

Validation of an automated end-to-end system for satellite-based wildfire detection in Sweden

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ABSTRACT

Following the severe 2018 fire season, a fully automated satellite based system for early wildfire detection was implemented in Sweden. Currently, it uses the VIIRS instrument onboard the three Suomi-NPP/JPSS spacecraft. The Swedish wildfire suppression strategy relies heavily on fast response, requiring accurate geo-location, low latency, and a small number of false alarms. Here, we describe the system, measures taken to reduce false and multiple alarms, and assess the outcome from the first years of operation. We also describe validations of (1) detections against large experimental wood crib fires with well-defined heat release rates and temperature distributions and (2) the 41 brightest wildfires detected in 2023 and their relation to forest characteristics. Average end-to-end latency from overpass to alert is 17 min. The satellites satisfactorily reproduce location and pixel temperatures, although an increasing forest timber density reduces the pixel temperature. Verified false alarms accounted for approximately 10% of the detections since 2022, mainly attributed to reflections on large arrays of solar panels, large greenhouses, or large metal farmhouse rooftops. Although satellites still fail to detect many fires due to unfavorable timing, cloud cover or sensitivity, 29% of the wildfire detections submitted an alarm before any other means of detection. High fire localization accuracy was also confirmed, further reducing suppression time, even when the satellite system is not the first to trigger an alarm. Regional coverage is further expected to increase substantially with the addition of the first satellite in the European Metop-SG programme, Metop-D, launched in August 2025.

1. Introduction

Wildfires are next to ubiquitous, and present where there is vegetation and possibilities for at least short dry spells and ignitions. While historically used for agricultural expansion and pastoralism (Pyne, 2020), fires also pose a severe threat to people, property, and landscapes already stressed by human exploitation (Kelley et al., 2025). As anthropological climate change (Quilcaille et al., 2023) and land use changes (Gómez-Sal et al., 2024) alter the occurrence and behavior of wildfires, adaptation to these changes requires understanding of regime changes and new strategies to mitigate their negative consequences (Elmqvist et al., 2025).

Near real-time satellite remote sensing has become essential for wildfire monitoring (Flannigan and Haar, 1986), global burned area assessment (Andela et al., 2017), and fire management (Chuvieco et al., 2020; Hope et al., 2024), providing coverage and latency beyond what ground-based methods can achieve over large areas. Satellite detection of fires in remote areas began in the late 1980s (Matson and Holben,

1987; Setzer and Pereira, 1991) but global fire monitoring from space was greatly improved by the provision of data from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Justice et al., 2002; Giglio et al., 2003) since the early 2000s. In the last decade geostationary based systems with good temporal coverage (every ≈5–10 min) have seen substantial improvements in pixel resolution. The latest European Meteosat Third Generation system via the Flexible Combined Imager onboard Meteosat-12 is now much more sensitivity to fires compared to the previous Meteosat Second Generation system (Pampanoni et al., 2025). However, MODIS is in this regard still the benchmark.

The ability to detect smaller fires on a global scale was enabled by the Visible Infrared Imaging Radiometer Suite (VIIRS) (Schroeder et al., 2014). It was refined for active fire detection (Csiszar et al., 2014) and Fire Radiative Power (FRP) (Li et al., 2018) by comparison to MODIS output. While the data from VIIRS continue to allow for studies over large areas throughout the world (Aditi et al., 2025; Beetz et al., 2025; Forkel et al., 2025) there is a need for local validation of

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both the detection of active fires and associated FRPs (Li et al., 2018; NASA, 2024). Such local validation could enable tailoring the global parametrization to local conditions and extend implementation in fire management practices. Therefore, validation cannot rely on MODIS output but needs more detailed and local ground truth data.

In the European boreal, the main fire management strategy is a fast response, utilizing the accessibility provided by the forest road network (Granström et al., 2023; Ring et al., 2024). A long delay until inception of suppression activities is highlighted as one of the most important factors for large forest fires in the region. Expected final burnt area increases exponentially with the response time, which, from a boreal perspective, is relatively short (median <30 min for fires > 10 hectares) (Sjöström and Granström, 2023a). This suggests that improvements could focus on the time to detection rather than response itself.

Sweden, representing the European boreal region, is almost 70% forested, with settlements, industry, and agriculture interspersed within these landscapes. As such, the country is highly shaped by wildfires although their numbers and size have decreased significantly during the last 150 years as modern forestry introduced effective suppression (Niklasson and Granström, 2000). Nevertheless, municipal rescue services annually respond to around 5000 wildfire incidents with a combined burnt area of ~3500 hectares, and trajectories for future fire danger point at increased forest fire activity (Cunningham et al., 2025; Berg et al., 2024). The fire season is two-fold, most ignitions occur during the spring grass fire season between snow melt and green-up (Sjöström and Granström, 2023b), during which most building ignitions (annual average 30 y⁻¹), human injuries (18 y⁻¹) and fatalities (1.1 y⁻¹) are recorded (Plathner et al., 2025). In contrast, high-summer forest fires account for most of the burnt area, particularly in rural regions (Sjöström and Granström, 2023a).

Since 2014, the region has experienced several high-consequence fires, including the complex winter fires in Norway (+120 buildings damaged, 2 500 ha scorched Log and Gjedrem, 2022), the severe crown fire in Västmanland (40 buildings, 13 000 ha, 1 fatality Köhler et al., 2018), and the forest fire summer of 2018 completely depleting suppression resources (~30 buildings, 25 000 ha Granström, 2020), particularly in sparsely populated areas.

Swedish wildfire detection has previously relied on public reporting (~90%) and, during high fire danger periods, on a national system of forest fire surveillance by small manned aircraft. Public reporting is, however, not a reliable means for early detection and precise localization in sparsely populated parts of Sweden (Granström et al., 2023). Furthermore, while surveillance by aircraft is in general effective in daytime even under cloudy skies, it is very expensive (Hertzberg and Lundqvist, 2022) and not applicable at night. Thus, there is scope for an automated remote sensing based system, provided such a system:

- is timely
- is sensitive to small fires
- is reliable (few false alarms and providing accurate geo-location)
- has a sufficient areal coverage
- has a sufficient revisit time (many observations over the day)

Since the severe 2018 fire season several improvements have then been made to the Swedish emergency management system (MCF, 2025a). Among these is a novel system for early wildfire detection based on real-time VIIRS data. To our knowledge, it is unique in its high degree of automation, low latency, and alignment with the operational requirements outlined above.

Readily available global or European near-real-time hotspot services, such as Fire Information for Resource Management System (FIRMS) and European Forest Fire Information System (EFFIS) (Hope et al., 2024), do not provide sufficiently low latency over Europe. In addition, they lack adequate filtering of false alarms (e.g., stationary heat sources in Sweden). Over China an advanced automated system

based on a combination of Landsat 8, Sentinel-2 and geostationary GF-4 data has recently been developed (Gao et al., 2025-09). However, the early detection part of the system is based on the specific ability of GF-4 to provide addressable narrow views of very high spatial and temporal resolution data, and thus not applicable to our region of interest.

This paper presents the fully automated detection system and evaluates its performance based on wildfire detections and incident outcomes from its initial years of operation. Additionally, we validate the system's output using controlled experimental burns involving well-characterized wood crib fuels.

The study aims to address the following questions:

- What is the duration of the processing steps in the automated end-to-end system, and how does the time of alarm compare to other means of detection for the same incidents?
- What are the characteristics of the detected fires (fuel types, human activity) and the occurrence and nature of false alarms?
- Are controlled and accidental forest fires detected differently, and what role do forest characteristics play?
- How do VIIRS localization, cell temperature, and FRP (derived from pre-launch laboratory calibration, vicarious checks over homogeneous Earth targets and against MODIS fire products) perform for small fires near the detection threshold?

2. The operational system

The Swedish Meteorological and Hydrological Institute (SMHI) has operated a direct-readout (DR) ground station in Norrköping, Sweden, for the real-time reception and processing of data from weather and environmental polar orbiting satellites since the 1980s. Around 50 overpasses are acquired each day from several different weather satellites, including the JPSS missions Suomi-NPP, NOAA-20 and the latest NOAA-21, added August 2023. The real-time operational active fires detection system currently utilizes direct broadcast VIIRS data from all three JPSS spacecraft.

2.1. VIIRS scanning characteristics and sensitivity

The multi-purpose VIIRS instrument measures the upwelling radiation in 22 spectral bands covering the visible, near-infrared, and thermal infrared regions, from 412 nm to 12 µm. It was first launched aboard the sun-synchronous polar orbiting Suomi-NPP satellite in 2011, and has since been included on NOAA-20 (2017) and NOAA-21 (2022). All three satellites orbit the Earth 14 times a day crossing the equator at the same local solar time every day, with a local time of the ascending node equal 13:25.

The 22 VIIRS bands include five high-resolution imaging bands (I-bands), 16 moderate-resolution bands (M-bands), and one low-light, pan-chromatic Day/Night Band. The instruments' Earth-view swath spans 112.56° centered on the ground track (NOAA, 2017). At a satellite altitude of 824 km, this yields an approximate swath width of ~3000 km for both band types (NOAA, 2017; OSCAR, 2025).

Each of the three satellites provide full VIIRS coverage of the entire country twice a day, at approximately midnight (00:00 to 03:00 UTC) and noon (around 09:30 to 12:30 UTC). Two satellites with maximum separation of 180 degrees (currently NOAA-20 and NOAA-21) provide coverage every 50 min during those intervals. With Suomi-NPP around 29 min after NOAA-21, the temporal coverage is currently even slightly better. However, due to the country's latitudinal extent, the temporal coverage varies strongly between southern and northern Sweden. In the very north this sub-50 min coverage is uninterrupted from 23:00 to 14:00 UTC. Further south, a gap in coverage during late night and morning emerges so that the southernmost tip of Sweden has no VIIRS coverage from around 3:00 to 9:30 UTC (see Supplementary material, Fig. 1).

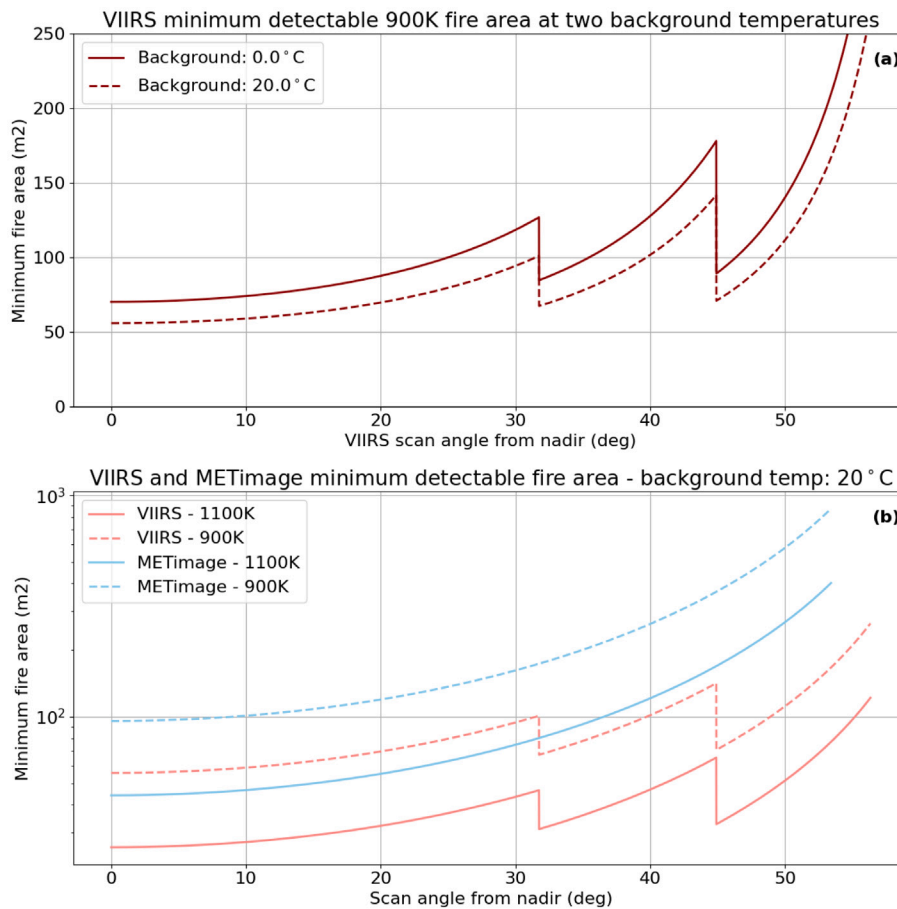


Fig. 1. The theoretical minimum detectable size of a 900 K fire as a function of scan angle for VIIRS only (a) depending on background temperature, and for both VIIRS and METImage (b) assuming a background temperature at 20 °C and two fire temperatures of 900 (dashed lines) and 1100 K (solid lines). Calculations are based on the criteria for thresholds $Thr(BT_4)$ and $Thr(BT_{45})$ in the daytime VIIRS-AF algorithm candidate fire pixels tests (Section 2.2).

The nominal nadir pixel resolutions for the M- and I-bands are typically reported as 750 m and 375 m, respectively (see e.g. Schroeder et al., 2014 and OSCAR, 2025). Naturally though, pixel sizes grow further from nadir. However, unlike the heritage sensors Advanced Very High Resolution Radiometer (AVHRR) and MODIS (Flannigan and Haar, 1986), VIIRS has a very high across track pixel resolution (high sampling rate and short integration time). It also uses a special on-board pixel aggregation scheme to achieve a pseudo constant across-track pixel resolution (Schroeder et al., 2020). This unique across-track pixel aggregation limits I-band pixel growth to sizes on average around 0.26 km² and anywhere below 0.7 km². Within ± 1225 km from nadir (83 % of the swath width), pixel sizes are less than 0.37 km².

2.2. Summary of the VIIRS I-band active fires algorithm

The active fire algorithm uses a multi-spectral thresholding approach to active fire detection and characterization for each VIIRS granule (Schroeder et al., 2014, 2020), not much different from the heritage algorithms of MODIS (Giglio et al., 2003) and AVHRR (Giglio et al., 1999). Both absolute and contextual (comparing a pixel to the background) tests are used. The I-bands, primarily the mid-wave infrared I4 (3.55–3.93 μm) and the long-wave infrared I5 (10.5–12.4 μm) channels, are used in the detection steps while M13 is used for FRP estimations.

The algorithm has a daytime (solar zenith angles lower than 85°) and a nighttime part. The daytime algorithm is more constrained due to contributions from reflected solar radiation in I4, making daytime detection less sensitive (Schroeder et al., 2014).

There are several tests for interference from clouds and reflections in e.g. metallic rooftops or small water bodies, not present in the static land use data maps. Of particular relevance for this paper are the so-called *candidate fire pixels* tests. These require a warm I4 brightness temperature anomaly ($BT_4 > Thr(BT_4)$) and a high positive difference in the I4 minus I5 brightness temperatures, $\Delta BT_{45} > Thr(BT_{45})$ (Schroeder et al., 2020).¹ In daytime, the $Thr(BT_4)$ is background dependent but always between 325 and 330 K, while at night it is 295 K. The $Thr(BT_{45})$ is 25 K for daytime conditions and 10 K at night.

Fig. 1a, show how the sensitivity of the current daytime VIIRS-AF algorithm decrease with a lower background temperature. A wildfire in a 0 °C background environment need around 25% larger size in order to be detected compared that in a 20 °C background.

2.3. Processing orchestration and implementation

The processing orchestration is based on the open source Pytroll software framework (Raspaud et al., 2018) and implemented as micro services using a publisher/subscribe pattern, see Fig. 2. Each micro-service running either third party or customized software for a particular task is triggered by incoming Posttroll (2025) messages.

Data is acquired and processed in real-time by streaming the raw satellite data through the Real-Time Software Telemetry Processing

¹ Please note that there is an error regarding the algorithm description in the original paper (Schroeder et al., 2014) where an *or* should have been an *and* concerning this test (I. Csiszar, 2025, personal communication).

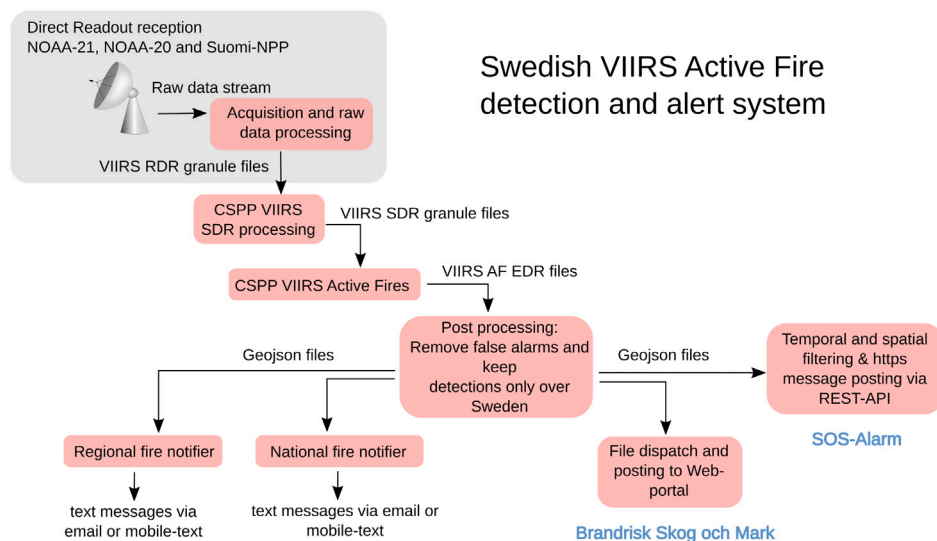


Fig. 2. Dataflow of the automated end-to-end system implemented and running in real-time at SMHI in Norrköping. SOS Alarm is Sweden's national emergency dispatch and call center, equivalent to the Public Safety Answering Point (PSAP) in the USA. *Brandrisk Skog och Mark* (Swedish for “Fire risk Forest and Land”) is a national civil protection wildfire web portal, including national fire danger forecasts.

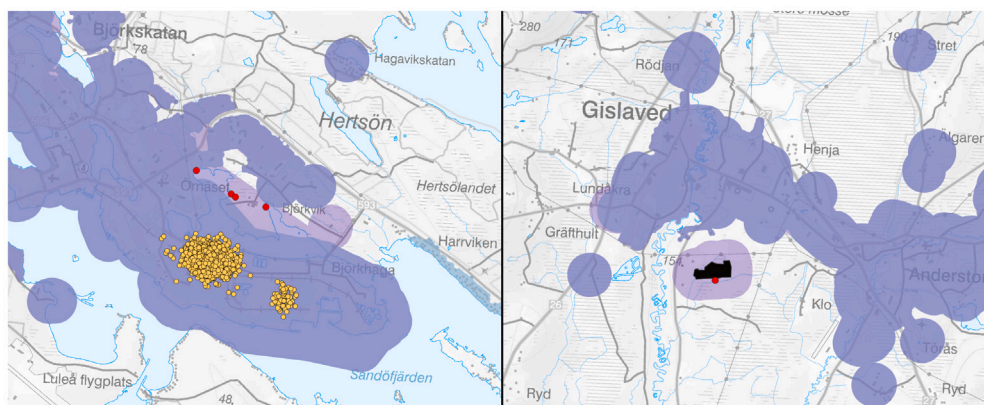


Fig. 3. The filter mask at two different locations, the SSAB steel factory in Luleå (left) and a new large scale solar power park (*Henja Solpark*) outside Gislaved (right). Here we show both the mask used during the 2024 season (transparent blue) and that implemented for the 2025 season (transparent purple). Left panel: All (1409) detections during the year 2022 caught by the filter mask over the SSAB factory facilities (yellow dots) and four false detections recorded during the summer of 2024 (red dots). Right: the only false detection (red dot) over the Gislaved solar power park (outlined in black) recorded in 2024, now included in the mask as of May 15, 2025. The background image on which the detections are displayed is combining data from three different sources: (1) Background map - © Lantmäteriet, (2) Selected datasets such as buildings, industries and energy production - data source: Topografi 10, © Lantmäteriet under CC BY 4.0, the data have been modified, and (3) Urban areas - © Statistics Sweden under CC 0.

System (NOAA, 2025a) to produce Raw Data Records (RDR), one RDR granule file per 86 s of VIIRS observations. These RDR files are then provided to the Community Satellite Processing Package (CSPP) VIIRS-SDR algorithm (NOAA, 2025b) to produce geolocated and calibrated radiances, brightness temperatures and reflectances, so-called Science Data Records (SDRs). The VIIRS Active Fires (VIIRS-AF) I-band algorithm implemented in CSPP (SSEC, 2025) (version 2.1) transforms SDR granules to Active Fires Environmental Data Records (EDRs) in netCDF and ascii format. The VIIRS EDR files contain the center I-band pixel position of each hotspot detection, the M-band based FRP for the I-band pixel, the brightness temperature of the I4-band of the active fire and a quality flag (Schroeder et al., 2020).

To minimize the amount of false alarms from stationary heat sources like thermal power plants or metal production, a post-processing step is applied on the VIIRS-AF EDR data (Dybbroe and Raspaud, 2025). The most influential component of this algorithm is a static mask to filter

out hotspots in urban and industrial areas and other persistent heat signals. A growing contributor to false detections is also direct solar reflections (sun glints) from rapidly expanding large-scale solar energy installations, necessitating annual mask updates. The mask is stored as a standard GIS shape-file format and based on the latest available map layers including urban areas from Statistics Sweden (Statistikmyndigheten SCB, 2025).

The mask extracts false alarm sources from the latest *Topografi 10* dataset provided by the Swedish mapping, cadastral and land registration authority (Lantmäteriet, 2025), and is updated close to annually since the start of service in 2022. Buffer zones are applied, accounting for uncertainties in VIIRS navigation. These sources include:

- Industrial buildings - buffer zone = 500 m
- Areas used by industries (mines, petroleum refineries, metal production and trade areas) - buffer zone = 500 m

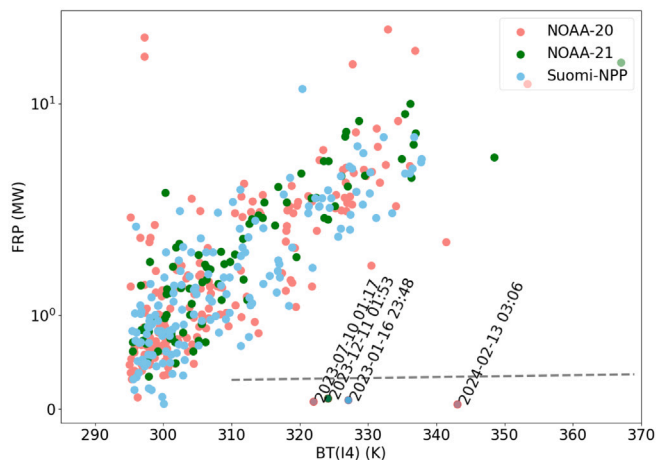


Fig. 4. Fire Radiative Power (FRP) as a function of the $BT(I4)$ for all nighttime detections recorded during 2023 and 2024. The dashed gray line illustrate the sanity check below which further alerts are not triggered.

- Areas for energy production, for example solar energy and thermal power plants - buffer zone = 500 m
- Buildings previously identified and verified giving rise to false fire alarms because of sun reflection (mostly farm houses with metal roofs) - buffer zone = 600 m

Two examples of the mask and the iterative process to update it are shown in Fig. 3. While this masking approach effectively reduces false positives, it may also exclude real fires occurring near urban or industrial areas. This trade-off is considered acceptable, as such fires are typically reported quickly through other channels.

In addition to the mask-based filtering, a sanity check has recently been introduced to reduce spurious detections. It is well known that the VIIRS I4 band can occasionally report anomalously high brightness temperatures, particularly over the South Atlantic Magnetic Anomaly (SAMA), (Schroeder et al., 2014). Such spurious signals can also occur elsewhere, although with less frequency, especially during periods of elevated solar activity.

These events are typically characterized by unusually high I4 brightness temperatures combined with very low (M-band) FRP values. When $BT(I4) > 310$ K and $\frac{BT(I4)}{FRP} > 1000$ K/MW, the detection is therefore classified as spurious and no alarm is triggered. Over the last four years, we have recorded eight such events over Sweden, to which deployed fire brigade personnel could not relate any real fire incident. Fig. 4 provides an example for 2024.

The post-processing step generates one GeoJSON file per EDR granule, which is stored on disk and accompanied by a message for downstream dissemination. All detections passing the post-processing are published on the wildfire web portal *Brandrisk Skog och Mark*, accessible to firefighting personnel and rapid response decision-makers across Sweden. The portal also provides a wealth of other, mostly weather-related, information essential for wildfire monitoring and mitigation. In addition, users can subscribe to real-time notifications via email or SMS. For mobile notifications, an additional regional filter is applied to ensure that fire brigades only receive alerts for active fires within or near their area of responsibility, see Fig. 2.

2.4. Unique alarms derived through spatial-temporal filtering of detections

Finally, since November 2022, the full value chain from observation to first responders has been closed via the implementation of an automated alert system using a REST API between SMHI and the national emergency dispatch and call center, *SOS Alarm*. For this, a spatio-temporal filtering of the active fire detections has been implemented,

with the purpose to avoid unnecessary repeated alarms on the same fire:

1. New active fire detections do not generate new alarms if they are detected within 800 m and 6 h of a previous alarm.
2. Active fire detections recorded at the same time within 800 m of each other are considered to originate from the same fire. The alarm will be defined by the detection with the highest FRP.
3. However, if the maximum distance between detections in such a group of detections exceeds 1200 m, the group is divided in sub-groups generating one alarm each.

All thresholds above are subject to configuration. The current values have been agreed in dialogue with the emergency dispatch operators and first responders prior to the introduction of the service.

The 800 meter threshold has been chosen to take into account the expected VIIRS geolocation errors and the typical pixel sizes (see Section 2.1). The VIIRS geolocation errors are in general within 50 m both cross-track and along track and does not show a strong scan angle dependency (Wolfe et al., 2013-10-27).

The 6 h threshold has been chosen to span over a typical contiguous VIIRS observation period² at night and day over Sweden (Supplementary, Figure 1). This means that if the same hotspot position which gave rise to an alarm at night is again triggering a fire detection later in the day it should cause a new alarm.

The division in sub-groups using the 1200 meter threshold described above is to properly account for potentially long fire fronts. Grass fires (Sjöström and Granström, 2023b), particularly those ignited along train tracks, can spread over long distances. Early assessment of their extent is critical for an effective response.

3. Assessment and validation methods

3.1. Operational performance

All signals meeting the active fire algorithm criteria were traced through post-processing to the final detections, which were subsequently filtered into individual alarms. Processing times for each step were recorded, along with the end-to-end latency from satellite observation to alarm.

3.2. Natural fires

The alarms leading to dispatch registered by the VIIRS instrument during 2022–2024 were assessed and identified using communication with the appropriate rescue services combined with media coverage. If no fire could be confirmed from these sources, multi-spectral imagery from Sentinel-2 data have also been used to identify possible active fires or burnt areas. All non-fire events were investigated to identify the source of the false alarm.

Multiple detections were associated with the same fire event. These events were subsequently classified as forest fires, prescribed burning, grass fires, building fires (including dwellings, barns, cottages etc.), controlled burning (legal burning activities which were under control), military (events on firing ranges), non-fire events and other/unknown. Each event was also linked to the time of the first non-satellite alarm received by the emergency call and dispatch center.

Additionally, a subset ($n = 41$) of the detections registered 2023 with the highest pixel temperature that had been verified to originate from wildfires or prescribed burns were individually assessed. Fire behavior at the time of detection was estimated according to the following procedure:

² A time period of day where there is never more than 50 min to the next VIIRS coverage.

Table 1
Wood crib properties and timing of satellites.

Nr	Date m/d/y	Time (UTC)	Satellite	Orig. crib dim. L × W × H (m)	mc ^a (%)	Mass ^b (kg)	Orig. Mass ^c (kg)	T _{amb} (°C)	θ _{sat} ^d (°)
1	2/28/23	10:43:20	NOAA-20	5 × 1.2 × 0.6	17	200	1000	1	47
2	2/28/23	11:34:47	S-NPP	5 × 1.2 × 0.6	17	40	1000	1	5
3	3/1/23	11:14:00	S-NPP	8.8 × 1.9 × 0.9	14	270	1656	4	24
4	3/2/23	11:45:52	NOAA-20	9 × 2 × 0.9	17	1046	1735	3	9
5	5/14/24	11:38:17	NOAA-21	32.4 × 1.2 × 0.75	12	2640	3150	25	2
6	5/14/24	12:05:10	S-NPP	32.4 × 1.2 × 0.75	12	156	3150	25	29
7	5/14/24	12:31:00	NOAA-20	32.4 × 1.2 × 0.75	12	139	3436	25	48

^a Moisture content.

^b Remaining fuel mass at satellite overpass.

^c Fuel mass at ignition.

^d Satellite zenith angle.

1. The location and extent of burnt area at different instances were determined by other satellite data using the “Fire severity” (Keeley, 2009) or “Wildfire” (Markuse, 2017) filters from Sentinel-2 or the following day registrations of “Burned Area Index” or “Burned Area Detection” from same sources.
2. The incident commander (for accidents) or the burn leader (for prescribed fires) was contacted to gather photos and assess the extent (width and length of the flaming area) and location of flames and burnt land at the time of VIIRS detection.
3. Forest stand quantities were gathered using laser scanning data from the Swedish Forest Agency, defining tree species, height and basal area (Swedish forest agency, 2023).
4. Current weather and fire danger indices were collected from the Swedish civil contingencies agency (MCF, 2025b).
5. Estimated Fire Radiative power FRP^{Est} was modeled using the Canadian Forest Fire Behavior Prediction System (Wotton, 2009) through the REDapp application with appropriate fuel models (Conifer plantation, Spruce-lichen woodland or Mature Jack or Lodgepole pine). The pixel brightness temperature (BT(14)^{Est}) was estimated using the method outlined in Section 3.3 (Eqs. (2) and (3)), by assigning an average temperature of 550 °C to the estimated flaming area in addition to an area of 250 °C on 0.5 m behind the flaming area and additional 70 °C on the adjacent 3 m. These numbers are estimates from an ongoing research project executing a series of experimental burns in Swedish coniferous forests (MSB 2023-05749).
6. To investigate the effect of forest canopies and that of spread type (accidental or prescribed) on the VIIRS output, the differences between the estimated and satellite detected BT and FRP were thereafter assessed in relation to forest attributes such as basal area.

3.3. Experimental fires

To validate VIIRS output in typical Swedish boreal spring and summer conditions around the VIIRS detection limit, seven well-characterized experimental fires (Test 1 – Test 7) were conducted in south Sweden (Södra Älvsborgs Räddningstjänstförbund, coordinates: 57.675861 N; 12.900245 E). The tests were performed on February 28th to March 2nd, 2023, as well as May 14th 2024, covering outdoor temperatures between 1 and 25 °C.

Wood cribs of spruce sticks with 75% porosity were built on steel platforms resting on four load cells (force sensors measuring weight) each with a resolution of 0.13 kg (the smallest detectable change in mass) (Table 1). For the larger (and elongated) tests, only a portion of the cribs rested on the load cells and the rest of the fuel pack (constructed identically) was assumed to burn equivalently. Sticks were randomly tested for moisture content (mc) and density. Thermocouples were inserted in the top layer of each crib and the fire was monitored with visible and IR video imagery to define the temperatures on and around the fires.

Tests 1, 3, 4 and 5 exhibited full flaming combustion during satellite overpass whereas Tests 2 and 6 constituted the glowing and smoldering combustion after Tests 1 and 5 during next satellite overpasses. To mimic the common situation of a small surface fire next to one torching spruce or residue pile, we added additional fuel to the hot charcoal of Test 7, such that limited flaming occurred as well as a fully flaming crib of 286 kg (Fig. 5).

Combustion heat release rates (HRR) were calculated from the mass loss rates of the timber and its moisture content,

$$HRR = \Delta H_c (1 - mc)^{-1} \times \partial m / \partial t, \quad (1)$$

with assumed heat of combustion $\Delta H_c = 17 \text{ MJ kg}^{-1}$, corrected for moisture content (mc) and the time derivative of mass (m). Note however that a hot area even without any combustion will exhibit radiant losses and thus also contribute to FRP.

The fires covered varying characteristics from hot glowing char of only 300 kW combustion to vigorously flaming at 100 MW. Temperature distributions were calculated from the IR imagery where three areas ($A_1 - A_3$) of higher than ambient temperatures ($T_1 - T_3$) were defined at the exact time of the satellite overpass (Fig. 5). During glowing combustion, the temperatures were cross-checked against the inserted thermocouples.

The spectral intensity at a satellite sensor from a fire pixel of area A_p and ambient temperature T_{amb} was thus approximated as

$$I_\lambda^{Est} = B_\lambda(T_{amb})A'_p + \sum_{i=1}^3 B_\lambda(T_i)A_i \quad (2)$$

where $B_\lambda(T_i)$ is the spectral radiance for black body temperature T_i at wavelength λ according to Planck's law, and A'_p the pixel area excluding the area of the fire.

Since I_λ^{Est} can be estimated from the definition of the three fire areas, the expected pixel brightness temperature observed by a satellite (neglecting atmospheric absorption) could be estimated as

$$BT^{Est} = \frac{hc}{\lambda k_B} \frac{1}{\ln \frac{2hc^2}{\lambda^5} \frac{A_p}{I_\lambda^{Est}} + 1} \quad (3)$$

where h is Planck's constant, c the speed of light in vacuum, λ the central wavelength of the detector, k_B Boltzmann's constant. FRP was calculated from the same areas and the measured thermocouple temperatures assuming a char emissivity of 0.5 (range 0.3–1, for uncertainty estimation) and a flame emissivity of 0.5 (range 0.4 – 0.8) (Panahi et al., 2019-09; Schiemann et al., 2019-11-15).

The on-ground estimated cell temperature, combustion HRR and FRP were thereafter compared to the co-incident observed satellite measurements, regardless if the satellite signal resulted in an active fire after post-processing or not.

4. Results

4.1. Operational performance

The VIIRS-AF algorithm produced around 5500 active fires signals yearly over Sweden during 2022–2024. However, on average around

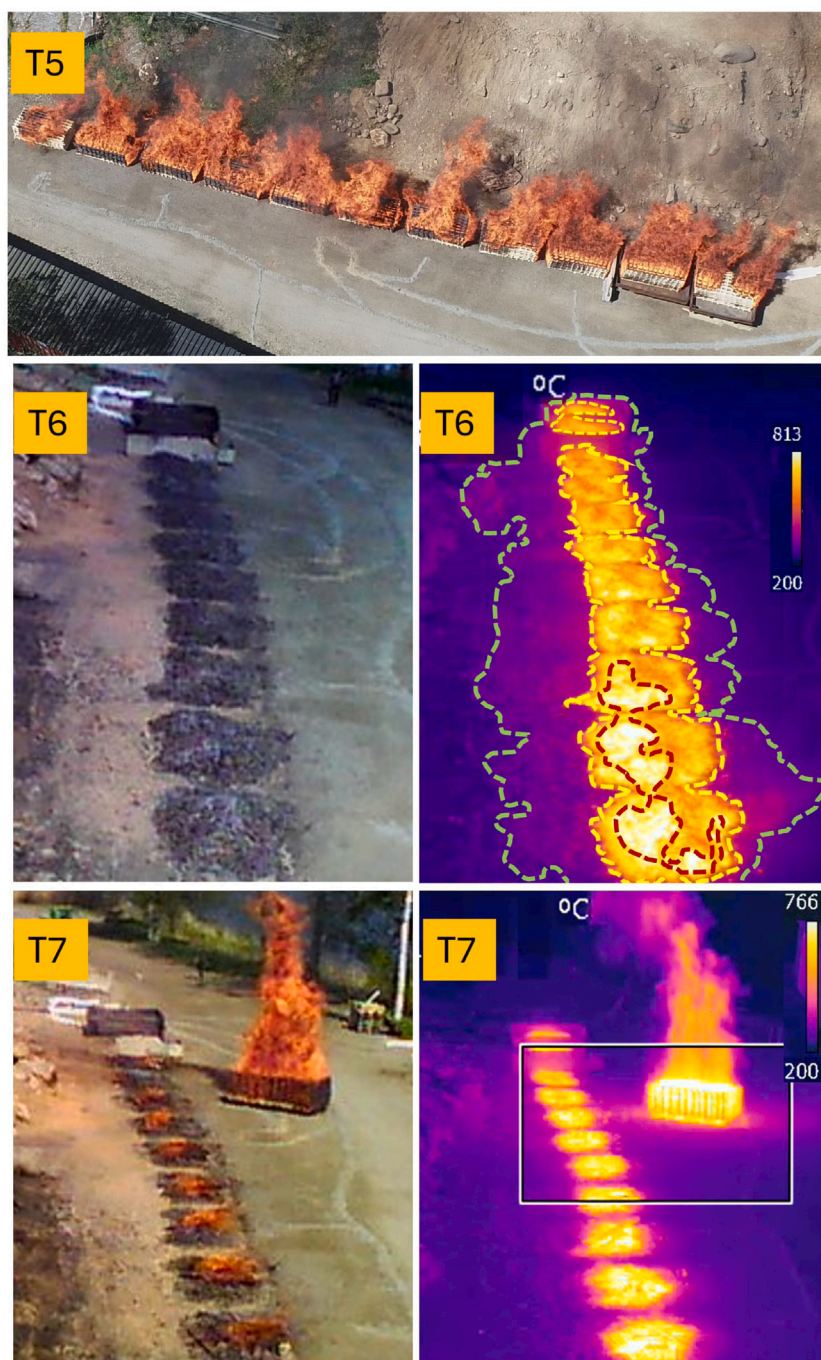


Fig. 5. Drone footage of Test 5 and visible and IR-images of Test 6 and 7. The three areas (green, yellow and red dashed lines) for defining temperature areas are shown for Test 6 (IR).

90% of these get caught in the geographical filter mask. During 2023 and 2024, the spatio-temporal filtering and the interface to the national emergency call and dispatch center was in place. A total of 539 (503) detections during 2023 (2024) then resulted in 245 (266) unique alarms sent to SOS Alarm.

The end-to-end latency, calculated as the time delay from the satellite observation to an alarm that first responders could act upon, was on average less than 17 min, see Fig. 6. This was the average sum of the processing times spent in each of the sequential steps (Fig. 2) from raw data acquisition to output and alarm to the national emergency call and dispatch center. The CSPP VIIRS SDR processing was most computationally demanding, responsible for more than 80% of the time delay.

4.2. Natural fires

While 2022 was a normal fire season, both 2023 and 2024 were unusually wet during the high summer and exhibited lower than average number of wildfires. In total, 1487 satellite detections were nevertheless registered, mainly during the dry periods, fairly evenly distributed between the years.

These detections corresponded to 627 distinct events, of which ~78% were verified fire events, ~11% unknown and ~12% were identified as non-fire events that ideally should not have triggered an alarm, see Fig. 7. Of the 74 non-fire events, 50 were attributed to sun glint, and the remaining 24 were detections from hot industrial activities not filtered out by the static geographical mask.

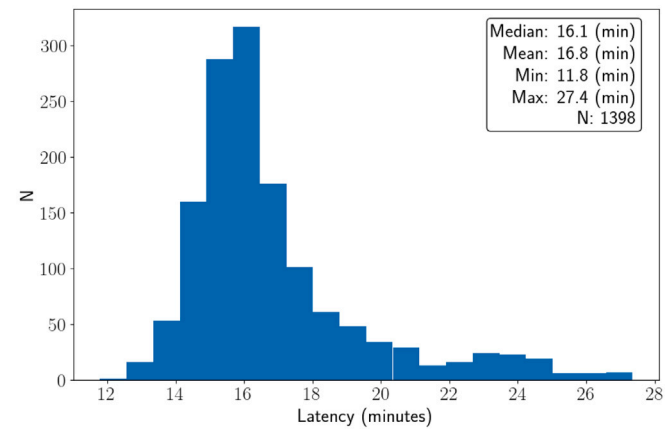


Fig. 6. Histogram of the end-to-end latency, measured as the time delay between observation and reception of alarm on the end-user side, of all active fire detections passing the post-processing step. Data from a period of more than 4 years, June 12, 2020 till end of 2024.

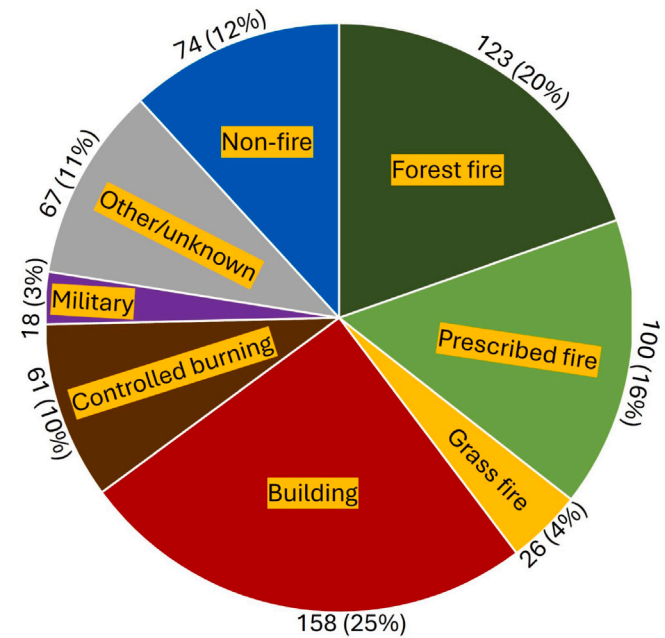


Fig. 7. The 627 incident between 2022 and 2024 resulting in active fire registration from the satellites broken down into categories of origin.

The VIIRS-AF algorithm includes tests to minimize the amount of false detections due to sun glint reflections in the mid-ir channel, occurring over small water bodies via the spectral profiling approach (Schroeder et al., 2014). However, sun glint reflections may also occur on large tilted non-natural objects. During 2022–2024 three types of tilted objects were identified causing false detections; large metal farmhouse rooftops (20), large greenhouses (16) and large arrays of solar panels (14).

Of the 120 verified forest fires, 72% were limited to burning forest floors, while 28% also involved buildings or piles of forestry residue. These structures or residue piles were either ignited by the wildfire or served as its point of origin. The building fires were dwellings (39%), barns (28%), industries (6%) and the rest cottages, outbuildings or deserted buildings. The controlled burns were situations where burning of grasslands or forest/garden residues were performed and either notified in advance to the fire and rescue services or judged to be safely executed once the dispatch arrived at the scene.

Table 2

Key values from the satellites during passage and on-ground estimated instantaneous properties of the fires.

Nr	Satellite detections			Estimated test values		
	FRP	BT(I4)	ΔBT_{45}	HRR ^d	FRP ^{Est}	BT(I4) ^{Est}
1 ^a	56 kW	285 K	9.3 K	8000 kW	96 kW	281–284 K
2 ^b	138 kW	287 K	7.7 K	300 ^e kW	360 kW	295–298 K
3 ^a	8000 kW	308 K	31.9 K	10 000 kW	711 kW	308–311 K
4 ^a	731 kW	314 K	37.6 K	39 000 kW	915 kW	313–316 K
5 ^a	2887 kW	331 K	34.5 K	100 000 kW	1604 kW	329–338 K
6 ^b	1686 kW	322 K	27.4 K	3000 kW	1013 kW	318–331 K
7 ^c	1539 kW	313 K	32.9 K	20 000 kW	852 kW	316–328 K

^a Flaming combustion.

^b Smouldering combustion.

^c Flaming and smouldering combustion.

^d Based on mass loss rate and 17 MJ/kg for wood.

^e Based on estimates of residual weight due to a load cell malfunction.

Among the fires that required a dispatch, the system managed, in 24% of the cases, to notify the alarm center before the fire was notified by any other means. Sorting only for wildfires the fraction increases to 29%.

To assess if controlled and accidental forest fires were detected differently and what role the forest characteristics played, we studied the 41 events during 2023 with the highest pixel temperatures in more detail. 20 of them originated from wildfires and 21 from prescribed burns. The highest 14 brightness temperatures were found in areas with little or no trees. The difference between the satellite observed pixel brightness temperatures and the estimated ones based on the surface fire extent during detection, exhibited a dependence on basal area. For clear-felled areas or severely thinned stands, the fire models underestimated the VIIRS I4 brightness temperatures compared to that obtained from the satellite data. For stands with normal basal areas ($> 12 \text{ m}^2\text{ha}^{-1}$) the fire models instead overestimated the temperature compared to the satellites (Supplementary, Figure 3 top panel). This dependence was similar for both wildfires (which mostly spread downwind) and prescribed fires (which mostly spread against the wind).

Fig. 8 shows detections and Sentinel-2 MSI imagery of a wildfire during 2023, which serves as an example of spatial-temporal filtering of detections to unique alarms. This fire was well captured by several VIIRS scenes from its start around noon June 12, through its westward spread to the final burnt area of 75 ha during the night of June 13. The fire was first registered (not by VIIRS) at the national emergency call and dispatch center at 10:15 UTC. The first VIIRS detection (from S-NPP) at 10:44 UTC led to a registered alarm to SOS Alarm at 11:02 UTC, centered over Lake Fagrasjö (see panel b, Fig. 8) next to the bright fire spot from Sentinel-2 in panel a.

The alarm filtering of the 20 satellite detections over 2 days resulted in three more alarms. One was for a S-NPP detection some 1.3 km to the west at 12:25 UTC (the westernmost detection in panel b), exceeding the 1200 m threshold for grouping. Then again, due to the 6 h time threshold for spatio-temporal alarm filtering, two new alarms were triggered for detections at 00:35 UTC the next morning by S-NPP, for the eastern and western parts, respectively (Fig. 8 panel d).

4.3. Experimental fires

Only one of the wood crib fires, Test 5, fulfilled the criteria for active fire detection (Schroeder et al., 2020). No other test induced a channel I4 brightness temperature surpassing the criterion of 325–330 K (depending on background temperature), see Table 2. On the other hand, ΔBT_{45} exceeded 25 K for all flaming tests except the smallest (Tests 1) and also for the almost 40 m² large, but strictly smouldering Test 6.

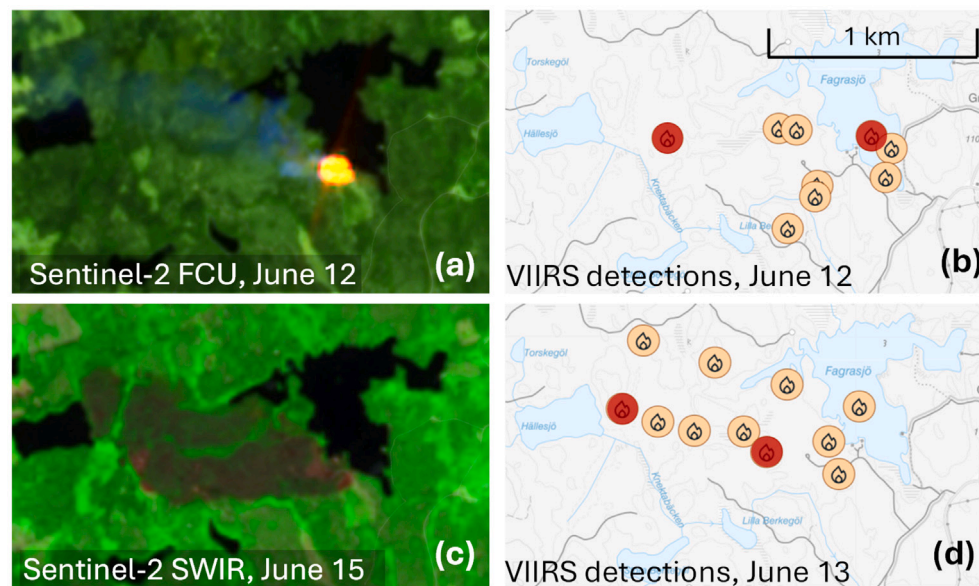


Fig. 8. Example of a fire in Nybro, southeastern Sweden, June 2023. (a) Sentinel-2 image with the wildfire filter (Markuse, 2017) shortly after initial spread, June 12th at 10:15 UTC. (b) VIIRS detections, June 12th by Suomi-NPP at 10:44 UTC and NOAA-20 at 11:33 UTC. (c) Final damages at June 15 from Sentinel-2 Short Wave Infrared RGB Composite (SWIR). (d) VIIRS detections during the morning of June 13th. Red detections indicate those generating an alarm. (Panel b and d: Background map by Lantmäteriet ©).

The detected FRP were orders of magnitude smaller than the total heat release rate based on mass loss, Fig. 9a. However, the $BT(14)^{Est}$ estimated from IR imagery matched the satellite results almost within estimated ranges. The agreement was fair even for events far from the active fires criteria and for a span of almost 50 °C in cell temperature, Fig. 9b. Also the FRP (estimated from IR and ranges of emissivities for char and flames) matched the satellite detected FRP to within an order of magnitude, Fig. 9(c).

5. Discussion

5.1. Operational performance

Approximately half of the incidents recorded during 2022–2024 were actual wildfires or rural building fires that required dispatches from the fire and rescue services, thus situations where rapid response is a priority. Furthermore, 83% of the dispatched alarms originated from fires that the system is expected to detect. Some of these can later be ignored at the dispatch center due to prior knowledge (of e.g. pre-reported burn activities) or when arriving at the scene.

As about 1/4th of the dispatch center alarms from the system arrive before any other means of detection, the system implemented has proven highly valuable in decreasing the time to suppression activities. Response times are generally already very low in Sweden (Sjöström and Granström, 2023a), thus any few minutes gained during detection will impact time to suppression and thus have a high societal benefit, especially during periods of high forest fire danger. Further, as the best VIIRS temporal coverage is found in the north of Sweden (Supplementary, Figure 1) the efficiency of the system is biased towards remote areas. Here the risk is higher that fires go undetected by other means and potentially become more difficult to suppress.

In these sparsely populated areas, increased preparedness during high fire danger periods are otherwise covered by forest fire surveillance flights. During the same period (2022–2024) these flights discovered on average 89 annual fires at a cost of 1.4 M€/year (~16 k€/detection) (MCF, 2025c). By comparison, the present system averaged at 230 annual alarms for real fires at an estimated cost of 50

k€/year (~0.2 k€/detection) (Andersson, 2025). Currently, the limited temporal coverage of VIIRS still justifies using surveillance flights. As satellite coverage improves, flights may be required only when cloud cover is forecasted to obscure satellite viewing.

5.2. Natural fires and false alarms

The verified non-fire events almost entirely occurred during daylight hours and were mostly due to sun glint over large metal rooftops, large greenhouses, and large solar power plants. In theory, all these non-fire events could be avoided via the static mask implemented in the current system, provided continued high and stable VIIRS geolocation accuracy. However, this requires well-known positioning of buildings and facilities present in an accessible and regularly updated database, and that the mask is accordingly continuously updated, Fig. 3.

In practice, however, national databases may not always be kept up to date. This is well illustrated by the emerging sustainable energy sector, where several large solar power plants have appeared as a false fire alarm in our system before entering the national public databases. With apriori knowledge of the slope and orientation of these large structures it would be straightforward using the actual sun-satellite viewing geometry to know if sun glint is likely occurring, information that could be passed to the end users. But, in practice, the possible variations of slopes and orientations are probably too wide in order for this to provide real added value.

Masking out the positions of all barns with sufficiently large metal roofs would also limit detection of wildfires in their proximity. We have seen several examples, mainly during the night, where the satellite system is first to issue an alarm of an ongoing barn fire. While early detection of remotely located farmhouses may not suffice to save the structure itself, it plays a pivotal role in preventing further spread (Plathner et al., 2025). Currently the mask is applied all the time, but disabling the reflective part of the mask during nighttime could constitute a significant improvement.

The decreasing cell temperature and FRP with increasing basal area indicate obscuration of radiation from canopies. However, this dependence could also indicate different burning behaviors due to

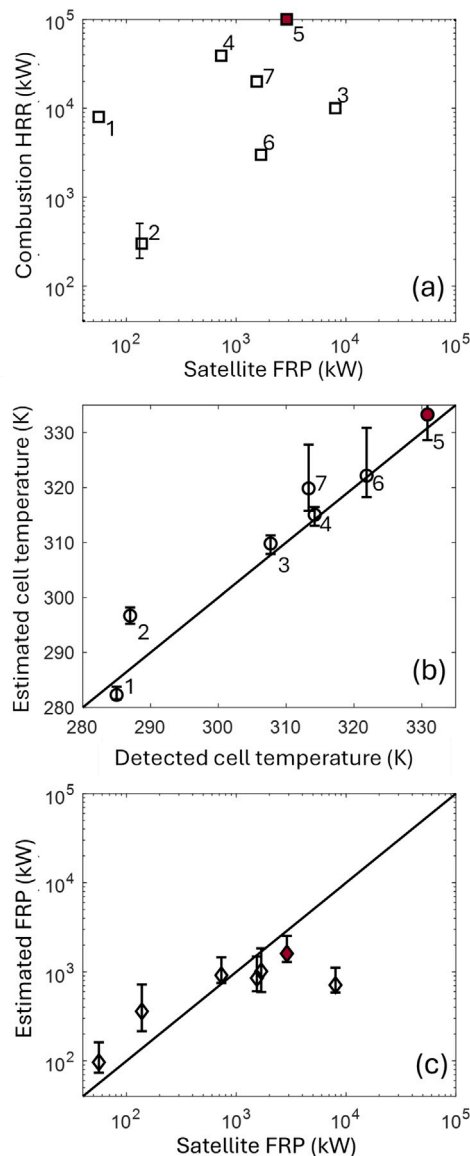


Fig. 9. (a) Experimental HRR (derived from mass loss rates, assuming 17 MJ/kg) against satellite registered FRP. (b) Estimated pixel temperature $BT(I4)^{Est}$ from the controlled fires against the satellite detected pixel temperature. The numbers refer to the test number. (c) Estimated FRP from the temperature logging and IR cameras against satellite registered FRP. The red markers represent the detection that passed the criteria for active fire.

increased solar radiation through the canopy or increased surface wind speeds (Tirén, 1924). Likewise, on fertile soils, increased sunlight would yield a higher herbaceous fuel component, reducing intensity and rate of spread except during the early spring season (Hedwall et al., 2013).

5.3. Validation against experimental fires

We confirm a good technical performance of the VIIRS geolocation accuracy, fire detection sensitivity and calculated pixel temperature compared to the well-defined and non-obscured experimental fires. Even pixel temperatures well below the BT_4 detection limit agree within reasonable limits with the on-ground estimations from IR imagery. The location of the tests were for Test 5 to 7 very close to the pixel boundary and considerable spill-over could be found for adjacent pixels. This could potentially have decreased the detected

pixel temperatures (c.f. Test 7 in Fig. 9), most of which nonetheless are within the reasonable interval estimated from on-ground assessment. The location of the verified fires were always within the detecting pixel, and this has been highlighted as one of the strengths of the operational system. Incident commanders frequently highlight that localization from satellite detections is used even when this information arrives after the fire crews have already departed from the station (Andersson, 2024). Localization is often one of the most difficult tasks in the initial attack, and a few hundred meters accuracy provides considerable improvements for the dispatch personnel (Aguilar, 2021-07-16).

While the temperature and the HRR of the experiments are relatively well known, estimating FRP is more challenging. This is because the total radiation from wildfires is difficult to quantify, partly because intensity estimates based on Byram's equation (Byram, 1959) are often crude. Further, radiation from flames is not isotropic but varies with direction depending on flame geometry, while satellite sensors typically measure it in one direction only.

Most of the combustion HRR goes into convective heating of large gas volumes, with only a minor fraction lost through radiation. Examples of reported radiant fraction include 0.12 for bio fuel in lab (Freeborn et al., 2008) and 0.20 for field-scale wildfires (Knight and Dando, 1989). Fractions for wood cribs vary with size, but is often cited as 0.21 (McCarter and Briodo, 1965). By comparing HRR and FRP based on temperature measurements, our tests suggest an even lower energy fraction lost through radiation.

All tests presented here generated a satellite FRP well below the mass loss based HRR (Fig. 9), as expected from fires where most of the energy is transferred to heating gasses. On the other hand, even non-combusting but still hot surfaces will generate a non-zero FRP. Thus, the temperatures and areas caught by IR imagery serves as a more reliable estimate of FRP compared to a fraction of HRR. The range of surface-estimated FRP from temperature imaging and the FRP estimates from VIIRS were within one order of magnitude, which is significantly worse than the cell temperature estimates.

The active fire algorithm requires that the I4 brightness temperature surpasses both an absolute threshold of between 325 and 330 K and a relative difference against the I5 channel of 25 K. All except the two smallest of our tests passed the relative criterion with a margin but only the largest test (5) passed the absolute criterion. Many wildfires in Sweden occur during the early spring with a rather cold background (Sjöström and Granström, 2023b). Tests 1 to 4 were conducted in just $\sim 1-4^\circ\text{C}$ and the background temperature clearly decreased the satellite detected pixel temperature.

There might therefore be room for local optimization of the active fire algorithm, possibly by replacing the strict thresholding approach and use a more flexible concept. One suggestion is to allow for a decrease of the absolute $BT(I4)$ threshold with increasing ΔBT_{45} . However, given the limited experimental basis of 7 experiments, this would need to be preceded by a validation to wildfires. Any such alterations of criteria must also be checked against a possible increase in false alarm ratio before implementation.

5.4. Scalability and lessons learned from implementation

The system is developed for and evaluated over Sweden, but can most likely be expanded to countries with similar landscapes and climate. A first step in this direction has just been initiated via a development project between the national meteorological services of Norway, Finland, Estonia and Sweden with funding from Nordic Forest Research (SNS) (SNS, 2025). However, nothing in the method or validation approach hinders its application to other regions beyond Fennoscandia, with different landscape and vegetation characteristics. Nevertheless, some system limitations must be addressed.

The static mask removes around 1 km^2 for each point. Thus, for regions with scattered industries and widespread urban areas the relative fraction of land covered by the system would be small if not risking

increasing the number of false alarms. However, in such regions the need for an automatic space-based detection is presumably low.

The characteristics of the polar orbiting satellites implies increasingly better coverage closer to the poles, and therefore greatly favoring higher latitude applicability of this system. Each individual VIIRS satellite pass over Sweden 4–6 times a day but a point around the equator is covered only twice daily. Thus, for e.g. the South American Chiquitano and Pantanal regions, severely affected by wildfires during last season (Kelley et al., 2025), the system presented here will give good coverage only around one hour twice a day just after local midnight and noon (Supplementary, Figure 2). Over Romania, with frequent severe spring fires, the coverage increase with two 2-hour windows a day (Supplementary, Figure 2), increasing the benefit-cost ratio implementing a system like this one. South Africa, also frequently hit by intense wildfires, have latitudes less favorable for coverage by polar satellites than in Europe. However, the Advanced Fire Information System (AFIS) very recently added a 30 min fire detection capability for VIIRS active fires over South Africa (AFIS, 2025) indicating that a VIIRS based system is considered giving added value there. Additionally, for other regions where fires can occur even in cold backgrounds, a more nuanced approach to the absolute criterion for active fires might be required as discussed above.

The system for Sweden took advantage of already available infrastructure to acquire and process VIIRS data in real-time via the DR station at SMHI. Adding the hotspot detection via the CSPP-AF EDR processing in real-time was quick. It was running in operational test-mode one year after the severe 2018 season that triggered the development. In 2020 the first Pytroll-based processing pipeline including post-processing and end-user notifications via SMS and e-mail was running in test. Most of the development prior to the operationalization of the system in 2022 was devoted to evaluation, user-interaction, understanding the false alarms and fine tuning the mask filtering. During 2022 the spatio-temporal alarm filtering was developed in collaboration between the Swedish Civil Defence and Resilience Agency, SOS Alarm and SMHI.

With existing real-time VIIRS access via an operational DR station or network of such, setting up the same system elsewhere should be straightforward. We estimate that it can probably be achieved within the order of around 10 person-months of work. It can build upon the open source Pytroll tools using the already developed and openly available framework (Dybbroe and Raspaud, 2025). Thus, the main challenges for successful local implementation is likely to create an adequate local filter mask, engage with and learn from the end-users and establish the interface to the national emergency dispatch center.

For Sweden, the static mask was easily obtained through detailed public maps (Lantmäteriet, 2025) but for regions with less detailed records, globally available datasets of buildings, e.g. Microsoft Building Footprints (Microsoft, 2022), would probably be a sufficient start. The dynamic part of the mask requires regular updating, for Sweden not necessary more than once a year. Another lesson from the Swedish implementation is the importance of early engagement of end-users (here municipal fire and rescue services) for participation in evaluation and to maintain communication regarding both benefits and limitations of the system. Many updates of the dynamic mask and the final usage of the alarms stem from direct feed-back from fire and rescue services.

Access to low-latency data is essential for this service. The global network of Direct Readout stations (WMO, 2025a,b) provides coverage for most parts of the world with polar-orbiting satellite data delivered within 30 min. Consequently, countries or regions without their own DR station can still obtain timely access to the data. The regional Direct Broadcast Network of services (WMO, 2025a,b) under the World Meteorological Organisation could be enhanced to include fire hotspots in the service portfolio for a low cost along side the existing services traditionally tailored for weather forecasting. For instance, the entire Europe from Ural and Caucasus to the Atlantic are covered by the European Advanced Retransmission Service (EARS, 2025) including

VIIRS M-band radiance data as a service, labeled EARS-VIIRS. A potential future service delivering VIIRS fire hotspots with latency below 30 min could provide data directly to EUMETSAT Member States for integration into this system.

6. Conclusions and outlook

This paper describes a fully automated system, from satellite to alarm, for early detection of Swedish wildfires based on VIIRS data and the VIIRS-AF I-band algorithm (Schroeder et al., 2014). It has been carefully validated both by conducting controlled fire experiments in typical springtime and summer conditions and by analyzing past detections between 2022 and 2024. The satellite based system has proven a valuable complement to the existing means of detection relying on the public and on the forest fire surveillance by small manned aircraft. In 29% of detected forest fire cases the satellites were the first to issue an alarm to the national emergency and dispatch center.

Generally, the system has been very well received by regional fire and rescue services, which we attribute to the following requirements being sufficiently addressed:

1. It is timely, with an average latency around 17 min
2. It is sensitive to relatively small fires
3. There are relatively few false alarms and the geo-location is very accurate — often the precise localization has proven to lower the time to suppression even when the satellite is not the first to detect the fire
4. The areal coverage of Sweden is good as the VIIRS sensor has a wide swath (~3000 km) and a quasi-constant spatial resolution
5. The revisit time of VIIRS over Sweden is fairly good at some parts of the day with currently 3 spacecrafts operating

An obvious limitation of the system is the large gaps in observation coverage during late afternoon and early evening, where fire danger typically peaks. This gap is potentially partly mitigated with the introduction of the EUMETSAT Metop-SG A-series of satellites. The first satellite (Metop-D) launched August 13, 2025. Once operational, these resources will add coverage over northern Sweden from early evening, near peak hours for typical slow detection fires such as those from lightning strikes (Sjöström and Granström, 2023a) (Supplementary, Figure 1). However, the METImage horizontal pixel resolution is inherently less sensitive than VIIRS, Fig. 1. At nadir a 1100 K fire has twice the detectable size by METImage compared to VIIRS, see Fig. 1b. METImage sensitivity also decrease faster with swath angle. While METImage requires an area of 900 m² for detection of a 900 K fire throughout its entire swath, VIIRS only requires 150 m² for the same swath width.

However, this comparison and argumentation is based on the formulation of the existing VIIRS-AF algorithm and not considering any radiometric aspects of the two sensors. It may well be that a future METImage (as well as VIIRS) active fire algorithm can be made more sensitive without compromising the false positives significantly.

The system is not limited to Sweden or the Fennoscandian region and can be implemented elsewhere, provided access to VIIRS or VIIRS-like data with sufficient latency. Implementation of the system is comparatively fast and cost efficient once the space assets (like VIIRS) are flying and data freely available in real time. However, given the evolution of Earth Observation (EO) systems, either via the international space agencies like EUMETSAT or via the emerging New Space sector, it is advisable to make the system interoperable with data from different satellite sources, not only VIIRS.

CRediT authorship contribution statement

Adam Dybbroe: Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Johan Sjöström:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Stefan Andersson:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Anna Jansson:** Writing – review & editing, Formal analysis. **Robert Svensson:** Writing – review & editing, Investigation.

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

During the final editing and reviewing of this paper prior to submission the authors used online generative AI services, such as ChatGPT, at a few occasions in order to try to improve the English language and the overall readability. At every such use, the authors reviewed and edited the content as needed. The authors take full responsibility for the content of the published article.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.pyro.2026.100004>.

Data availability

The modeled and experimental data will be made available on request.

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