

# Wildfires and air quality anomalies: smoke source attribution and characterization on the Island of Montreal

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## Abstract

In this study, anomalous  $PM_{2.5}$  concentrations on the Island of Montreal (2007–2025) are identified and attributed to upwind wildfire activity using the intersection of HYSPLIT back trajectories with clustered hotspot detections from the Canadian Wildland Fire Information System (CWFIS). A trajectory–source plausibility metric is developed based on the fraction of back trajectories that intersect spatially clustered wildfire events. The robustness of this metric is evaluated across a physically motivated range of DBSCAN clustering parameters and spatio-temporal buffering distances. Four days exhibiting simultaneous extremes in both  $PM_{2.5}$  concentration and trajectory–wildfire intersection ratio are identified, corresponding to 175 contributing wildfire events. These events are subsequently characterized by ecozone and fuel type, revealing that most correlated fires occurred within Boreal Shield ecozones and predominantly involved Boreal Spruce fuels.

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## 1. Introduction

This past summer, Montreal experienced several days of extremely poor air quality [1, 2]. Notably, on August 8th, CBC News reported that Montreal briefly had the worst air quality out of all global urban centers, with Environment Canada attributing the event to ongoing wildfires in the Canadian Prairies [3]. Similar events occurred during 2023’s wildfire season, when Montreal’s Réseau de surveillance de la qualité de l’air (RSQA) [4] reported that the majority of smog days were associated with smoke transport from Northern Quebec.

These events reflect a broader, global trend of increasing wildfire frequency [5], spatial footprint, and duration [6] in response to the warming of our climate. The most rapid increase has been observed within Canada’s Boreal ecological zones, which contain large, continuous regions of flammable coniferous forest. Wildfires are also known to be major emitters of pollutants, and in particular, fine particulate matter ( $PM_{2.5}$ ) [7].  $PM_{2.5}$  is known to have significant adverse health effects, as the particles are small enough to deeply penetrate lung tissue and collect in the bloodstream [8]. Moreover, the toxicity of fine particulate matter is related to its specific chemical composition and origin [9], reinforcing the motivation for this investigation. Recent work by Fahkri *et. al* [10] further highlights the importance of understanding the dominant emission sources when determining mitigation strategies for population health, particularly in urban centres such as Montreal.

This investigation focuses on source-attribution through transport, and aims to (i) identify anomalous  $PM_{2.5}$  days using the long-term RSQA observations, (ii) evaluate the plausibility of wildfire influence using HYSPLIT back trajectories spatio-temporally intersected with satellite-derived fire hotspots, and (iii) classify the ecological and fuel-type properties of the wildfire events most strongly associated with Montreal’s air quality extremes.

## 2. Methods

The conceptual basis of this investigation follows a typical source-receptor model used in atmospheric transport analysis. Wildfire emissions enter into the planetary boundary layer, undergo long-range transport by synoptic winds, and can reach downwind receptors hundreds to thousands of kilometers away [11, 12]. If Montreal experiences a period of anomalously high  $PM_{2.5}$  concentration and a substantial fraction of back trajectories pass through regions with verified active burning, then wildfire smoke constitutes a physically plausible source of that particulate matter. This is

the standard source–receptor logic employed in long-range transport studies, where trajectory–source overlap is used as a proxy for transport connectivity [13]. The strength of this connection can thus be quantified using the fraction of trajectories encountering active fire regions.

Through the generation of HYSPLIT back trajectories on days of anomalous air quality, a plausibility metric is constructed for wildfire influence from the fraction of back trajectories that spatially and temporally intersect identified wildfire events (the intersection ratio). While this method does not directly measure wildfire emission attributes, it quantifies the relative likelihood that air parcels arriving in Montreal encountered active fire regions along its trajectory.

Fire regions are identified through the spatial clustering (DBSCAN) of hotspot detections. A spatial buffer around cluster boundaries is then applied before testing trajectory intersections to account for geolocation uncertainty in satellite hotspot data and unaccounted-for event bleed into adjacent pixels. The chosen buffer and DBSCAN parameters were selected on a physical basis after sensitivity testing to ensure the  $\epsilon$  parameter would not split single fires into multiple events or merge distinct, nearby fires into a single event.

Through statistical validation between the plausibility metric for pollutant transport and poor air quality concentrations on the Island of Montreal, several wildfire events are determined, within the metrics of this study, to be sources of pollutants. These identified wildfire events are then characterized by their ecological region and satellite-identified fuel source.

## 2.1 Data

The datasets used in this analysis, including their spatial and temporal resolutions and roles in the workflow, are summarized in Table 1. They include long-term RSQA air quality observations, GDAS1 meteorological fields for trajectory modelling, CWFIS hotspot detections, and the National Ecological Framework for characterizing ecozones.

Table 1: Data products used for the analysis.

Product Name	Spatial Info	Temporal Info	Usage
RSQA - indice de la qualité de l'air (historique) [14]	Single locations	Hourly intervals, 2007–2025	Air quality anomaly identification
NCEP - GDAS1 [15]	1° resolution	Every 3h, 2004–2025	HYSPLIT inputs
CWFIS Fire M3 Hotspots [16]	375m-2km <sup>2</sup>	Hourly intervals, 1994–2025	Wildfire event clustering
National Ecological Framework for Canada - Terrestrial Ecozones [17]	1: 7 500 000	N/A	Wildfire event characterization

## 2.2 Air quality trend analysis and anomaly identification

The RSQA dataset was filtered for fine particulate matter from April to September, corresponding with Canadian wildfire season [18]. Hourly measurements from all stations were averaged to produce daily means, and the standard error on the mean was computed to characterize sampling uncertainty across stations. A seasonal climatology was constructed by averaging all April–September daily means between 2007–2025. This climatological mean serves as a reference for anomaly identification. An anomaly measurement at the station level was defined as a daily PM<sub>2.5</sub> mean exceeding three standard deviations above the aforementioned mean. Days were designated as anomaly days when at least two stations reported anomalies, reducing the likelihood of misclassifying highly localized events (e.g., industrial fires) as citywide air quality events. See Figure 1 and Figure 2 in Appendix A for visualization.

### 2.3 HYSPLIT Modeling

The NOAA’s Hybrid Lagrangian Single Particle Integrated Trajectory model is frequently employed in wildfire smoke transport models [19, 20], in both puff and single particle capacities. This investigation utilizes the single particle model, due to the fact that single particle trajectory models are particularly equipped to model wildfire pollutant transport due to their robustness under strong vertical wind shear and their established performance for transport distances exceeding 1000 km [13]. To accelerate the trajectory generation workflow, the usage of the Python library, PySplit [21], was employed, with NOAA’s GDAS one-degree data inputs for model parameters.

Back trajectories were initiated every four hours on each anomaly day from five altitude levels above ground level: 10 m, 50 m, 100 m, 250 m, and 500 m. These altitudes span elevations where pollutants are most likely to impact residents of the city of Montreal. Each RSQA station thus contributed 30 trajectories per anomaly day. Backward integration was performed for 120 hours (5 days), as done in Wilmot *et al.* [20]. Several generated trajectories are presented in Figure 3 in Appendix A.

### 2.4 Wildfire event classification

Hotspot detections from the CWFIS Fire M3 product (CHECK), derived from the MODIS (1 km) and VIIRS-I (375 m) satellite instruments, were used to identify active fire locations. MODIS provides long-term continuity, while VIIRS offers improved detection of small or low-intensity fires due to its finer spatial resolution [22, 23].

To classify coherent fire events, hotspots were clustered using DBSCAN [24, 25]. Due to the quadratic scaling of spatio-temporal clustering algorithms with sample size (e.g., ST-DBSCAN [26]), these more sophisticated algorithms were computationally impractical for this study. The hotspots were thus flattened over a two-week window preceding each anomaly day. Fires that remain spatially coherent over a two-week period can be reasonably assumed to be temporally coherent as well, whereas flattening over longer periods (e.g., months to years) would risk merging unrelated fires.

Initial parameters were set with an  $\epsilon$  of 1000m and a minimum sample size of 5 samples to exceed geolocation uncertainty while remaining below the spatial threshold separating independent burn events [25]. Sensitivity testing on  $\epsilon$  was later used to select a physically consistent value for the final plausibility metric. A sample clustering result is shown in Figure 4 in Appendix A.

### 2.5 Geospatial and temporal trajectory-wildfire intersection

To confirm that these particles originate from wildfires, the geospatial and temporal intersections of their trajectories with identified wildfire events was determined. The likelihood evaluation of the origin being a wildfire event takes a simplified approach to the work conducted by Wilmot *et al.* [20]. While back trajectory intersection does not directly estimate resultant pollutant concentrations, it is a common proxy for establishing transport plausibility in source-receptor investigations [11, 13, 20]. Thus, if a large fraction of trajectories pass through active fire regions, the probability that Montreal’s air parcel contained wildfire-derived PM<sub>2.5</sub> increases.

A “smokestack” geometrical approximation was adopted, wherein each fire cluster is treated as generating a vertical column of potential smoke influence above the burn area [12, 27], thus allowing for the omission of altitude during the determination of trajectory and wildfire event intersection. To account for geolocational uncertainty and the finite area of burning within a satellite pixel, each fire cluster was expanded by a radial buffer equal to one-third of the  $\epsilon$  parameter used in DBSCAN. Additionally, hotspot detections were temporally buffered by  $\pm 6$  hours to reflect satellite revisit times and the nature of detected thermal anomalies, which do not represent exact ignition or extinction times.

Trajectory points were considered intersecting if they fell within the buffered fire perimeter and within  $\pm 6$  hours of the buffered fire detection time. This dual constraint ensures that only physically plausible smoke–parcel encounters are counted.

## 2.6 Evaluation of candidate smoke sources

For each anomaly day, the intersection ratio was computed as the fraction of trajectories intersecting at least one wildfire event. Sensitivity testing was conducted by increasing  $\epsilon$  from 1 to 15 km and adjusting buffer geometries proportionally (see Figure 5 in Appendix A). Intersection ratios increased monotonically with  $\epsilon$  as expected from expanding fire-cluster footprints. However, values of  $\epsilon > 5$  km produced unrealistic cluster merging, inflating connectivity. However, intersection ratios remained stable for  $\epsilon \approx 1\text{--}3$  km. Based on this behaviour,  $\epsilon = 2$  km was selected for statistical validation between intersection ratio and pollutant concentration. Colarco *et al.* [11] similarly validates transport attribution by comparing HYSPLIT back trajectories with satellite-derived fire locations, demonstrating that trajectory-wildfire intersection is a reasonable indicator of smoke influence at receptor sites.

With an identified strong positive correlation from the Spearman rank correlation, days were classified as strongly connected to wildfire activity when both their intersection ratio and  $\text{PM}_{2.5}$  concentrations exceeded the 75th percentile of their respective distributions. This combined criterion thus isolates days where wildfire influence is most plausible. These days form the basis for identifying specific fire events contributing to Montreal’s degraded air quality.

## 2.7 Characterization of identified smoke sources

For the subset of strongly connected days, correlated wildfire events were extracted and characterized. Ecozones were assigned using the National Ecological Framework for Canada [17], and fuel types were taken from the CWFIS Fire Behaviour Prediction (FBP) system [28]. Cluster-level attributes were determined using the modal value of all hotspots within the cluster. In cases where water appears as the modal fuel type, this indicates that the hotspot lies on a mixed land–water pixel, not that water served as combustible material.

As fire intensity data for 2025 remains incomplete at the time of analysis, all contributing wildfire events were treated equally in the characterization stage.

## 3. Results

Across the wildfire seasons (April–September) of 2007–2025, the Island of Montreal exhibited a mean  $\text{PM}_{2.5}$  concentration of  $11.26 \mu\text{g}/\text{m}^3$  with a standard deviation of  $6.9 \mu\text{g}/\text{m}^3$ . Using the  $> 3\sigma$  criterion, 32 anomaly days were identified in which at least two RSQA stations recorded extreme  $\text{PM}_{2.5}$  values. For reference, the World Health Organization’s annual target for  $\text{PM}_{2.5}$  is  $5 \mu\text{g}/\text{m}^3$  [29], indicating that many of the anomaly events far exceeded recommended exposure thresholds.

Sensitivity testing of DBSCAN  $\epsilon$  values revealed that intersection ratios behaved as expected: increasing monotonically with  $\epsilon$  and the associated buffer size. For  $\epsilon > 5$  km, multiple visually distinct fires merged, producing artificially inflated connectivity. Intersection ratios remained consistent between  $\epsilon \approx 1\text{--}3$  km, indicating a physically meaningful range where clustering reflects true burn perimeters rather than over-aggregation. This range informed the selection of  $\epsilon = 2$  km.

A Spearman rank correlation yielded a  $\rho$  of 0.60, with a  $p$  of  $2.4 \cdot 10^{-4}$ , indicating a strong and statistically significant monotonic association, confirming that days with high particulate matter concentration are strongly positively correlated with days with high intersection ratios.

Uncertainty in both trajectory pathways and hotspot detection implies that intersection ratios should be interpreted probabilistically rather than deterministically. Therefore, all results refer to plausible, not definitive, transport connectivity. Particularly, back trajectories are subject to model uncertainty, particularly over extended distances, and do not fully represent smoke plume dynamics such as plume rise, injection height, and initial dispersion due to prevailing wind patterns.

However, while this method cannot directly prove causation, the strong monotonic association between intersection ratio and anomalous  $\text{PM}_{2.5}$  provides significant evidence for wildfire influence on air quality in Montreal.

From the dual-threshold classification (>75th percentile in both metrics), four days were identified as strongly connected to upwind wildfire activity: 2023-06-06, 2023-06-25, 2025-06-06, and 2025-07-26, with mean concentrations of 44.7, 128.4, 65.8, and 82.7  $\mu\text{g}/\text{m}^3$  respectively. Across these four days, 175 wildfire events intersected back trajectories under the parameters of this study. These events were subsequently characterized by ecozone and fuel type.

### **3.1 June 6th, 2023**

For June 6th, 2023, 38 wildfire events were identified to be correlated within the metrics of this study with poor air quality in Montreal. It was found that 97.4% of the correlated events were located within Quebec's Boreal Shield region, with Boreal Spruce identified as the primary fuel source (79%), with secondary contributions from Mature Jack or Lodgepole Pine, Green Boreal Mixedwood, and Leafless Aspen. Results are presented in Figure 6 in Appendix A.

These results are consistent with fire activity patterns documented during the early 2023 wildfire season, when extensive burning occurred across Quebec's Boreal forests [4].

### **3.2 June 25th, 2023**

On June 25th, 2023, 33 wildfire events were identified as correlated. Again, the majority occurred in the Boreal Shield, primarily in Quebec but with additional contributions from fires in adjacent regions. Boreal Spruce remained the dominant fuel type, accompanied by Spruce–Lichen Woodland, Leafless Aspen, and Grass.

Results are presented in Figure 7 in Appendix A.

### **3.3 June 6th, 2025**

For June 6th, 2025, 38 wildfire events were identified as correlated. Unlike the 2023 cases, all contributing fires originated in Western Canada, with none located in Quebec. Most events were situated within the Boreal Plains ecozone, with additional contributions from the Boreal Shield and Taiga Plains. A wider diversity of fuel types were also identified, consistent with the land cover of western ecozones.

Results are presented in Figure 8 in Appendix A.

### **3.4 July 26th, 2025**

On July 26th, 2025, 88 wildfire events were identified as correlated, significantly more than any other day in the strongly connected subset. As with the June 2023 events, most fires were located within the Boreal Shield, although substantial numbers were also found in the Boreal Plains and Taiga Shield ecozones. A wide variety of fuel types were identified across the correlated clusters, including coniferous, mixedwood, and grassland fuels.

Results are presented in Figure 9 in Appendix A.

## **4. Discussion**

While this analysis does not directly evaluate long-term trends in fire activity, the concentration of correlated events within the Boreal Shield is consistent with broader findings that this ecozone is experiencing rapid increases in burn area and activity longevity [6]. While this investigation does not attempt to infer future fire behaviour from four case-study days, the identification of 116 Boreal Shield fires that have influenced Montreal over four smoke events in recent years suggests that future summers may involve more frequent long-range smoke transport from this region if current climate-driven trends continue.

The strong Spearman correlation between trajectory–fire intersection ratio and  $\text{PM}_{2.5}$  concentration supports the usefulness of simple transport-based metrics for evaluating wildfire influence. Nevertheless, several methodological limitations are important to acknowledge. Back trajectories contain inherent uncertainty that increase with travel time

and may not fully capture plume-rise dynamics, particularly injections into the free troposphere. Similarly, the DB-SCAN clustering approach, while computationally efficient, relies on flattening over a two-week window, muddying the temporal evolution of individual fires and potentially merging distinct events.

These limitations imply that the intersection ratio should be interpreted as a plausibility indicator rather than a quantitative measure of transported smoke mass. More advanced modelling approaches such as full chemical transport models, plume-rise parameterizations, and emissions estimations from fire radiative power would be required for mass-based attribution. Despite these constraints, the method employed here successfully isolates days with strong wildfire influence and provides a meaningful characterization of their upwind sources.

## 5. Conclusion

This study applied a trajectory-based plausibility framework to identify wildfire smoke sources associated with extreme PM<sub>2.5</sub> concentrations in Montreal from 2007 to 2025. By combining RSQA air quality observations, HYSPLIT particle trajectories, and CWFIS hotspot detections, a transport connectivity metric was developed and assessed across a physically motivated range of clustering parameters. Four days were identified in which both measured PM<sub>2.5</sub> and trajectory–fire intersection ratios were high, indicating strong wildfire influence.

A total of 175 wildfire events were correlated with these episodes. Characterization of these fires showed that most were located in the Boreal Shield ecozone and primarily involved coniferous fuel types such as Boreal Spruce. These findings align with broader evidence of increasing fire activity in boreal regions and highlight the significant role of upwind boreal fires in shaping Montreal’s smoke exposure during recent summers.

There are several improved methodologies that could enrich the results obtained in this investigation. First, the utilization of dynamic plume-rise models and emissions predictions from fire radiative power would enable mass-based attribution rather than the plausibility-based approach employed in this study. Second, using spatio-temporal clustering algorithms rather than temporal flattening would more accurately represent the evolution of fire complexes. Finally, establishing a null model (eg. random or climatological trajectories intersected with historical hotspots), would allow for formal hypothesis testing of the intersection metric.

Despite the simplified assumptions required by computational constraints, this study demonstrates that trajectory-based methods can effectively identify wildfire smoke sources impacting Montreal and provide a useful basis for characterizing their ecological and fuel-type properties.

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### Air Pollution Over Time by Station

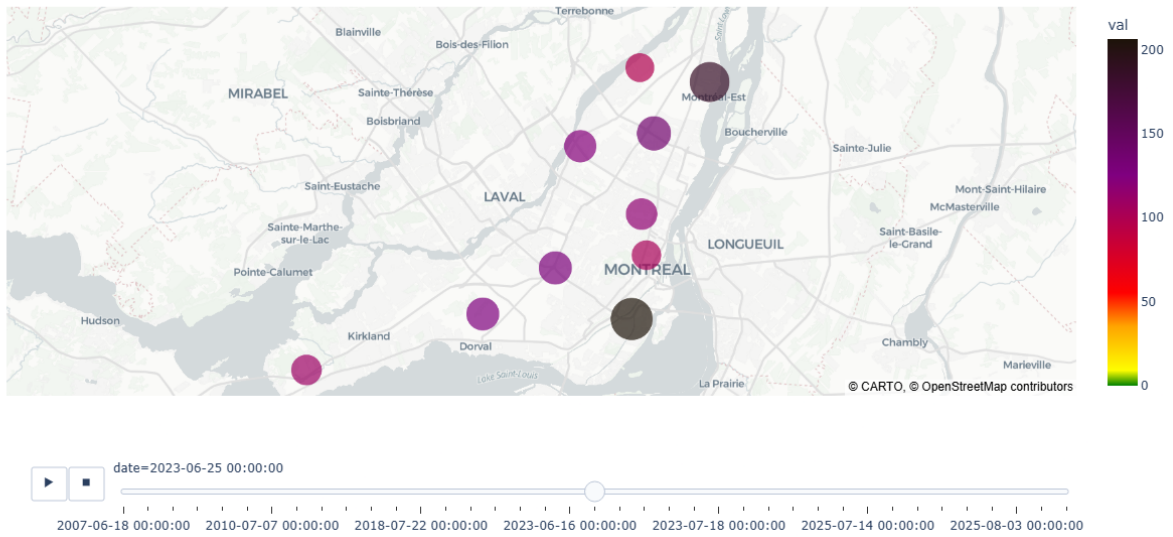


Figure 2: Mean PM<sub>2.5</sub>  $\mu\text{g}/\text{cm}^3$  concentration for June 25th, 2023. Note that any color above orange on the scale indicates an air quality unhealthy for selected groups or worse.

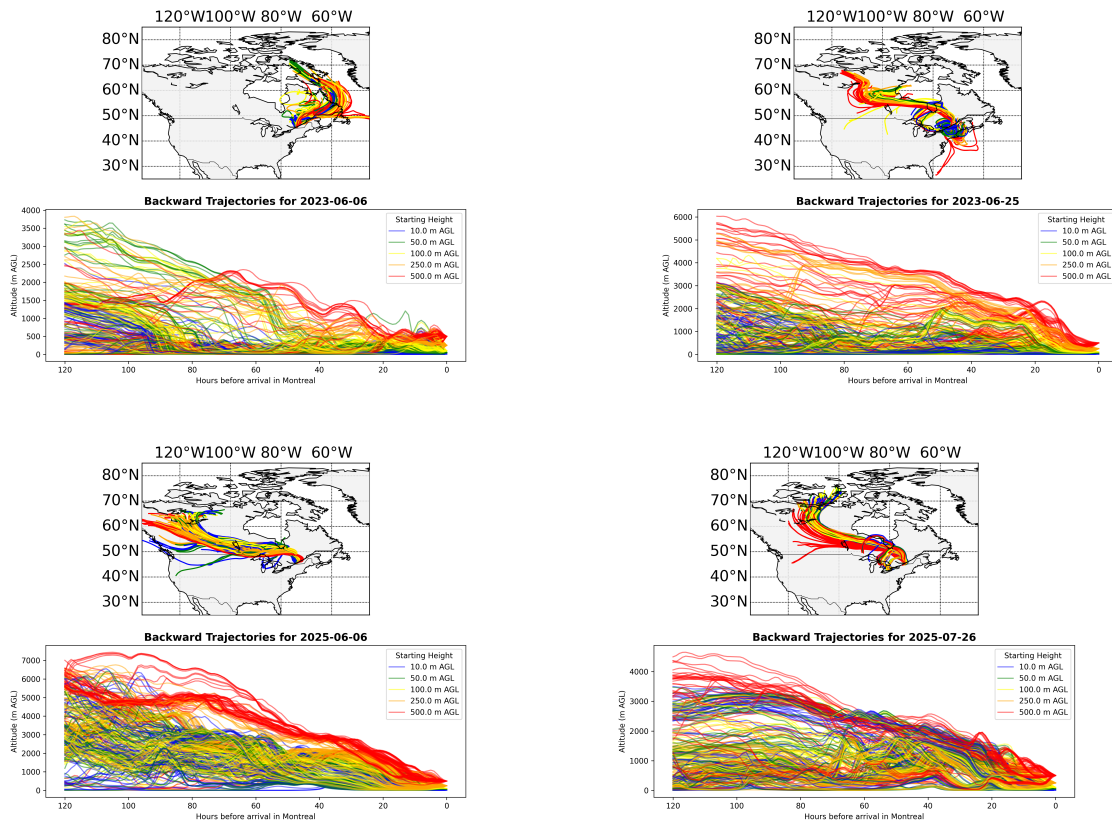


Figure 3: Sample trajectory plots for 2023-06-06, 2023-06-25, 2025-06-06, 2025-06-25.

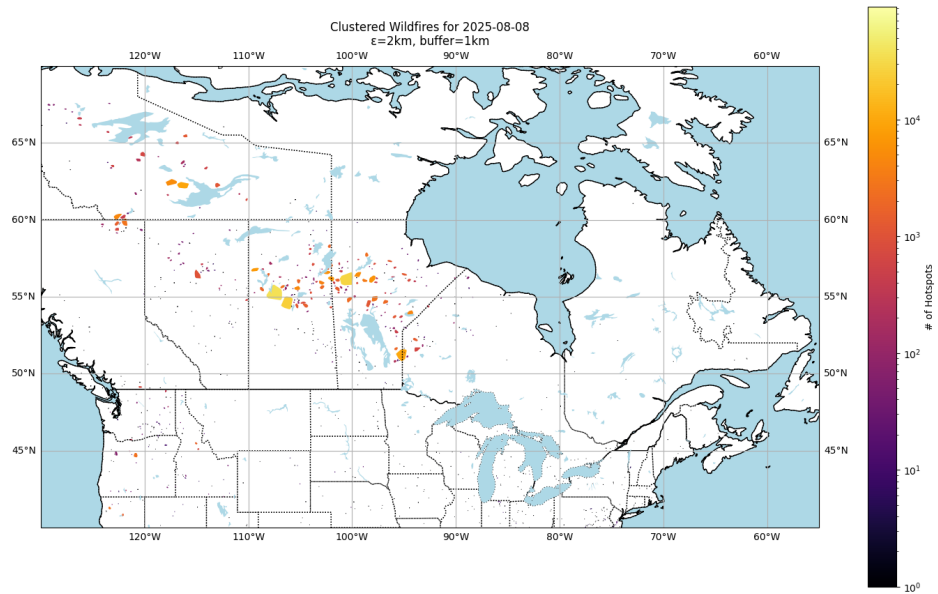


Figure 4: Sample wildfire hotspot clustering result for Canada on August 8th, 2025 for an epsilon of 2km, and an associated buffer of 1km.

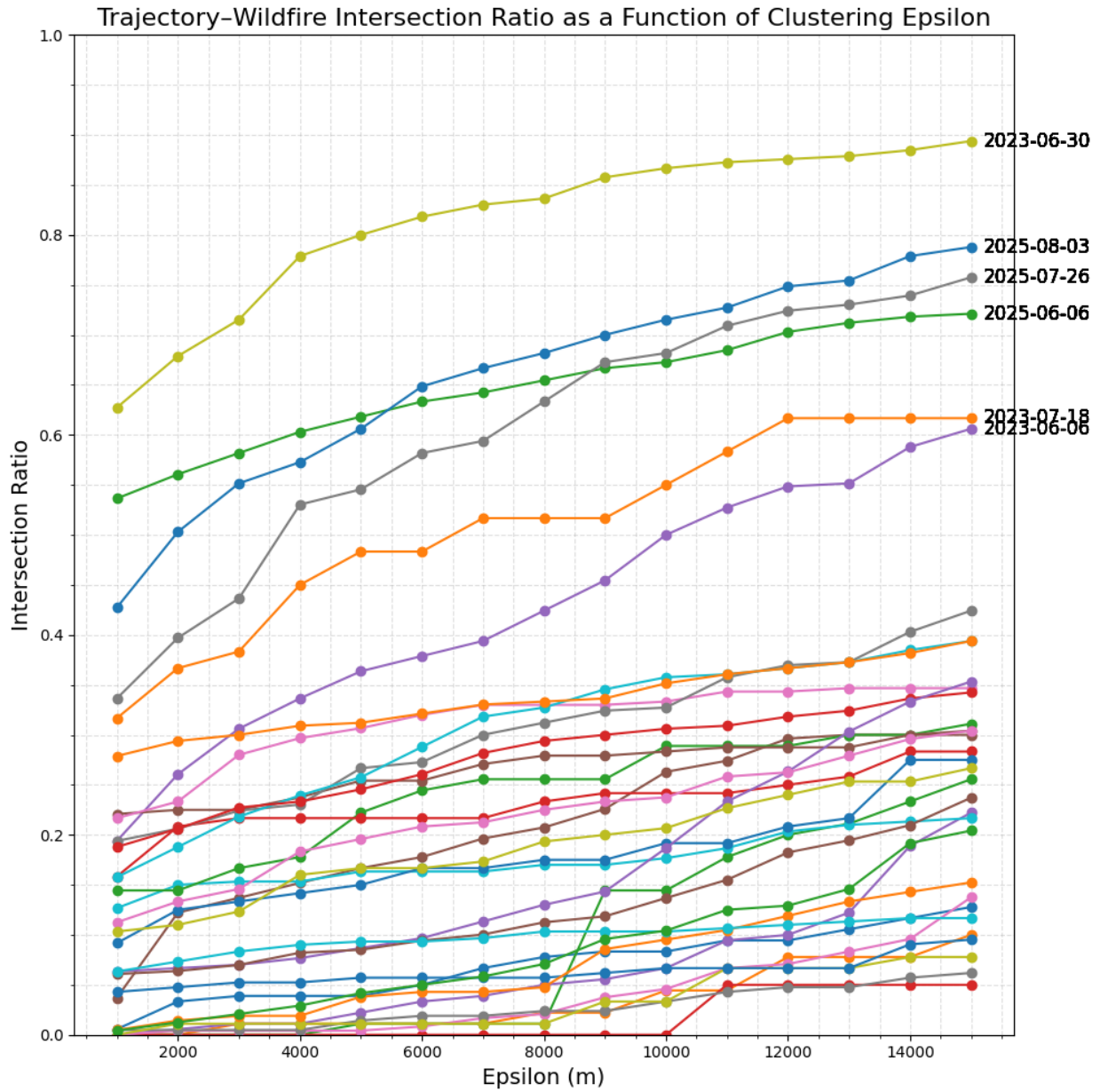


Figure 5: Intersection ratio as a function of increasing epsilon and associated buffer geometry.

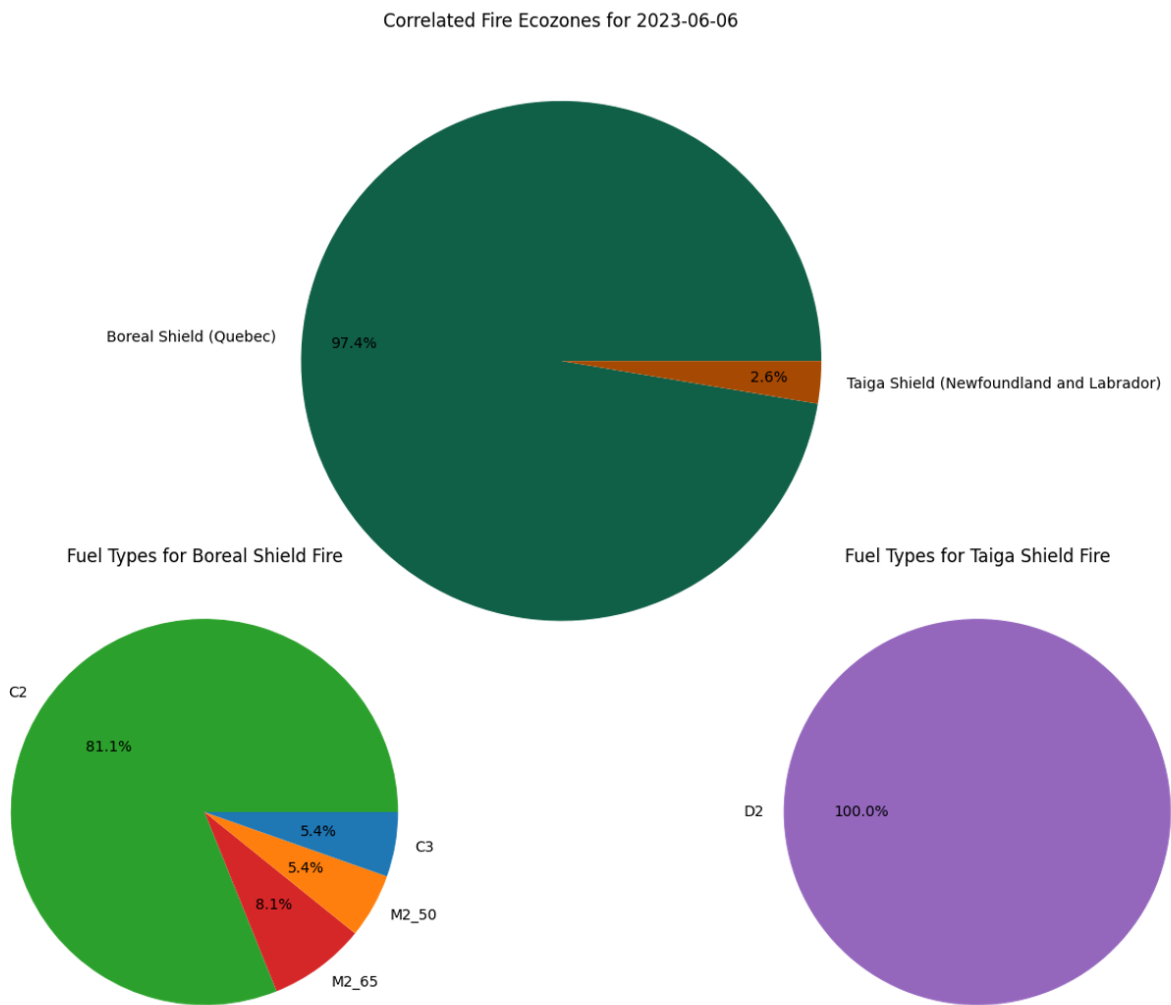


Figure 6: Regional classification of wildfire events for June 6th, 2023, with modal fuel types per ecozone. Fuel classification is listed in [28].



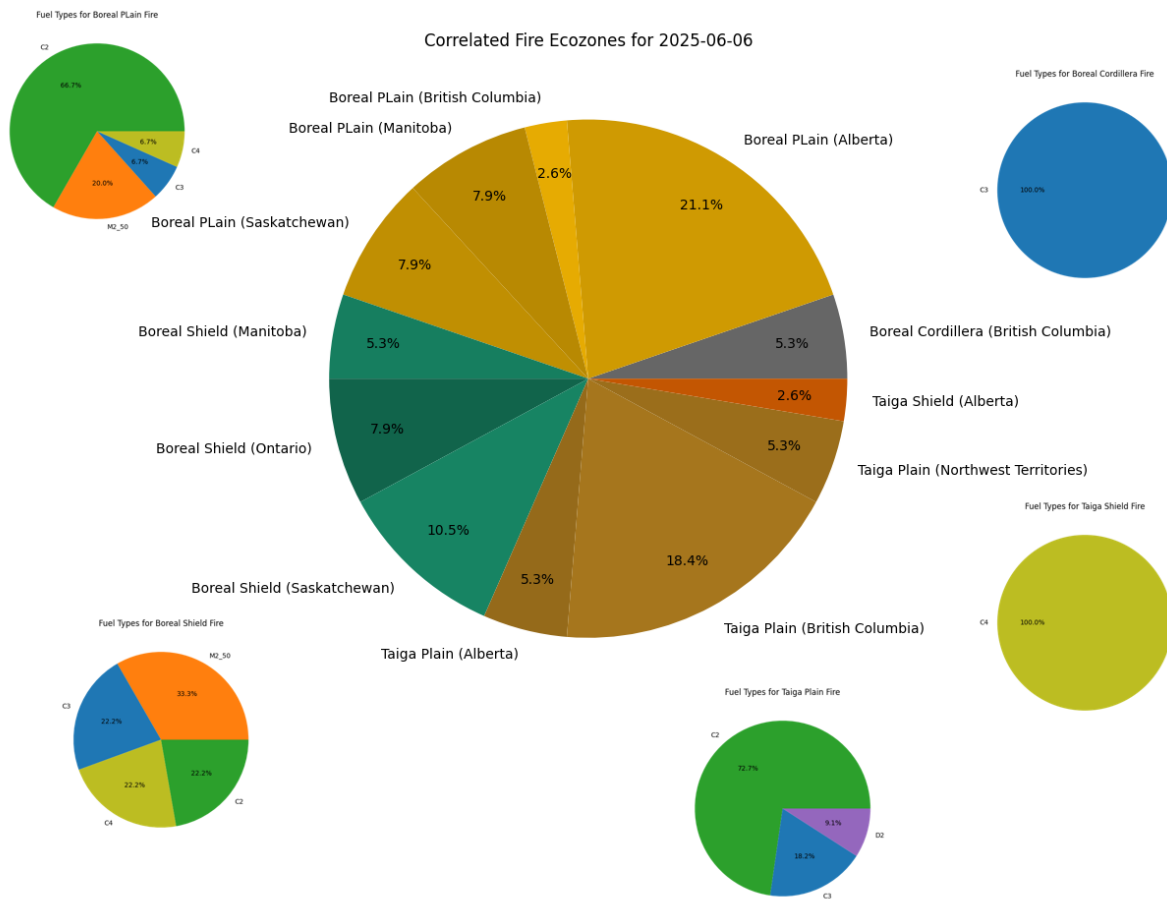


Figure 8: Regional classification of wildfire events for June 6th, 2025, with modal fuel types per ecozone. Fuel classification is listed in [28].

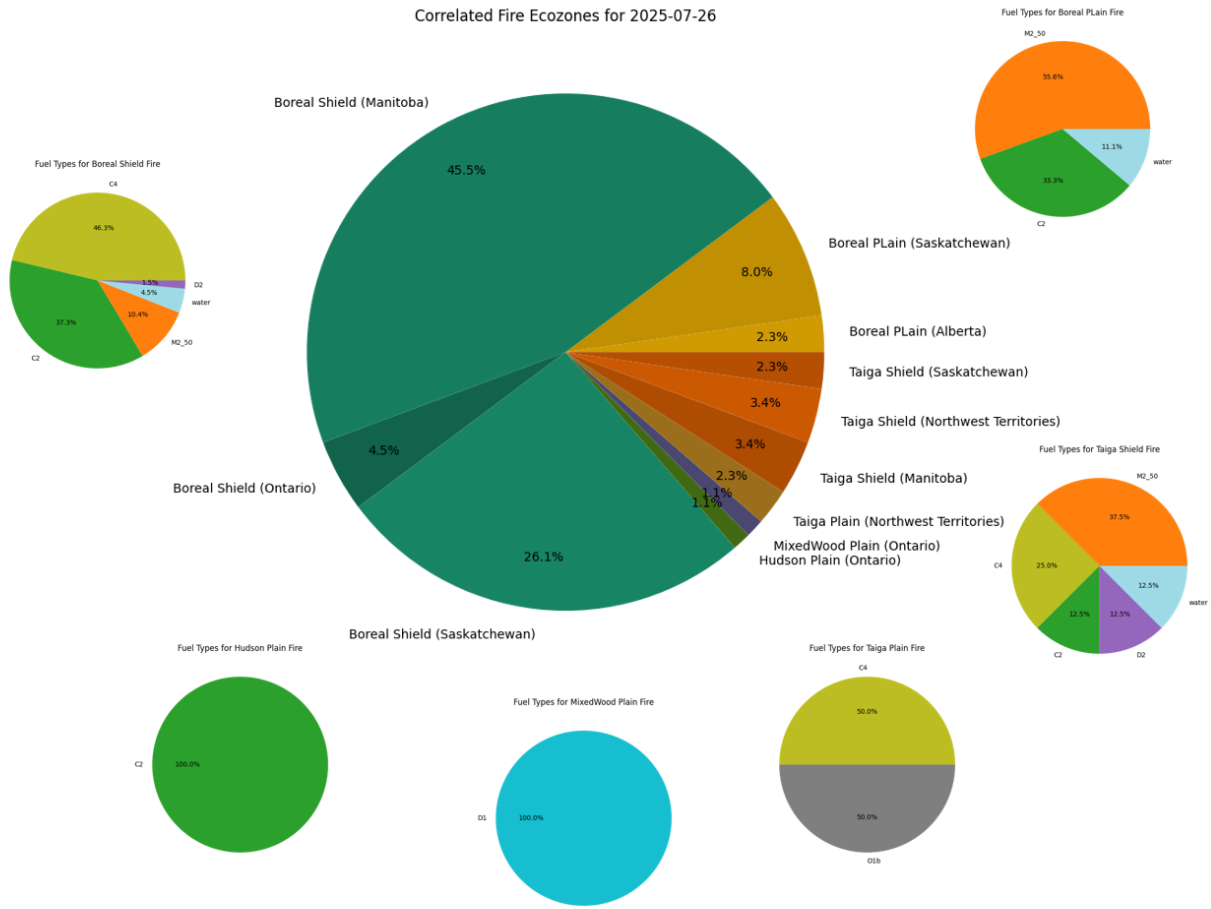


Figure 9: Regional classification of wildfire events for July 26th, 2025, with modal fuel types per ecozone. Fuel classification is listed in [28].