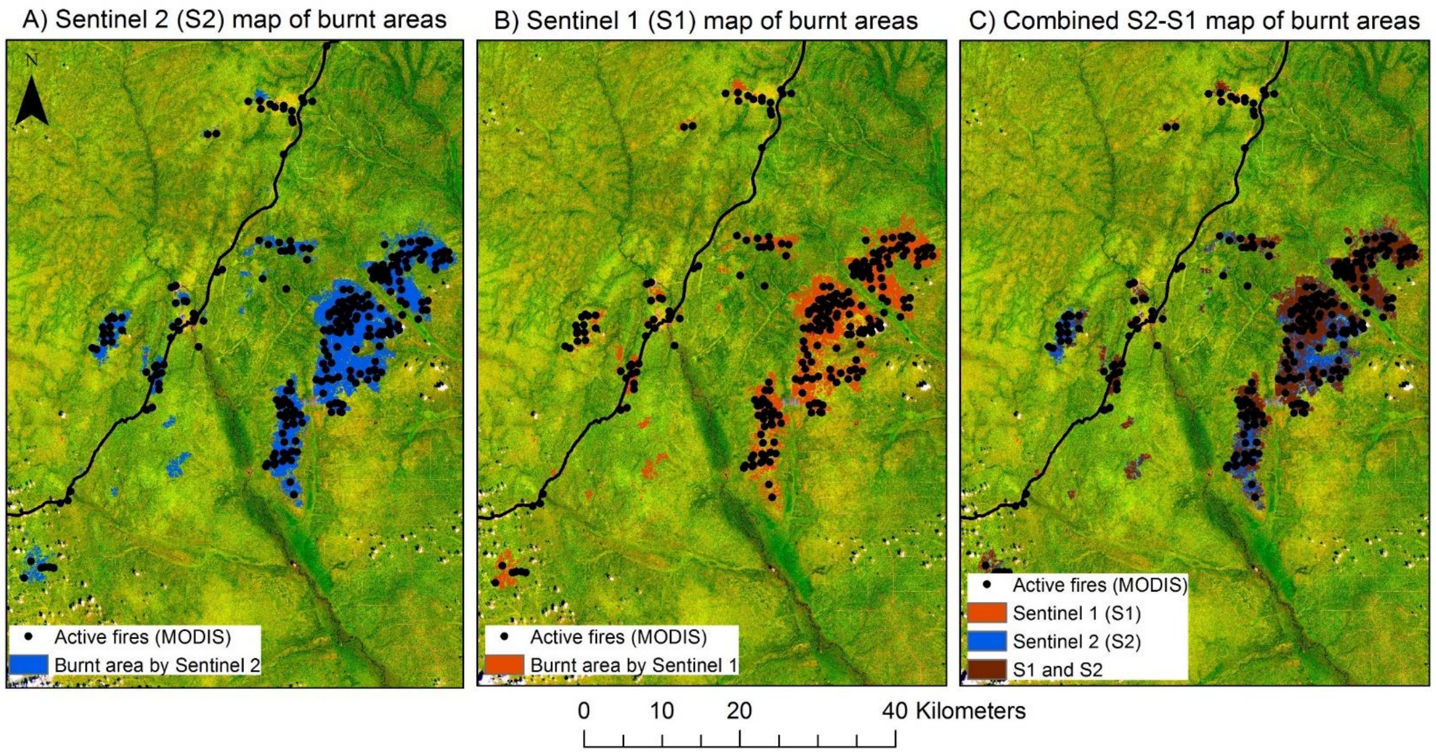
7. SAR and optical remote sensing for mapping wildfires

Wildfires

Research Objectives

- To develop innovative and globally applicable methods for *early detection, near real-time monitoring of wildfires and rapid damage assessment* using Earth Observation (EO) big data and deep learning
- Combining SAR and optical Remote Sensing

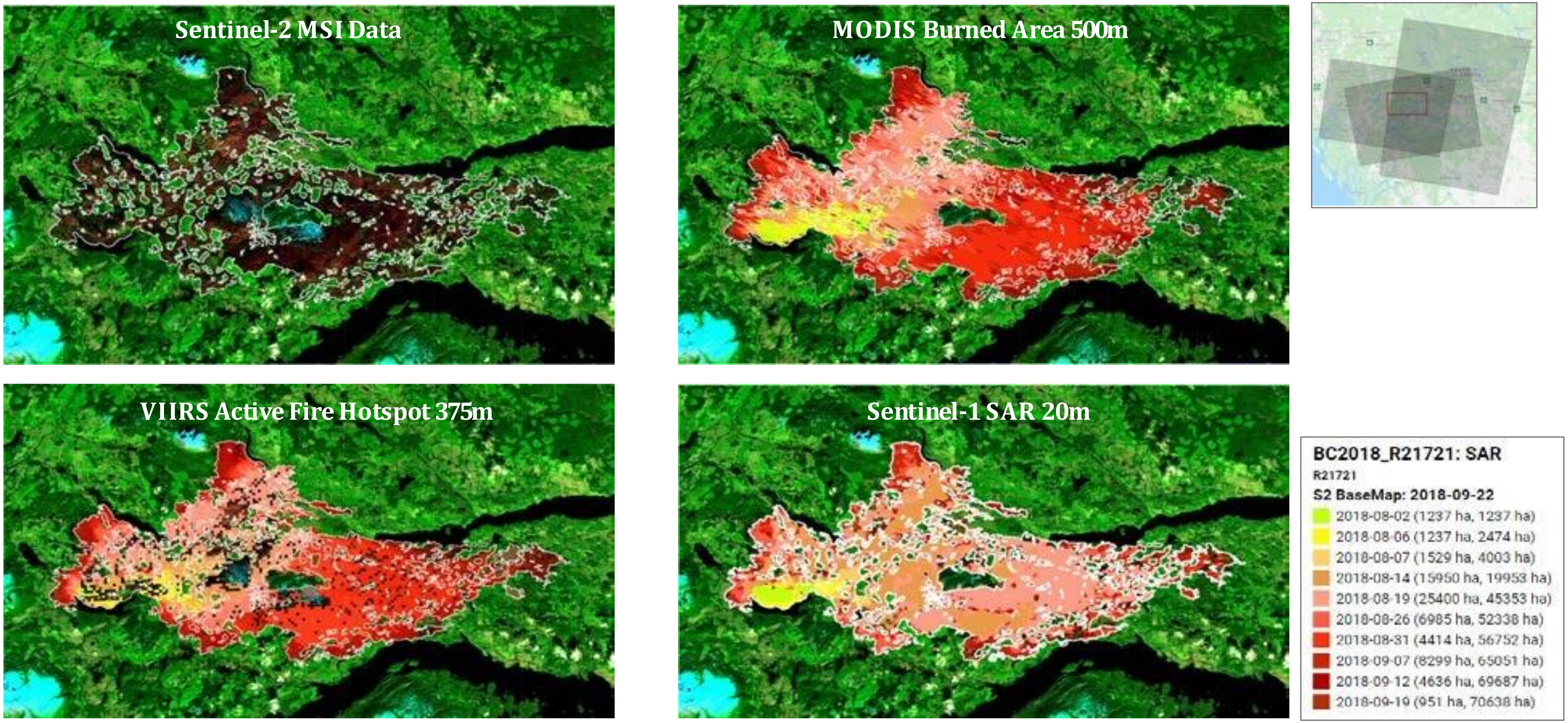


Spatial coherence in the location of the burnt areas as detected by Sentinel-2A (A) and Sentinel-1A (B) and MODIS active fire product (black dots). The map on the right (C) combines Sentinel-2 and Sentinel-1 based maps. Sentinel-2 data are in the background.

Comparison of different ESA satellites for detection of wildfires

Comparison of different satellites for detection of wildfires

Comparisons



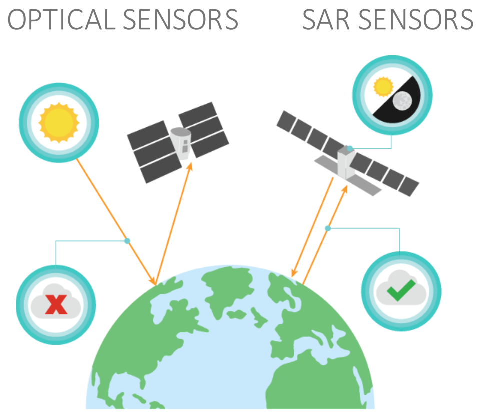
Sentinel-1 C-Band SAR for Detection of Wildfires

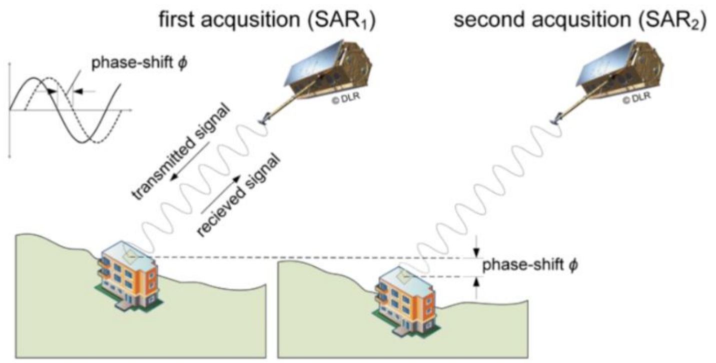
Physical Basis: SAR Data for Wildfire

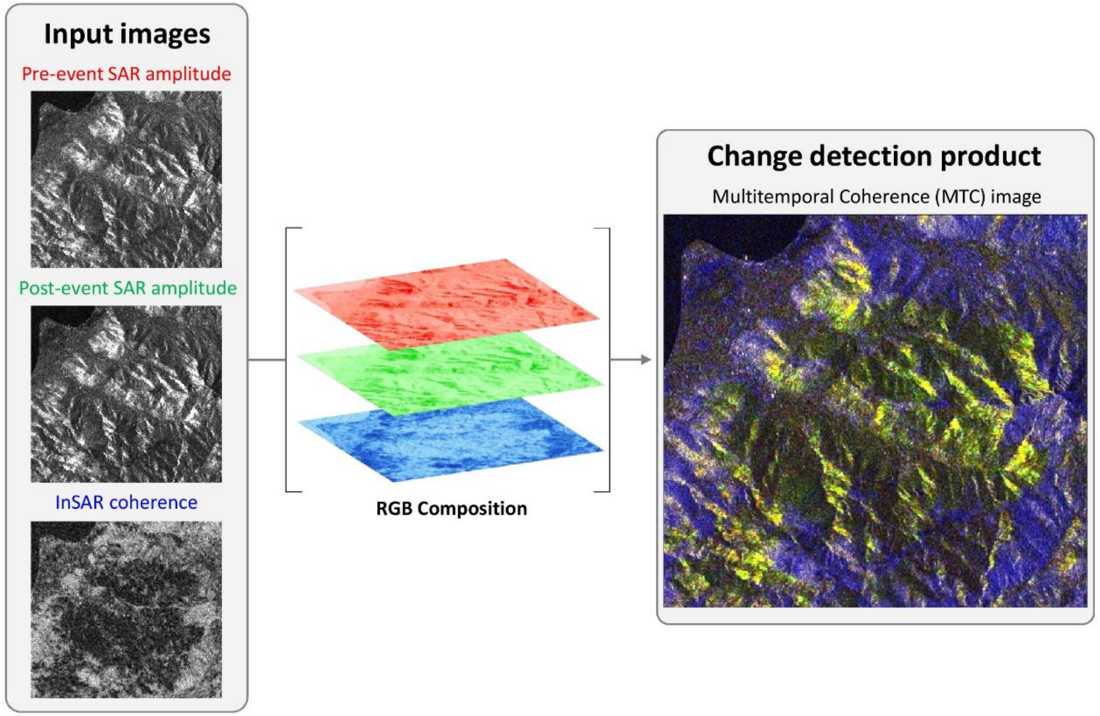
- Synthetic Aperture Radar (SAR) is an active imaging system, it is able to see through smoke and clouds to view changes on the earth's surface → track the fire burn areas while the fire is occurring, even with covering smoke

- SAR collects both intensity and phase, allowing us to track minor surface changes that you can not see with remote sensing data otherwise. In particular, phase can easily pick out areas that were once urban or vegetated that a major change has occurred in.

- Coherence Change Detection is a technique that uses both the intensity and phase to track changes between images.







Sentinel-1 C-Band SAR for Detection of Wildfires

Physical Basis: SAR Data for Wildfire

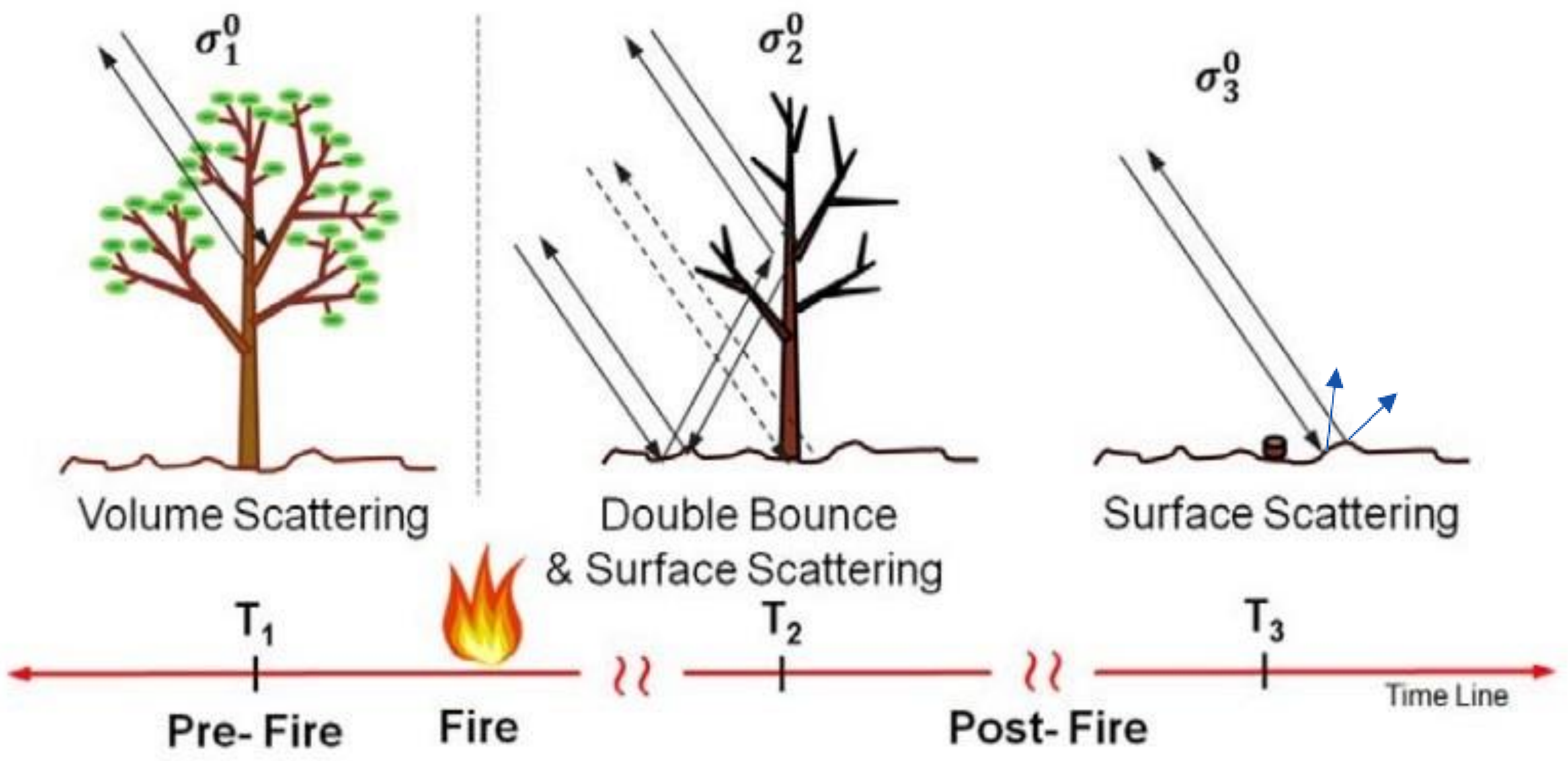
Scene Properties

- Roughness
- Surface Geometry
- Moisture
- Burn Severity

Sensor Properties

- Wavelength
- Polarization
- Incidence Angle
- Imaging Geometry

$$RBR_{xy} = \frac{\gamma^0 \text{postfire}_{\ xy}}{\gamma^0 \text{prefire}_{\ xy}}$$



Sentinel-1 C-Band SAR for Detection of Wildfires

Physical Basis: SAR Data for Wildfire

Examples of SAR imagery supporting BLM wetlands monitoring and wildfire management, respectively.

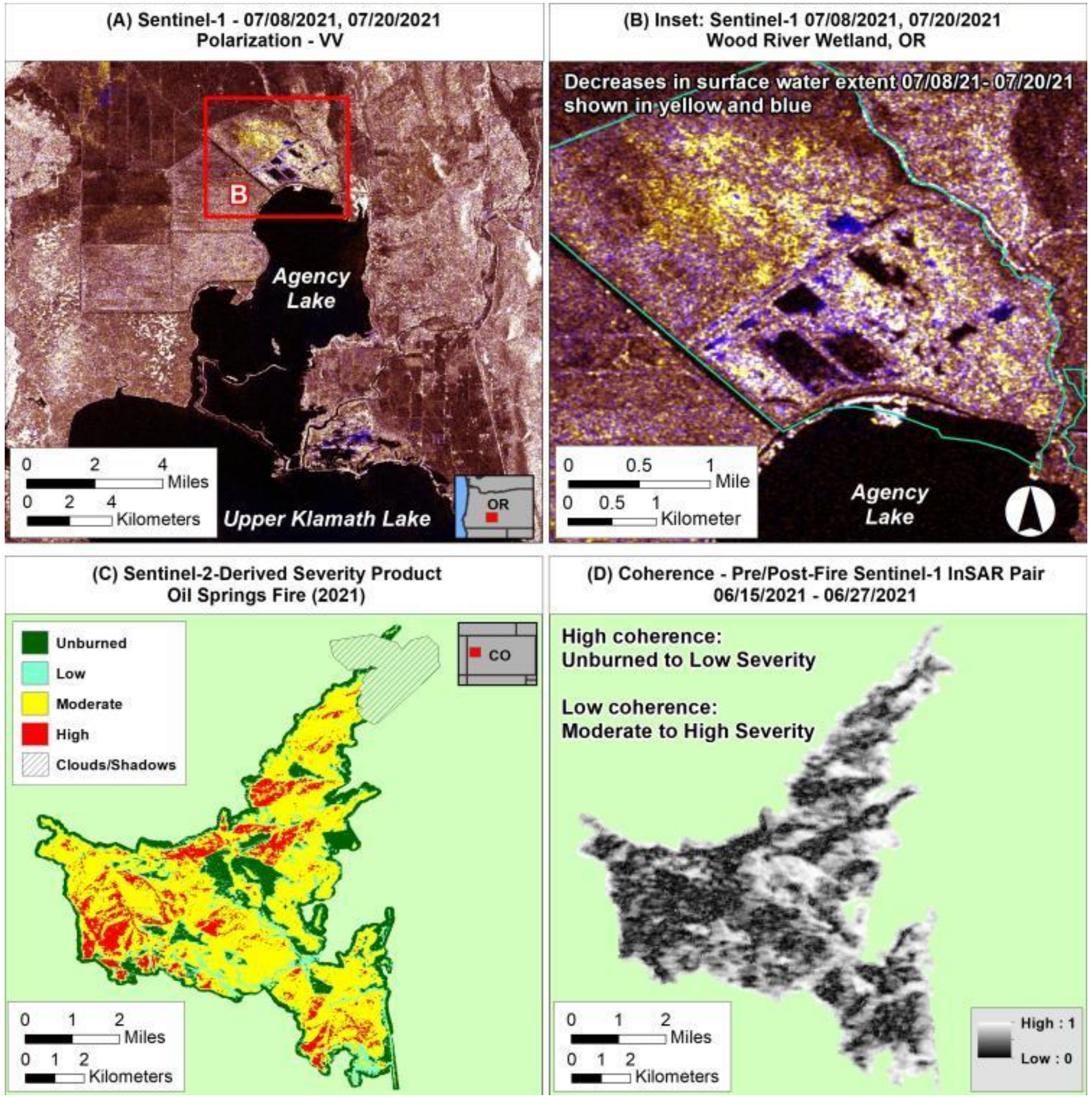
(A) Sentinel-1 image composite of data collected over southern Oregon on July 8 and July 20, 2021.

(B) Inset showing water decreases at BLM-administered Wood River Wetland between these dates at full image resolution. These decreases are identified in water cover with and without inundated vegetation, shown as yellow and blue pixels, respectively.

(C) Severity product for Oil Springs Fire in Colorado, derived from Sentinel-2 electro-optical imagery.

(D) Coherence product derived from pre- and post-event Sentinel-1 imagery using InSAR techniques.

→ SAR products can be useful for post-fire management when electro-optical imagery is unavailable

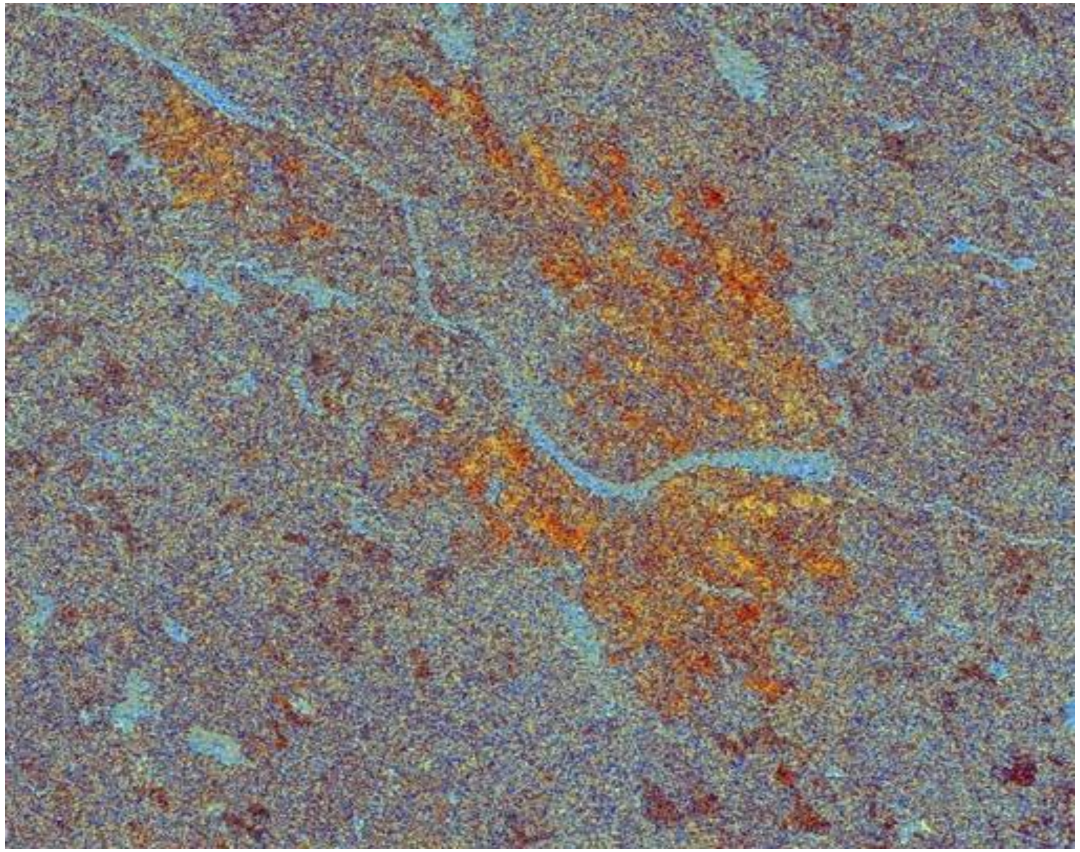


Sentinel-1 C-Band SAR for Detection of Wildfires

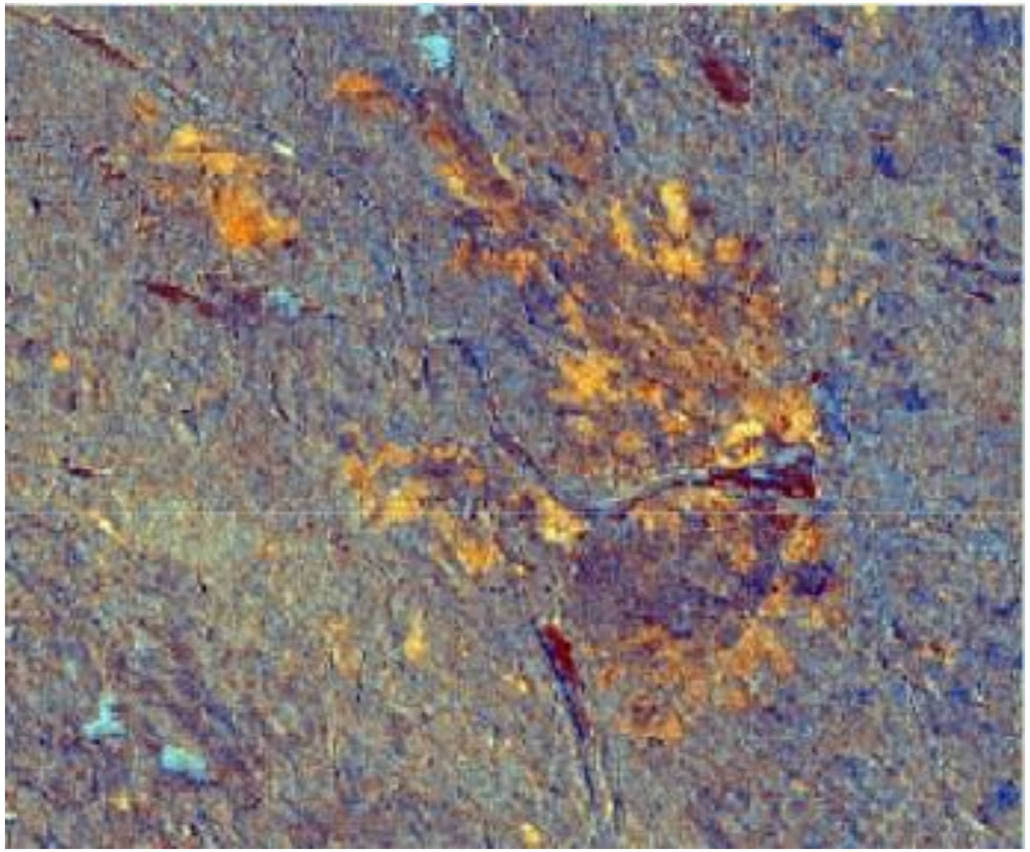
Physical Basis: SAR Data for Wildfire

SAR Detection of Ljusdals-komplexet in 2018

Sentinel-1 C-Band SAR



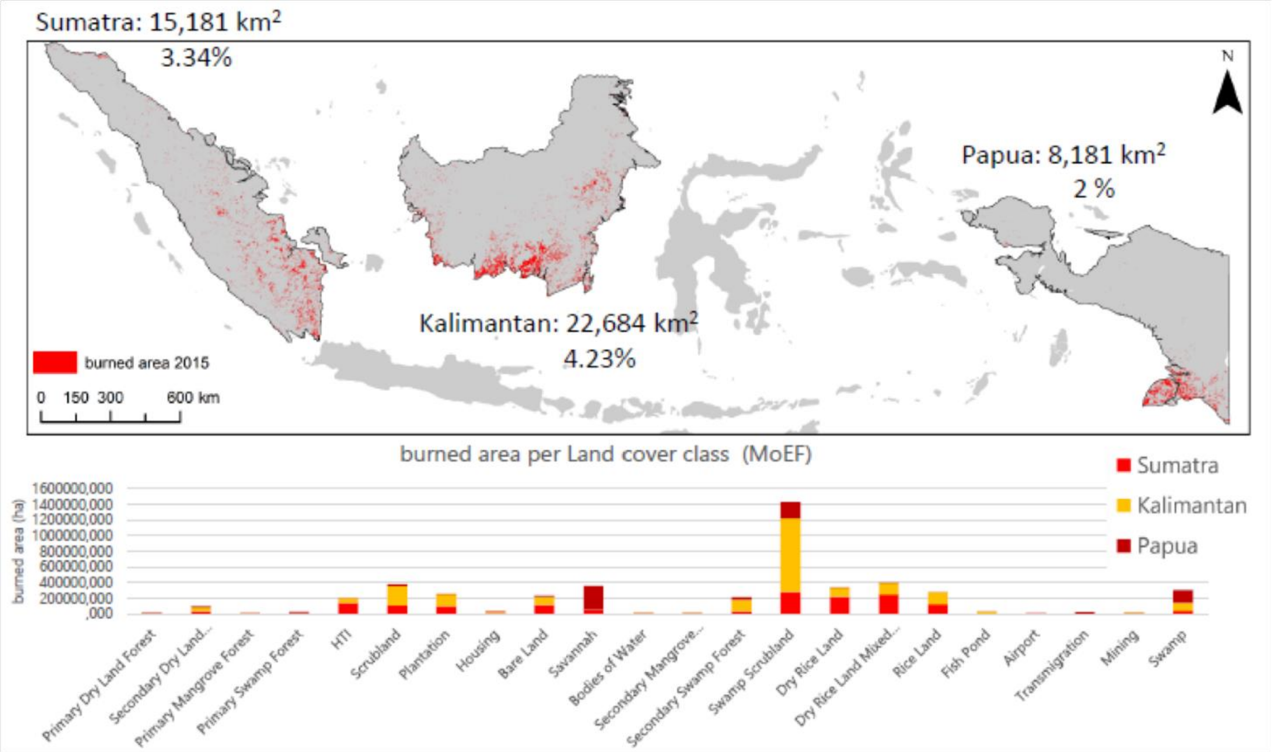
ALOS L-Band PalSAR



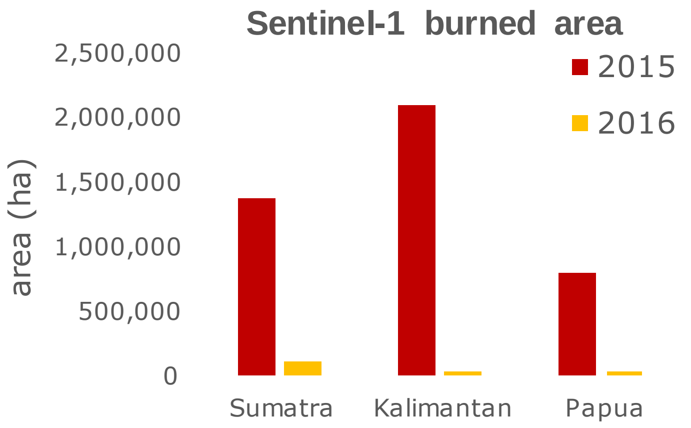
Sentinel-1 C-Band SAR for Detection of Wildfires

Indonesia SAR analysis for 2015-2016

Sumatra 480,000 km² Kalimantan 536,000 km² Papua 320,000 km²



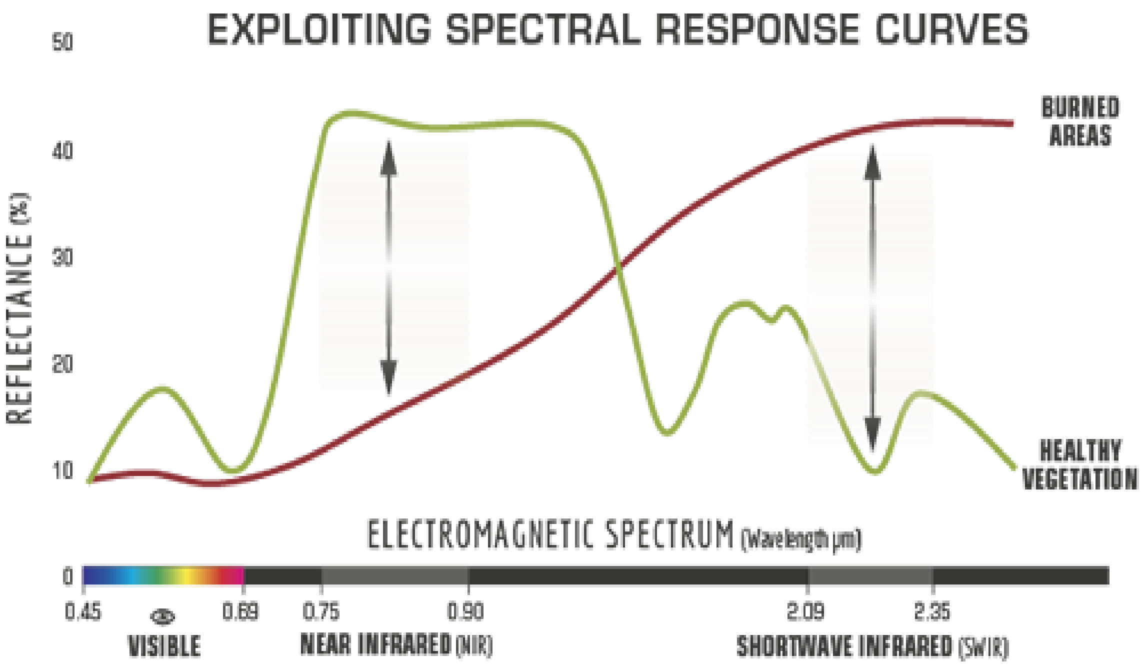
Lohberger et al., 2017

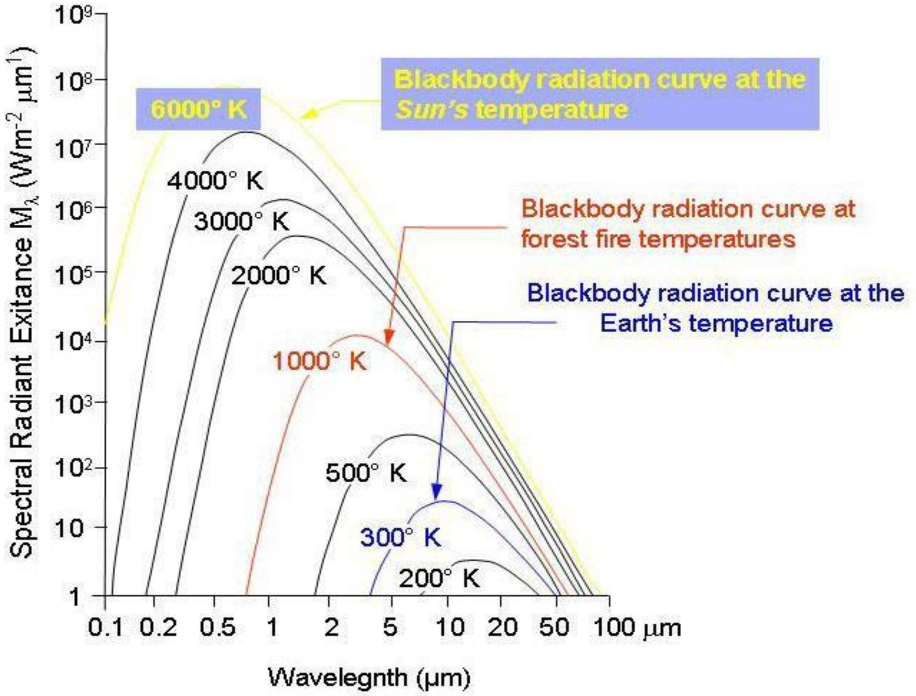


Burned area in ha	Sumatra	Kalimantan	Papua	Total
Year 2015	1,518,127	2,268,352	818,090	4,604,569
Total	1,830,342	2,412,763	865,861	5,108,965

Burning in Indonesia often begins as farmers clear land for crops or grazing animals. Fire that escapes control in Borneo and Sumatra can become difficult to extinguish because of the islands' large deposits of peat—a soil-like mixture of partly decayed plant material that can fuel smoldering fires for months

Sentinel-2 MSI for Detection of Wildfires

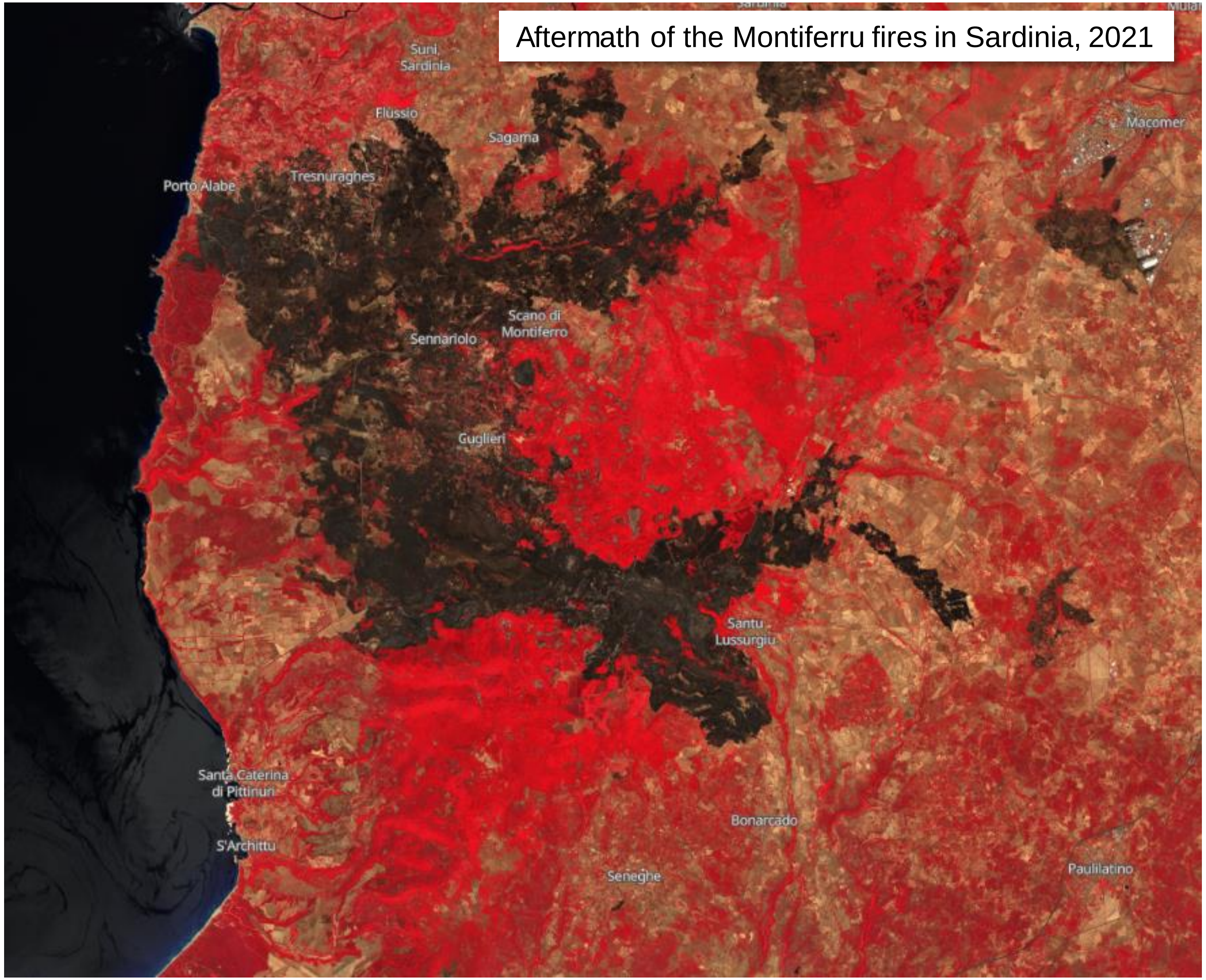




Healthy plant species reflect more energy in NIR but weakly in SWIR. This spectral characteristic is useful for detecting burned areas such as dead soil/plant material on forest floor.

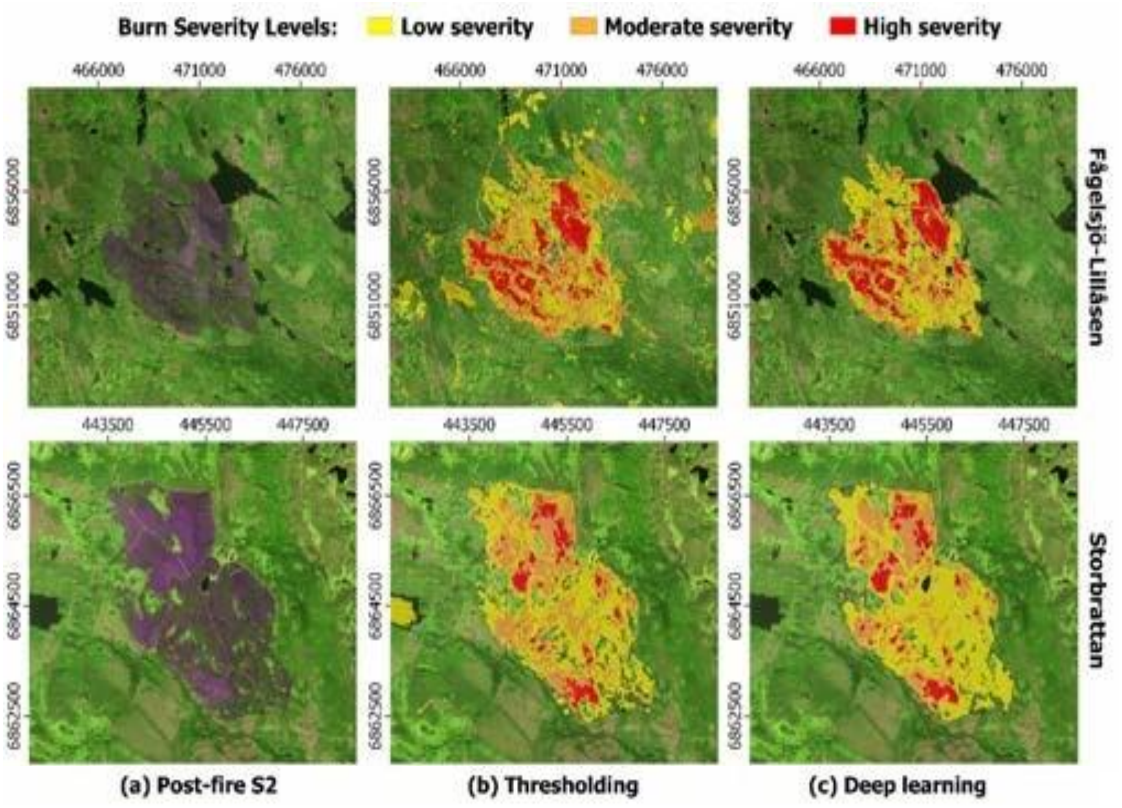
Source: US Forest Service

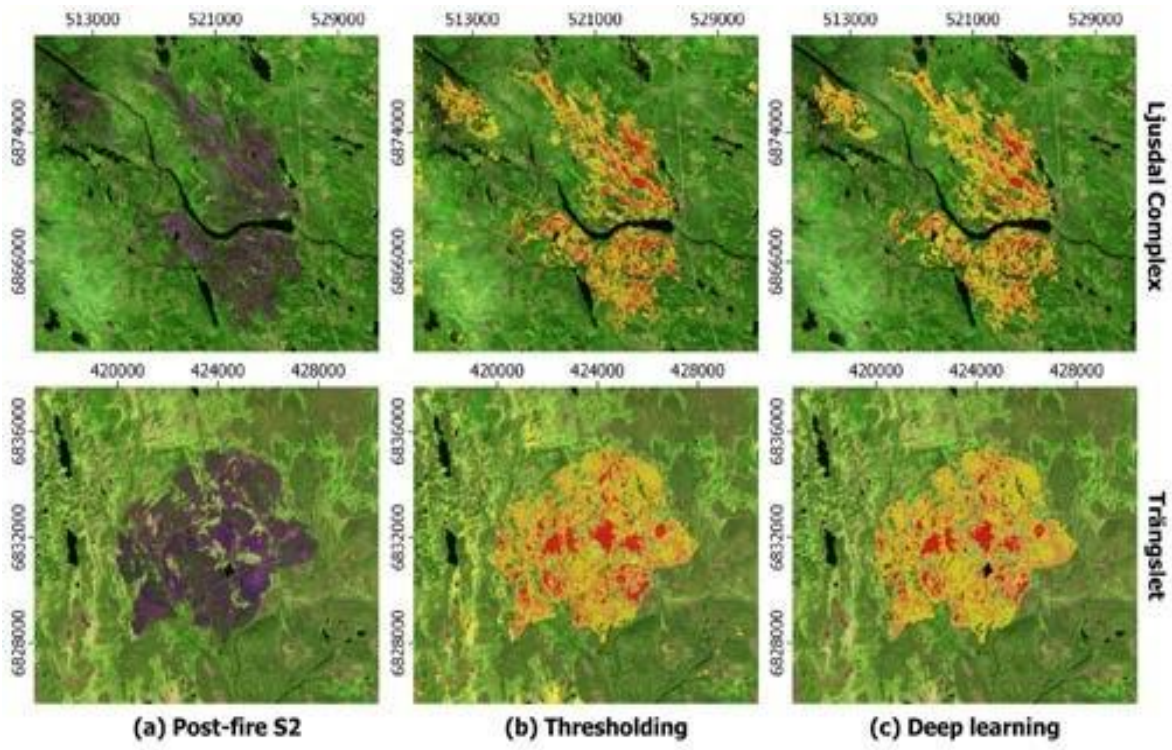
Sentinel-2 MSI for Detection of Wildfires



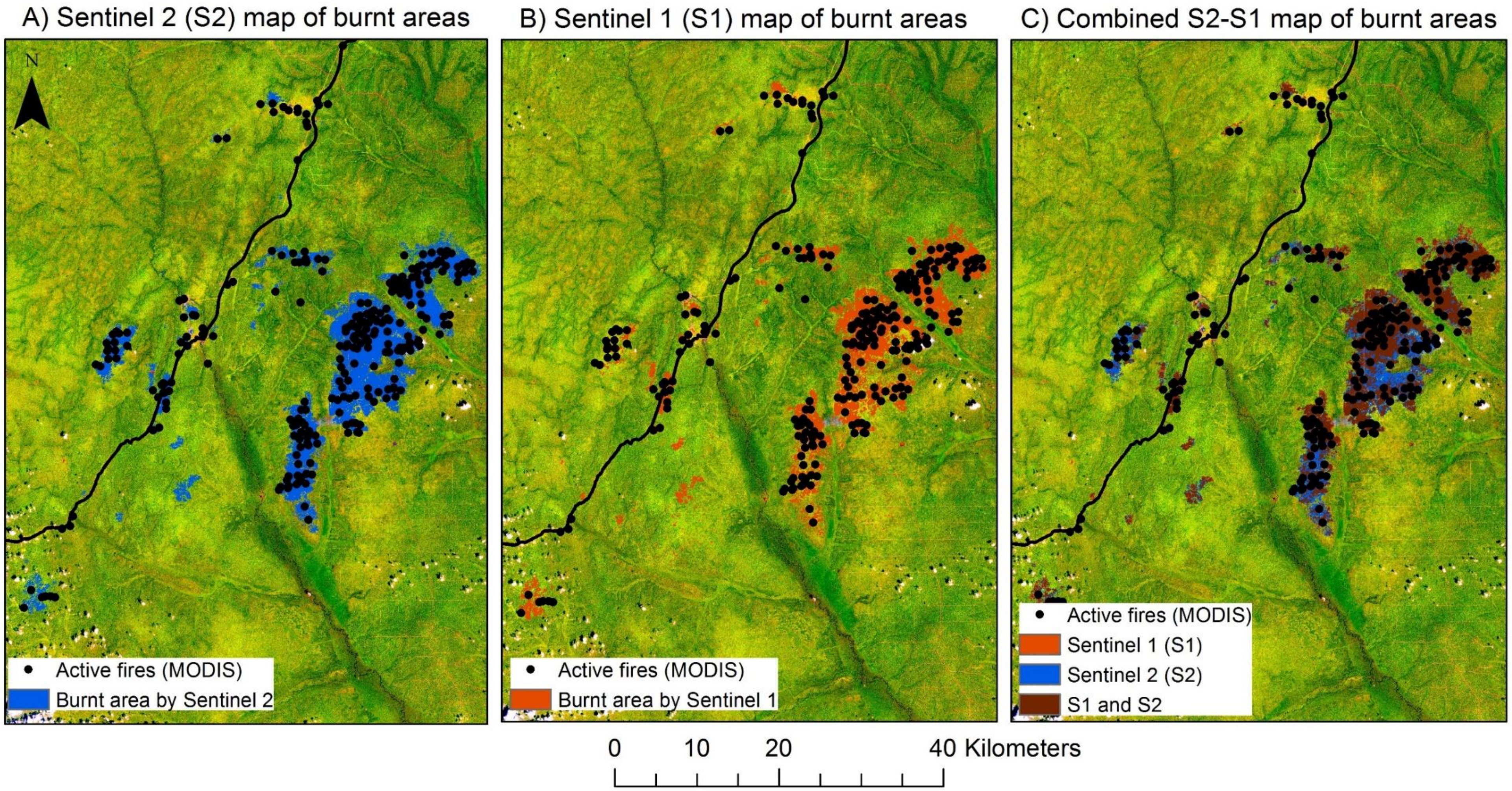
Sentinel-2 MSI for Detection of Wildfires

Sentinel-2 MSI Data for Burn Severity Mapping in Sweden with Deep Learning





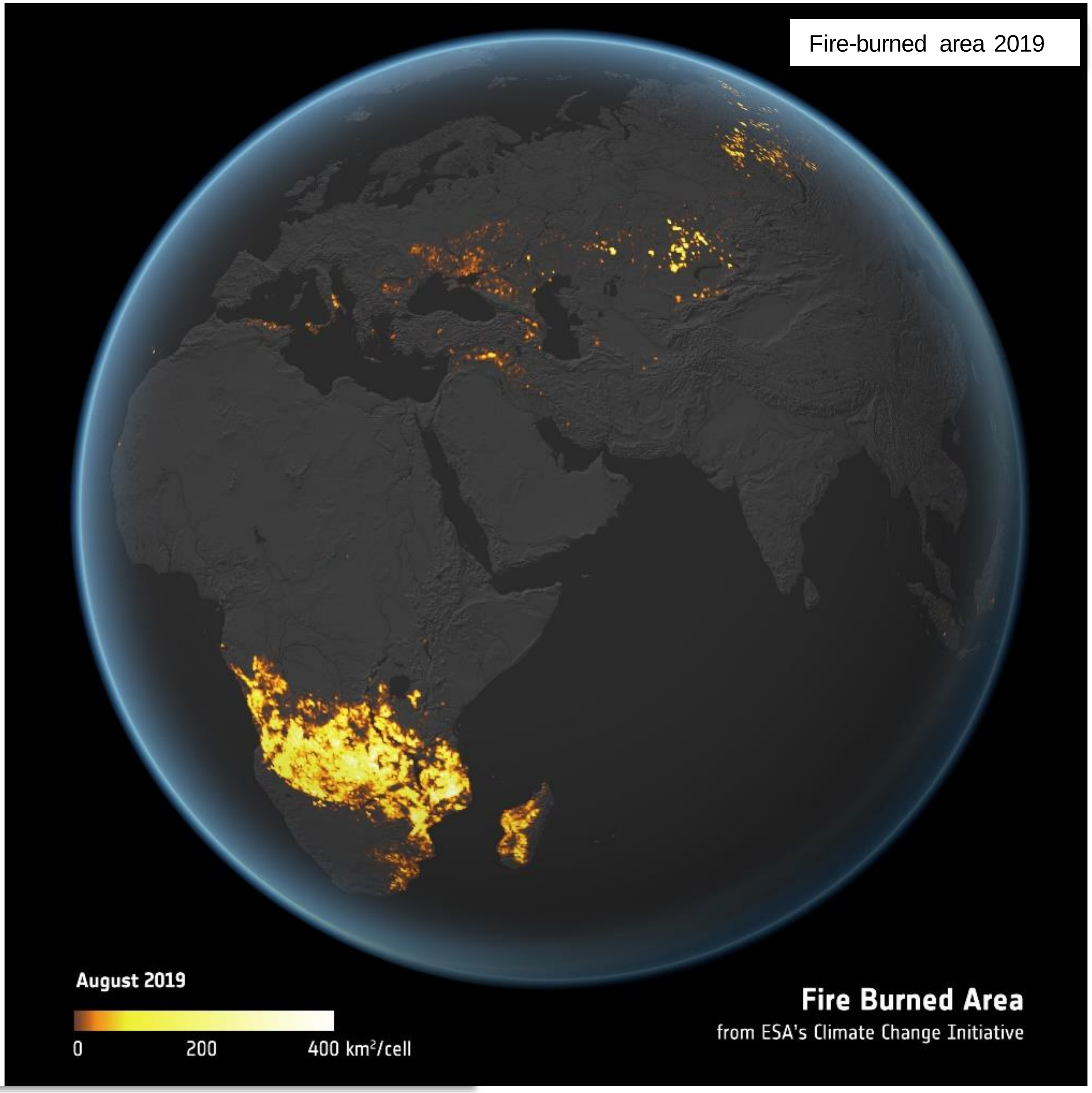
Combining Sentinel-1 and Sentinel-2 to determine the source of the fires



https://skywatch.com/monitoring-forest-fires-with-satellites/

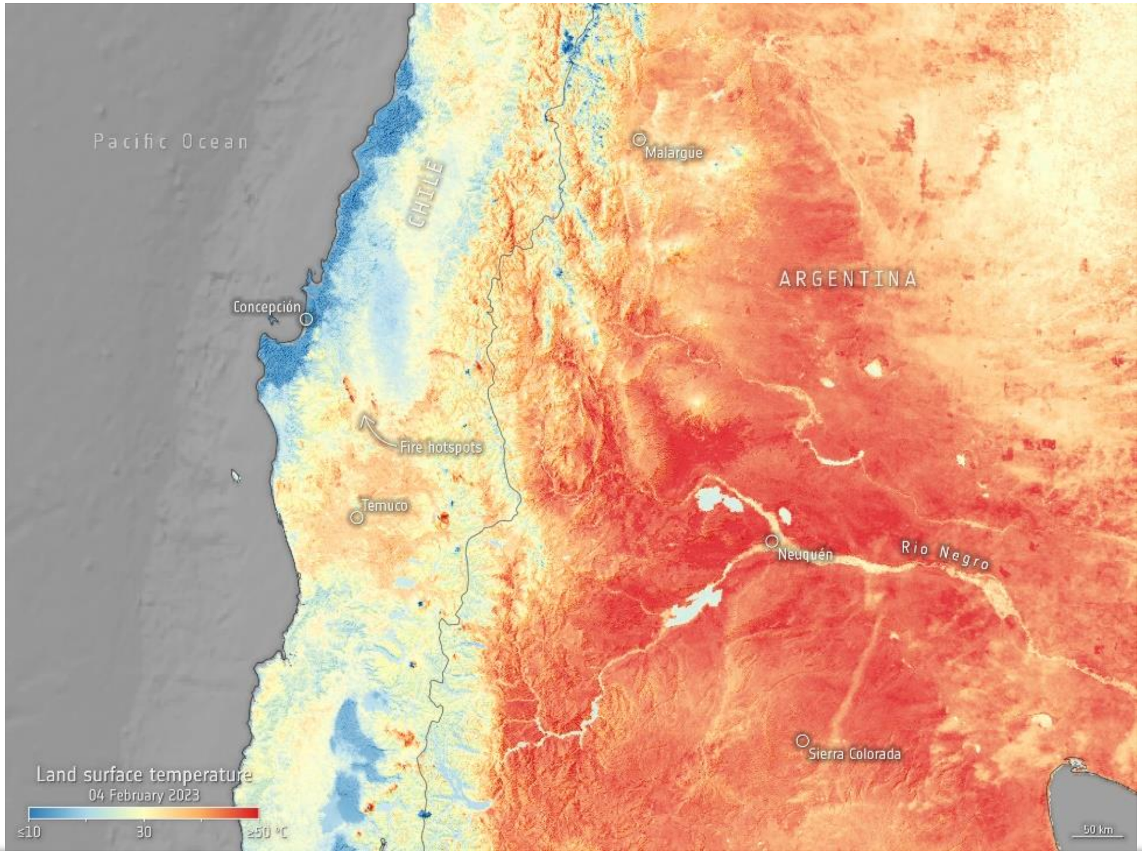
Sentinel-3 for Detection of Wildfires

- Sentinel-3 OLCI and SLSTR identifies active fire points, offering valuable information for monitoring fire spots in any area.



Sentinel-3 for Detection of Wildfires

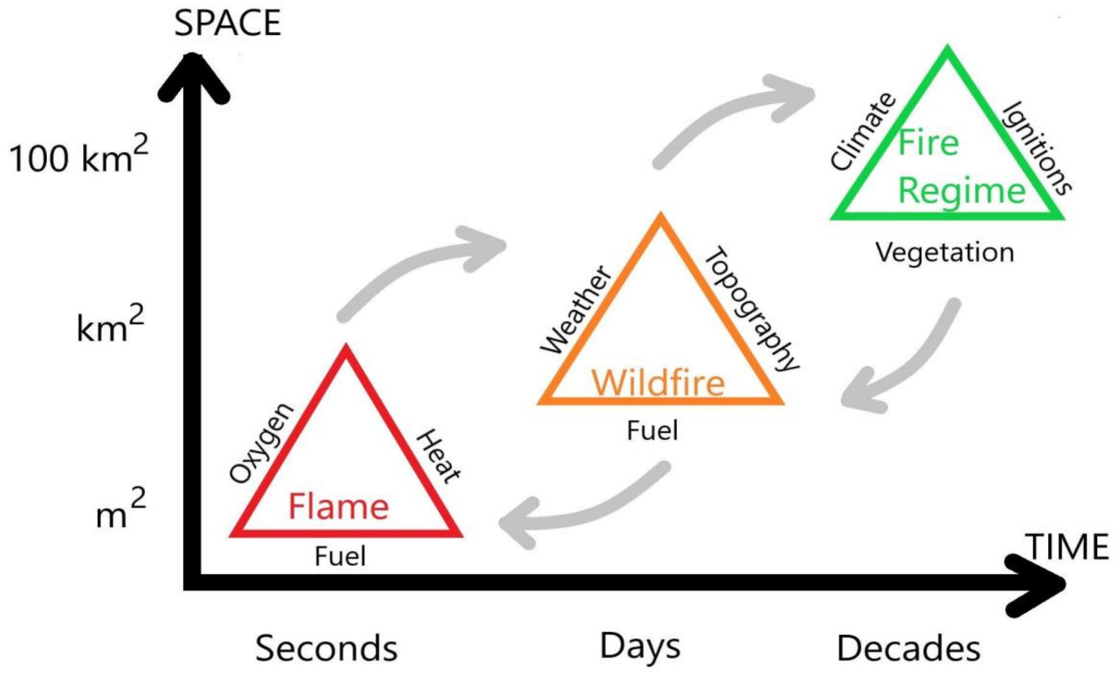
Chile battles raging wildfires



Satellite images captured by the Copernicus Sentinel-3 mission on 4 February show the ongoing fires and heatwave in South America. The optical image on the left is a combination of images from the Ocean and Land Colour Instrument (OCLI) and Sea and Land Surface Temperature Radiometer (SLSTR) onboard the Sentinel-3 satellite. This allows us to highlight the fire hotspots visible in shades of orange and red in the image. The map on the right, generated using data from Sentinel-3's SLSTR instrument, shows the temperature of the land surface. The data show that ground temperatures in Neuquén reached 49°C, Sierra Colorada reached 45°C and Malargüe 38°C.

Remote sensing observations and forest fires stages

Remote sensing observations and forest fires

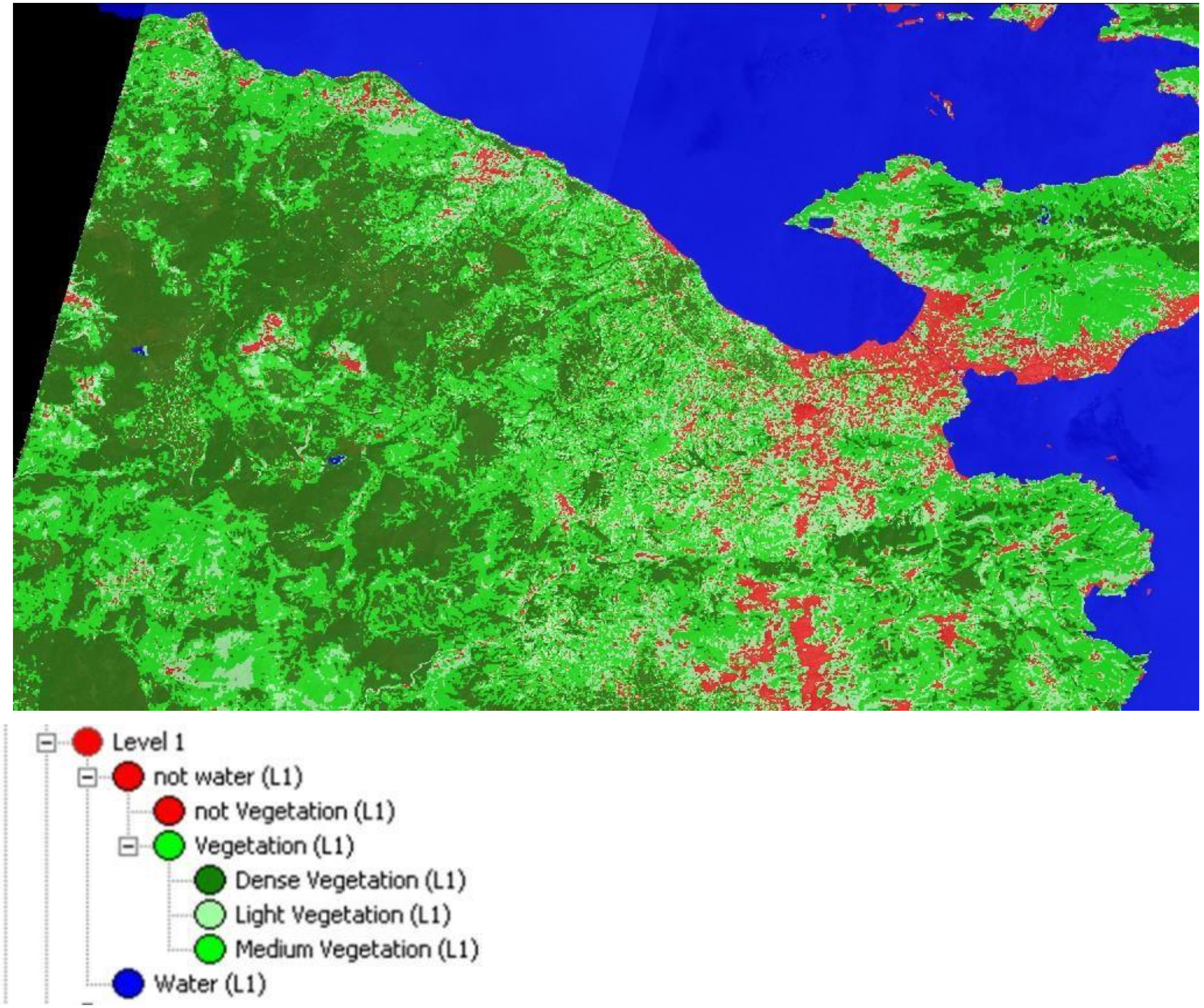


Pre-Fire Risk Assessment	Vegetation density and extent Soil moisture/drought severity Topography Fire risk mapping
Active Fire Detection	Hot Spot Detection Total area burning Fire Radiative Power and Thermal Infrared Pyro cloud formation
Post Fire Assessment	Total area burned Burn severity Post fire vegetation regrowth Landscape regeneration

The pre-fire stage

Vegetation density

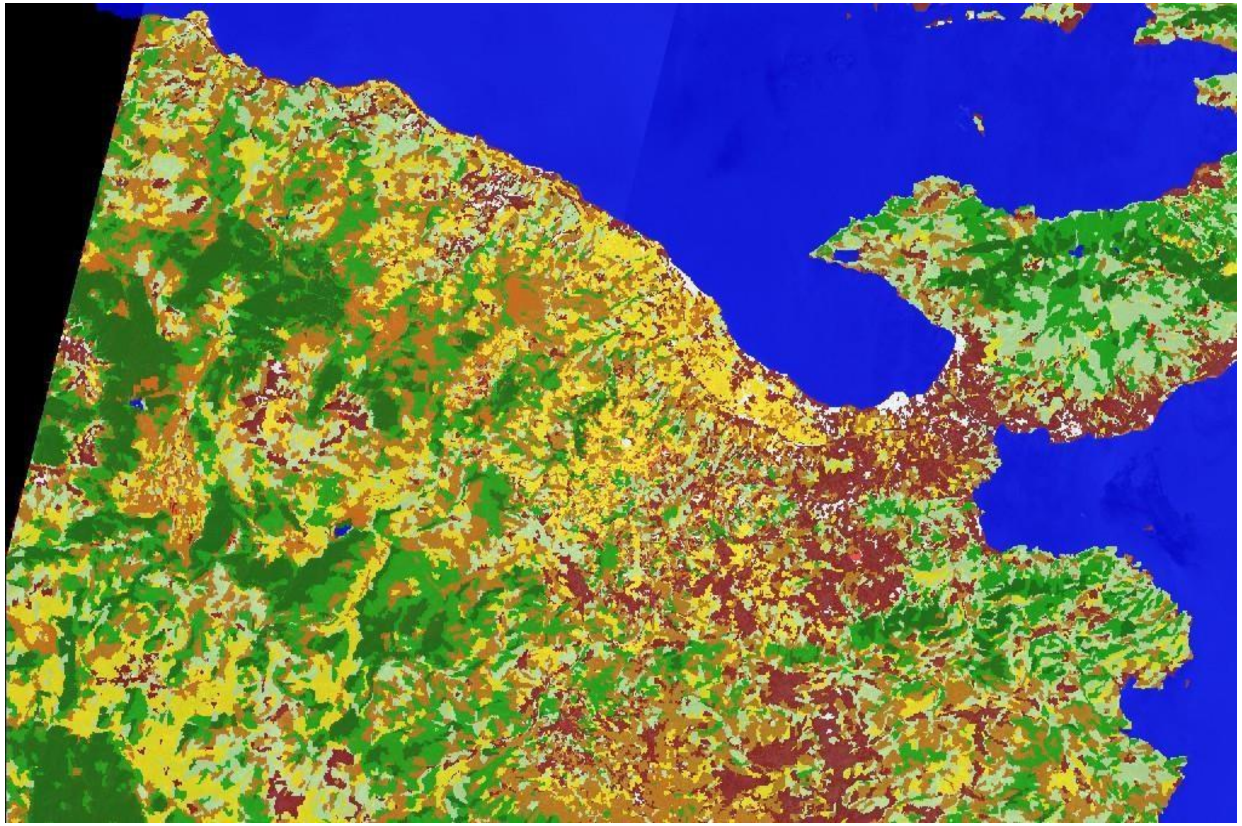
- Fire risk as varies with vegetation density VD. VD also influences fire dispersion.
- Classification of a forest in terms of VD depends strongly on spatial resolution



The pre-fire stage

Vegetation type

- Urban areas slow down forest fires, a fact which is important for fire modelling.
- **Fuel behavior (ignition and dispesion) varies with vegetation type (VT).**
- For instance, areas with olive trees slow down the fire. On the contrary, areas with pine trees (typical species for the Mediterranean biodiversity), ignite and disperse easier.



Brown: olive trees; Yellow: agricultural cultivations; Green: conifers; light green: Shrubs

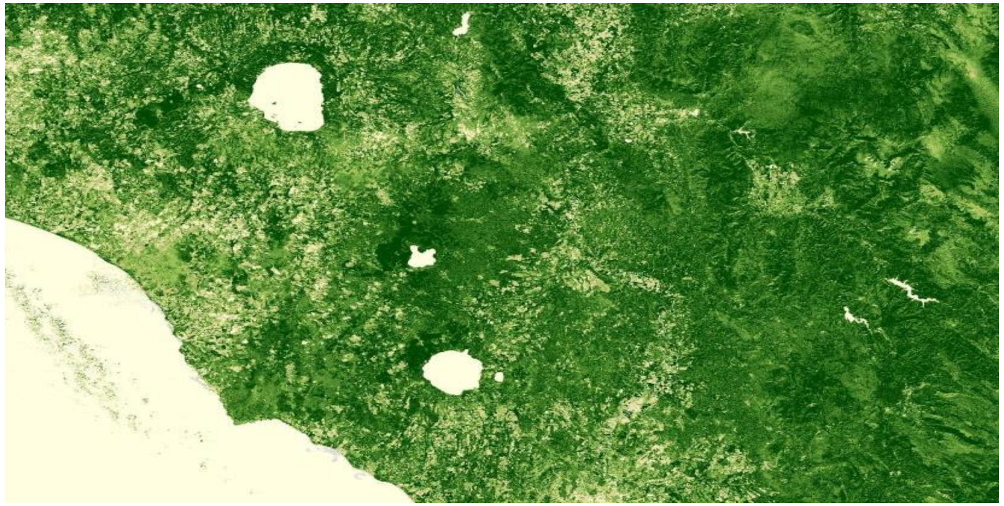
The pre-fire stage

Vegetation stage - Land Surface Phenology

Unhealthy vegetation has a higher percentage of dead leaves, providing easier to burn fuel for fires

Satellites can be used to track seasonal patterns of variation in vegetated land surfaces through indices:

- NDVI - Normalized Difference Vegetation Index
- EVI - Enhanced Vegetation Index
- SAVI - Soil-Adjusted Vegetation Index
- Vegetation index anomalies



1/ **NDVI is widely used as a metric for vegetation health**

- Values range from -1.0 to 1.0
  - Negative values to 0 mean no green leaves.
  - Values close to 1 indicate the highest possible density of green leaves.
- NDVI Formula: **(NIR – Red)/(NIR + Red)**

$$EVI = G * \left(\frac{(NIR-R)}{(NIR+C1*R-C2*B+L)}\right)$$

Constants
$G = 2.5$
$C1 = 6$
$C2 = 7.5$
$L = 1$

2/ **Enhanced Vegetation Index (EVI)**

More sensitive in areas with dense vegetation, making it better for fuels assessment in dense forests

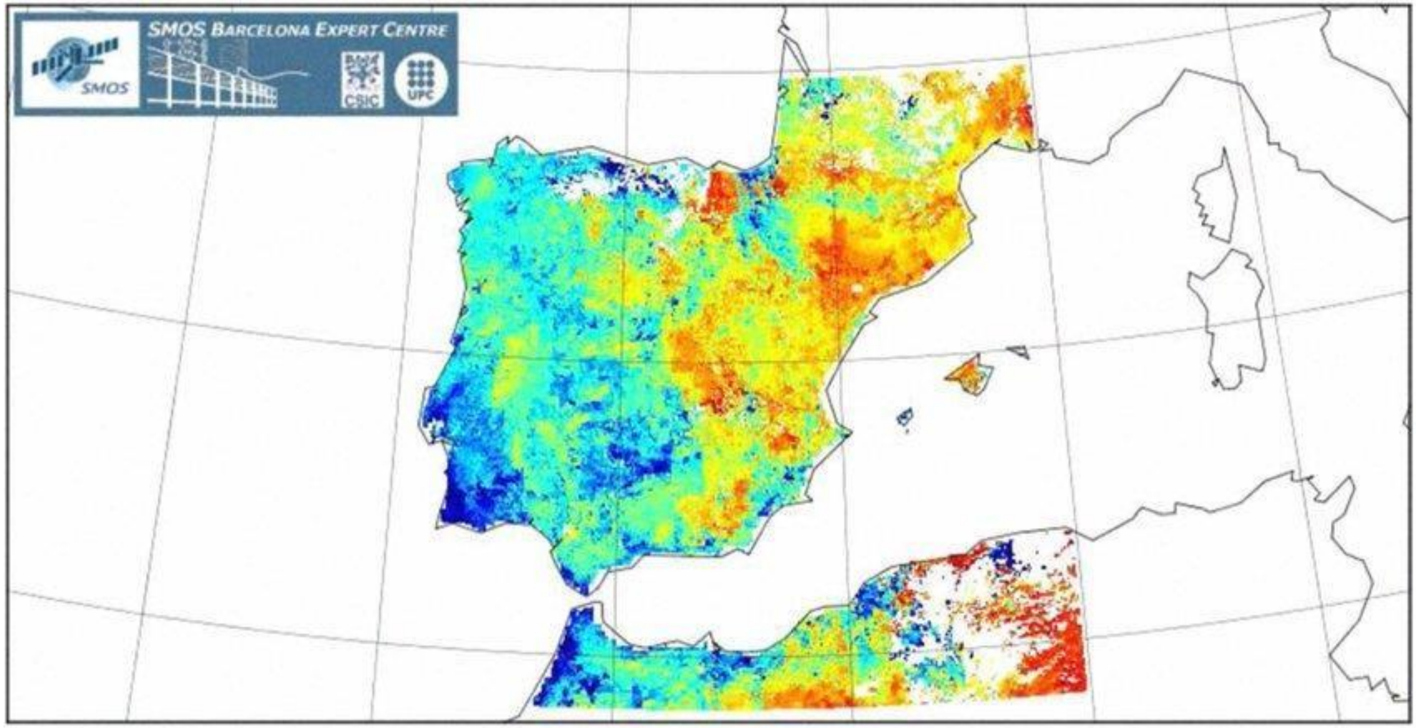
The pre-fire stage

Soil Moisture

Vegetation-Based Fire Applications:

- Vegetation Moisture: Soil moisture acts as a proxy for vegetation moisture and evaporative stress.
- Drought information can also identify areas with dry fuel.
- Soil moisture is measured by active microwave scatterometers, e.g. ERS1&2/AMI and MetOp/ASCAT as well as by passive microwave radiometers such as Sentinel 1, Aqua/AMSR-E, Coriolis/WindSat…

- SMOS measures the moisture in the top 5 cm of the soil globally every 3 day

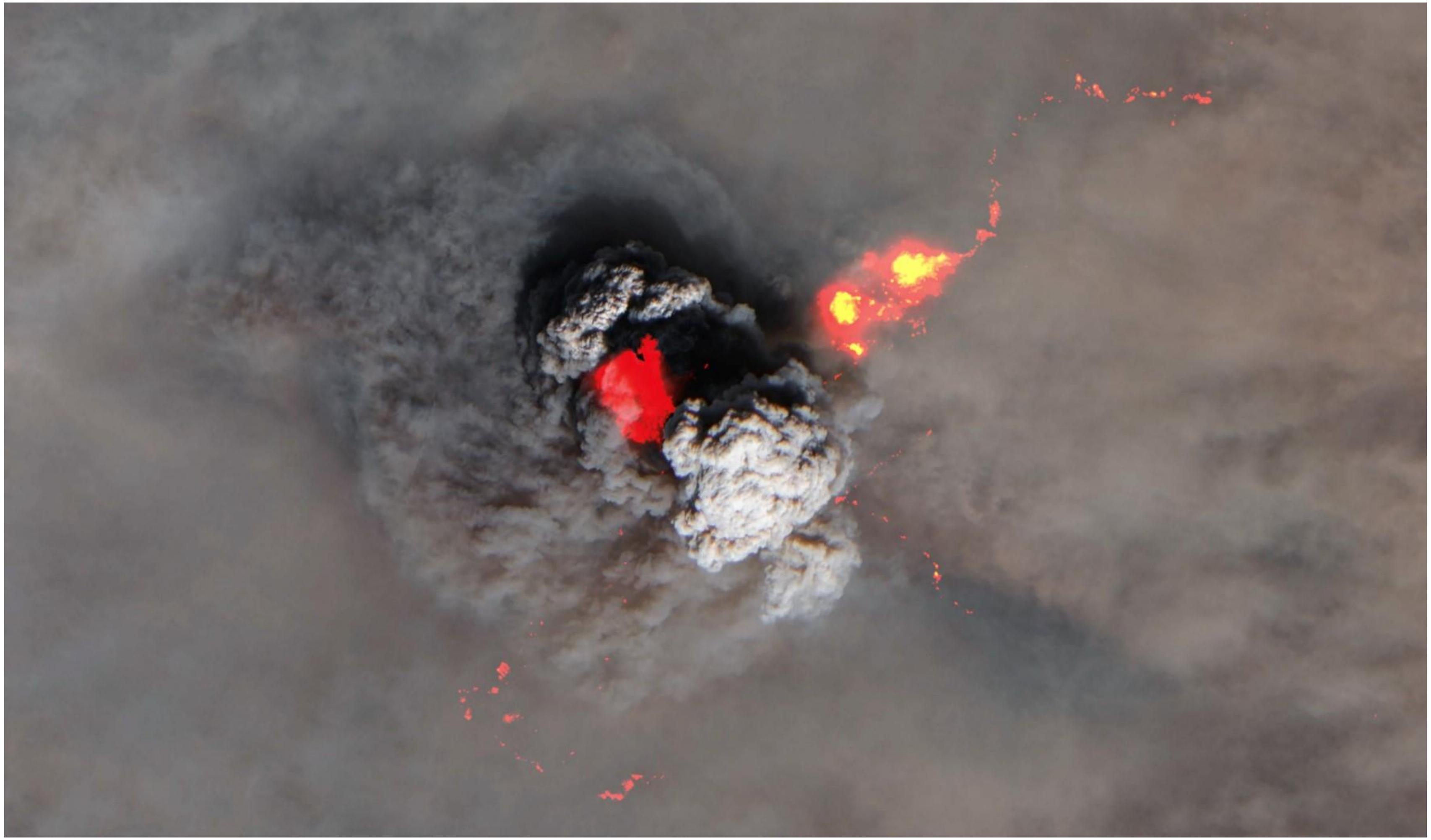


Example of high resolution (1 km) soil moisture maps of the Iberian peninsula generated from SMOS data (10 days average)

https://directory.eoportal.org/web/eoportal/satellite-missions/s/smos

The pre-fire stage

Local meteorology (pyrocumulus)



Copernicus Sentinel-2 catches impressive smoke cloud

This image acquired on 9 September 2020, by Copernicus Sentinel-2 features the impressive pyrocumulus cloud forming over the complex wildfire in California. This true-colour image is combined with short-infrared bands to highlight the location of the fire hot spots.

Contains modified Copernicus Sentinel data (2020)/processed by P. Markuse

The pre-fire stage

SAR in support of optical remote sensing for forest fires

Sentinel-1 SAR (C-band SAR data, 12-day revisit, Resolution: 5 x 20 meters)

- Vegetation-Based Fire Applications:

– Vegetation Type and Extent: Land classification, fuels mapping

– Vegetation Structure: Density and height

– Vegetation Moisture: Fuel moisture content and dryness

Sentinel-2 (-day revisit, Resolution: 10 meters)

- Vegetation-Based Fire Applications:

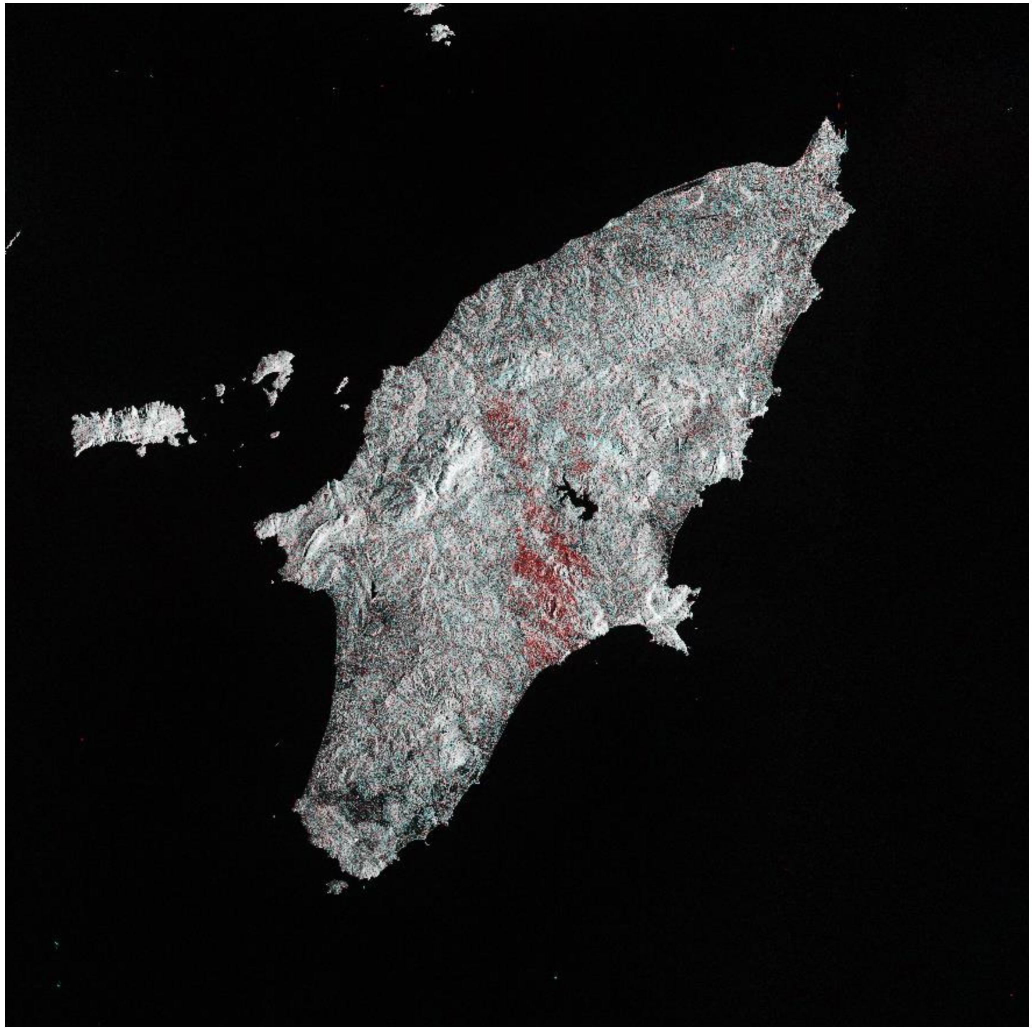
– Vegetation Extent and Type: Land cover classification

– Vegetation Stage and Health: Variety of vegetation indices, including NDVI, EVI, SAVI

– Vegetation Moisture: NDWI

The pre-fire stage

SAR in support of optical remote sensing for forest fires



Between 18 and 28 July 2023, wildfires broke out on Rhodes. Fierce blazes ravaged almost 18,000 hectares of land, destroyed buildings, trapped animals and led to a mass evacuation of thousands of tourists.

This Copernicus Sentinel-1 image shows the burn scars left by fires on the Greek island of Rhodes.

The pre-fire stage

Fire Risk Mapping	Ignition	NO	-
	Land cover	YES	VIS and SAR
	Soil moisture and drought severity	YES	Microwaves
	Vegetation type and stage	YES	VIS
	Burning fuel	YES	VIS
	Topography	YES	VIS and SAR
	Meteorological parameters	LIMITED	VIS and TIR
	Land surface temperature	YES	TIR

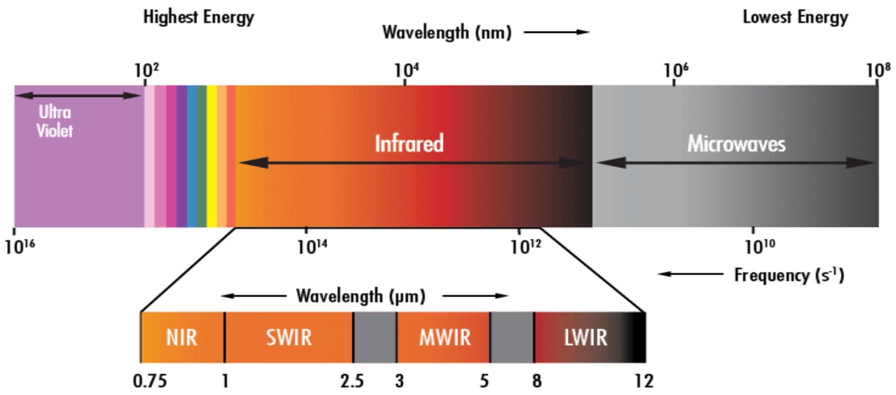
To provide reliable Fire Risk Mapping, spatial resolution needs to be high

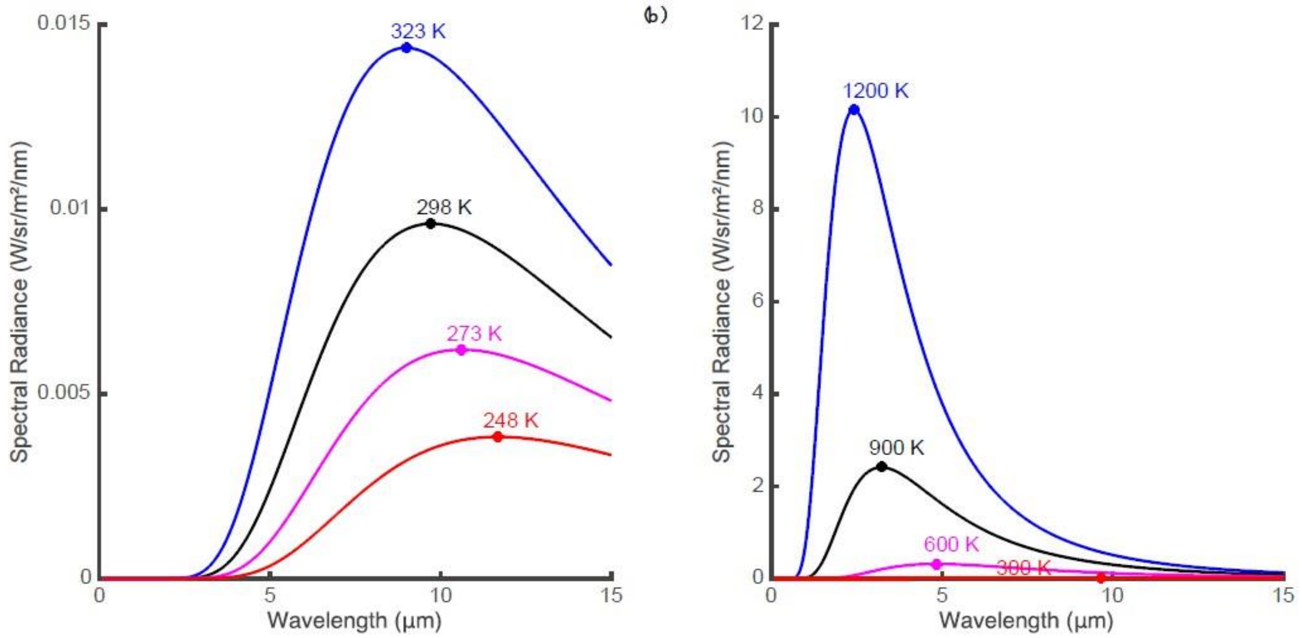
The Active fire stage

As fires burn much hotter than the typical temperature of surfaces on the Earth, heat provides a strong signal for the detection of fire.

The total energy radiated from a surface increases rapidly with its temperature (proportional to the fourth power of temperature as described by the Stefan-Boltzmann law).

However, the radiance is not uniform across wavelength and the distribution peaks at a wavelength that varies inversely with the temperature.



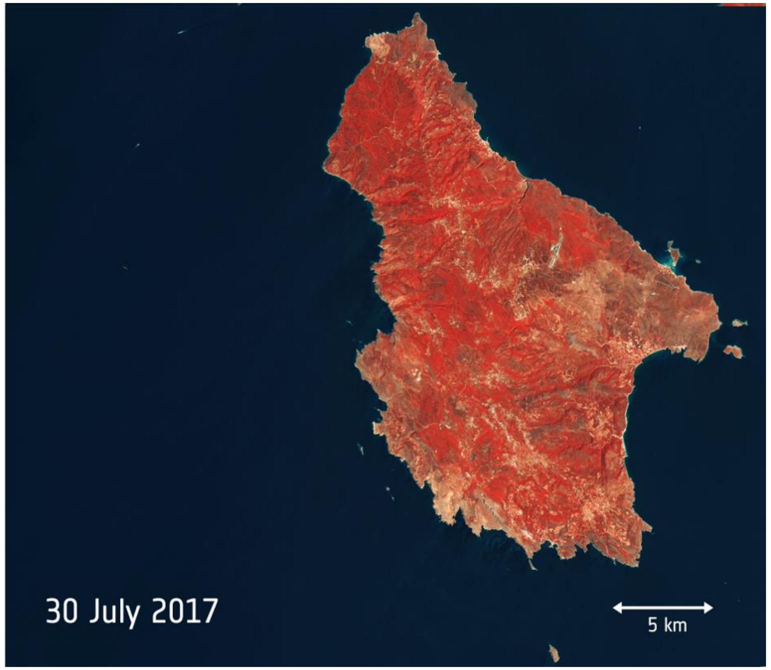


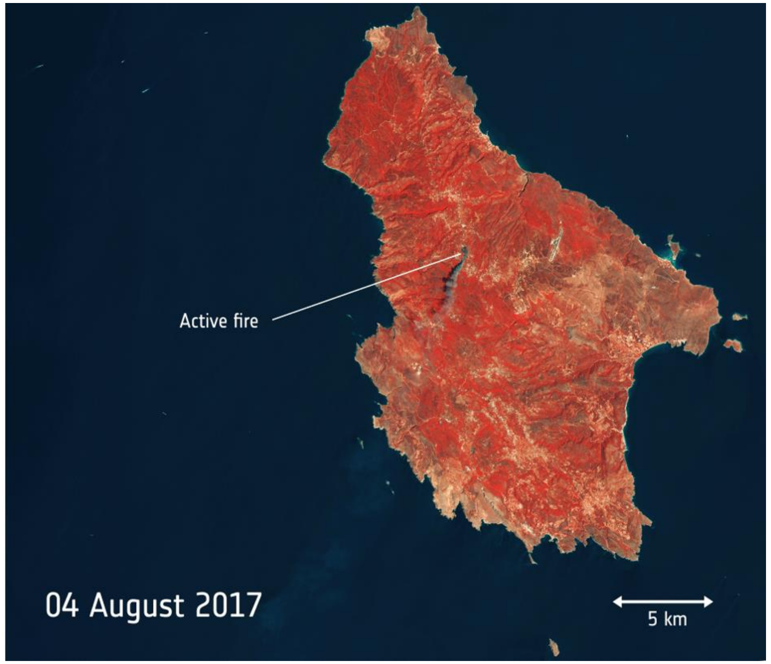
At normal ambient temperature, the peak is in the range 8–12 µm and most of the radiant energy lies at wavelengths greater than 5 µm (left image).

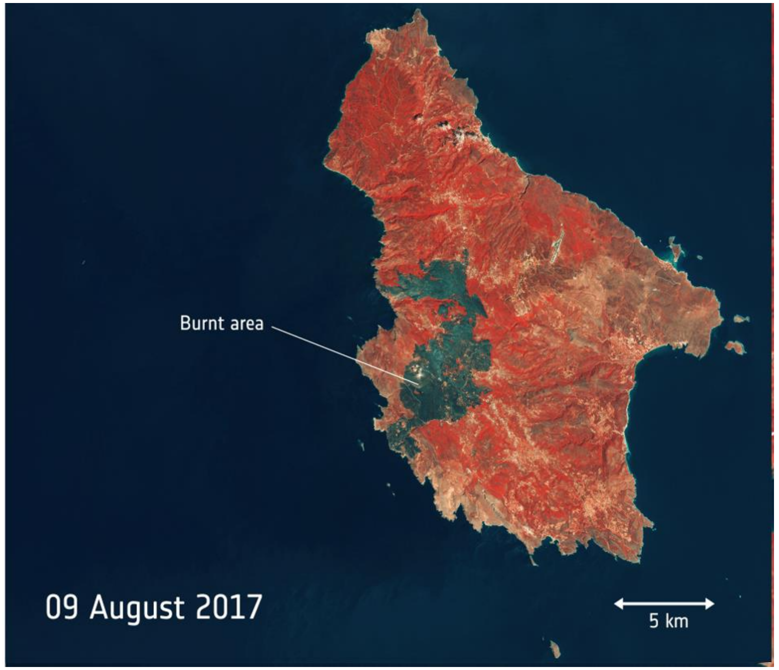
At higher temperatures typical of forest fires, the peak of the response shifts to mid-wave infrared (MWIR, 3–5 µm) or shorter wavelengths (right image).

The Active fire stage

Detecting hotspots and Total area burning







Kythira wildfires

Southern Europe experienced a relentless heatwave this summer, fuelling wildfires in a number of countries. The Copernicus Sentinel-2 satellite pair captured the start of a fire on the Greek island of Kythira on 4 August. Five days later, a huge burn scar is visible across the western part of the island.

Source: modified Copernicus Sentinel data (2017), processed by ESA

The Active fire stage

Fire Radiative Power and Thermal Infrared

Comparing window channels in near and thermal infrared

Near infrared (1.6 µm)	More adequate for smoke detection than 3.9 µm Small fires not visible No CO_2 absorption (higher fire temperature) High sub pixel sensitivity
Middle infrared (3.9 µm)	High temperature sensitivity - major sub pixel effects (hotspots are easily detected) Negligible absorption by atmospheric humidity Close to a CO_2 absorption band, 4-7 Kelvin signal reduction Brightness is temperature of the CO_2 layer above the fire
Thermal infrared (10.8 µm)	1-2 Kelvin absorption by atmospheric humidity No signal reduction by CO_2 Lower temperature sensitivity (small subpixel effects) No risk of sensor blinding by fires Low values compared with 3.9 µm due to semi transparent cloud or smoke

The Active fire stage

Temporal resolution – a critical parameter

- The majority of satellites providing earth imagery are either geostatic or in the near-polar sun-synchronous orbit and include multispectral imaging sensors.
- Sun-synchronous satellites provide data with **high spatial resolution but low temporal resolution**
- while geostationary satellites have **high temporal resolution but low spatial resolution.**

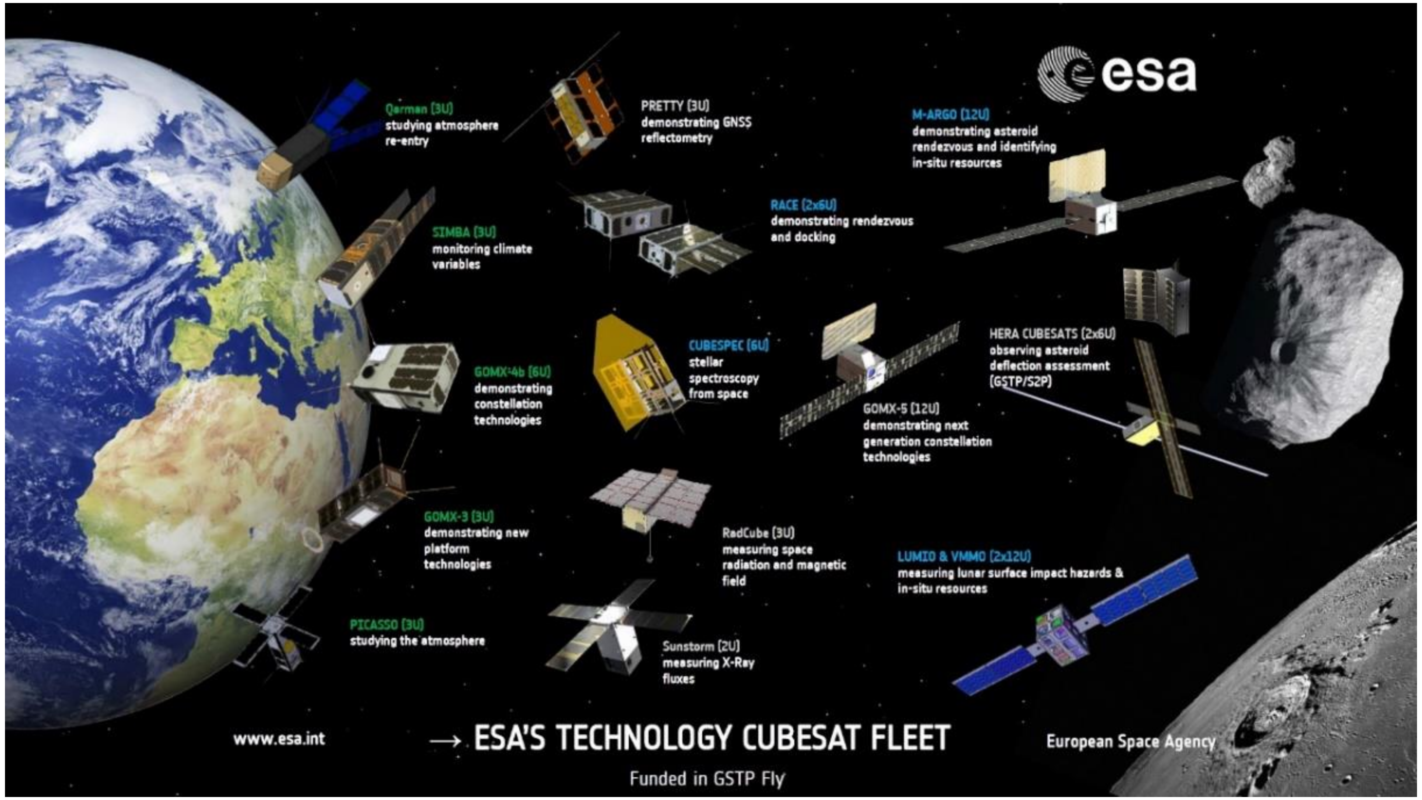
Sensor/Satellite	Channels	Product	Spatial/Temporal
SEVIRI/Meteosat	3.9µm, 10.8µm	FIR (Active Fire Monitoring)	3 km/5 min
MODIS/Aqua and Terra	4µm, 11µm	Active Fire	1km/ 1-2 days per satellite
SLSTR/SENTINEL 3	3.7µm, 10.8µm	Active Fire	1km/approx. 1 day
SENTINEL 1	Radar	Burned area	5m/2 days at mid-latitudes
SENTINEL 2	Vis	Burned area	10 m/2-3 days at mid-latitudes
AVHRR/NOAA	3.7µm	FIMMA	1km/ 5-6 times per day
VIIRS/ Suomi-NPP	4µm, 11µm	Active fire	375m/ 3-4 times per day

The Active fire stage

Temporal resolution – a critical parameter

Recently, advances in nanomaterials and micro-electronics technologies have allowed the use of tiny low-Earth-orbiting satellites, known as **CubeSats**.

CubeSats by launched in constellations succeed in improving considerably the temporal resolution while at the same time they reflect high spatial resolution (due to their low orbit).



The post-fire stage

Normalized Burn Ratio (NBR)

- Used to measure burn severity by distinguishing areas that have been significantly altered in their spectral signature after a wildfire event
- It is calculated using the energy intensity from the NIR and SWIR wavelength bands from the remotely sensed satellite imagery.

- Healthy vegetation has very high NIR reflectance and low reflectance in the SWIR portion of the spectrum
- Burned areas on the other hand have relatively low reflectance in the NIR and high reflectance in the SWIR band

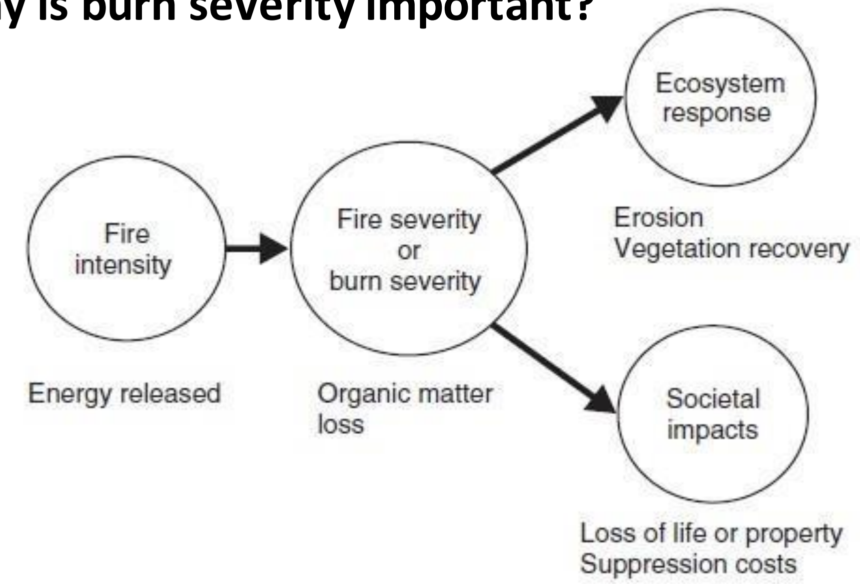
$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)} = \frac{(Band\,8 - Band\,12)}{(Band\,8 + Band\,12)}$$

The post-fire stage

Burn Severity and the delta normalized burn ratio

- **Burn severity** - degree to which an ecosystem is impacted by a wildfire event.
- **The difference between pre-fire and post-fire NBR (the delta normalized burn ratio (dNBR) index) -** frequently used to identify recently burned areas and differentiate them from other non- vegetated areas.
- Areas with high dNBR value correspond to a higher degree of damage or burn severity. In contrast, low dNBR values represent areas that are unaffected from the fire event or regions that have rebounded via regrowth of plant species following a wildfire incident.

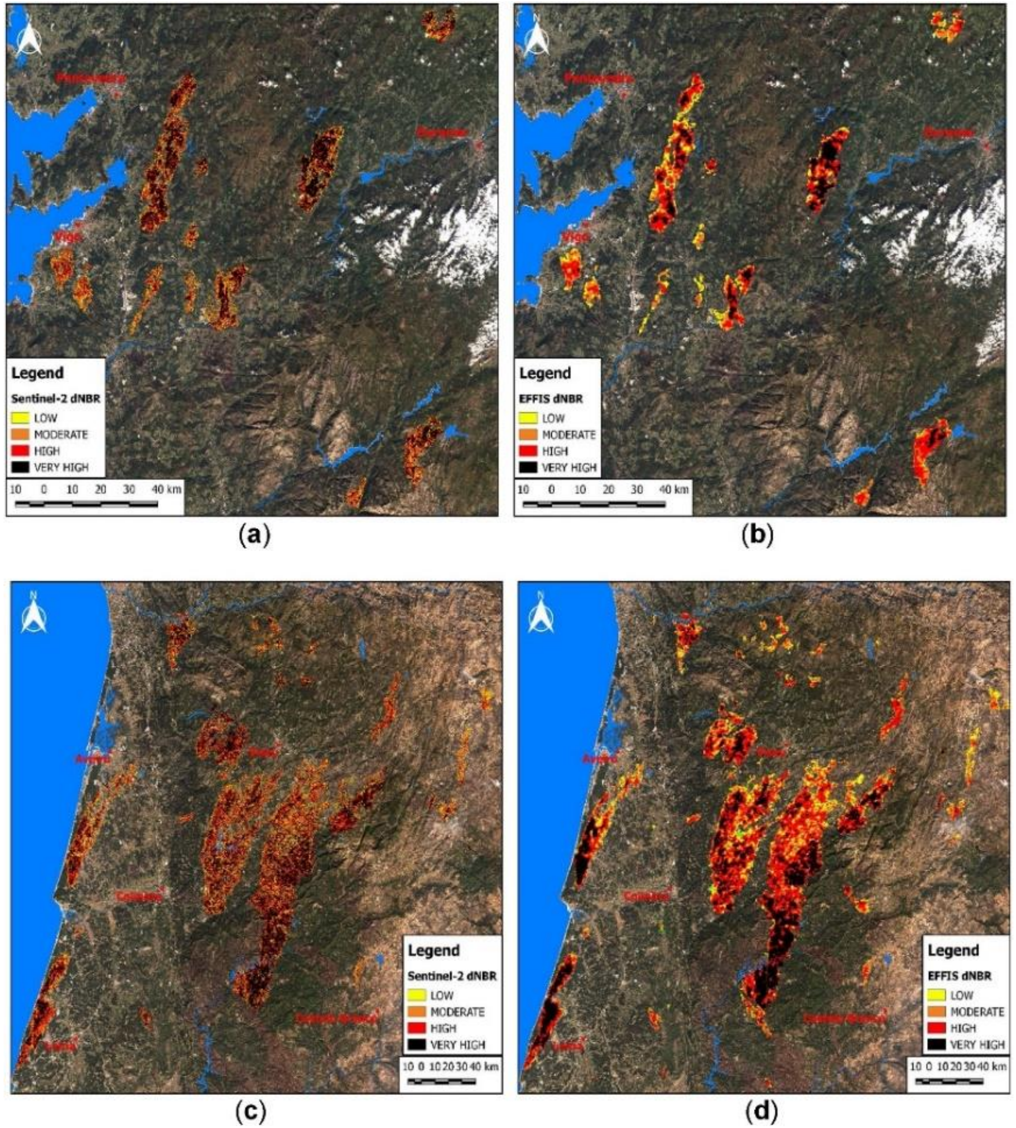
Why is burn severity important?



EFFIS thresholds	Severity Level
dNBR < 0.100	Unburned / Very Low
0.100 ≤ dNBR ≤ 0.255	Low
0.256 ≤ dNBR ≤ 0.419	Moderate
0.420 ≤ dNBR ≤ 0.660	High
dNBR > 0.660	Very High

The post-fire stage

Burned areas and burn severity – Spain and Portugal 2017



(a) Sentinel-2 dNBR image using Post-1 images in Galicia wildfires;
(b) EFFIS dNBR image in Galicia wildfires;
(c) Sentinel-2 dNBR image using Post-1 images in Portugal wildfires;
(d) EFFIS dNBR image in Portugal wildfires. Water areas are masked (blue color).

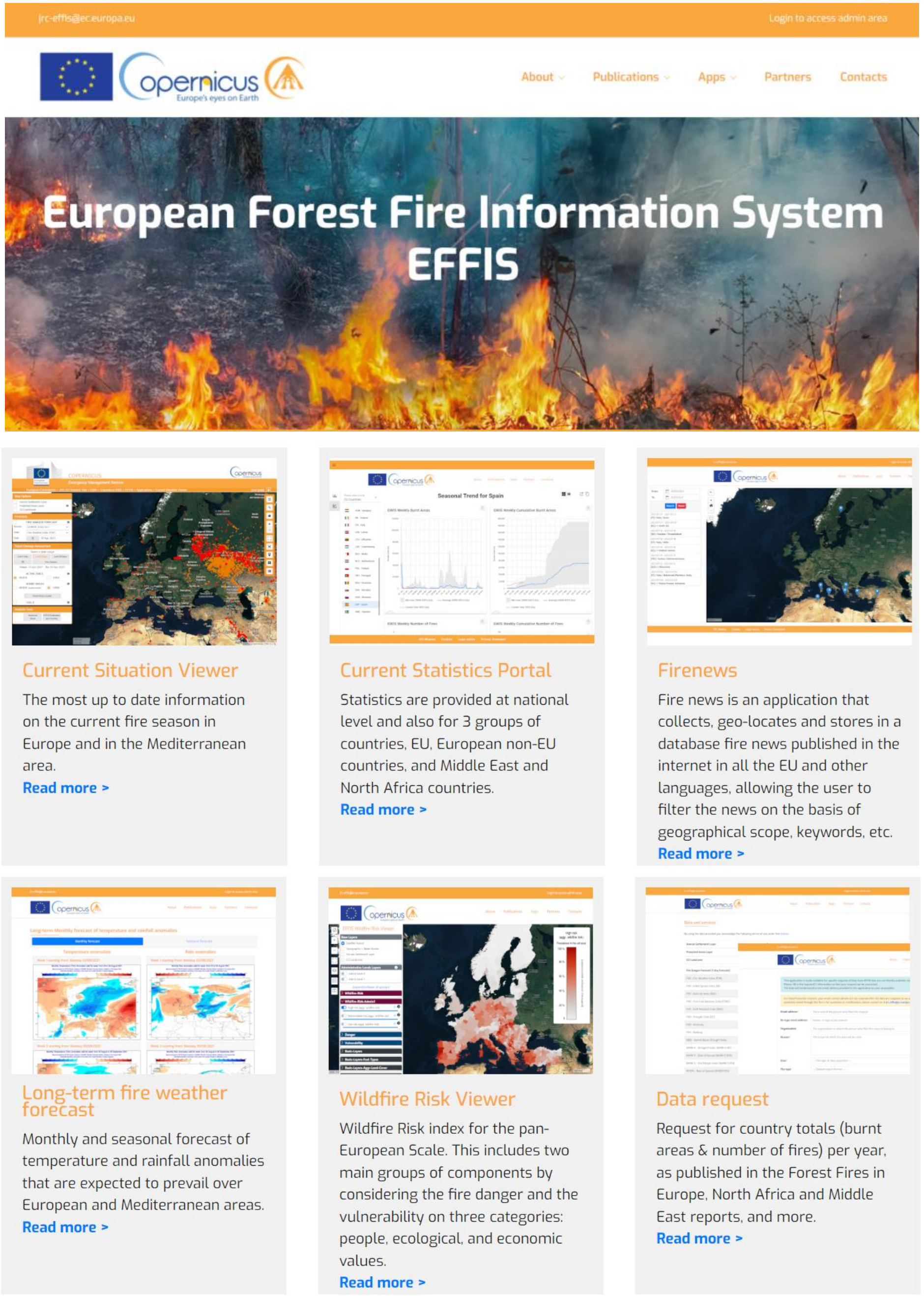
from:
Rafael Llorensa, José Antonio Sobrino, Cristina Fernández, José M.Fernández-Alonso, José Antonio Vega, A methodology to estimate forest fires burned areas and burn severity degrees using Sentinel-2 data. Application to the October 2017 fires in the Iberian Peninsula, International Journal of Applied Earth Observation and Geoinformation Volume 95, March 2021, 102243
https://doi.org/10.1016/j.jag.2020.102243

Sources of information

The European Forest Fire Information System (EFFIS)

- The European Commission has developed the European Forest Fire Information System (EFFIS) (http://effis.jrc.ec.europa.eu/) to provide a fire risk forecast and a fire danger assessment in EU countries.

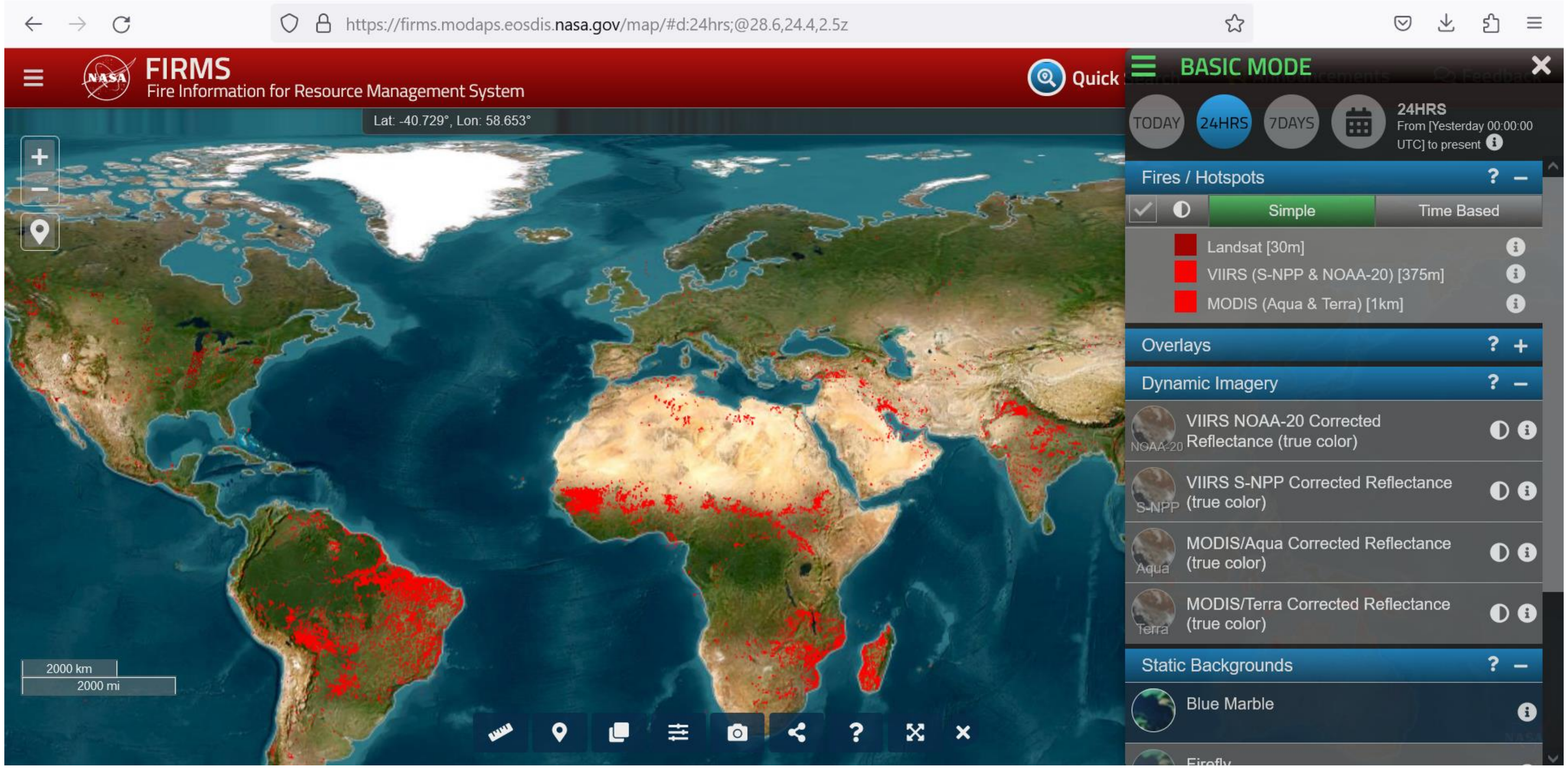
- EFFIS is one of the **Copernicus Emergency Services** and becomes an essential tool for providing most up-to date information on fire danger in EU



The Global Wildfire Information System (GWIS)

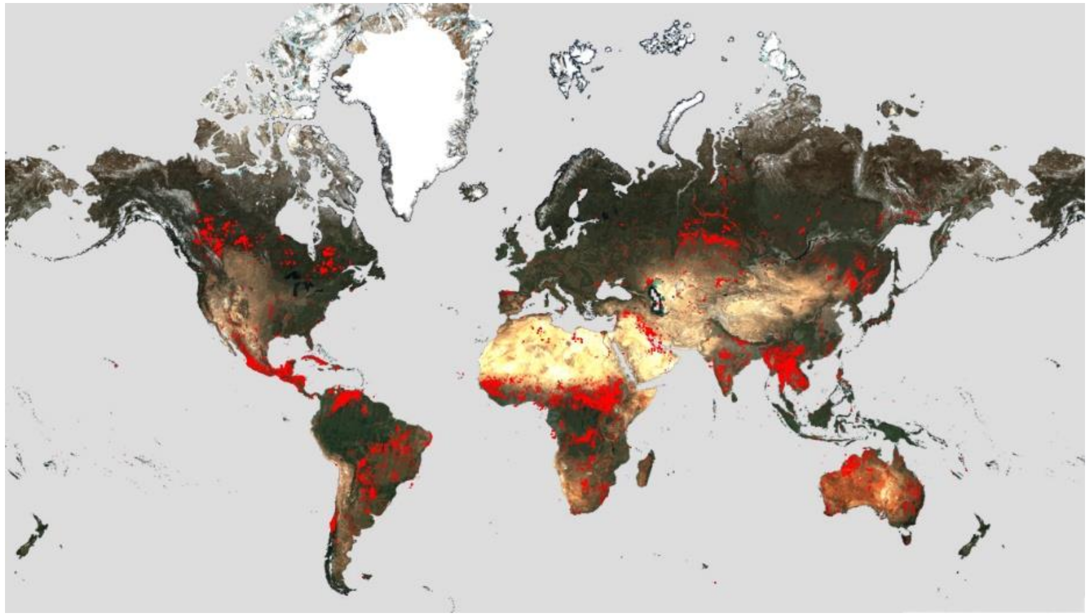
Joint initiative of the Group on Earth Observations (GEO), the NASA Applied Research and the EU Copernicus work programmes. Using advanced methods on data processing for wildfire detection and monitoring, numerical weather prediction models, and remote sensing, GWIS enables enhanced wildfire prevention, preparedness and effectiveness in wildfire management.

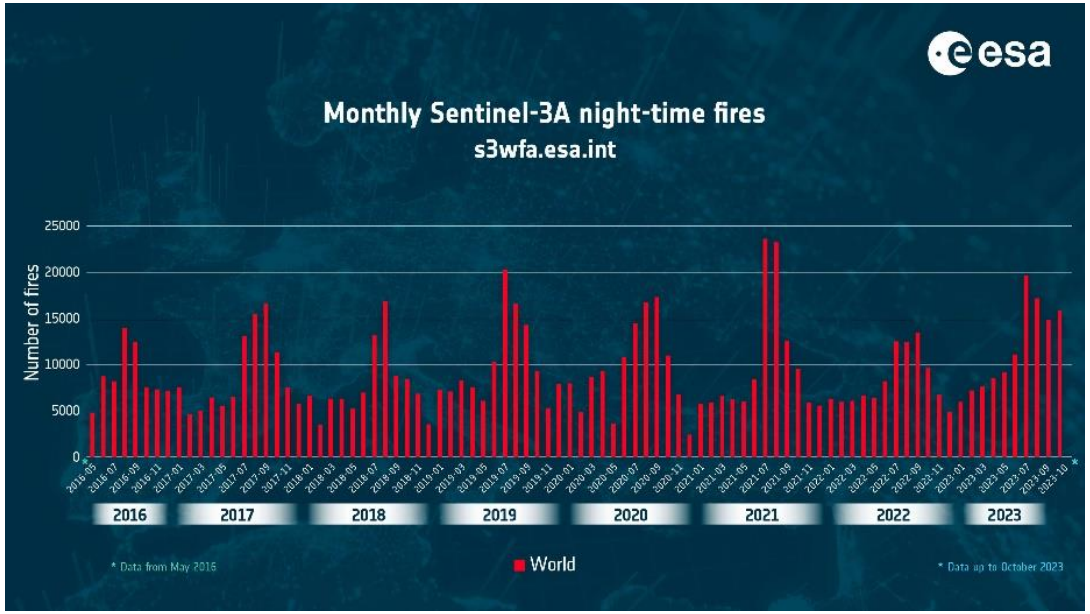
Fire Information for Resource Management System (FIRMS)



NASA's FIRMS distributes Near Real-Time (NRT) active fire data within 3 hours of satellite observation from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and NASA's Visible Infrared Imaging Radiometer Suite (VIIRS). https://firms.modaps.eosdis.nasa.gov/

Worldwide fires from ESA's Sentinel-3 World Fire Atlas





- The atlas provides a detailed analysis of wildfires across the globe and utilised nighttime data from the Sea and Land Surface Temperature Radiometer (SLSTR) onboard the Sentinel-3A satellite. The data have been overlaid onto ESA's World Cover map which uses data from the Copernicus Sentinel-2 mission from 2021.

- The map and graph shows fires taking place across the globe between May 2016 and June 2023, using data from the World Fire Atlas.

Source: https://s3wfa.esa.int/

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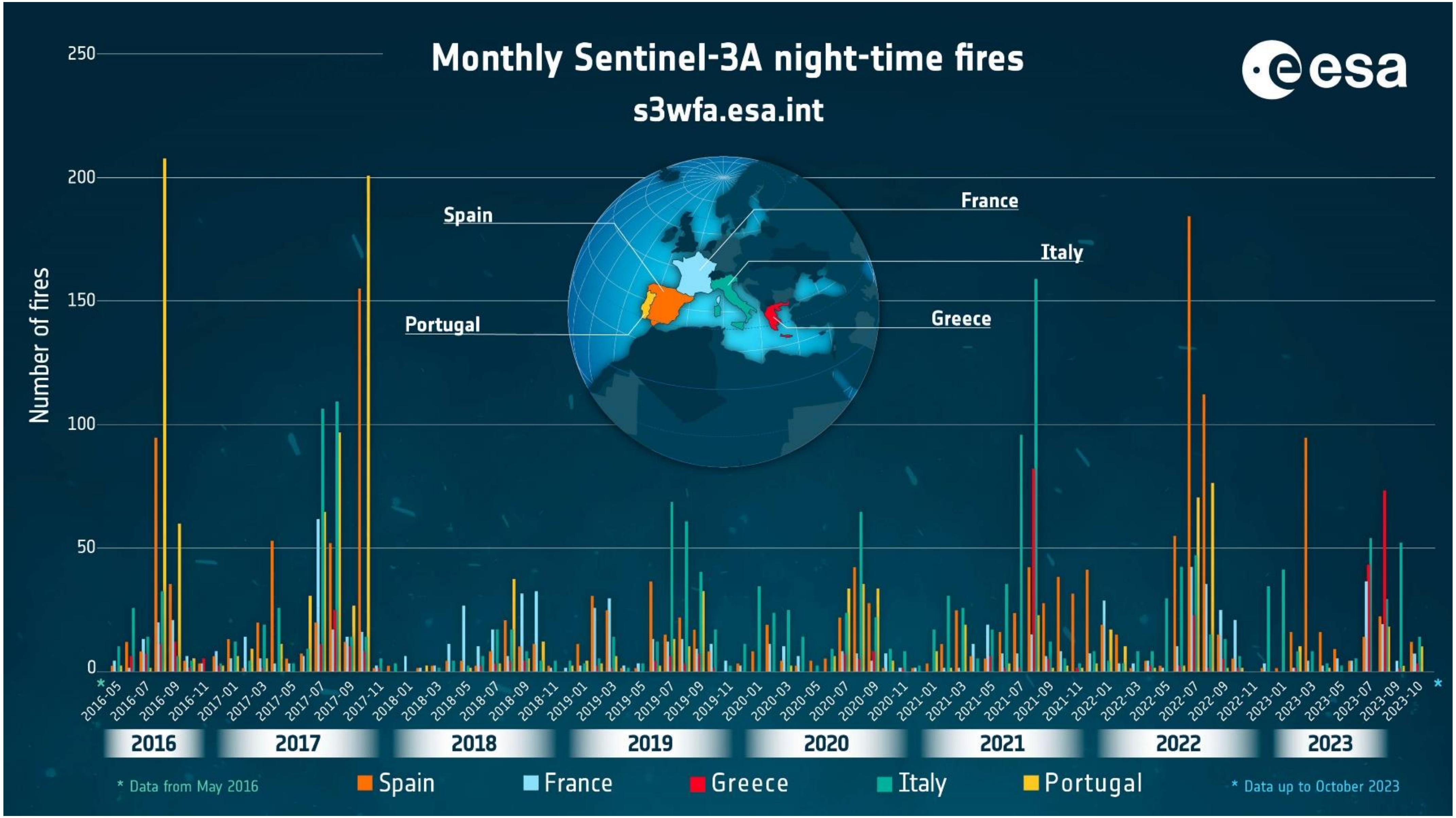

Conclusions

- Optical and thermal infrared RS observations → supportive for the pre-fire and post-fires stages
- Fire detection is technically feasible (in mid and thermal infrared; Sentinel 3, SEVIRI on Meteosat, Landsat TM), yet satellites with good temporal resolution have poor spatial one and vice versa → contribution to operational plans in the active fire stage is constrained
- Sentinel 2 and 3 facilitate research and operation applications with respect to forest fires. Results are complemented by Sentinel 1 SAR observations
- Low spatial resolution satellites/sensors (VIIRS, MODIS) - used for pre-fire risk mapping; satellites of high spatial resolution - during the post-fire stage - may be used instead (Sentinel- 2, Landsat, Worldview, etc.)
- Cubesats reflect a promising development to improve both temporal and spatial resolution
- Several forest fire related applications have been developed in the framework of the EU, ESA, as well in other parts of the world.

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Thank you for the attention