satellite imagery, ground observation and GIS have been used to map forest resources in mountainous regions where it is harder to undertake large scale field surveys.

The predominance of coniferous and oak forests highlights their crucial role in carbon storage, water regulation, and biodiversity conservation in the region. In contrast, the presence of degraded scrub vegetation near human settlements shows the effects of grazing, lopping, and other human-induced disturbances on forest ecosystems. These observations emphasise the need of regular ecological monitoring and appropriate management practices for the long-term conservation and sustainable management of forest ecosystems in the region.

The accuracy of forest type mapping can be improved by utilizing multi-season Sentinel-2 imagery, along with hyperspectral and LiDAR datasets, by employing machine learning classifiers such as Random Forest and Support Vector Machines classifiers (SVM). This would further improve mapping accuracy and provide better understanding of the composition and distribution of Himalayan forests.

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CRediT authorship contribution statement

Manoj Thakur: Conceptualization, methodology design, data acquisition, analysis, interpretation of results, and manuscript preparation.**Krishan Thakur:** Assisted in data processing, GIS analysis, data validation, and critical manuscript revision.

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Conflict of interests

The authors declare that they have no competing financial or non-financial interests that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used generative AI and AI-assisted technologies for language refinement, grammar correction, formatting support, and improvement of academic presentation. The authors carefully reviewed and edited the content and take full responsibility for the accuracy, originality, and integrity of the manuscript. No AI tool was used for data generation, analysis, interpretation of results, or drawing scientific conclusions.

Data availability statement

The data used in this study were derived from Sentinel-2B satellite imagery, field observations, and secondary sources obtained from publicly accessible databases and government records. Processed datasets generated during the current study are available from the corresponding author upon reasonable request.

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