A Spatiotemporal Evaluation Framework for MODIS-Derived Fire Events

Bahareh Kalantar [1], Naonori Ueda [1], Husam Al-Najjar [2]

[1] RIKEN Center for Advanced Intelligence Project, Tokyo, Japan- bahareh.kalantar@riken.jp; naonori.ueda@riken.jp
[2] School of Computer Science, Faculty of Engineering and IT, University of Technology Sydney, Sydney, NSW, Australia-Husam.Al-Najjar@uts.edu.au

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Abstract

The MODIS burned area product is widely used to extract ignition locations and delineate individual fires for wildfire probabilistic loss modeling. However, limited studies have systematically evaluated the accuracy of these derived fire events through detailed spatial and temporal comparisons with reference datasets. This study addresses this gap by developing a robust framework to assess the accuracy of MODIS-derived individual fires across the United States. In this study, the MODIS Collection 6 MCD64 burned area product was used to extract ignition locations and individual fire events using the Fire Events Delineation (FIRED) algorithm. A comprehensive evaluation framework was then implemented to assess the delineated fire events against the Monitoring Trends in Burn Severity (MTBS) reference dataset, accounting for both spatial overlap and temporal consistency. The results show that the proposed approach achieved an average Intersection over Union (IoU) score of 0.54, an F-score of 0.701, an overall accuracy of 0.77, precision of 0.90, and recall of 0.57. These metrics represent averages across the period 2001–2020. Collectively, the results highlight the strengths and limitations of the event detection system and provide a quantitative assessment of its performance. This comprehensive evaluation offers valuable insights into the reliability of MODIS-derived individual fire events and improves understanding of their suitability for wildfire probabilistic loss modeling and related applications.

1. Introduction

Over the past two decades, the Moderate Resolution Imaging Spectroradiometer (MODIS) burned area product has played a pivotal role in identifying wildfire ignition locations and delineating individual fire events (Giglio et al., 2016). The latest version of this dataset is generated using an upgraded burned area mapping algorithm based on Collection 6 surface reflectance data, which significantly reduces the number of unclassified grid cells. The product maps the spatial extent and approximate timing of biomass burning worldwide at a spatial resolution of 500 m and has been widely used across a broad range of wildfire and ecological studies (Moreno et al., 2014; Ramo & Chuvieco, 2017; Santana et al., 2020; Prosperi et al., 2020; Katagis & Gitas, 2022).

Several studies have leveraged MODIS burned area products to extract individual fire events and analyze fire dynamics. For example, Frantz et al. (2016) introduced a multilevel object-based methodology to extract ignition points and characterize fire dynamics from MODIS burned area data (MCD64). Their study, conducted in sub-Saharan Africa, provided detailed insights into fire behavior and spatial patterns. Andela et al. (2018) further advanced this field by developing the Global Fire Atlas, which tracks individual fire characteristics such as size, duration, spread speed, and direction using daily 500 m MODIS Collection 6 MCD64A1 burned area data for the period 2003–2016. Similarly, Laurent et al. (2018) developed FRY, a comprehensive global database of fire patches constructed using morphology-based functional traits derived from MODIS MCD64A1 Collection 6 and MERIS burned area imagery through a flood-fill algorithm. More recently, Balch et al. (2020) introduced the Fire Events Delineation (FIRED) algorithm, which extracts individual fire events from the MODIS MCD64 burned area product across the conterminous United States (CONUS) from January 2001 to May 2019, providing a detailed dataset for analyzing fire dynamics in this region.

Despite the growing use of MODIS burned area products for identifying individual fires, relatively few studies have systematically evaluated the accuracy of these derived fire events. Such evaluations must consider both the spatial and temporal dimensions inherent in individual fire events. Balch et al. (2020) conducted a comparative analysis between FIRED-derived fire events and the Monitoring Trends in Burn Severity (MTBS) dataset for events detected by both products. Their analysis first evaluated the relationship between burned areas derived from FIRED and those reported by MTBS using a linear regression model, where FIRED-derived burned area served as the predictor for MTBS-reported burned area. To further investigate how this relationship varied across fire sizes, the authors divided the fire events into 50 equal size classes and developed separate regression models for each class. Their results demonstrated a strong relationship between FIRED and MTBS burned area estimates, with a correlation coefficient of $R^2 = 0.92$.

Similarly, Andela et al. (2018) compared fire perimeters derived from the Global Fire Atlas with those reported by the MTBS project for the overlapping period of 2003–2015. The analysis involved matching fire perimeters from both datasets and prioritizing the largest overlapping area when multiple perimeters intersected. The study also evaluated the temporal accuracy of the Global Fire Atlas by comparing its fire duration estimates with those derived from MTBS fire perimeters and VIIRS active fire detections. The results indicated moderate correlations (R^2 ranging from 0.3 to 0.5) between the Global Fire Atlas estimates and the reference datasets.

Despite the widespread use of MODIS burned area products to derive individual fire events, comprehensive evaluations of their accuracy that jointly consider spatial and temporal agreement with reference datasets remain limited. To address this gap, this study develops a framework to evaluate the accuracy of MODIS-derived individual fire events in the United States. Ignition locations and fire events are extracted from the MODIS Collection 6 MCD64 burned area product using the FIRED

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algorithm. The derived fire events are then compared with reference fire perimeters using multiple evaluation metrics, including Intersection over Union (IoU), F-score, precision, recall, and overall accuracy. This evaluation provides insights into the reliability of MODIS-derived fire events for wildfire probabilistic loss modeling and related applications.

2. Methodology

Figure 1 illustrates the workflow of the present study. First, individual fire events are derived from the MODIS burned area product for the period 2001–2020. Next, the MTBS perimeter reference data are rasterized onto the 500 m MODIS sinusoidal grid, ensuring alignment with the MODIS spatial framework. Subsequently, a novel evaluation approach is applied to compare the two datasets and quantify the accuracy of the derived fire events.

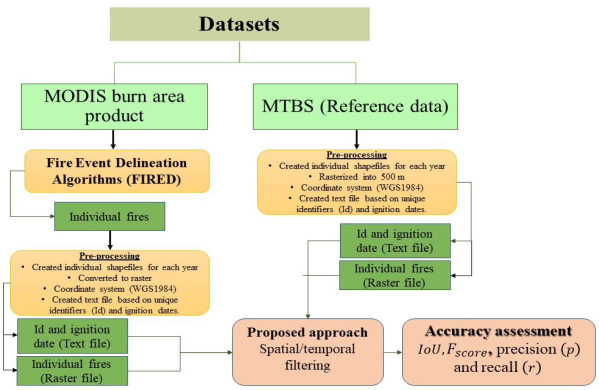

Figure 1. The flowchart of the present study.

2.1 Individual fires

In the first phase of the analysis, the primary objective was to identify wildfire ignition locations and track the development of individual fire events. To achieve this, we utilized the MODIS Collection 6 MCD64 burned area product (Giglio et al., 2016). This dataset contains five layers at a spatial resolution of 500 m, including burn date, first day, last day, quality assessment, and uncertainty information.

The dataset provides global coverage in a sinusoidal projection and is organized into 648 tiles (of which 268 correspond to land areas), each consisting of 2400 rows and columns at an approximate spatial resolution of 463 m. Each tile represents an area of approximately 1200 km × 1200 km (10° × 10° at the equator) (Wolfe and Roy, 1998). For this study, the complete monthly time series for all tiles intersecting the contiguous United States (CONUS) was acquired and processed (Figure 2), with a focus on extracting the burn date layer for the period 2001–2022.

In terms of methodology, we adopted the FIRED algorithm as described by Balch et al. (2020). The optimization of spatial and temporal parameters for clustering burned area pixels into fire events involved the use of an 11-day temporal window and a spatial distance of one pixel. This algorithm was selected due to its open-source nature and flexibility, which allow users to modify spatiotemporal thresholds. The FIRED framework can directly download, process, delineate fire events, and compute summary statistics, typically completing the workflow for the entire conterminous United States (CONUS) in approximately 30 minutes on a standard laptop.

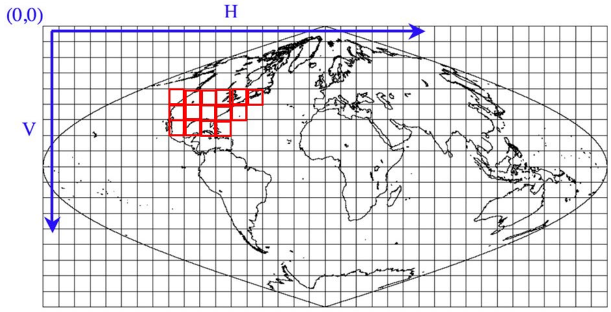

Figure 2. Tiles overlapping with Contiguous United States (CONUS) are highlighted with red.

To identify fire events, the algorithm employs a three-dimensional moving window approach (x, y, and t) to group burned pixels into distinct events. It requires two input parameters: a spatial parameter representing the number of pixels used to define spatial proximity and a temporal parameter specifying the number of days over which burn detections are aggregated. During this process, each burned pixel is assigned an event identification number corresponding to the fire event to which it belongs.

The data processing script, available at https://github.com/earthlab/firedpy, retrieves the complete series of HDF files from the University of Maryland FTP server, extracts the burn date information from each monthly tile, and integrates them into a three-dimensional NetCDF (Network Common Data Form) data structure. The NetCDF format provides a widely recognized and efficient framework for storing and processing spatiotemporal datasets.

The event perimeter script then reads the NetCDF file for each tile (Table 1), where each band represents one month, and records the fire detection date for each burned pixel as the number of days since January 1, 1970. The NetCDF file is subsequently converted into a three-dimensional array, and the moving window algorithm systematically traverses this array to identify and aggregate burned pixels into individual fire events.

Coterminous US	
h08v04	h10v06
h08v05	h11v04
h08v06	h11v05
h09v04	h11v06
h09v05	h12v04
h09v06	h12v05
h10v04	h13v04
h10v05	

Table 1. Tile numbers covering CONUS (h indicate a horizontal orientation and v represent a vertical orientation).

For each cell within the three-dimensional array where at least one fire detection occurs, the program generates a mask that identifies all burned pixels within the corresponding spatiotemporal neighborhood. If the current cell belongs to an existing event, any newly detected burned pixels are assigned the event ID associated with that event. If the cell represents the initiation of a new event, the current cell and all overlapping cells are assigned the next sequential event ID. In cases where multiple event IDs are present within the mask, this indicates that two fire perimeters have merged; these events are subsequently consolidated under the earliest assigned event ID.

Once the event perimeters are delineated within each tile, events that potentially overlap with adjacent tiles are flagged. After all tiles have been processed, the flagged events are segmented, and those exhibiting spatiotemporal overlap are merged. Finally, events across all tiles are combined into a single dataset and assigned new sequential event IDs. Figure 3 presents a simplified flowchart of the FIRED algorithm, illustrating the workflow from HDF data acquisition to the aggregation of burned pixels into individual fire events.

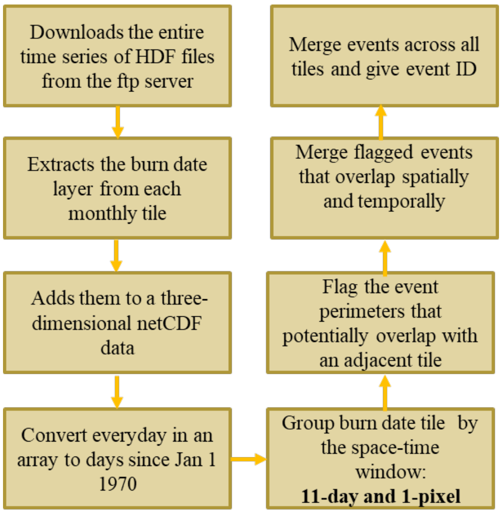

Figure 3. Flowchart of Fire Events Delineation (FIRED) algorithm (Balch et al., 2020).

2.2 Reference data

MTBS is a manually generated dataset derived from Landsat imagery and forms part of an interagency initiative aimed at consistently mapping the severity and extent of large fires in the United States from 1984 to the present day. This mapping effort encompasses wildfires exceeding 1000 acres in the western United States and those surpassing 500 acres in the eastern United States. The geographic coverage extends to include the entire continental U.S., along with Alaska, Hawaii, and Puerto Rico. To access the data, it can be downloaded from the following link: https://www.mtbs.gov/direct-download. Figure 4b illustrates the MODIS burn are product, where each pixel represents a day of burn. Additionally, the figure presents a comparison of individual fires detected using the FIRED algorithm (Figure 4b) with the reference data (Figure 4c).

2.3 Proposed method

This section describes the methodology developed to evaluate MODIS-derived fire events against the MTBS dataset. Prior to applying the proposed approach, a preliminary processing stage was performed. This included converting the MTBS shapefile into a raster format with a consistent spatial resolution of 500 m and a common coordinate system namely WGS 84. In addition, unique identifiers (IDs) and ignition dates were generated for events in both datasets.

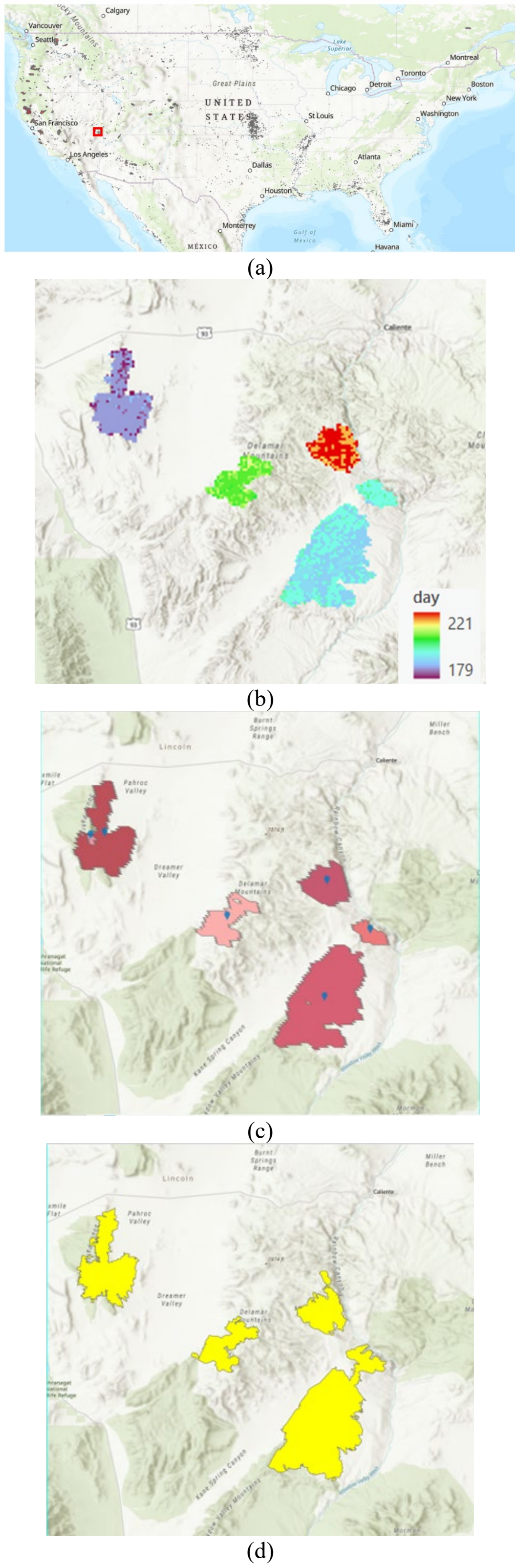

Figure 4. (a) The United States (red square denotes the selected area), (b) MODIS burn area product of 2020. (c) MODIS-Derived events using FIRED algorithm 2020, California State, (d) MTBS 2020.

The evaluation framework incorporates both spatial and temporal criteria to assess the accuracy of MODIS-derived fire event detections relative to the manually interpreted MTBS product (Figure 5). The core of the evaluation process involves iterating through each event ID from the MTBS dataset. For each event, the following steps are performed:

2.3.1 Spatial Filtering

The spatial filtering process begins by identifying regions of interest (ROIs) within the reference dataset (MTBS). The proposed approach uses the event ID information to extract these regions. Specifically, the method iterates through each ID and locates all corresponding occurrences within the reference data. Once identified, the minimum and maximum indices (Min and Max) that define the spatial boundaries of each ROI are determined. The ROIs are then extracted from the reference dataset and isolated for further analysis. A filtering operation is applied to emphasize the identified regions by assigning a value of 1 to matching elements and 0 to non-matching elements. This step highlights the relevant spatial areas within the reference data.

The procedure is subsequently extended to the segmented fire events dataset. Using the same minimum and maximum indices (Min and Max) derived from the reference data, the corresponding spatial region is extracted from the segmented fire events. A region of interest with the same spatial extent as the reference ROI is thus created for comparison. To facilitate the evaluation process, a tensor initialized with zeros and having the same dimensions as the ROI is generated. Unique labels within the ROI are then identified for further analysis. The method iterates through each unique label, excluding label 0, and applies temporal conditions to evaluate the segmented fire events associated with each label.

2.3.2 Temporal Filtering

Temporal filtering is applied to the MODIS-derived fire events within the same geographic region. The objective is to align the timing of MODIS-derived events with the corresponding reference events from the MTBS dataset. For each event label, the method evaluates whether the temporal conditions required for matching with the reference data are satisfied.

Specifically, the ignition time associated with each event ID in the MODIS-derived dataset is compared with the corresponding event time in the MTBS reference dataset. If the temporal condition is satisfied, defined as a time difference within a specified threshold of less than 17 days, accounting for the 16-day temporal resolution of Landsat observations, the corresponding pixels are assigned a value of 1, indicating a valid prediction for that event.

2.4 Accuracy assessment

Various classification metrics are calculated, including Intersection over Union (IoU), F-score, accuracy, precision, and recall for each class. These metrics provide insights into the model’s performance in detecting fire events while accounting for both spatial and temporal aspects. IoU is calculated as the ratio of the intersection between the segmented fire region and the reference region to the union of these regions. Mathematically, IoU is defined as shown in Equation (1).

$$IoU = \frac{Intersetion}{Union} \quad (1)$$

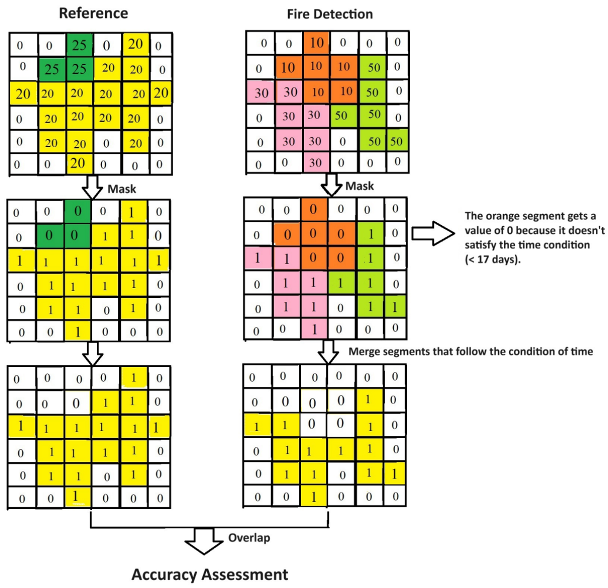

Figure 5. Workflow for evaluating MODIS-derived fire detection events against the MTBS reference dataset. The numbers shown in each grid cell represent the fire event IDs, indicating individual fire events identified in each dataset.

F_{score} is a metric that balances precision (p) and recall (r). Precision (p) refers to the ability of a model to correctly identify true positive cases among all predicted positive instances (Equation 2), while recall (r) measures the model’s ability to capture a substantial proportion of the actual positive instances (Equation 3). The F_{score} is particularly valuable when dealing with imbalanced datasets, as it provides a balanced measure that considers both precision (p) and recall (r). The F_{score} is defined in Equation (4).

$$p = \frac{True\ positives}{(True\ positives + False\ positives)} \quad (2)$$

$$r = \frac{True\ positives}{(True\ positives + False\ negatives)} \quad (3)$$

$$F_{score} = 2 \times \frac{p \times r}{p + r} \quad (4)$$

3. Results

The accuracy assessment results for individual years, presented in Table 2, provide a comprehensive overview of the performance of the proposed approach in evaluating MODIS-derived individual fire events against the MTBS reference dataset. The IoU values, which represent the spatial overlap between the derived and reference fire perimeters, range from 0.34 to 0.707 across the evaluated years. The IoU metric serves as a key indicator of the performance of the event detection system, reflecting the level of spatial agreement between the two datasets.

Examining the accuracy metrics, the proposed approach consistently demonstrates strong performance, with an average IoU value of 0.5468. This result indicates a substantial level of spatial agreement between the MODIS-derived individual fire events and the MTBS reference dataset. The F-score, overall accuracy, precision, and recall metrics further support the reliability of the event detection framework, with average values of 0.701, 0.77, 0.90, and 0.57, respectively. The results

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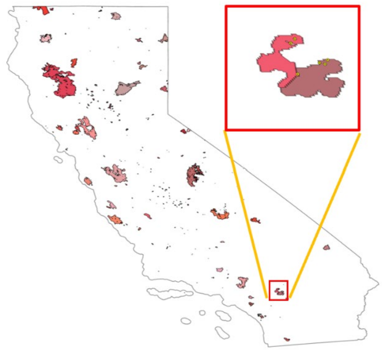
also reveal noticeable variations in accuracy across different years, highlighting potential temporal trends in the performance of MODIS-derived fire event detection. For example, 2012 and 2020 exhibit particularly high IoU values of 0.685 and 0.707, respectively, suggesting improved spatial correspondence between the datasets during these years. In contrast, 2009 shows comparatively lower accuracy metrics, indicating greater challenges in accurately identifying individual fire events during that period.

These findings underscore the importance of incorporating temporal considerations when evaluating the accuracy of MODIS-derived fire events, particularly with respect to the ignition date of fires. The high precision values indicate that the proposed approach effectively minimizes false positives, while the recall values demonstrate its capability to capture a substantial proportion of true fire events. Together, these metrics highlight the reliability of the proposed framework for wildfire event detection. Overall, the accuracy assessment provides valuable insights into the performance of MODIS-derived fire event datasets and supports their application in wildfire research, monitoring, and management.

Year	IOU	F1-score	Accuracy	Precision	Recall
2001	0.46	0.63	0.74	0.91	0.48
2002	0.65	0.79	0.805	0.935	0.68
2003	0.593	0.74	0.785	0.92	0.62
2004	0.46	0.63	0.73	0.90	0.48
2005	0.57	0.72	0.78	0.90	0.608
2006	0.593	0.74	0.83	0.93	0.619
2007	0.579	0.73	0.83	0.92	0.61
2008	0.513	0.67	0.74	0.92	0.53
2009	0.34	0.51	0.86	0.69	0.41
2010	0.425	0.597	0.71	0.93	0.437
2011	0.549	0.709	0.78	0.93	0.57
2012	0.685	0.81	0.83	0.955	0.708
2013	0.55	0.71	0.74	0.889	0.592
2014	0.52	0.68	0.73	0.896	0.55
2015	0.53	0.697	0.75	0.93	0.55
2016	0.526	0.689	0.74	0.9	0.55
2017	0.565	0.72	0.78	0.94	0.585
2018	0.642	0.78	0.81	0.93	0.67
2019	0.479	0.64	0.73	0.92	0.497
2020	0.707	0.828	0.85	0.94	0.73
Average	0.5468	0.701	0.77	0.90	0.57

Table 2. Accuracy assessment of MODIS-derived event against MTBS data.

Figure 6 illustrates MODIS-derived fire events in California for 2020 and their comparison with the MTBS reference dataset. The yellow points on the map represent the ignition locations of the detected fire events. Visual inspection indicates that a substantial proportion of individual fires are accurately identified by the MODIS-derived dataset. However, several smaller fires detected by MODIS are not present in the MTBS dataset. This discrepancy is primarily due to the inclusion criteria of MTBS, which typically records wildfires larger than 1000 acres in the western United States and those exceeding 500 acres in the eastern United States.



(a)

(b)

Figure 6. (a) MODIS-Derived events 2020, California State, (b) MTBS 2020, California State.

4. Conclusion

In conclusion, the proposed method enables a robust evaluation of burn area predictions by considering both spatial correspondence and temporal alignment with the reference dataset. The framework provides valuable insights into the accuracy of MODIS-derived fire event detections within a spatiotemporal context, thereby improving our understanding of the model's performance in real-world applications. In practical terms, the findings of this study provide a foundation for refining and optimizing wildfire monitoring systems, contributing to more effective monitoring and response to wildfire events with greater precision and reliability.

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