PROTEGE: A Near Real-Time Geospatial Information System for Wildfire Detection and Response in the Brazilian Amazon

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Abstract. *In 2024, fire-driven degradation in the Brazilian Amazon reached its worst level in two decades, yet Brazilian state agencies still depend on data portals that do not route alerts to operational jurisdictions. This paper presents PROTEGE, a geospatial information system that automates active-fire ingestion, PostGIS spatial intersection, and jurisdiction-based notification of fire brigade personnel. It ingests data from three VIIRS-equipped satellites via NASA FIRMS and sends geolocated email and WhatsApp alerts with maps and personalized routes. In 2025, PROTEGE processed 180,326 hotspots with 2.9 s median processing time and 99.3% pipeline success; from September to December, it produced 9,609 spatial intersections and delivered 7,096 alerts to Military Fire Brigade personnel.*

Resumo. *Em 2024, a degradação por fogo na Amazônia brasileira atingiu o pior nível em duas décadas, mas órgãos estaduais ainda dependem de portais de dados que não roteiam alertas por jurisdições operacionais. Este artigo apresenta o PROTEGE, um sistema de informação geoespacial que automatiza ingestão de focos ativos, interseção espacial em PostGIS e notificação jurisdicional ao Corpo de Bombeiros. O sistema integra dados de três satélites VIIRS via NASA FIRMS e envia alertas por email e WhatsApp com mapas e rotas personalizadas. Em 2025, processou 180.326 focos com mediana de 2,9 s e sucesso de 99,3%; entre setembro e dezembro, gerou 9.609 interseções e 7.096 alertas ao CBM.*

1. Introduction

The Amazon biome faces a severe and worsening wildfire crisis. In 2024, fire-driven degradation surpassed all records from the preceding twenty years [Bourgoin et al. 2025], with Brazil recording a historic fire season across all six biomes [Carvalho et al. 2025]. This escalation is tightly linked to deforestation [Lima et al. 2024, Mataveli et al. 2022], creating a feedback loop where clearing increases flammability and fire accelerates further forest loss. Rondônia, located on the Western Amazon arc of deforestation and historically among the states with the highest fire incidence [Ribeiro et al. 2021], recorded over 180,000 VIIRS hotspots in 2025 (Section 4.1, Fire Hotspot Detection). Its border with Bolivia, the second-largest contributor to Amazon fire activity [Silveira et al. 2022, Bourgoin et al. 2025], further exposes the state to transboundary fires.

Despite this severity, a critical gap persists between satellite detection and operational response at the subnational level. Brazil possesses well-established federal monitoring: NASA FIRMS distributes near real-time active fire data from the VIIRS instrument suite [Davies et al. 2009, Schroeder et al. 2014], and the National Institute for Space Research's (INPE) BDQueimadas provides public hotspot data by state. However, these are *data providers*: they allow filtering by administrative boundaries (state, municipality) but do not perform geometric intersection against operational jurisdictions (such as the fire brigade base areas used in Rondônia, which do not coincide with municipal boundaries) nor deliver push notifications to field responders [Tavella et al. 2025].

This disconnect has concrete consequences: state agencies must manually consult federal portals, cross-reference hotspot coordinates with local boundaries, and relay information to field teams, introducing delays incompatible with wildfire progression. International systems such as the European Forest Fire Information System (EFFIS) and the Canadian Wildland Fire Information System (CWFIS) demonstrate the value of integrated monitoring [Zacharakis and Tsihrintzis 2023], but no equivalent has been reported at the subnational level in Brazil. Prior Amazon work has primarily focused on predictive modeling [Silva et al. 2020, Cavalcante et al. 2021] rather than on the detection-to-notification pipeline.

Three factors make this problem particularly urgent. First, 78.7% of annual detections concentrate in August–October, with peak days exceeding 5,700 hotspots (Section 4.1, Fire Hotspot Detection), demanding automated processing beyond manual capacity. Second, fires in protected areas and indigenous lands require differentiated response protocols, making automated spatial intersection essential. Third, with weakening federal enforcement [Nunes et al. 2024], subnational monitoring systems may play an increasingly important role in environmental governance.

To address this disconnect, this paper presents **PROTEGE** (Environmental Monitoring Information System), a near real-time geospatial information system that closes the loop between satellite fire detection and subnational emergency response. The acronym is unrelated to the Stanford Protege ontology editor. The system automates: (i) continuous ingestion of active fire data from three VIIRS-equipped satellites (Suomi NPP, NOAA-20, and NOAA-21) via NASA FIRMS; (ii) spatial intersection against protected areas, indigenous lands, and fire brigade jurisdictions using PostgreSQL/PostGIS; and (iii) multi-channel notification delivery (email and WhatsApp) to authorized contacts of the state Military Fire Brigade (*Corpo de Bombeiros Militar*, CBM), who receive geolocalized alerts with maps and personalized routes within their operational jurisdictions.

This work makes three contributions: (1) the design and implementation of a geospatial information system integrating satellite ingestion, PostGIS spatial analysis, density-based clustering, automated notifications, and route generation into a single deployed pipeline, building on [Ljubojevic and Avramovic 2021, Li et al. 2023, Urbanelli et al. 2024], an integration not previously reported in the Brazilian fire monitoring literature (Section 2); (2) quantitative deployment results from the initial operational period: 180,326 hotspot detections ingested, 9,609 spatial intersections, median processing time of 2.9 s (P95: 9.2 s), 77.3% multi-sensor corroboration rate, and 99.3% pipeline success rate across 27,093 job executions (Section 4); and (3) evidence of operational deployment: 7,096 jurisdiction-based alerts delivered to Military Fire Brigade personnel, the first such automated pipeline at the state level in Rondônia (Section 2).

The remainder of the paper is organized as follows. Section 2 reviews fire monitoring and GIS-based systems; Section 3 describes the PROTEGE architecture; Section 4 reports operational results; Section 5 discusses impact, data quality, and limitations; and Section 6 concludes with future work.

2. Related Work

The related work is organized into three categories: operational fire monitoring systems (Section 2.1), satellite-based fire detection products (Section 2.2), and GIS-based fire systems in the academic literature (Section 2.3).

2.1. Operational Fire Monitoring Systems

INPE operates the primary federal monitoring infrastructure: BDQueimadas [INPE 2025a] provides public hotspot data from VIIRS and MODIS (Moderate Resolution Imaging Spectroradiometer) with filtering by state, municipality, and biome, and DETER [INPE 2025b] generates near real-time deforestation alerts. While these systems provide broad data access, neither performs spatial intersection against state-level jurisdiction boundaries or delivers push notifications to field responders. Internationally, EFFIS (Europe), CWFIS (Canada), and Sentinel Hotspots (Australia) integrate satellite detection with fire danger indices and forecasting [Zacharakis and Tsihrintzis 2023], but operate at the national or continental level and address different institutional contexts than those of Brazilian states.

2.2. Satellite-Based Fire Detection

NASA FIRMS [Davies et al. 2009] is the primary distribution system for near real-time active fire data from polar-orbiting satellites. The VIIRS 375 m product [Schroeder et al. 2014] provides higher spatial resolution than MODIS 1 km [Giglio et al. 2016], enabling more precise hotspot localization, particularly for intersection with small protected area polygons. Comparative assessments confirmed that VIIRS captures a broader range of fire activity than MODIS, including smaller and lower-intensity events [Coskuner 2022]. PROTEGE builds on this infrastructure by ingesting data from three VIIRS-equipped satellites (Suomi NPP, NOAA-20, and NOAA-21) to maximize revisit frequency over the Brazilian Amazon.

2.3. GIS-Based Fire Systems and Spatial Analysis

Academic works have explored GIS for wildfire monitoring. For fire risk modeling, Silva et al. developed a fuzzy-logic warning system for Acre [Silva et al. 2020] and Cavalcante et al. evaluated fire weather indices in the eastern Amazon [Cavalcante et al. 2021]. For spatial infrastructure, Ljubojevic and Avramovic proposed a PostGIS/GeoServer architecture for wildfire databases [Ljubojevic and Avramovic 2021] and Mangiameli et al. implemented fire spread modeling with an open-source GIS stack [Mangiameli et al. 2021]. In the Brazilian GeoInfo community, Macul et al. used Earth observation data cubes for burned-area mapping [Macul et al. 2022], complementing PROTEGE's focus on active-fire notification rather than post-fire mapping. Li et al. developed spatiotemporal clustering based on DBSCAN for NASA FIRMS data [Li et al. 2023], an approach related to

PROTEGE's density-based clustering pipeline. In emergency communication, Urbanelli et al. presented a chatbot for disaster risk reduction [Urbanelli et al. 2024].

Table 1 summarizes the key differences, including a recent SEMISH prototype for farm-level fire detection [Soares et al. 2025]. The comparison focuses on the detection-to-notification pipeline; other systems offer capabilities outside this scope. EFFIS is classified as "Partial" for spatial intersection because it aggregates by administrative regions but does not support custom jurisdiction polygons.

Table 1. Comparison of fire monitoring systems.

System	Scale	Spatial Intersect.	Notif.	Routes	Deployed
BDQueimadas	National	Filter	Email	No	Yes
NASA FIRMS	Global	No	Email	No	Yes
EFFIS	Continental	Partial	Web	No	Yes
Silva et al. [Silva et al. 2020]	State	No	No	No	No
Soares et al. [Soares et al. 2025]	Farm (400 m)	No	LoRa	No	No
PROTEGE	**State**	**Yes**	**WA+Email**	**Yes**	**Yes**

Positioning Federal systems serve as data providers and the academic works reviewed above address individual components (spatial databases, clustering algorithms, alert systems). To the best of the authors' knowledge, no prior work integrates the full pipeline (from satellite ingestion through spatial intersection to jurisdiction-routed notification with personalized route planning) into a deployed system at the subnational level in Brazil. PROTEGE addresses this gap.

3. PROTEGE Architecture

PROTEGE follows a service-oriented architecture with five loosely coupled components, each deployed as an independent service communicating through a shared PostgreSQL/PostGIS database and REST APIs. Figure 1 illustrates the overall architecture and data flow.

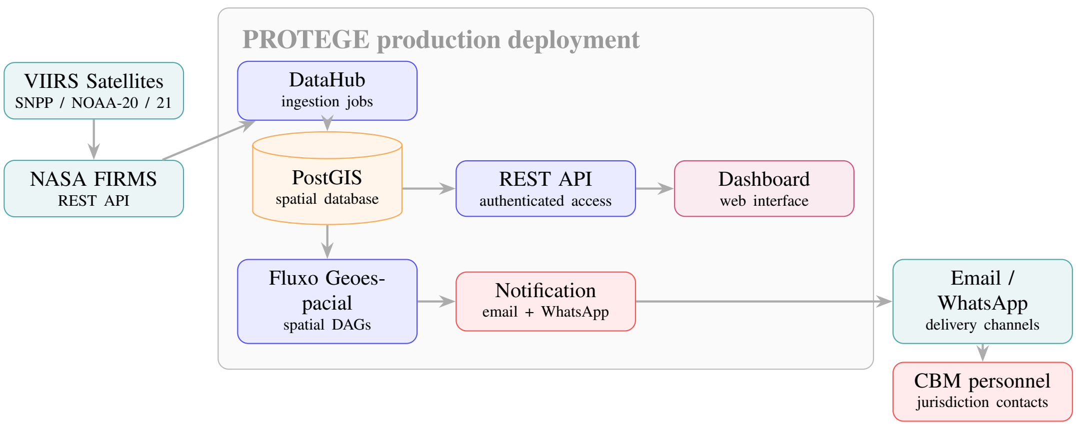


Figure 1. Deployment view of PROTEGE. External VIIRS/FIRMS data feed containerized services in the PROTEGE production environment; PostGIS acts as the shared spatial database, and notifications are delivered through email and WhatsApp to jurisdiction-specific CBM contacts.

Data ingestion layer (DataHub). The DataHub retrieves active fire detections from three VIIRS-equipped satellites (Suomi NPP, NOAA-20, and NOAA-21) via the FIRMS REST API, maximizing revisit frequency and spatial redundancy [Davies et al. 2009, Schroeder et al. 2014, Coskuner 2022]. The service queries the API every 3 minutes, comparing a hash of the retrieved dataset against the previously stored version; only new or updated records are parsed, validated, and inserted into PostGIS. Each record includes geographic coordinates (WGS 84), acquisition timestamp, satellite identifier, confidence level, and fire radiative power (FRP in MW). The end-to-end latency from satellite overpass to alert delivery is approximately 3–4 hours, dominated by upstream NASA FIRMS processing [Davies et al. 2009]. PROTEGE cannot reduce this satellite/FIRMS stage; its contribution begins once new data is available through the API, after which ingestion, intersection, and dispatch complete within minutes.

Spatial database layer (PostgreSQL/PostGIS). The analytical core is a PostgreSQL/PostGIS database, following the PostGIS/GeoServer architecture pattern for wildfire databases [Obe and Hsu 2021, Ljubojevic and Avramovic 2021]. It stores hotspot point geometries, administrative boundaries, protected areas (Conservation Units, Indigenous Lands), and CBM jurisdiction polygons provided by the Military Fire Brigade of Rondônia. Spatial indexes enable efficient point-in-polygon queries. The two core spatial operations are point-in-polygon intersection and DBSCAN (Density-Based Spatial Clustering of Applications with Noise) [Ester et al. 1996, Li et al. 2023], both implemented through PostGIS spatial functions. The DBSCAN clustering radius was set to 400 m, matching the VIIRS 375 m spatial resolution [Schroeder et al. 2014] and aligned with stakeholder expectations from existing tools such as the INPE Fire Dashboard, as confirmed during requirements meetings with CBM coordinators. On the production server (4-core CPU, 16 GB RAM, PostgreSQL 16 with PostGIS 3.4), the ingestion job completes with a median processing time of 2.9 s and a 95th-percentile of 9.2 s, measured across 7,713 successful ingestion executions (out of 27,093 total pipeline job executions with a 99.3% success rate). Even on the peak day (August 28, 2025; 16,722 hotspots), the pipeline processed all records within the 3-minute polling cycle.

Geospatial processing engine (Fluxo Geoespacial). The spatial analysis pipeline is implemented through *Fluxo Geoespacial*, a custom Python-based engine that defines directed acyclic graphs (DAGs) of geospatial operations, following open-source GIS processing approaches [Mangiameli et al. 2021]. Three independent pipelines run in production, one per VIIRS satellite, each triggered upon data arrival in PostGIS. This separation provides fault isolation and enables cross-sensor verification of concurrent detections.

Jurisdiction-based notification service. Notifications are not broadcast uniformly; instead, they are routed to the specific CBM base responsible for the affected area, extending targeted emergency communication [Urbanelli et al. 2024] to jurisdiction-level geographic routing. The state is divided into operational jurisdictions, each assigned to a CBM base. When spatial intersection identifies hotspots within a jurisdiction polygon, the system dispatches alerts only to authorized contacts registered for that base (Figure 2).

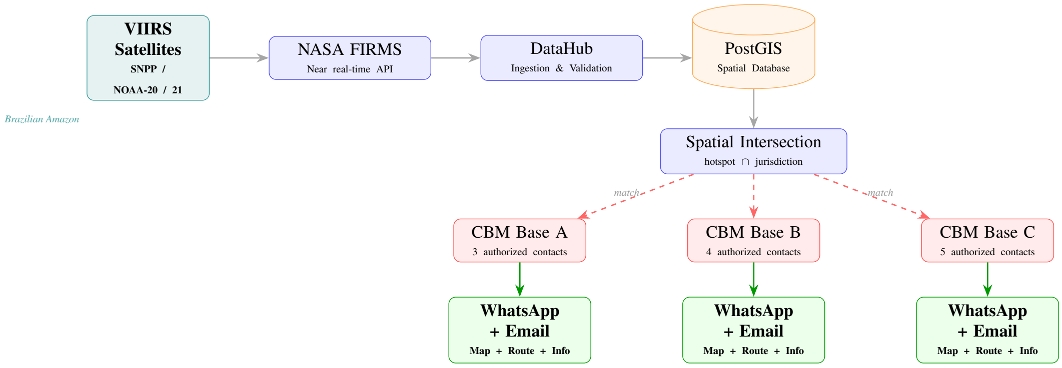
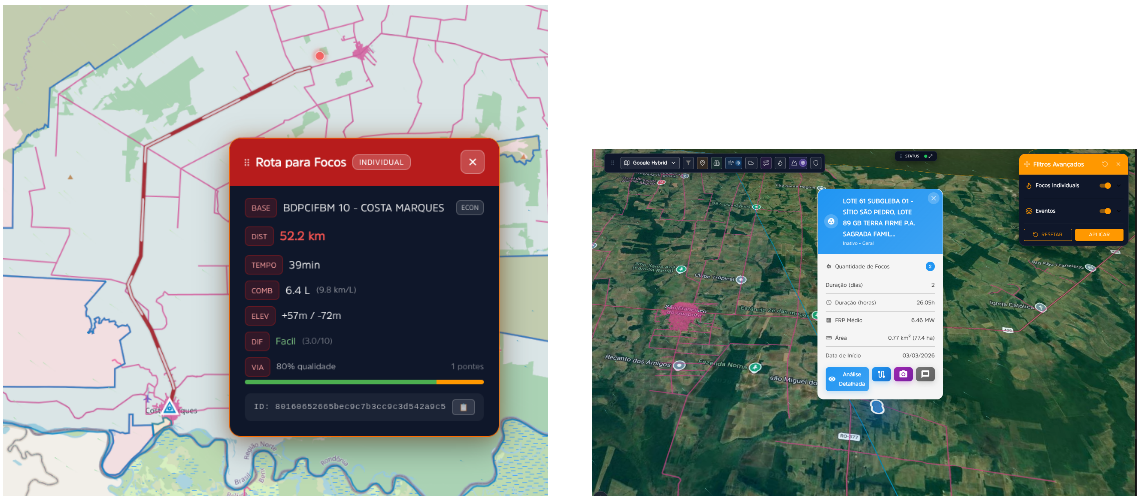


Figure 2. Jurisdiction-based notification routing. Hotspots are spatially intersected with CBM jurisdiction polygons; each base receives personalized alerts only for fires within its operational area.

Each notification includes: (i) a summary of detected hotspots (count, satellite, confidence); (ii) a localization map of the affected area within the recipient's jurisdiction; and (iii) a personalized route from the CBM base to the fire location, computed from OpenStreetMap (OSM) road network data [Haklay and Weber 2008] with distance, travel time, and road surface quality. Two delivery channels are used: email (detailed report) and WhatsApp (concise geolocalized alert for immediate action in remote areas).

Figure 3a illustrates a production example: a personalized route from CBM Costa Marques to a fire (52.2 km, 39 min), while Figure 3b shows the corresponding fire event detail with cluster metadata.



(a) Route from CBM Costa Marques to a fire (52.2 km, 39 min).

(b) Fire event detail with cluster metadata (duration, FRP, area).

Figure 3. Examples of PROTEGE notification content. (a) Route computed from OSM road network data. (b) Fire event aggregated by density-based clustering (DBSCAN).

Monitoring dashboard. The web-based dashboard (Figure 4) provides interactive visualization of hotspot data with satellite imagery, protected area overlays, temporal charts, and ranking tables by municipality and jurisdiction. As a supplementary feature, the dashboard includes a burn scar analysis tool that uses Sentinel-2 imagery [Drusch et al. 2012] (10–20 m resolution) to quantify fire-affected areas through temporal comparison; this module is not part of the evaluation scope of this paper.

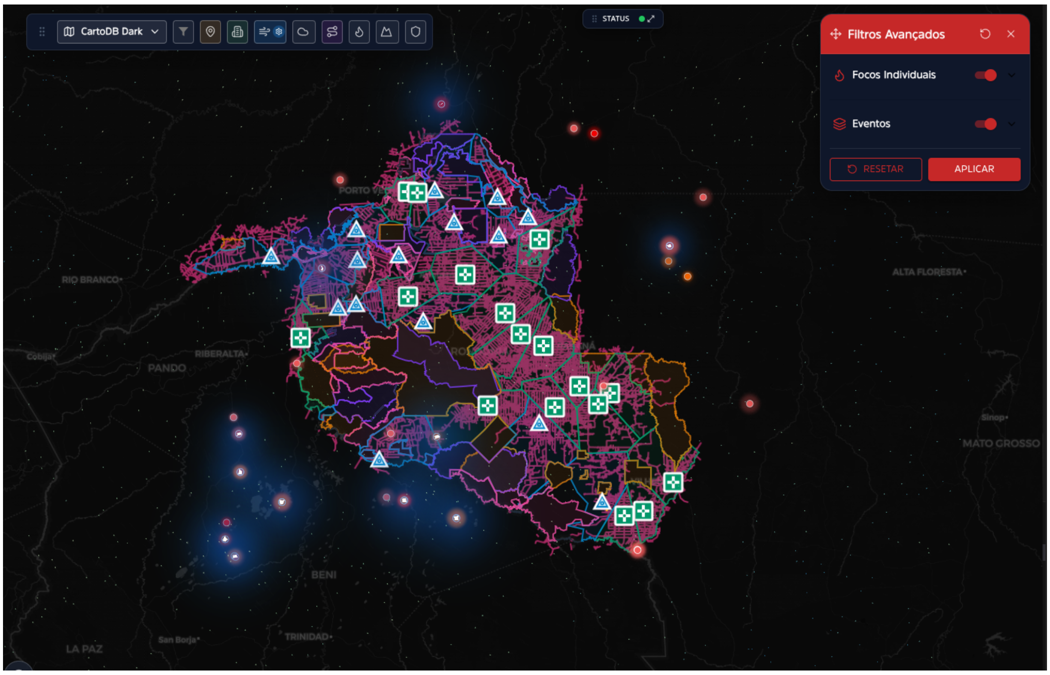


Figure 4. PROTEGE monitoring dashboard showing fire hotspot clusters and CBM jurisdiction polygons across the state of Rondônia. Individual hotspots and fire events can be filtered and inspected interactively.

4. Operational Results

PROTEGE has been in continuous operation since August 25, 2025, with spatial intersection deployed on September 12, 2025. Detection figures cover the full year 2025 (including data collected during development via the FIRMS archive API), whereas intersection and notification results cover September–December 2025.

4.1. Fire Hotspot Detection

During 2025, the system ingested 180,326 individual hotspot detections across Rondônia, distributed over 354 days with at least one detection (Table 2). This count represents raw satellite detections, not distinct fire events. To minimize notification redundancy, PROTEGE aggregates spatially and temporally coherent detections into *fire events* using DBSCAN clustering (400 m radius), analogous to the MapBiomas Fire Dashboard [Alencar et al. 2022]. Detections from different satellites within the same cluster are unified into a single event, and notifications are dispatched per event rather than per detection.

Table 2. Annual fire hotspot detection summary, Rondônia 2025.

Indicator	Value
Total hotspots detected	180,326
SNPP	60,424
NOAA-20	60,783
NOAA-21	59,119
Days with detection	354
Daily average	509.4
Peak day	Aug 28 (16,722 hotspots)

The three satellites contributed approximately equally to the total count (SNPP: 33.5%, NOAA-20: 33.7%, NOAA-21: 32.8%). Figure 5 shows the temporal distribution, which follows the established Amazonian fire season pattern [Ribeiro et al. 2021, Mataveli et al. 2022]: low activity during the rainy season (January–April), sharp escalation in July–August (peak: 66,337 in August), and rapid decline with the return of rains.

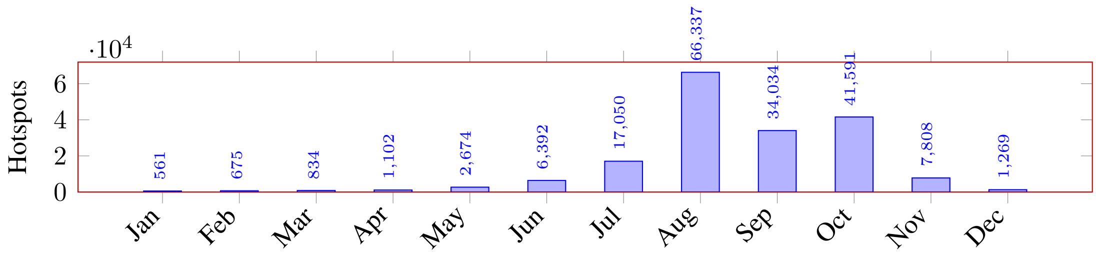


Figure 5. Monthly distribution of fire hotspots detected in Rondônia during 2025. The August–October trimester concentrated 78.7% of all annual detections, with August alone accounting for 36.8%.

4.2. Spatial Intersection Analysis

Between September 12 and December 31, 2025, the three analysis pipelines executed a total of 1,360 runs, producing 9,609 intersection results (Table 3).

Table 3. Spatial intersection results by satellite (Sep–Dec 2025).

Satellite	Results	Executions	Period
SNPP	3,111	456	Sep 12 – Dec 31
NOAA-20	3,442	455	Sep 12 – Dec 31
NOAA-21	3,056	449	Sep 12 – Dec 31
Total	**9,609**	**1,360**	

October concentrated 67.8% of intersection results (6,511 of 9,609). November showed the highest ratio of intersections to total hotspots detected that month (1,994 of 7,808; 25.5%), a pattern further analyzed in the discussion.

4.3. Notification Dispatch

PROTEGE serves two distinct user groups: (i) *general users*, i.e., state environmental agency personnel, researchers, and other registered stakeholders who receive notifications about fire activity in their areas of interest; and (ii) *CBM users*, i.e., authorized Military Fire Brigade personnel who receive jurisdiction-based alerts with localization maps and personalized routes for field deployment. During September–December 2025, the system dispatched 18,914 notifications: 11,818 (62.5%) to general users and 7,096 (37.5%) to CBM personnel (Table 4, Figure 6).

Table 4. Monthly notification dispatch by user type (Sep–Dec 2025).

Month	General	CBM	Total	CBM %
September	268	402	670	60.0%
October	5,860	3,516	9,376	37.5%
November	3,080	1,960	5,040	38.9%
December	2,610	1,218	3,828	31.8%
Total	**11,818**	**7,096**	**18,914**	**37.5%**

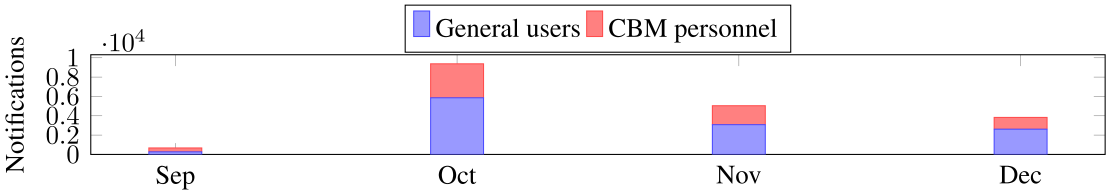


Figure 6. Monthly notification dispatch by user type. CBM personnel receive jurisdiction-based alerts with maps and routes; general users receive area-of-interest notifications.

October concentrated 49.6% of all notifications, mirroring the intersection peak. The CBM share was highest in September (60.0%), when fewer general users were registered, and stabilized at 35–39% as the user base expanded.

5. Discussion

Operational impact and coverage.

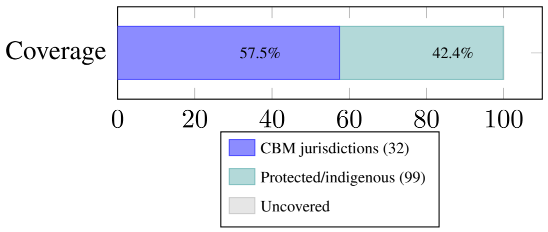
The primary operational contribution is the automated notification pipeline that delivered 7,096 alerts to Military Fire Brigade personnel in its first four months. Prior to PROTEGE, CBM personnel relied on manual consultation of federal portals (BDQueimadas, FIRMS) to identify fires within their jurisdictions. A state-level Telegram channel also distributes INPE-based alerts, but without jurisdiction intersection or route generation. Each PROTEGE notification comprises geolocalized fire data, a zone-specific map, and a personalized route, delivered directly to the responsible brigade base. During deployment, the registered contact base grew from 10 to 22 personnel across multiple CBM bases.

Because pre-PROTEGE CBM operations did not maintain comparable incident logs, this study does not claim a percentage reduction in response time. The measured change is the removal of manual filtering and routing after FIRMS publication; formal before–after evaluation remains future work.

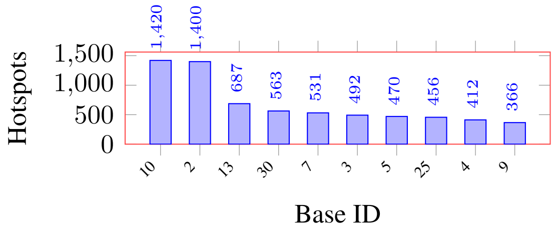
The scale of fire activity during peak season underscores the necessity of automation: on August 28 alone, 16,722 hotspots required intersection against 32 non-municipal jurisdiction polygons, a task infeasible through manual consultation of federal portals. The fire suppression literature quantifies the cost of delays: response failures account for 85% of total area burned [Arienti et al. 2006], and each hour of reporting delay increases suppression costs by ∼0.25% [Huang and Wichmann 2024]. Table 5 compares PROTEGE's pipeline latency against operational benchmarks.

Table 5. Detection-to-notification latency comparison.

System	End-to-end latency	Processing time	Jurisd. routing	Push notif.
BDQueimadas [Setzer et al. 2019]	3 h cycle	—	No	No
NASA FIRMS	1–3 h	—	No	Email
EFFIS	2–3 h	—	No	Web
CWFIS	1–7 h	—	No	Web
PROTEGE	**3–4 h**	**2.9 s (med.)**	**Auto**	**WA+Email**



(a) Territorial coverage composition.



(b) Top-10 CBM bases by hotspot count (Sep–Dec 2025).

Figure 7. Coverage and operational load. Hotspot counts are aggregated from VIIRS detections assigned to each CBM base by spatial intersection.

PROTEGE shares the same upstream FIRMS NRT constraint (1–3 h) as EFFIS and CWFIS, but eliminates the manual overhead that BDQueimadas users face: filtering is limited to state or municipality [Setzer et al. 2019], not operational CBM jurisdictions, and no push notifications are delivered. PROTEGE's automated pipeline adds only 2.9 s (median) of processing latency and delivers jurisdiction-routed alerts without human intervention.

The ratio of intersections to total hotspots increased from 15.7% in October (6,511 / 41,591) to 25.5% in November (1,994 / 7,808), suggesting that late-season fires disproportionately affect protected areas, consistent with the deforestation-fire feedback documented by [Mataveli et al. 2022]. These patterns reinforce the need for year-round monitoring at the state level [Nunes et al. 2024].

The geographic coverage of the operational CBM footprint is also quantified. The union of the 32 operational jurisdiction polygons (integrated and decentralized bases) covers 57.48% of the state's area. When including all polygons tracked in the PROTEGE base layer (131 polygons, including protected areas and indigenous lands used for routing and situational awareness), the total covered area reaches 99.88% (Figure 7).

Data quality and filtering.

False positive management relies on three complementary filters. First, the notification pipeline admits only nominal and high confidence VIIRS detections, excluding industrial heat sources and sun glint [Schroeder et al. 2014]. Second, 77.3% of fire clusters (3,659 of 4,732) contained detections from at least two satellites and 30.5% from all three [Coskuner 2022], providing independent spatial corroboration. Third, DBSCAN clustering [Ester et al. 1996, Li et al. 2023] groups only spatially and temporally coherent detections into fire events, discarding isolated outliers.

Lessons learned and limitations.

Two lessons relate to the detection stack: (1) multi-satellite redundancy is essential, as no single sensor exceeded 34% of detections; and (2) year-round coverage is critical, since the intersection pipelines missed the August peak due to their September 12 deployment, now corrected for 2026.

Two further lessons relate to delivery and adoption: (3) feedback from CBM coordinators during periodic review meetings (September–December 2025) indicated that WhatsApp alerts were generally seen within minutes, whereas email reports were checked once daily; and (4) user growth required institutional onboarding rather than organic adoption.

Limitations: intersection data covers only four months (September–December 2025); the system currently serves only one state; and no controlled study has yet measured the effect of PROTEGE notifications on CBM response times or area burned.

6. Conclusion and Future Work

This paper presented PROTEGE, a geospatial information system connecting satellite fire detection with subnational emergency response in the Brazilian Amazon. In Rondônia, it processed 180,326 hotspot detections, produced 9,609 spatial intersections, and delivered 7,096 jurisdiction-routed alerts to Military Fire Brigade personnel, with 2.9 s median processing time (P95: 9.2 s) and 99.3% pipeline reliability. These results show that open satellite data and spatial databases can be combined into an operational pipeline that removes manual filtering and routing after FIRMS publication.

Future work includes formal response-time evaluation, fire prediction with meteorological and vegetation data, integration with DETER/INPE and MapBiomas alerts, and multi-state deployment by replacing jurisdiction polygons and contact registries.

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