Multi-Task Learning for Fire Ignition Maps

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FONDAZIONE links PASSION FOR INNOVATION

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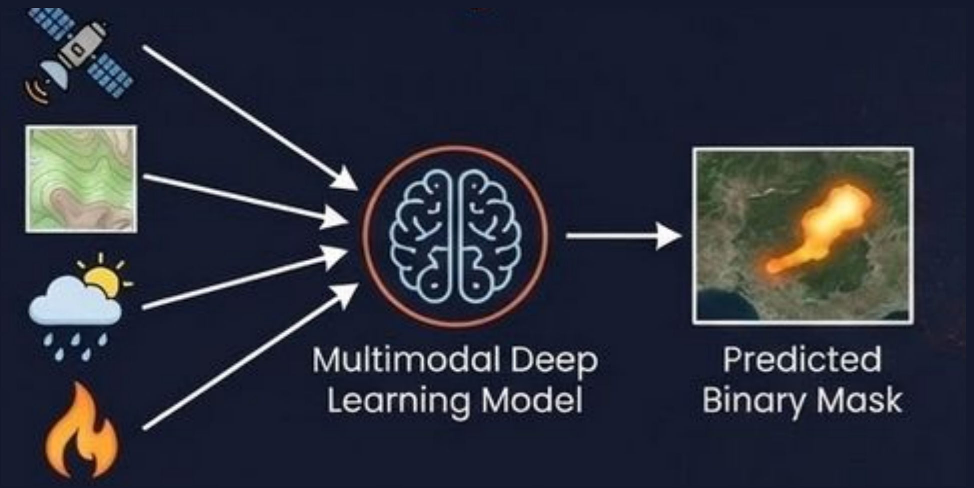
Project Objective

Core Objective

To develop a multimodal deep learning model capable of **Predicting the final burned area extent of a wildfire right at the moment of ignition,** using only pre-fire multimodal data that fused into a multimodal model

Input: Pre-fire environmental data (Satellite, Topography, Weather) + Ignition Point.

Output: Predicted binary mask of the final burned area.



The Paradigm Shift

Current State (Reactive): Remote sensing is primarily used for post-event damage assessment.

Target State (Proactive): To estimate the possible spread of fire immediately to allocate resources immediately during the "Golden Hour".

Value Proposition

Environmental Impact

Proactive predictions reduce environmental losses by enabling faster response before uncontrolled spread.
Fewer hectares burned → lower CO_2 emissions, preserved ecosystems, and reduced long-term regeneration costs.

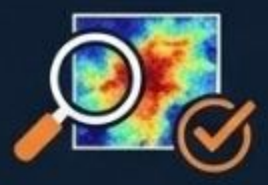
Response Efficiency

Early burned-area forecasts help Civil Protection allocate firefighting teams, helicopters, and ground units efficiently.
Better situational awareness during the first critical hours improves containment and reduces operational risk.

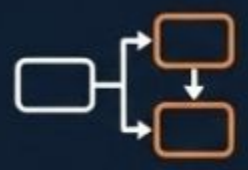
Innovation & Scalability

The multimodal AI system generalizes across regions where Sentinel-2, Landsat, DEM, ERA5, and infrastructure layers are available.
The framework can be replicated globally, providing a reusable template for data-driven wildfire risk management.

Research Questions



Can pre-fire multimodal data predict final burned area with sufficient accuracy to support early emergency decisions?



Do multi-task auxiliary objectives (e.g., land-cover segmentation) improve burned-area prediction?

which input data modalities contribute most to predictive performance?

Dataset Exploration

Piedmont Wildfire Dataset (2012–2024)

1090 wildfire events

Pre-Fire Data: Satellite Imagery & Environmental Drivers

Satellite Imagery (Sentinel-2 & Landsat)

Sentinel-2 Imagery: 12-band multispectral, 10-20m res.
- why needed? captures immediate pre-fire condition (vegetation & fuel availability)

Landsat Imagery: Extra spectral info (SWIR/NIR)
- why needed? Sensitive to vegetation moisture and fuel dryness.
- Complementary spectral response for fuel characterization.

Environmental Drivers (DEM & ERA5)

Topograph (DEM): Terrain , slopes and valleys (30m res).
- why needed? Fire spreads uphill, elevation is crucial for behavior.

ERA5 weather: Temperature & wind at ignition time.
- why needed? Meteorological conditions are key drivers of fire expansion.
- wind vectors provide essential dynamic information for propagation direction.

Ground-Truth Fire Labels
(BURNED AREA MASK & IGNITION DATA)

Burned Area Mask: Shape of the area that actually burned,
Binary Segmentation
(1 = burned, 0 = unburned)

why needed? Serve as a target label for supervised learning segmentation

Ignition Data: The exact location where the fire started. (Binary marker), derived from Civil Protection point data.

why needed? The model learns how the fire is likely to spread from that specific starting position.

Land cover , Roads

Land cover Classification: Categorical mask of vegetation types (Forest, Shrub, Grassland, etc.).

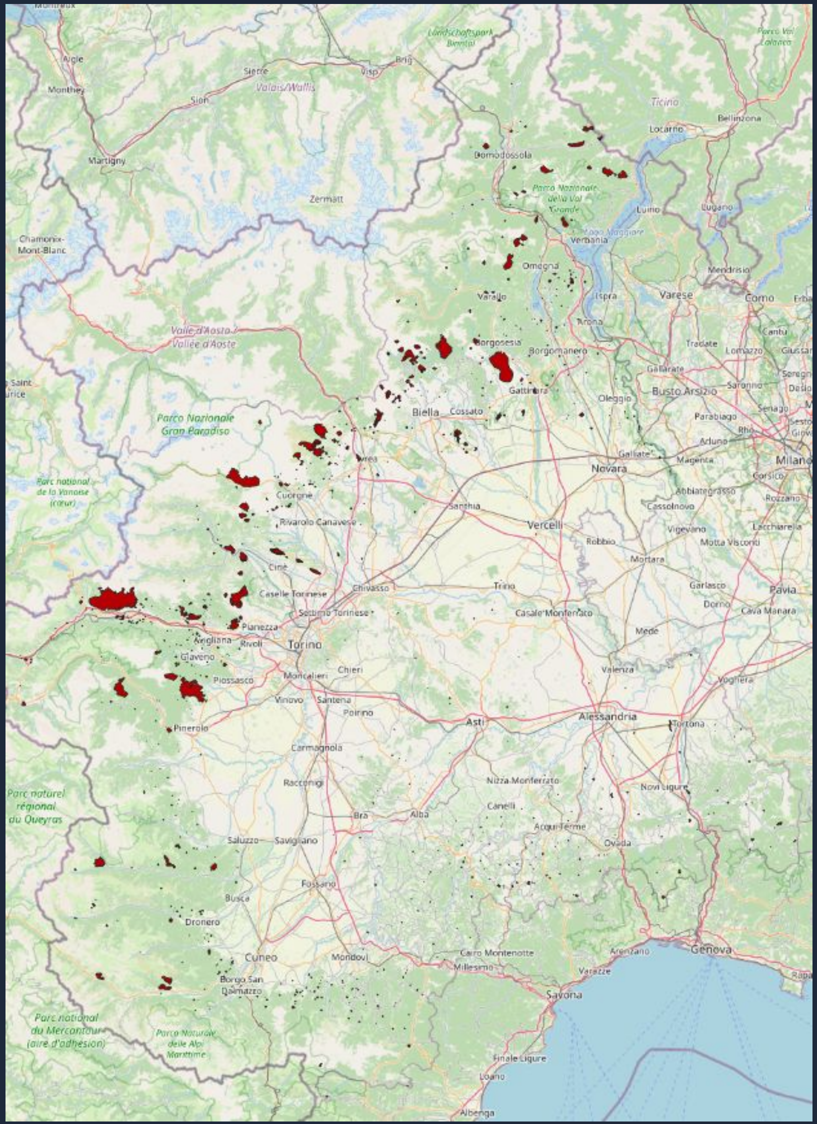
why needed? Critical for estimating fuel type, Assists the model in differentiating propagation potential based on available fuel.

Roads: Binary road mask (10m resolution).

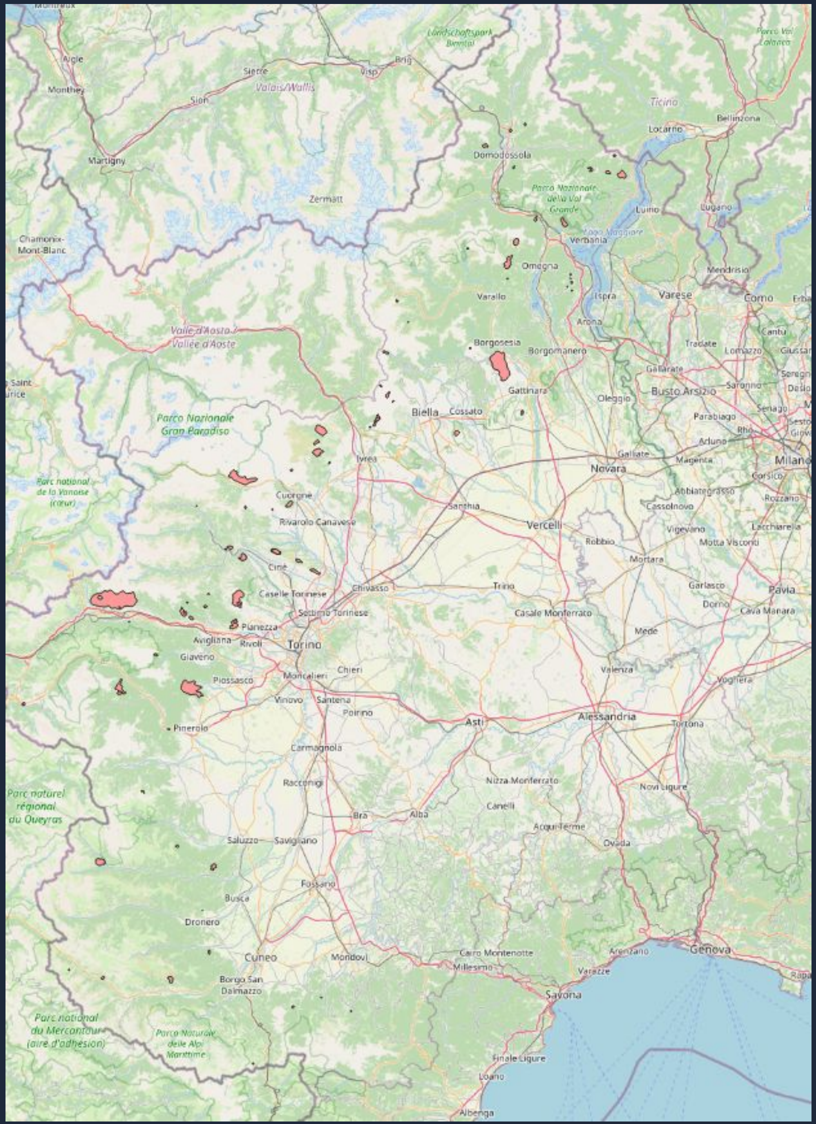
why needed? Captures both human-caused ignition likelihood and fire break potential.

Full comparison Fires in Piedmont (areas only)

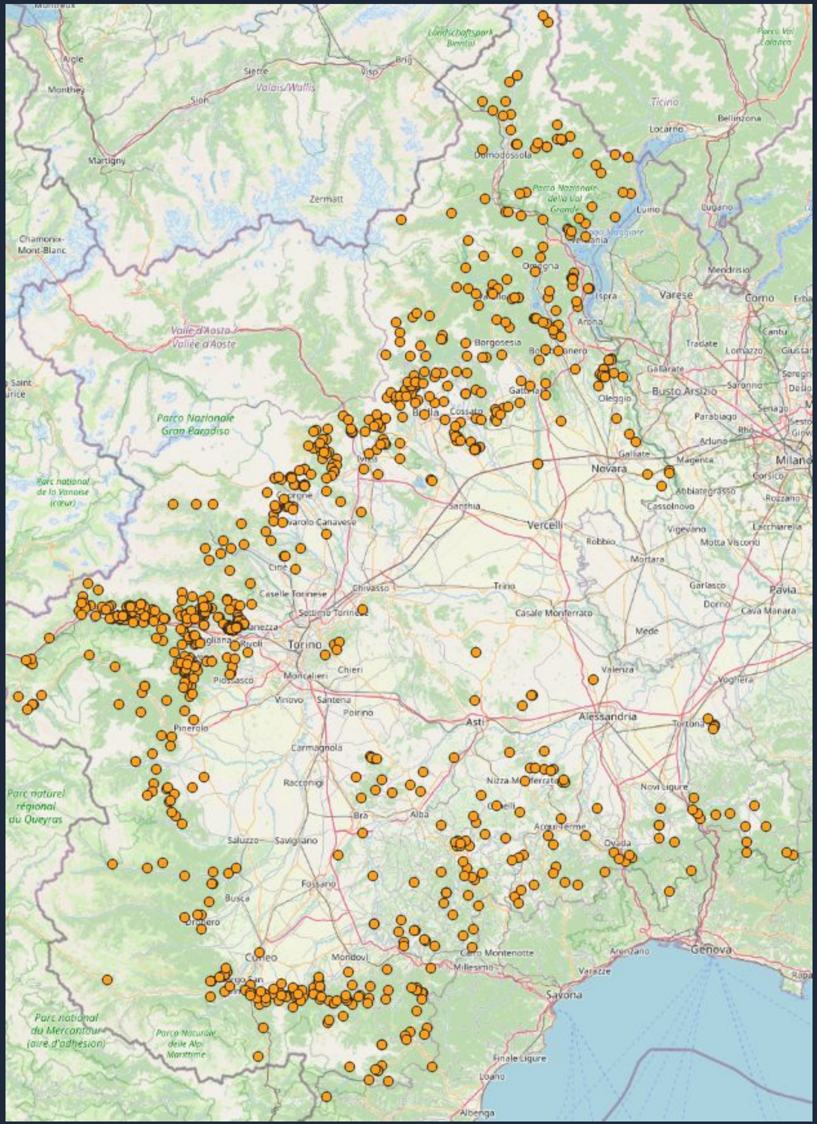
Civil Protection Area



EFFIS Area



Civil Protection Points



Data Preprocessing: Ground Truth layer

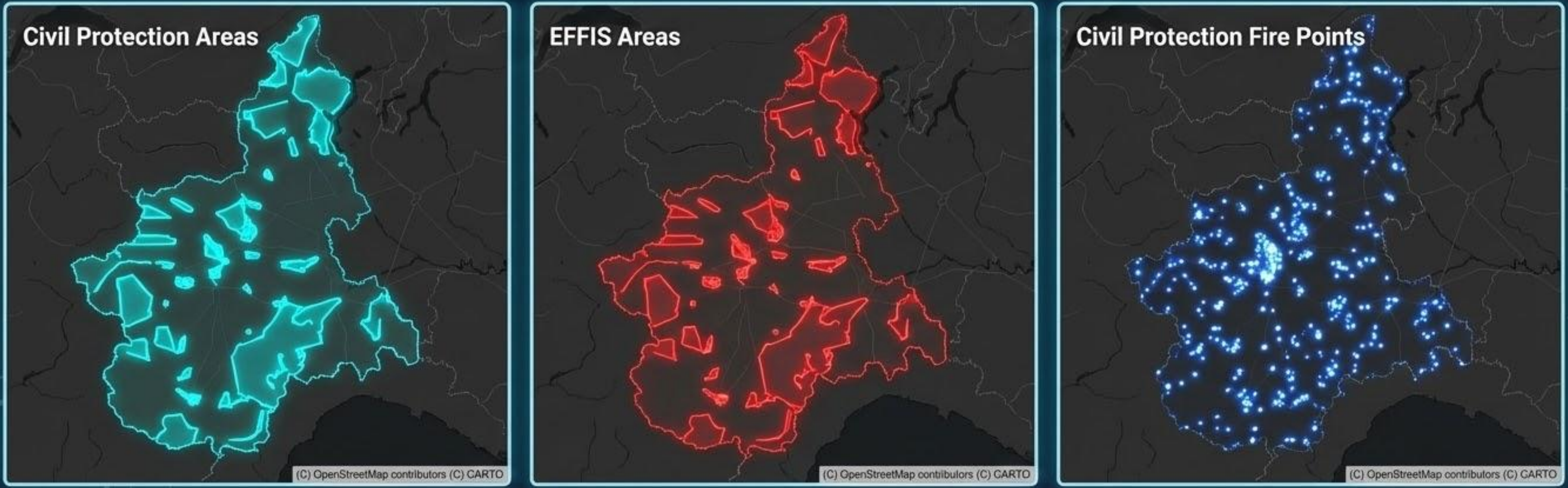
Data Origin & Projection:

Piedmont wildfires (2012–2024) stored as GeoJSON. Reprojected to UTM 32N (EPSG:32632) to serve as the unified coordinate reference system.

Rigorous Filtering:

Events retained only if:

- **Date ≥ 2015-06-23** (Ensures Sentinel-2 coverage)
- **Area ≥ 200 m²** (Eliminates sub-pixel noise at 10m)



Data Preprocessing: Satellite Imagery

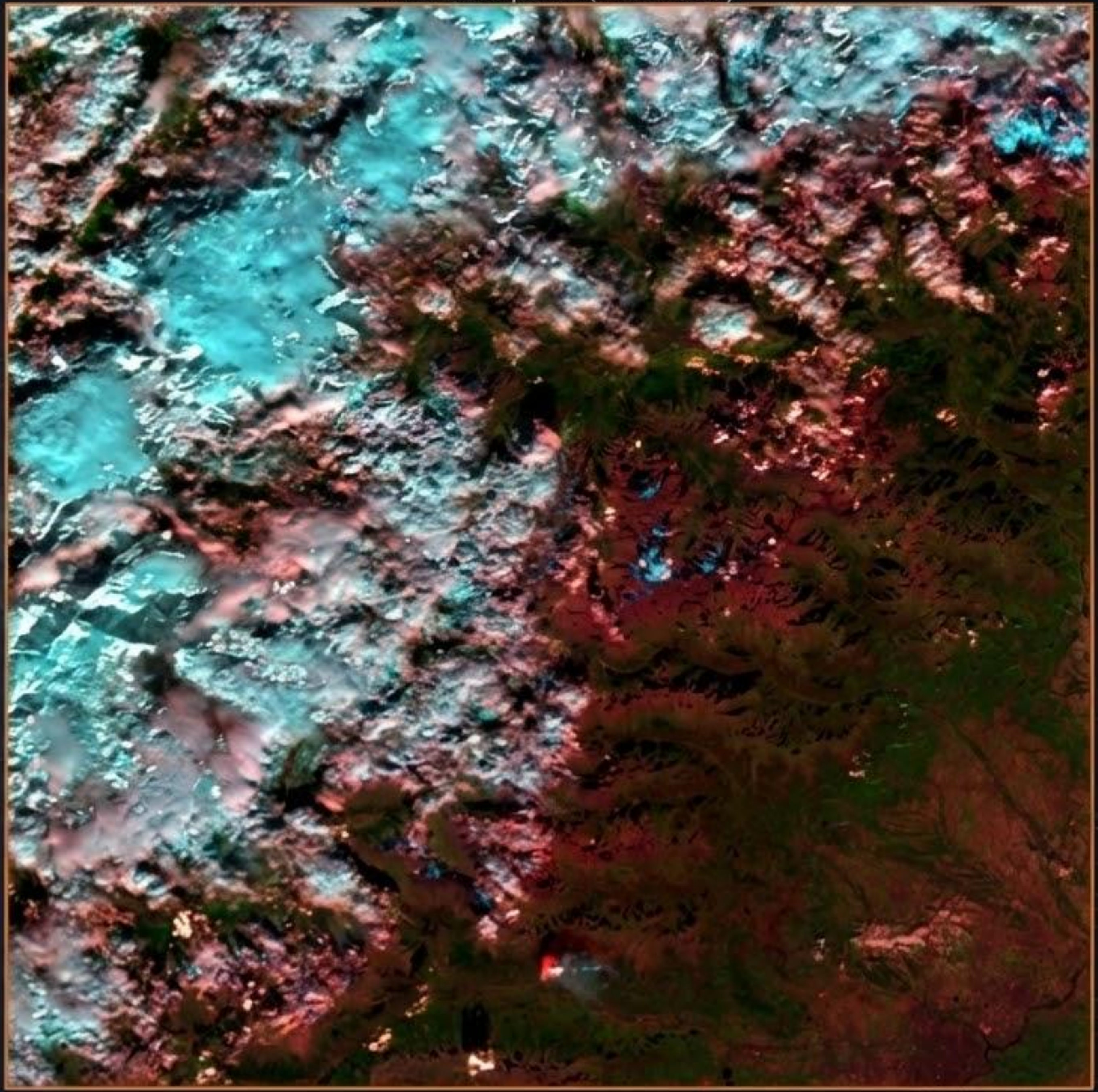
Sentinel-2 Acquisition

- Queried via Microsoft Planetary Computer with a **7-day pre-fire window**. This captures vegetation conditions immediately preceding the event.
- Multispectral Processing: All bands (10m, 20m, 60m) are reprojected and resampled to the **10m reference grid** using bilinear interpolation.

Optimization & Landsat

- **The 256×256 Reference Patch:**
  A fixed 2.56 km × 2.56 km square window centred on the fire geometry. This defines the target resolution (10m) and transform for all subsequent layers.
- **Landsat Integration:** Scenes are pre-resampled to **10m** to align perfectly with the Sentinel-2 spatial stack.

False color composition (SWIR/NIR/RED)



Data Preprocessing: Cloud Exclusion

Why it matters: Clouds obscure ground features (occlusion) and alter pixel reflectance values (radiometric noise), creating "blind spots" in the dataset.

Cloud Masking: Used CloudSen12 to select the clearest Sentinel-2 acquisition within a 7-day pre-fire window. including cloudy parts forces the model to learn atmospheric artifacts rather than actual terrain features

After: Clearest Acquisition (Selected)

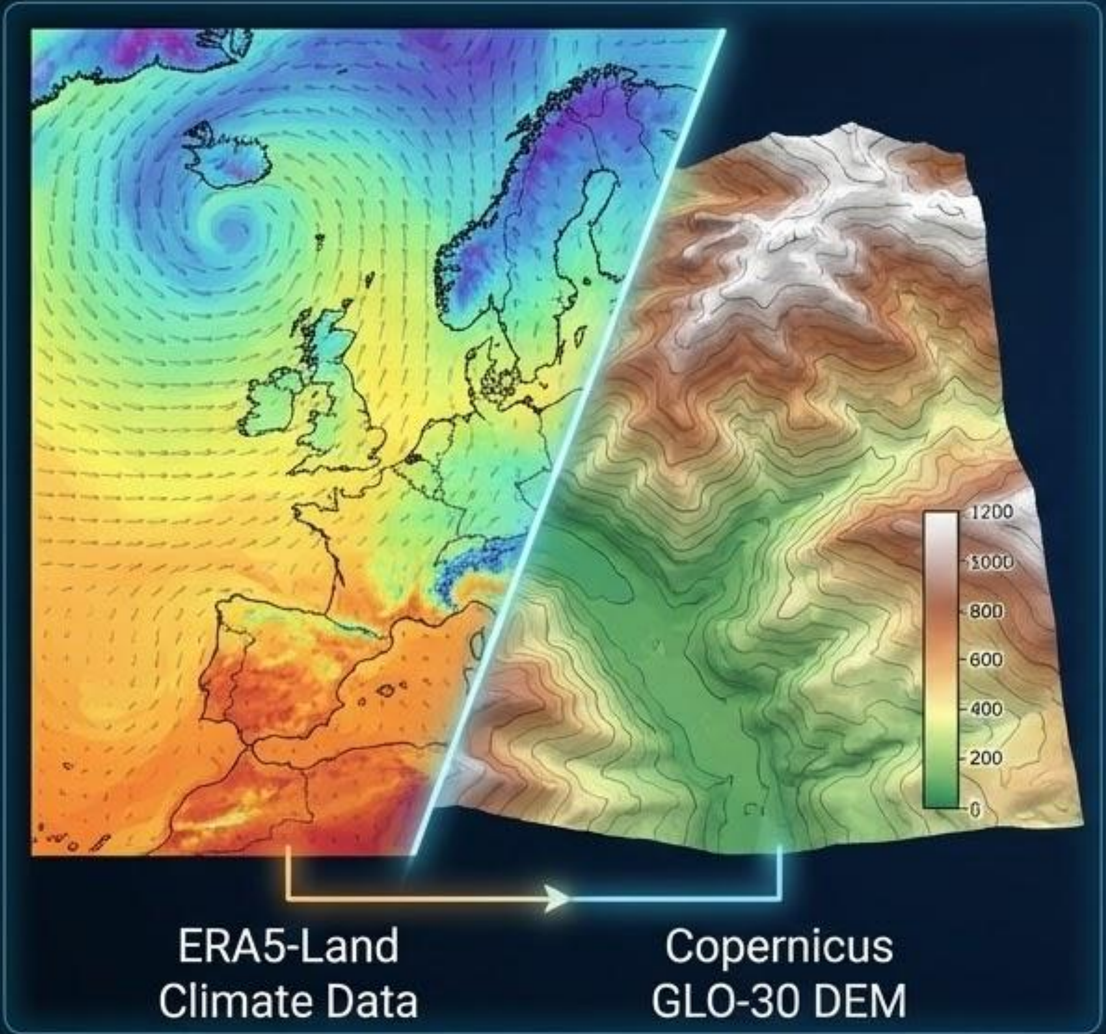
Sentinel-2 - Data: 2017-10-22 (Crop)

Filtering Process

Before: Cloudy Acquisition

Sentinel-2 - Data: 2017-10-27 (Crop)

Data Preprocessing: Climate & Terrain Features



ERA5-Land Climate Fields

- **Synoptic Meteorology:** Daily statistics inferred from the pre-fire date.
- **Variables:** Air temp (t2m), Dewpoint (d2m), Skin temp (skt), Soil temp profile (stll1–4), and Wind vectors (u10, v10).
- **Downscaling:** Raw 0.1° (~10km) data is cropped and resampled to the 10m reference grid.

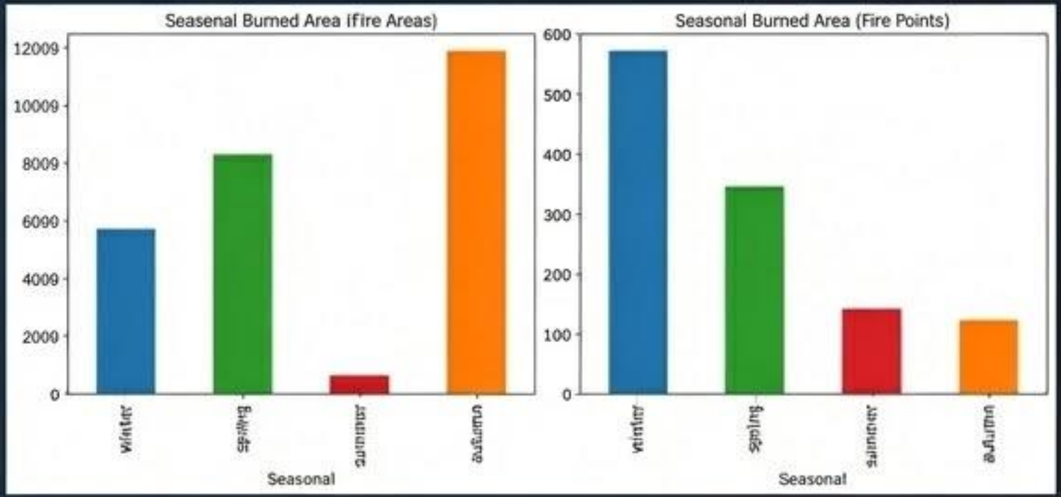
Copernicus GLO-30 DEM

- **Native Resolution:** 30m resolution is maintained to avoid artificial high-frequency artifacts.
- **Process:** Reprojected to EPSG:32632 and resampled to the 256×256 patch (covering approx. 7.68 km × 7.68 km).

Dataset Characteristics & Challenges

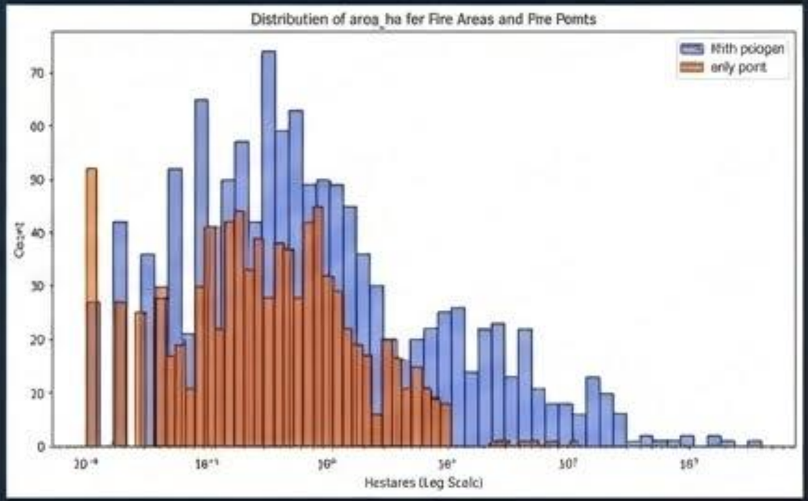
Scientific Context: Seasonal Patterns & Imbalance

Seasonal Disparities: Frequency vs. Severity



- The number of fires doesn't match how much land gets burned.
- Winter has the most fire starts, but they usually stay small.
- Autumn has fewer fires, but they grow much bigger and burn more land.
- This means we need to predict how *bad* a fire will be, not just if it will start.

Size Distribution & Dataset Imbalance



- Our data is very unbalanced, with a 'long tail' of rare events.
- Most fires are tiny (less than 1 hectare, like a small field).
- The "Polygon" data (blue) shows the rare but huge fires (>100 ha) that cause the most damage.
- This imbalance makes it hard to teach a computer model to predict the big, important fires.

Model Inference Example: Sentinel Input → Fire Mask Output

Model Output Visaulization - Baseline Performance

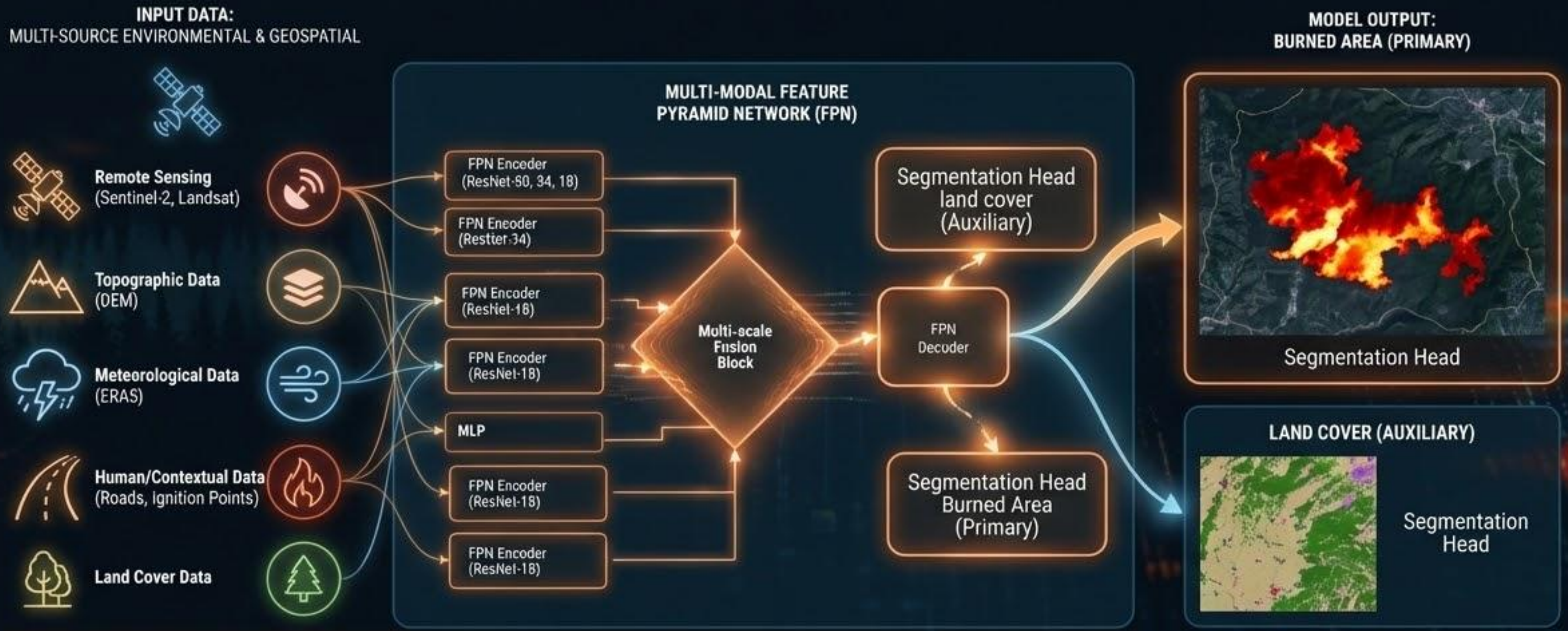
Input & Challenge

- Single Sentinel-2 crop (all spectral channels).
- Extremely small ground truth fire footprint creates severe class imbalance.

Baseline Result

- Model overpredicts and mis-localizes the burned area.
- Visual result matches quantitatale score (IoU ≤ 0.1).

METHODOLOGY: MULTI-MODAL FPN



A custom architecture extending the **Feature Pyramid Network (FPN)** design to handle 7 distinct input streams.

Key Innovation: Specialized encoders for each modality + Lateral Fusion + Multi-Task Heads.

FUTURE STEPS I: DATA, MODELING & EVALUATION

1. EXPAND BEYOND SINGLE-MODALITY INPUT

- Integrate multi-modal data sources: Sentinel optical bands, thermal anomalies, vegetation indices (NDVI), weather forecasts, topography (DEM).
- Objective: reduce reliance on RGB alone and prevent the model from “cheating” by using trivial cues.

2. IMPLEMENT SPATIOTEMPORAL MODELING

- Add temporal sequences (pre-fire + fire-progression windows).
- Explore ConvLSTM / Vision Transformer (ViT) temporal stacks.
- Outcome: capture fire evolution dynamics rather than static frames.

3. ROBUST EVALUATION FRAMEWORK

- Introduce IoU, precision/recall, F1, Dice Score, and per-class metrics.
- Build a standardized inference pipeline for region-level scoring.
- Add BCS (Burned-Area Consistency Score) to detect implausible segmentations.

Thanks for the attention

Any questions ?