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Wildfire Burn Severity Assessment In Uttarakhand During 2024

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Abstract:

During the 2024 fire season, the Himalayan state of Uttarakhand experienced widespread wildfire activity, particularly across the districts of Nainital, Champawat, and Udham Singh Nagar. These events caused substantial ecological disturbance within a region characterized by fragile mountain ecosystems and fire-prone forest types. This study presents a satellite-based assessment of wildfire burn severity using multi-temporal Landsat-8/9 and Sentinel-2 surface reflectance imagery. Burn severity was evaluated using the Normalized Burn Ratio (NBR) and its differenced form (dNBR), derived from pre-fire and post-fire observations. Changes in Near-Infrared (NIR) and Shortwave Infrared (SWIR) reflectance were analysed to identify relative variations in fire impact across the landscape. The resulting burn-severity map delineates zones of high, moderate, and low fire impact, providing spatially explicit information for post-fire restoration planning, erosion control, and long-term wildfire risk management in the Himalayan region.

Keywords: Burn Severity; dNBR; Forest Fire; Remote Sensing; Landsat-8/9; Sentinel-2; Uttarakhand.

Introduction:

Wildfires are a recurring environmental hazard in the Himalayan state of Uttarakhand, where complex terrain, seasonally dry climatic conditions, and the accumulation of combustible forest litter create a highly fire-prone landscape. During the 2024 fire season, extensive wildfire activity was reported across several districts, with notable impacts in Nainital, Champawat, and Udham Singh Nagar. Prolonged dry spells and elevated pre-monsoon temperatures have been widely reported as contributing factors to increased fuel dryness in the region.

Previous studies have highlighted that wildfire occurrence in Uttarakhand is influenced by the combined effects of climatic stressors and anthropogenic pressures, including land-use practices and forest-floor fuel accumulation. The impacts of these fires extend beyond immediate vegetation loss, contributing to biodiversity decline, soil erosion, atmospheric pollution, and long-term degradation of ecosystem services. Given that a substantial proportion of India's forest cover is considered fire-prone, there is a critical need for spatially explicit and data-driven assessments of wildfire impacts to support informed forest-management and mitigation strategies.

Remote sensing provides an effective and repeatable means of monitoring wildfire effects over large and topographically complex regions. Spectral indices such as the Normalized Burn Ratio (NBR) and differenced NBR (dNBR) are widely used to assess burn severity by capturing fire-induced changes in vegetation and surface reflectance. This study applies these established techniques to assess the spatial distribution of burn severity associated with the 2024 Uttarakhand wildfires, with the aim of supporting post-fire management and ecological restoration efforts.

Materials And Methods:

1. Study Area:

Uttarakhand is located in northern India within the Himalayan region, extending approximately between 28°43′–31°27′ N latitude and 77°34′–81°02′ E longitude. The state exhibits pronounced topographic variability, ranging from low-lying plains in the south to high-elevation mountainous terrain in the north. Elevation gradients, combined with diverse climatic regimes, support a wide range of forest types, including pine-dominated forests, oak forests, and mixed broadleaf vegetation.

Forests in Uttarakhand are particularly vulnerable to wildfire during the dry pre-monsoon months, when reduced soil moisture and accumulated forest litter increase fuel availability. Pine forests, which occupy extensive mid-elevation zones, are especially susceptible due to the presence of resin-rich needles that promote fire spread. These characteristics make Uttarakhand an appropriate region for evaluating wildfire burn severity using satellite-based approaches.

Methodology:

1. Methodology Chart:

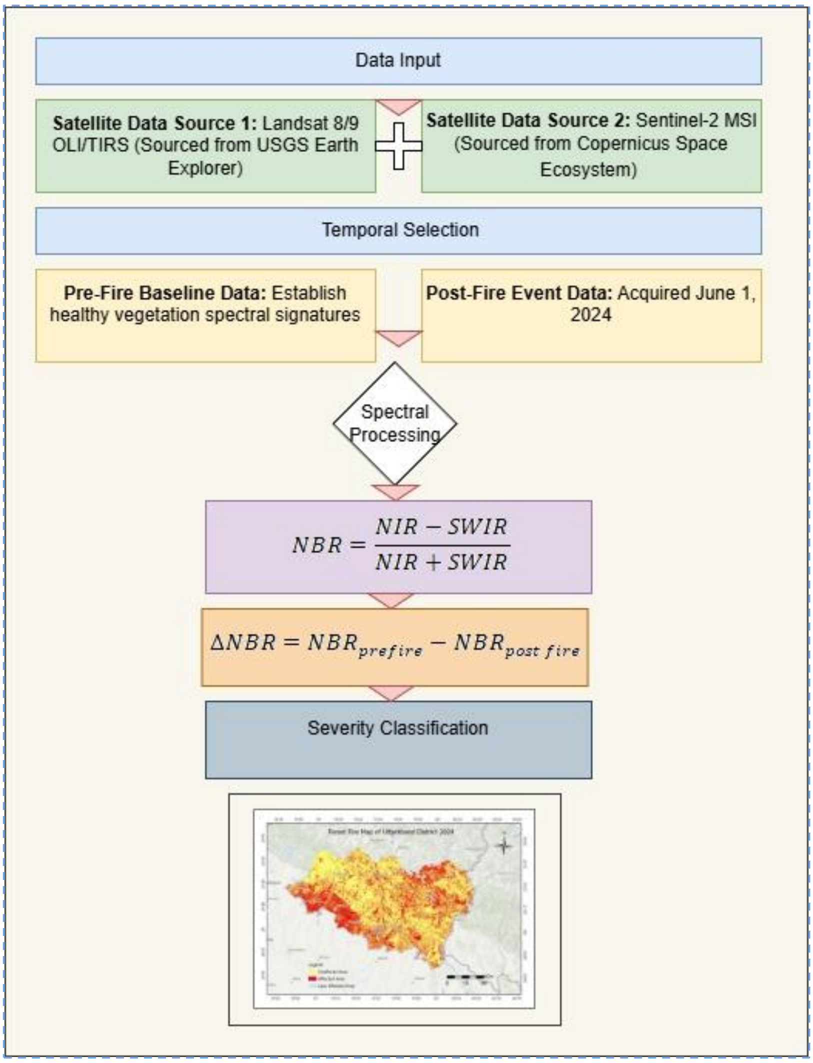

Figure 1:Methodology chart

2. Data Acquisition:

Multi-spectral satellite imagery from Landsat-8/9 Operational Land Imager (OLI) and Sentinel-2 Multispectral Instrument (MSI) was used in this study. Landsat Collection-2 Level-2 surface reflectance data with a spatial resolution of 30 m were obtained from the USGS Earth Explorer platform. Sentinel-2 Level-2A imagery, providing surface reflectance data at 10–20 m spatial resolution, was accessed through the Copernicus Open Access Hub.

Pre-fire imagery representing baseline vegetation conditions was selected from March–April 2024, while post-fire imagery was acquired from early June 2024, corresponding to the period immediately following the major wildfire events.

3. Pre-Processing:

Only surface reflectance products were used to ensure radiometric consistency and to minimize the influence of atmospheric effects. Landsat Collection-2 Level-2 data and Sentinel-2 Level-2A products (atmospherically corrected using the Sen2Cor algorithm) were employed. Cloud-affected pixels were excluded using quality assessment masks prior to index calculation.

4. Normalized Burn Ratio (NBR):

The assessment relies on the Normalized Burn Ratio (NBR), a spectral index specifically designed to highlight burned areas while reducing the influence of atmospheric and illumination effects. The NBR exploits the contrasting spectral behavior of vegetation in the Near-Infrared (NIR) and Shortwave Infrared (SWIR) regions. Healthy vegetation exhibits high reflectance in the NIR region, whereas burned surfaces and bare soil show increased reflectance in the SWIR region due to moisture loss and structural damage.

For Landsat-8 and Landsat-9 Operational Land Imager (OLI) data, NBR was computed using Band 5 (Near-Infrared) and Band 7 (Shortwave Infrared). For Sentinel-2 Multispectral Instrument (MSI) imagery, Band 8 (Near-Infrared) and Band 12 (Shortwave Infrared) were employed. These band combinations are widely adopted in burn-severity assessments due to their sensitivity to fire-induced changes in vegetation structure and surface moisture.

The mathematical expression for NBR is defined as

$$NBR = \frac{NIR - SWIR}{NIR + SWIR}$$

5. Differenced Normalized Burn Ratio (dNBR):

To quantify the change caused by the 2024 fire event, a differenced NBR (dNBR) approach was employed. This process involves the following sequential steps:

1. Baseline Selection: Collection and processing of pre-fire satellite data to establish a healthy vegetation baseline.
2. Post-Event Analysis: Acquisition of post-fire data, specifically targeting the period following the June 1, 2024, incidents.
3. Differencing: The post-fire NBR is subtracted from the pre-fire NBR to generate the dNBR layer, expressed as:

$$dNBR = NBR_{prefire} - NBR_{post\ fire}$$

The resulting dNBR values are then categorized into severity classes—high, moderate, and low—based on the magnitude of the spectral shift, allowing for a precise spatial visualization of the fire's intensity across the landscape.

6. Burn Severity Interpretation:

In this study, burn-severity classes were interpreted qualitatively based on the relative magnitude and spatial contrast of dNBR values across the study area. Areas exhibiting comparatively higher dNBR values were interpreted as high burn severity, while intermediate and lower values represented moderate and low burn severity, respectively.

This relative approach allows for spatial comparison of fire impact without relying on fixed numerical thresholds.

Results And Discussion:

The results of the burn severity analysis provide a comprehensive spatial assessment of the ecological impact following the forest fires in Uttarakhand as of June 1, 2024. The analysis reveals an uneven distribution of fire intensity across the landscape, shaped by a complex interplay of vegetation type, fuel load, and meteorological conditions. High burn severity zones are primarily concentrated within forested regions characterized by dense fuel loads, particularly in mid-elevation pine-dominated landscapes. Moderate burn severity areas are generally distributed around these core zones, indicating partial vegetation damage with potential for natural regeneration. Low burn severity and minimally affected areas are mainly associated with regions of sparse vegetation and reduced fuel continuity.

The observed spatial patterns are consistent with findings from previous wildfire studies in Himalayan environments, where vegetation type, fuel accumulation, and seasonal climatic conditions strongly influence fire behaviour. The burn-severity maps generated in this study provide essential spatial information for prioritizing post-fire interventions, including reforestation, erosion-control measures, and long-term ecological monitoring.

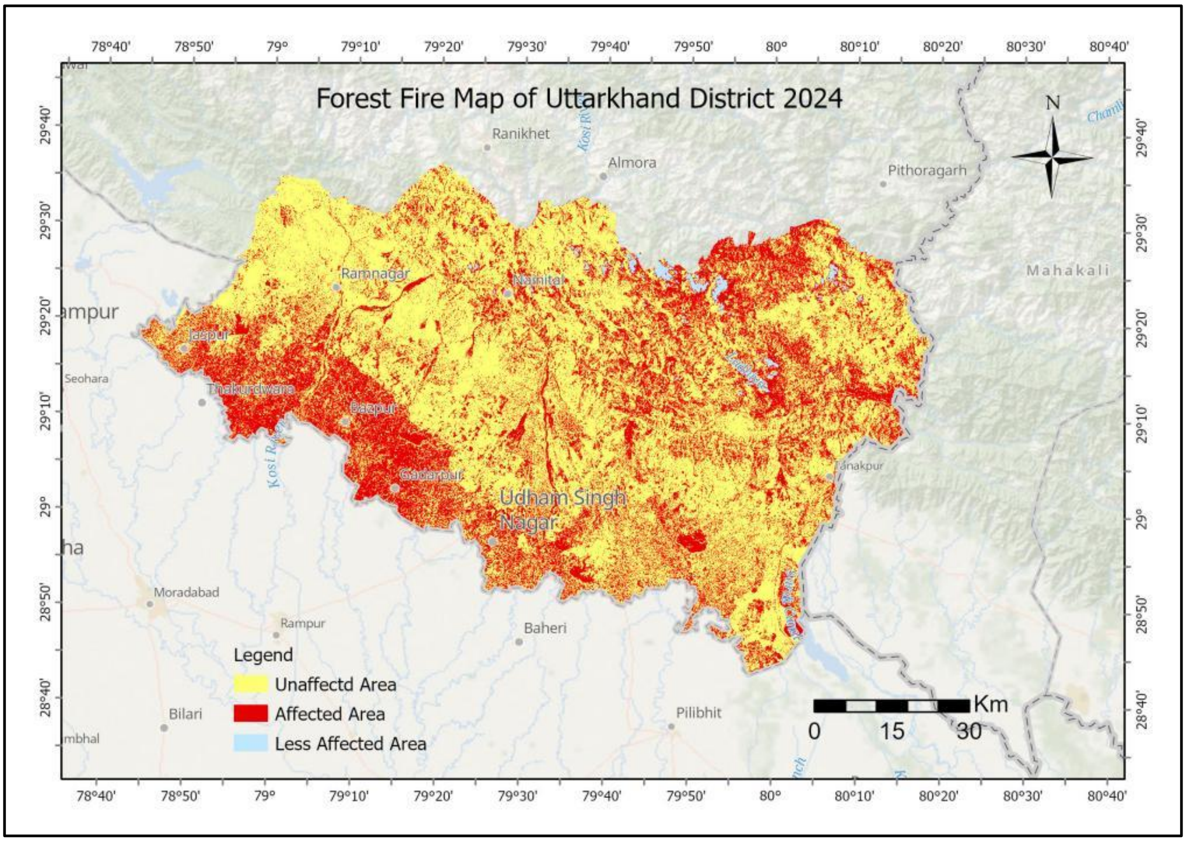

Figure 2:Forest fire map of Uttarakhand 2024

Conclusions And Recommendations:

This study demonstrates the effectiveness of multi-temporal Landsat-8/9 and Sentinel-2 imagery combined with NBR and dNBR indices for assessing wildfire burn severity in the complex Himalayan terrain of Uttarakhand. The results highlight significant spatial variability in burn severity associated with the 2024 wildfire events, underscoring the vulnerability of fire-prone forest types within the region.

The findings support the use of satellite-derived burn-severity products as a decision-support tool for post-fire management and ecological restoration planning. Future research should incorporate field-based validation, multi-year fire records, and ancillary environmental datasets to enhance understanding of wildfire drivers and to strengthen early warning and mitigation strategies in Himalayan Forest ecosystems.

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