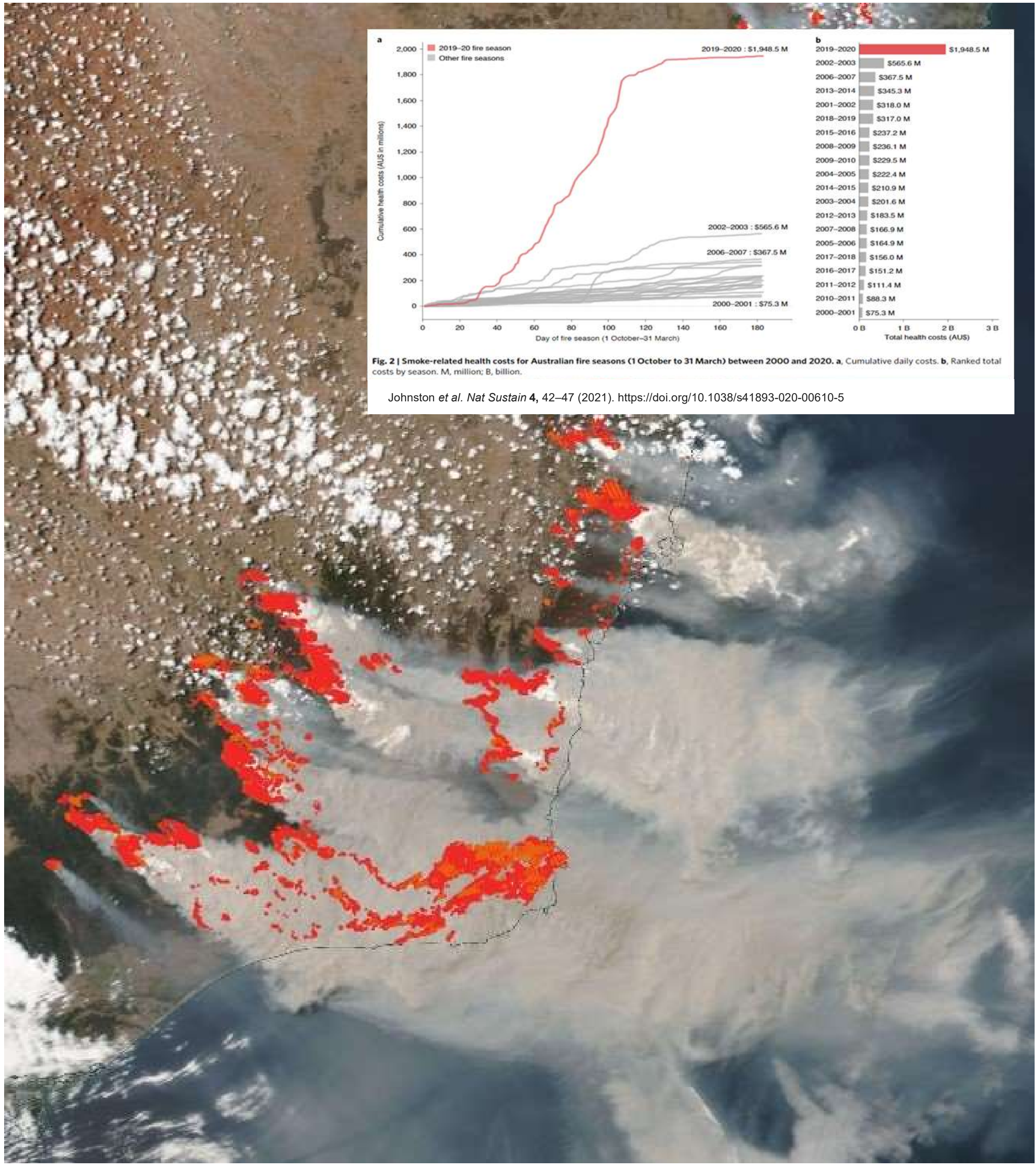
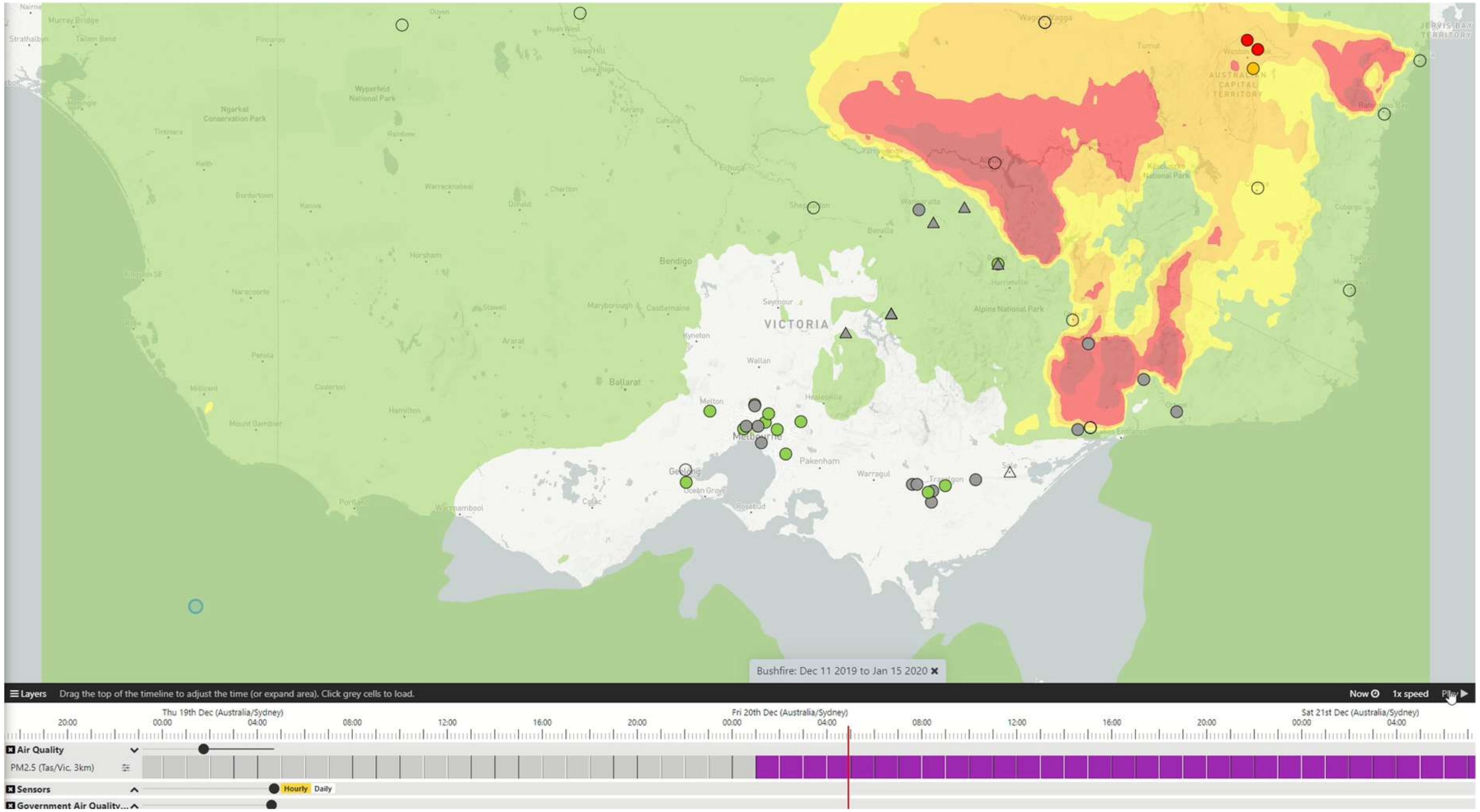
AQFx- a national smoke forecasting system: From emissions to forewarning

Fabienne Reisen (on behalf of the AQFx project team)
20 February 2024

Australia's National Science Agency



A tactical air quality forecasting tool – an aid for managing population exposure to smoke



Provide forecast advisories of when smoke will impact communities

Enable preventative actions

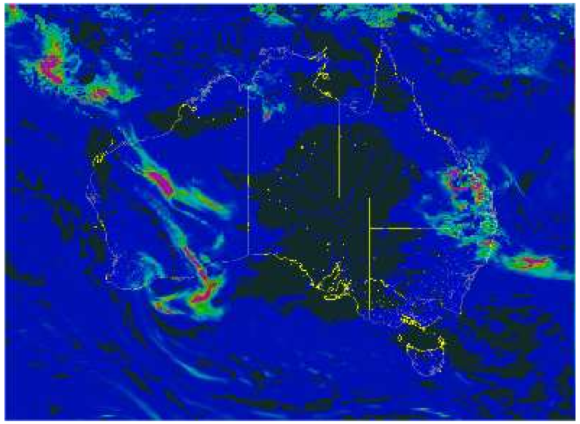
Better planning for burn-offs

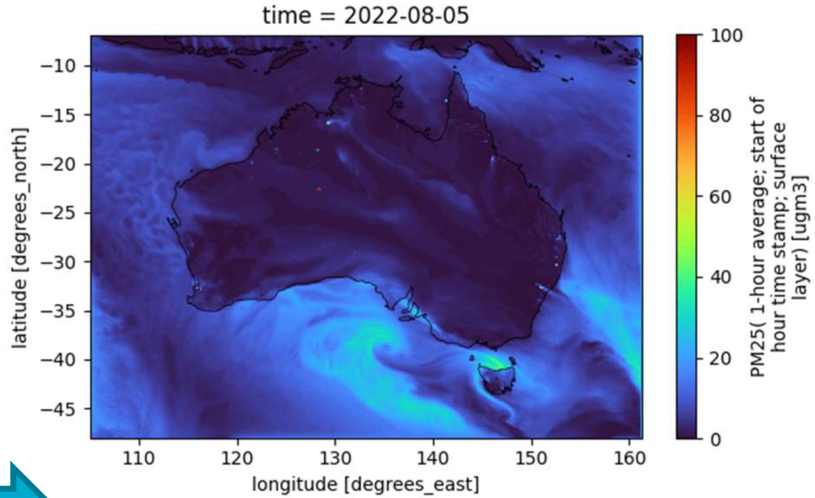
Reduce population health risk from smoke exposure

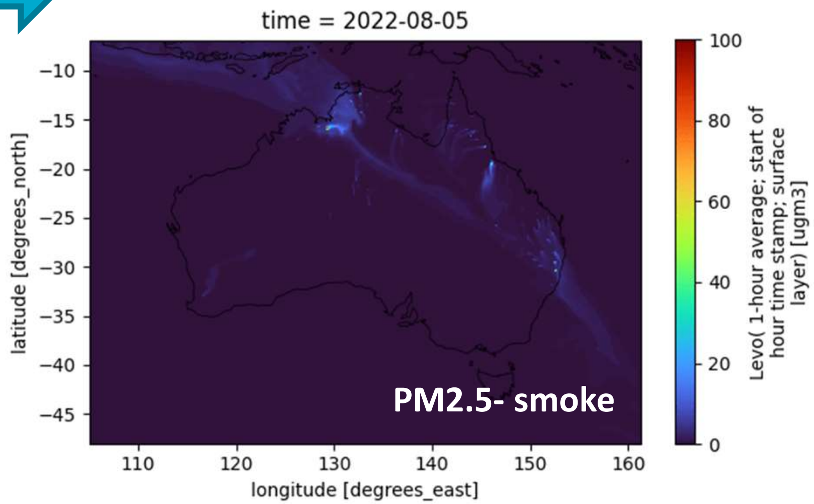
Minimise agricultural impacts

How are forecasts generated?

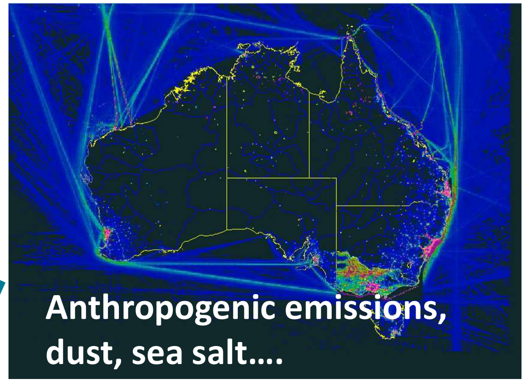
Weather forecasts
(Bureau of Meteorology)





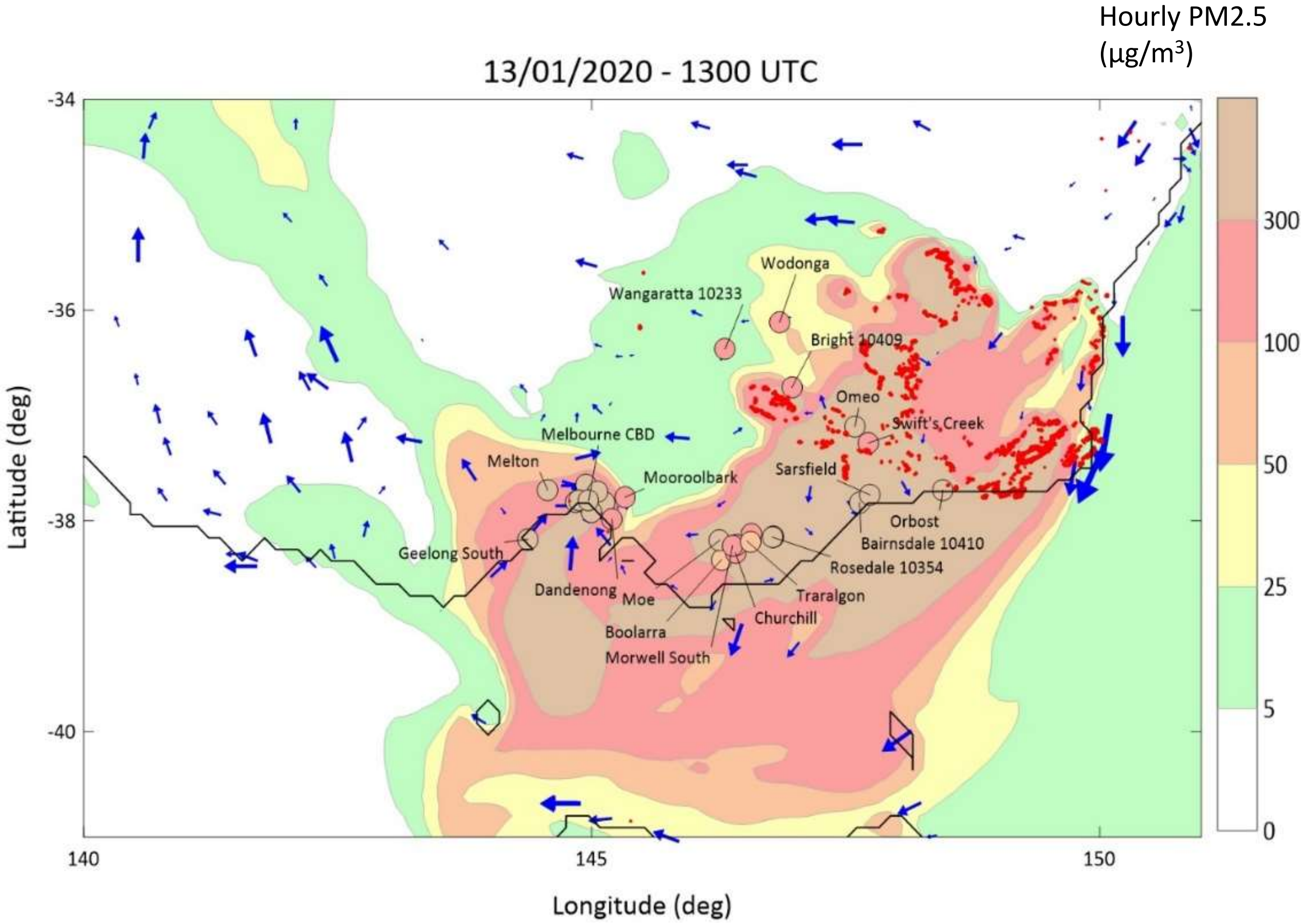


National emissions



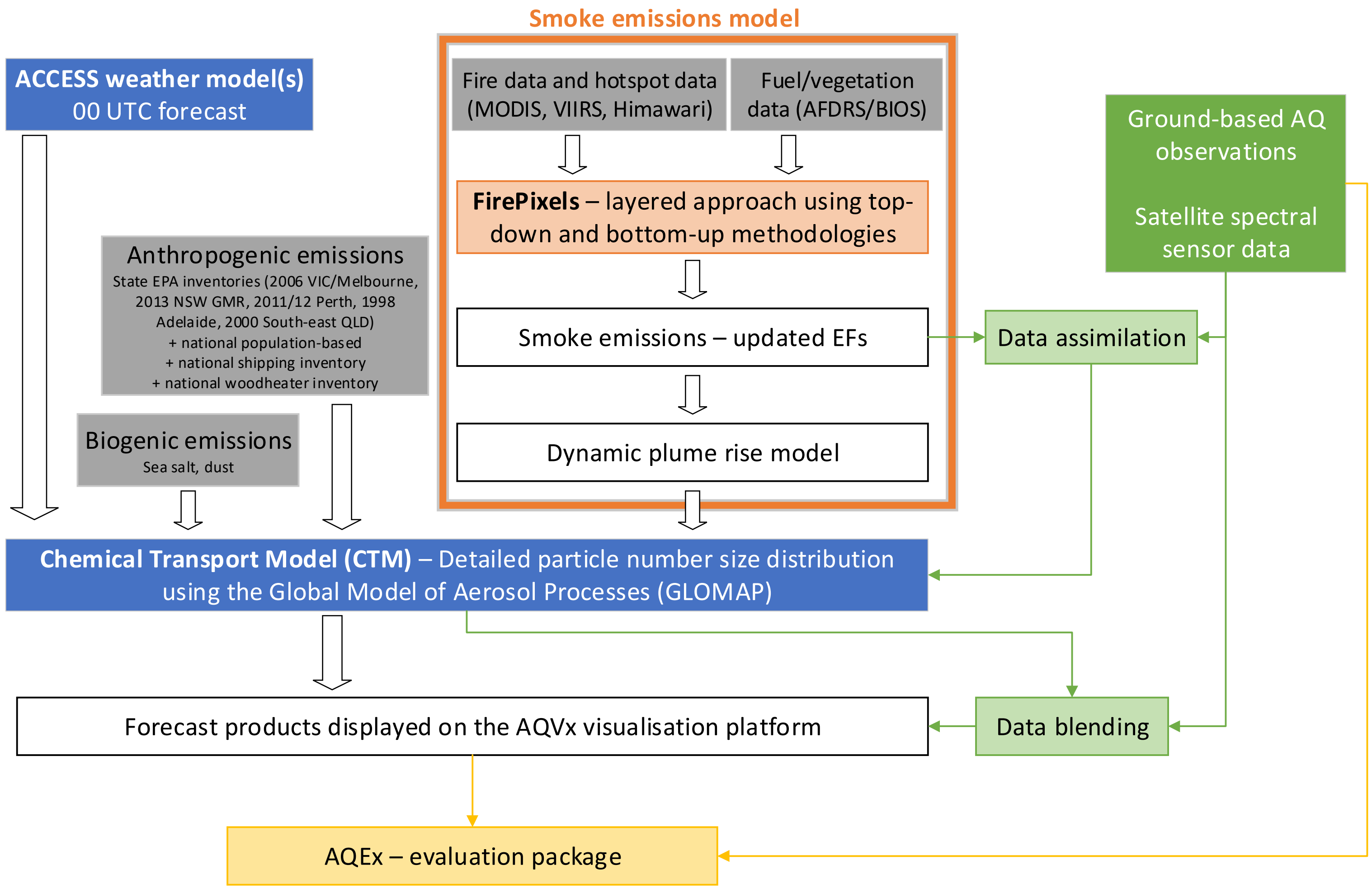
Major uncertainties in smoke forecasts

Source: The Guardian (14th Jan 2020)

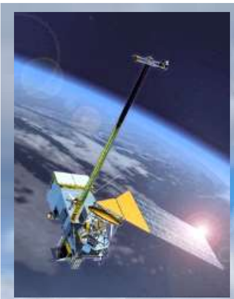


- Complicated wind patterns which can affect the onset and duration of smoke events
- Timely identification and location of fires
- Complexity and variability in fuel loads and fuel consumption
- Temporal distribution of emissions
- Plume rise which affects smoke plume dispersion

Workflow diagram of the CSIRO Prototype National Air Quality Forecast System (AQFx_p)

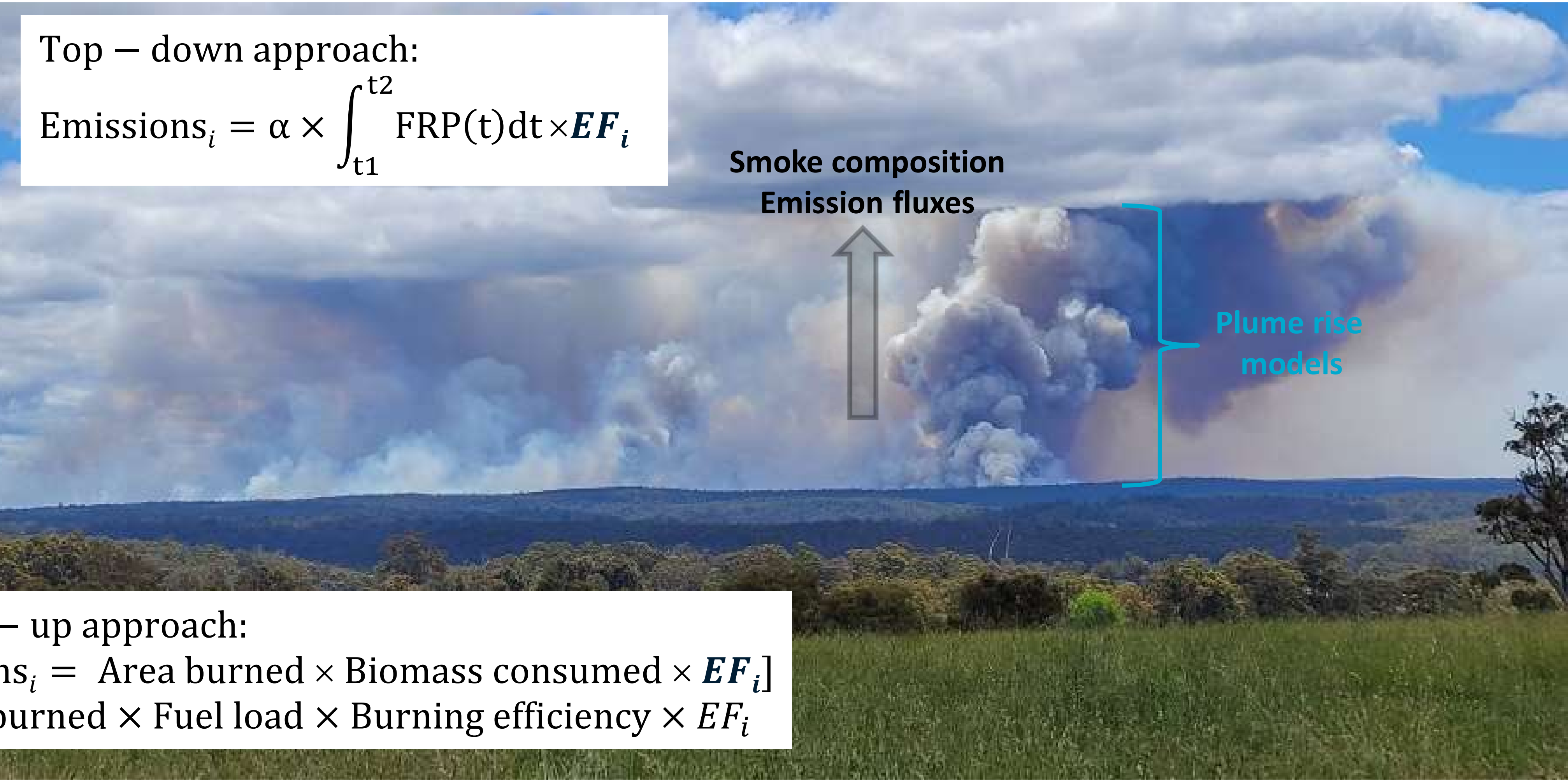


How are smoke emissions derived?



Top − down approach:

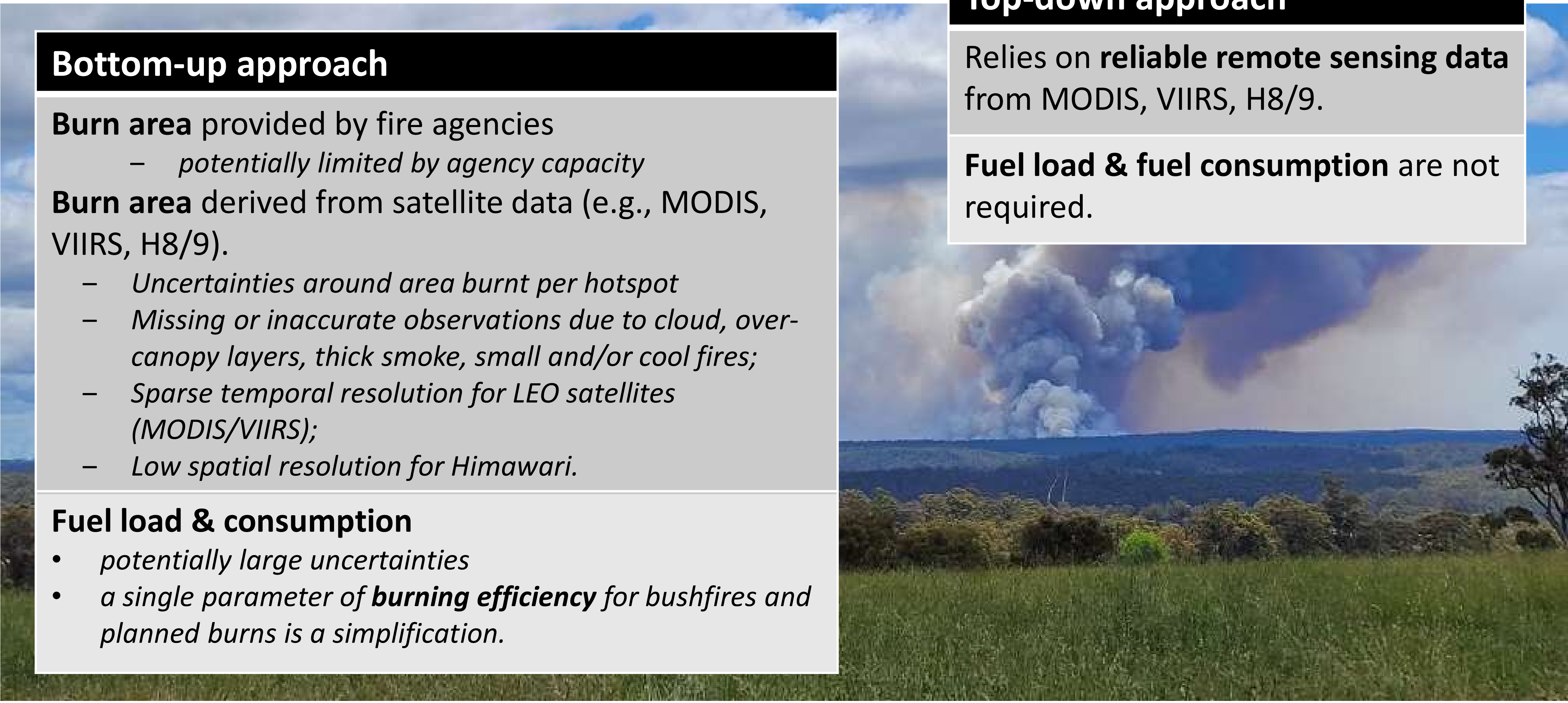
$$\text{Emissions}_i = \alpha \times \int_{t1}^{t2} \text{FRP}(t)\text{d}t \times EF_i$$



Bottom − up approach:

$$\text{Emissions}_i = \text{Area burned} \times \text{Biomass consumed} \times EF_i]$$
$$= \text{Area burned} \times \text{Fuel load} \times \text{Burning efficiency} \times EF_i$$

Input parameters, data and uncertainties



Bottom-up approach

Burn area provided by fire agencies

- *potentially limited by agency capacity*

Burn area derived from satellite data (e.g., MODIS, VIIRS, H8/9).

- *Uncertainties around area burnt per hotspot*
- *Missing or inaccurate observations due to cloud, over-canopy layers, thick smoke, small and/or cool fires;*
- *Sparse temporal resolution for LEO satellites (MODIS/VIIRS);*
- *Low spatial resolution for Himawari.*

Fuel load & consumption

- *potentially large uncertainties*
- *a single parameter of* ***burning efficiency*** *for bushfires and planned burns is a simplification.*

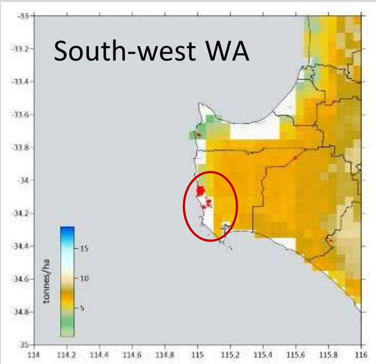
Top-down approach

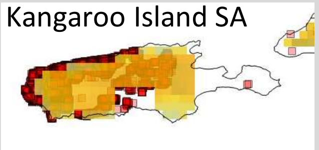
Relies on **reliable remote sensing data** from MODIS, VIIRS, H8/9.

Fuel load & fuel consumption are not required.

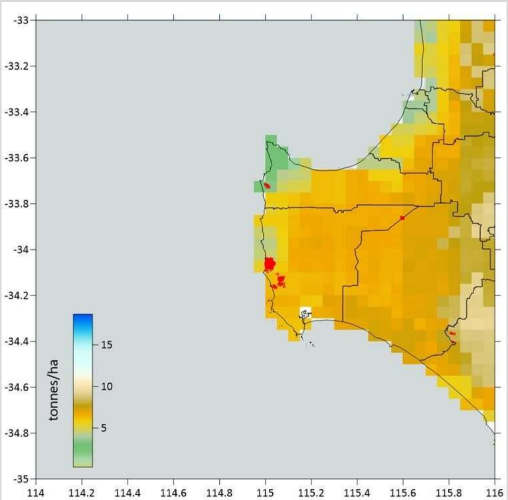
Fuel load & consumption - source of uncertainty in forecast model

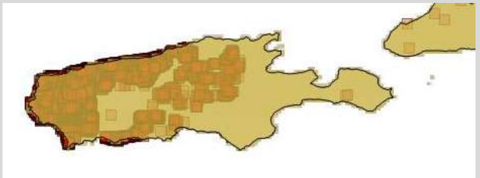
AQFx_p (v01)
Empirical fuel load data & semi-empirical model VAST (Barrett, 2002)
Problem:
coarse resolution of VAST fuel load data sets
⇨ areas close to the coast with zero fuel load





AQFx_p (v02)
AFDRS fuel maps for fine fuel & process-based carbon cycle model BIOS2 for coarse fuel





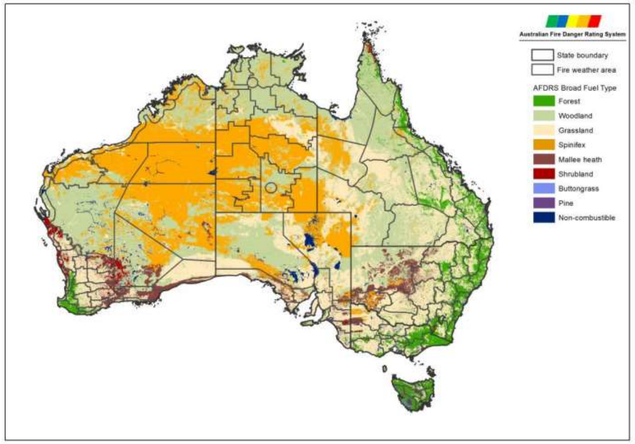
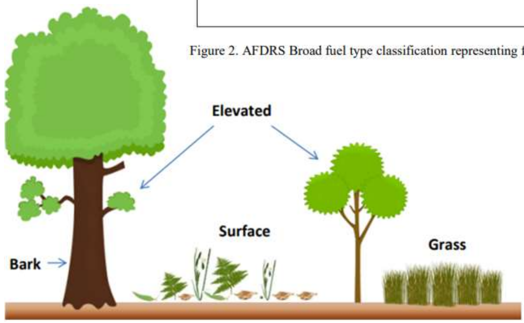
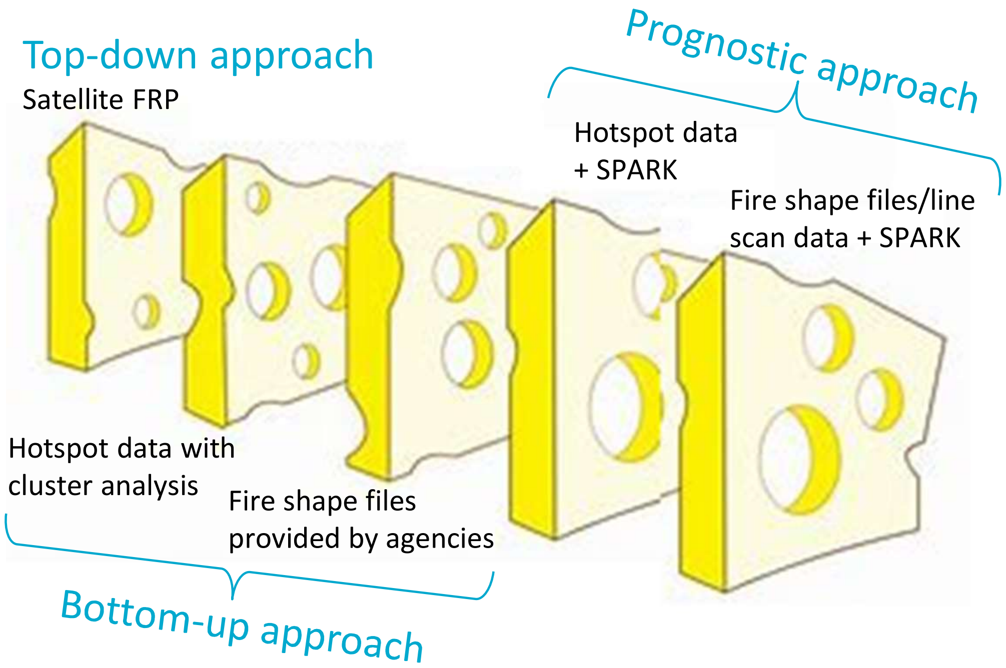


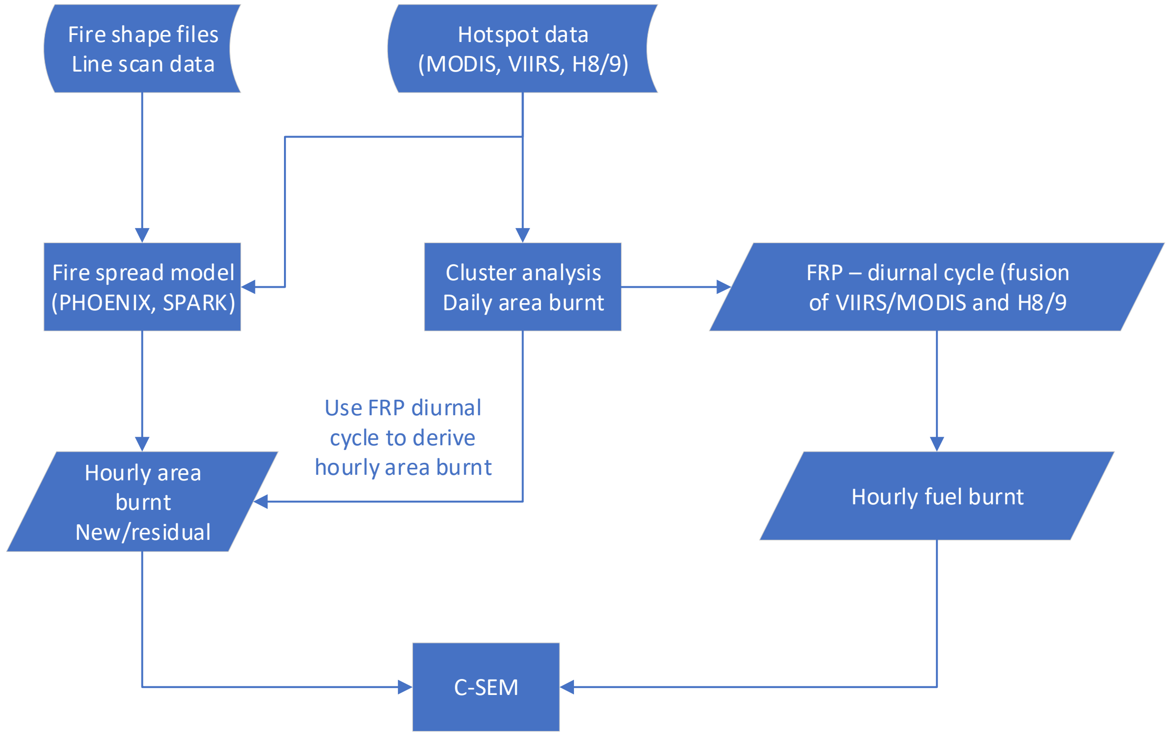
Figure 2. AFDRS Broad fuel type classification representing fire behaviour models



Fire pixel - a layered approach to derive smoke emissions

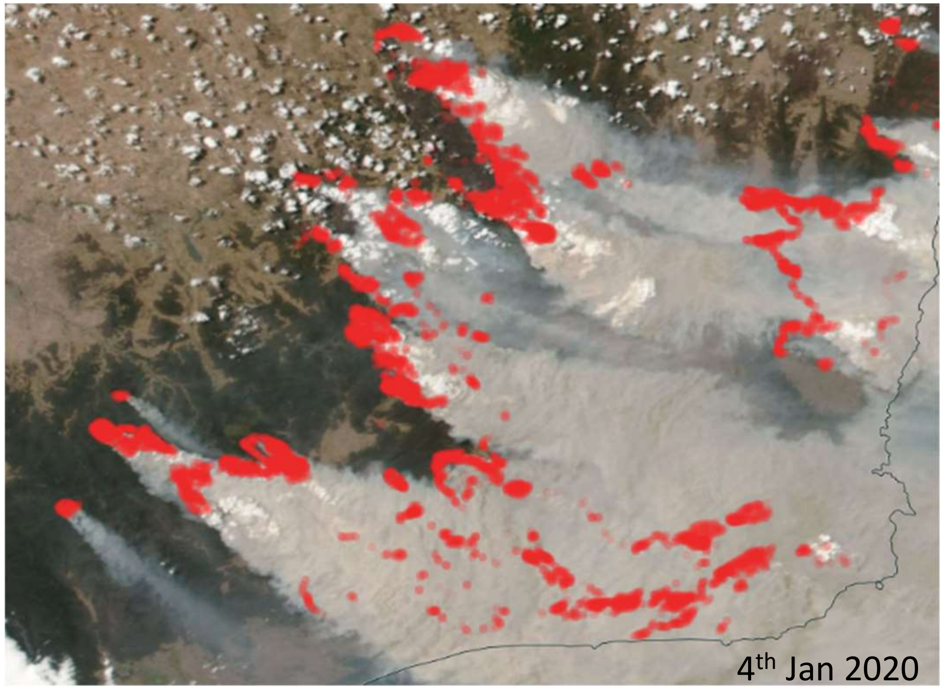
The data required to model smoke emissions are imperfect but can be improved by adopting a layered approach of different methodologies and data requirements.



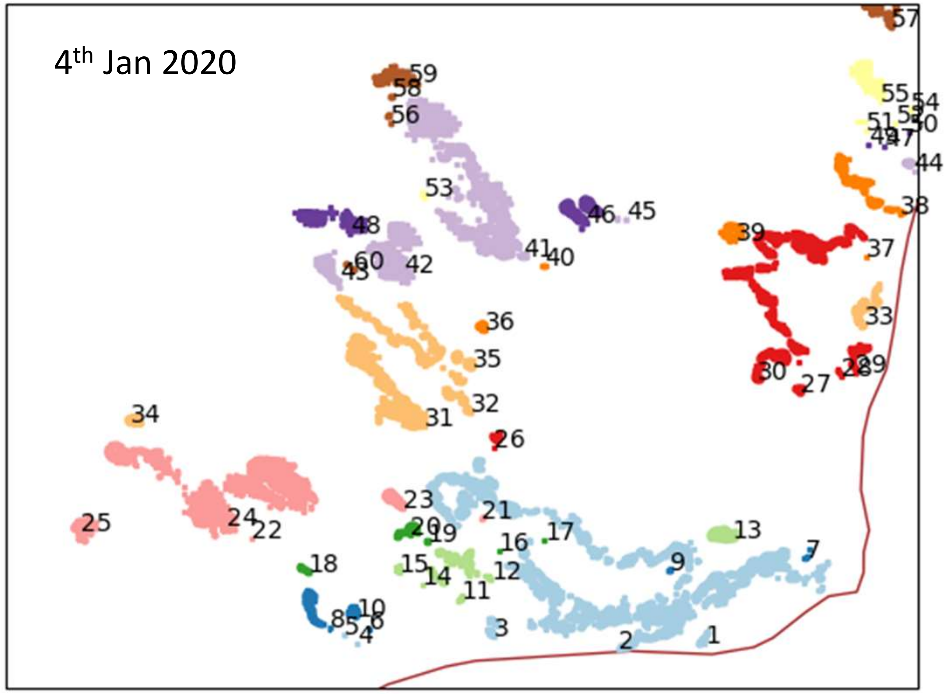


Cluster analysis – Step 1

Identify individual fire fronts using a cluster analysis methodology.



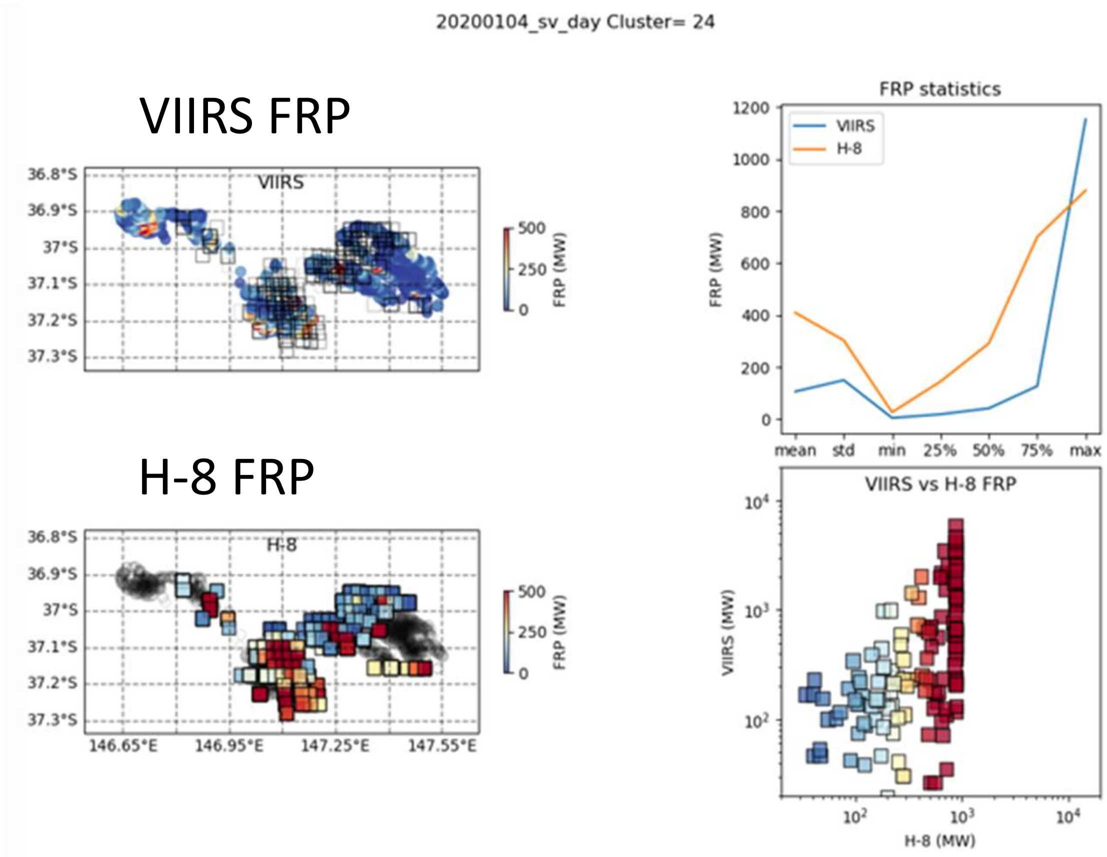
Suomi NPP/VIIRS hotspots and visible reflectance. 1:30 pm EST

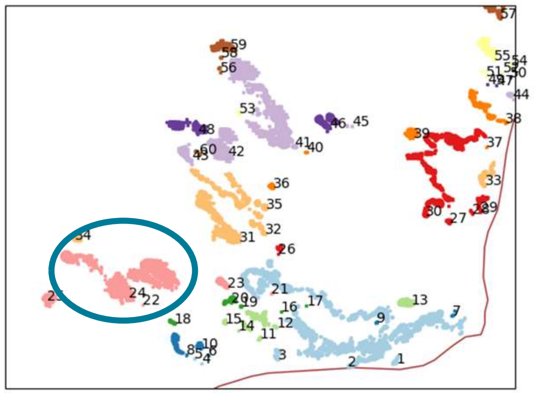


Cluster analysis results (60 fire clusters)

Cluster analysis – Step 2

Identify clusters where VIIRS and Himawari-8 (H8) pixels overlap in time and space
- quantify the ratio of VIIRS / H8 for later temporal interpolation

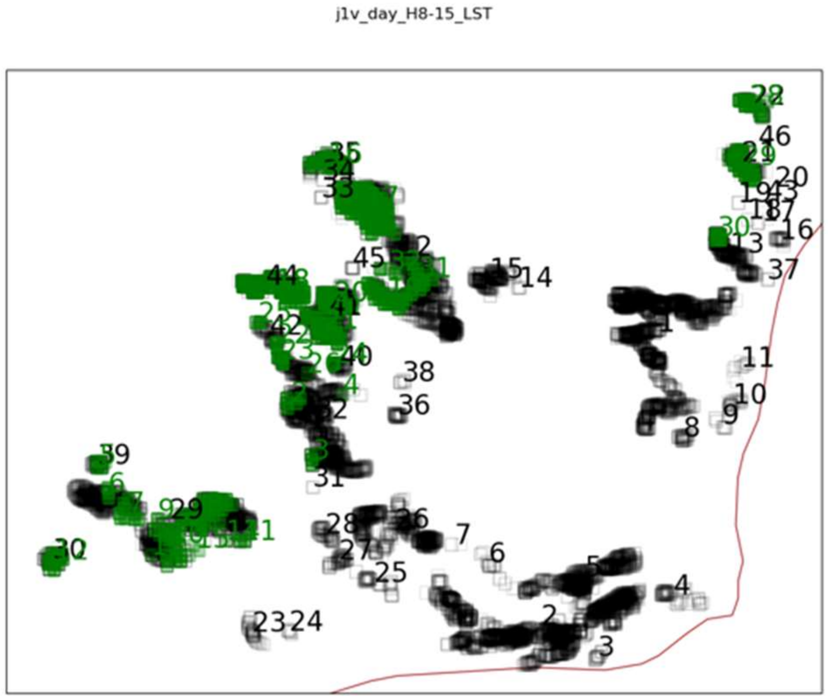




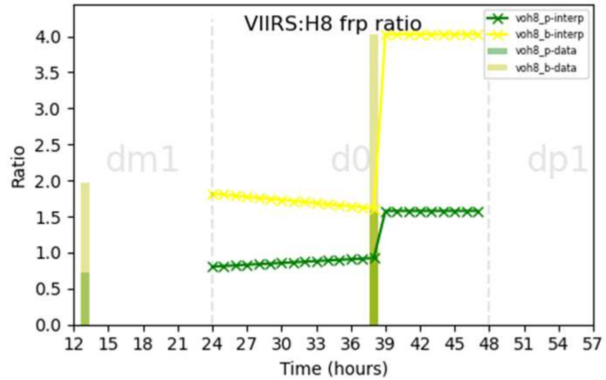
The scatter plot shows VIIRS FRP vs H8 FRP for coincident locations in space and time.
Note how the H8 FRP saturates at about 1000 M- problem for big fires!

Cluster analysis – Steps 3 & 4

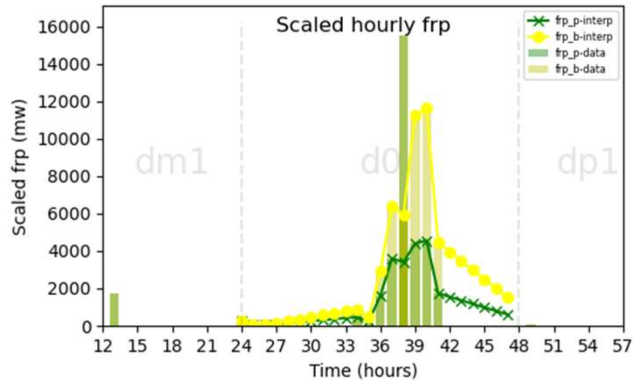
For a 24-h period, identify all 10-min H-8 data which spatially overlap a VIIRS cluster (the latter available at up to 4 time points in the day). Use the average 1-h H8 FRP data to estimate the hourly FRP, and hence FRE, and fuel burnt using the TD equation.



H8 clusters (green) for 3 pm EST which overlap VIIRS (black) 1:30 pm clusters



Two ratio estimates of VIIRS:H8 FRP for cluster 24



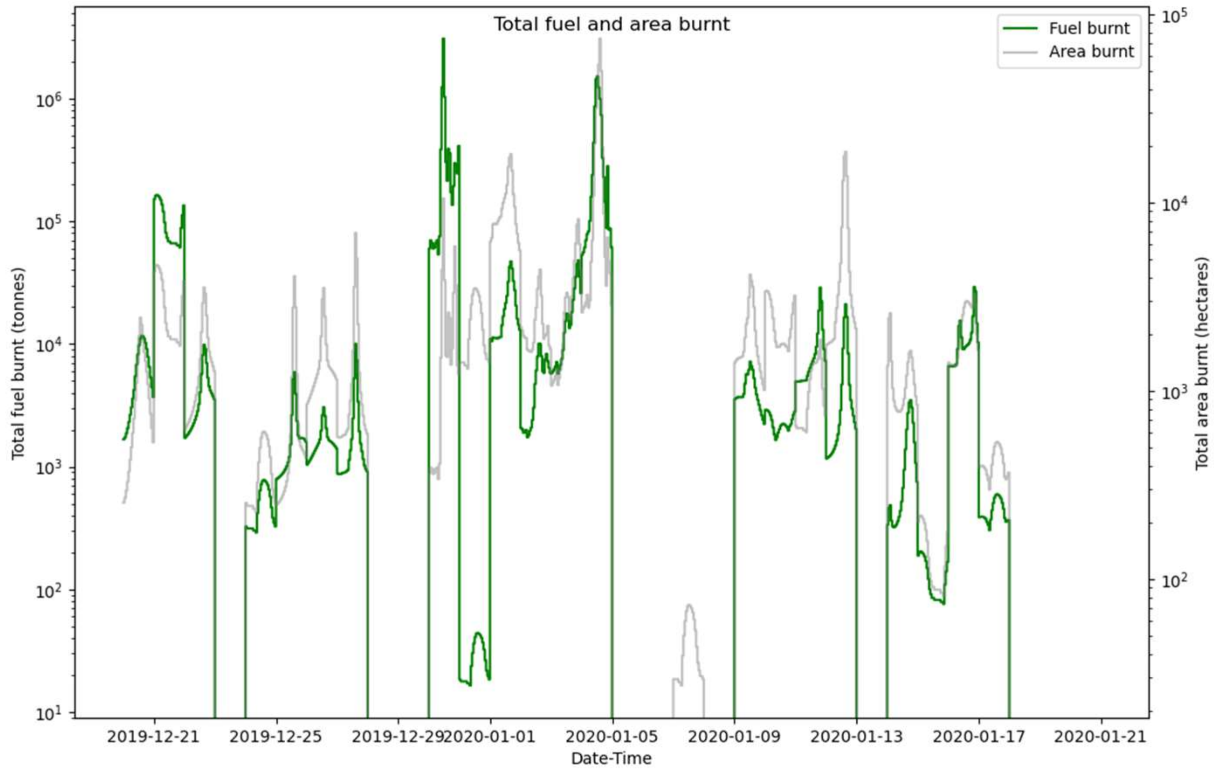
Estimated hourly FRP for cluster 24 using 10-min H8 data (here- simple linear interpolation)

Cluster analysis methodology

Steps 1-4 are repeated for all clusters in the study domain, for all days of the study period.

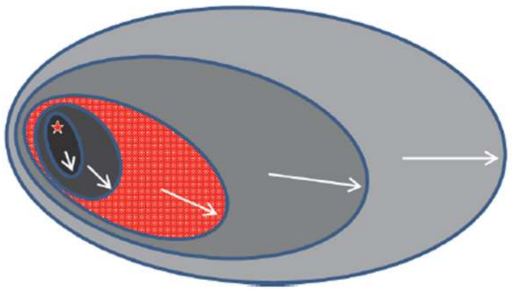
This plot shows the calculated hourly fuel burnt (and area burnt) for the entire study domain for the period 20 Dec 2019 to 20 Jan 2020.

The data gaps correspond to days with significant cloud or smoke cover when thermal anomalies are not detected. Data gaps are filled using a persistence assumption or prognostic modelling (Phoenix or SPARK).

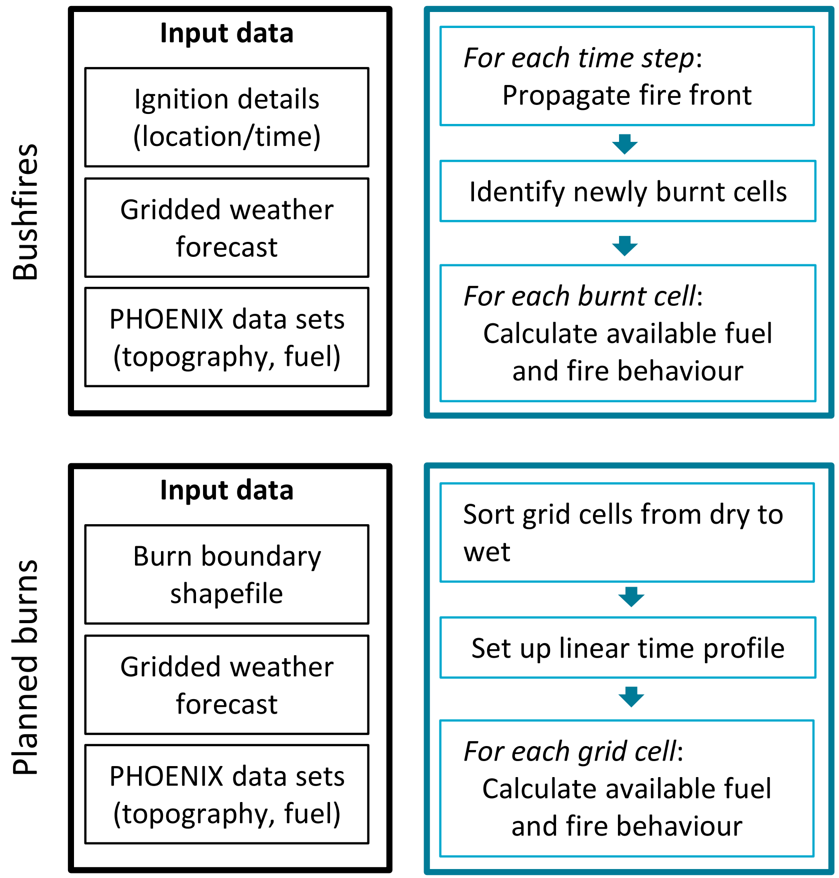


Prognostic method

In the prognostic method, outputs of fire spread models are used to derive hourly area burnt. The fire spread is forced by Bureau of Meteorology Graphical Forecasting Editor (GFE) data grids and detailed fuel load and land attribute data sets.
Emissions are calculated as per bottom-up method.



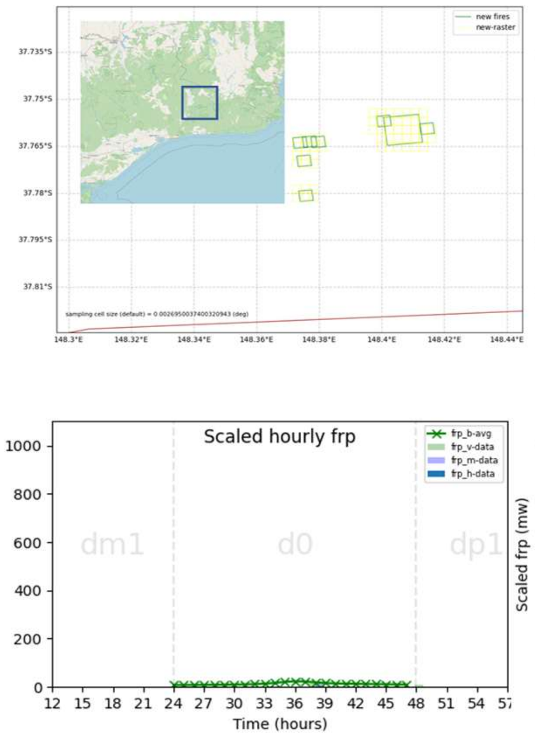
PHOENIX FireFlux bushfire simulator with modifications - at the end of a time step the area burnt is identified as a polygon and the total amount of fuel consumed is calculated



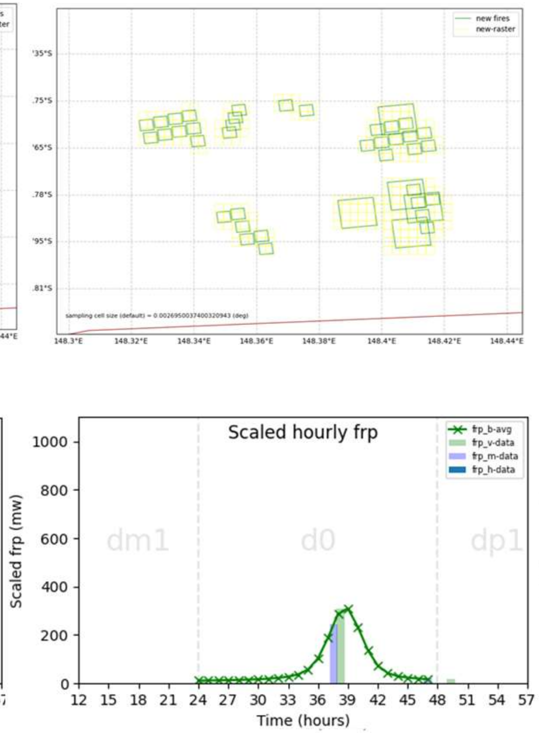
Reference: Walsh S, Duff T and Tolhurst K (2019). Fire activity modelling for use in smoke predictions. In: Cope et al, *Smoke Emission and Transport Modelling*. Research Report 102, The State of Victoria Department of Environment, Land, Water and Planning.

Example

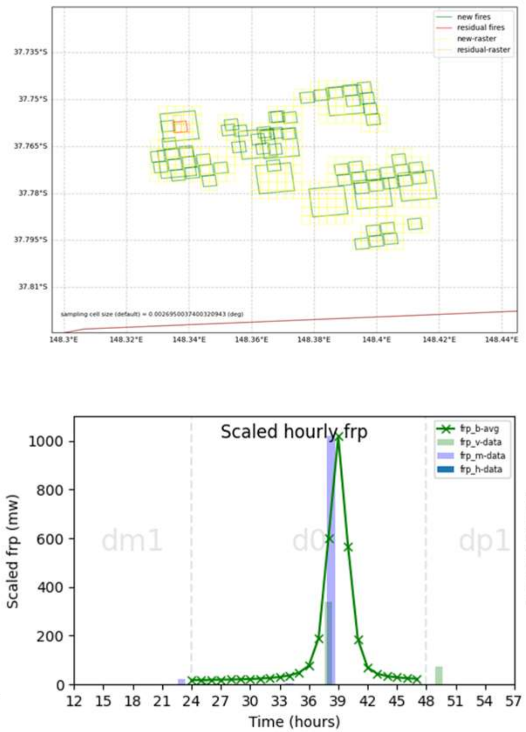
4th April 2017



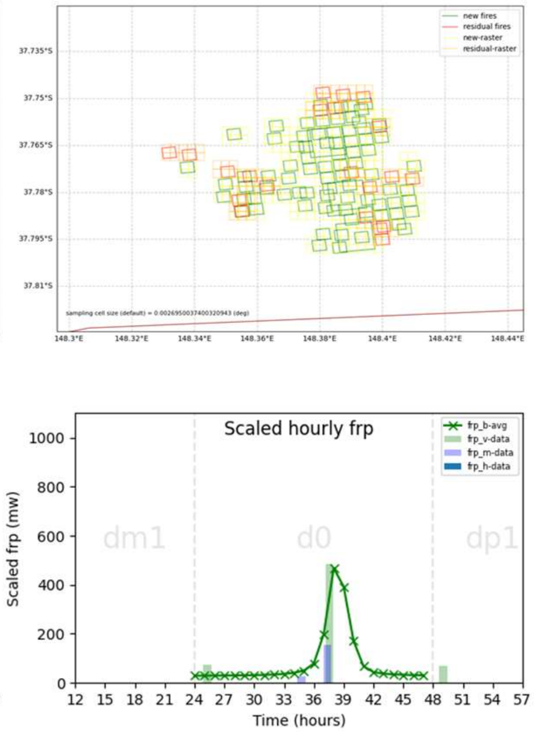
5th April 2017



6th April 2017



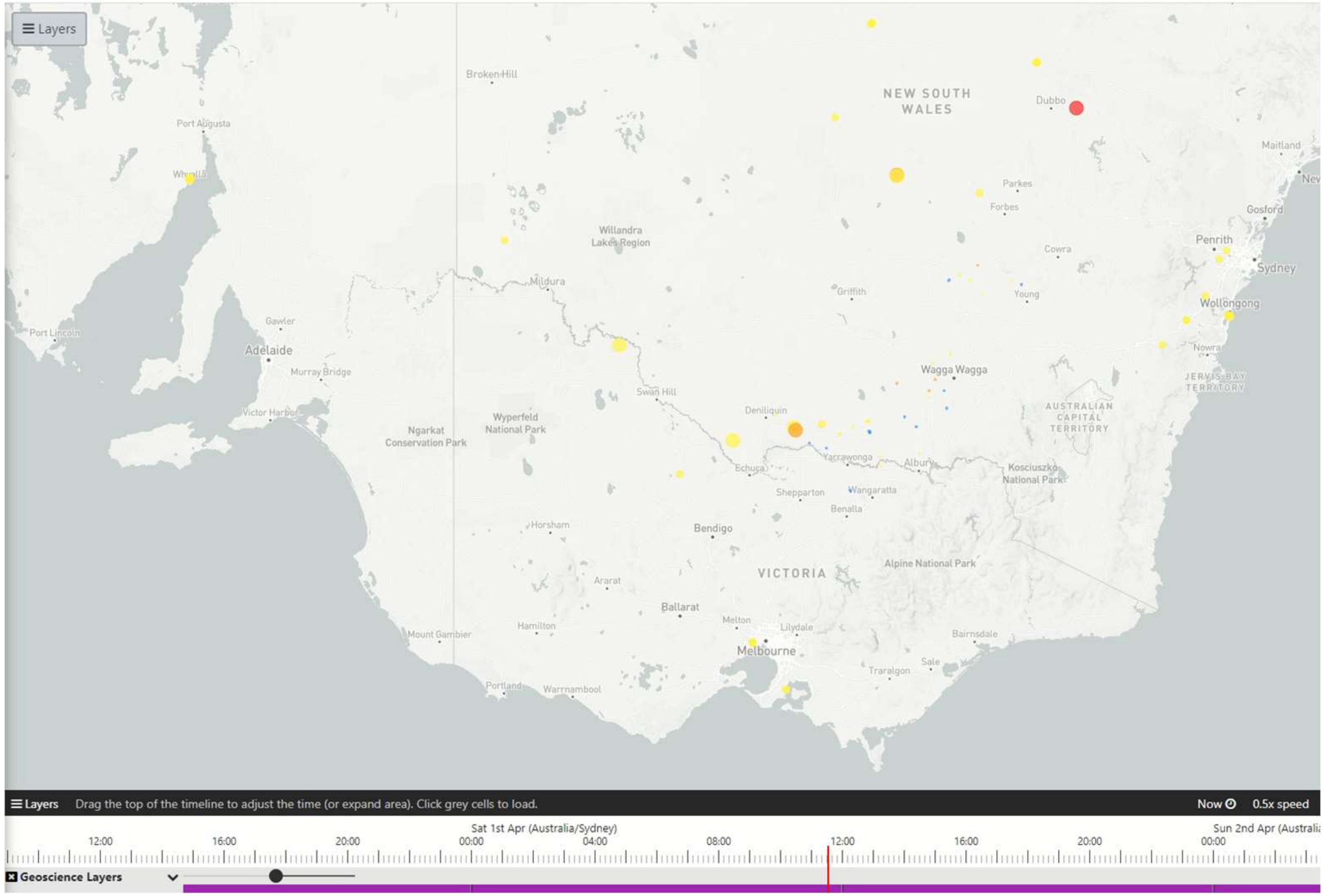
7th April 2017



Hotspot detection- agricultural burning

Significant hotspot activity over central VIC/NSW captured by the MODIS/VIIRS satellite overpass at ~1pm each day. This is primarily due to agricultural burning.

The hotspot activity is significantly lower overnight (as captured by the 1am VIIRS satellite overpass).
This may be due to short-lived fast-moving burns (e.g., agricultural burns) or under-canopy smouldering fires not well captured by MODIS/VIIRS.

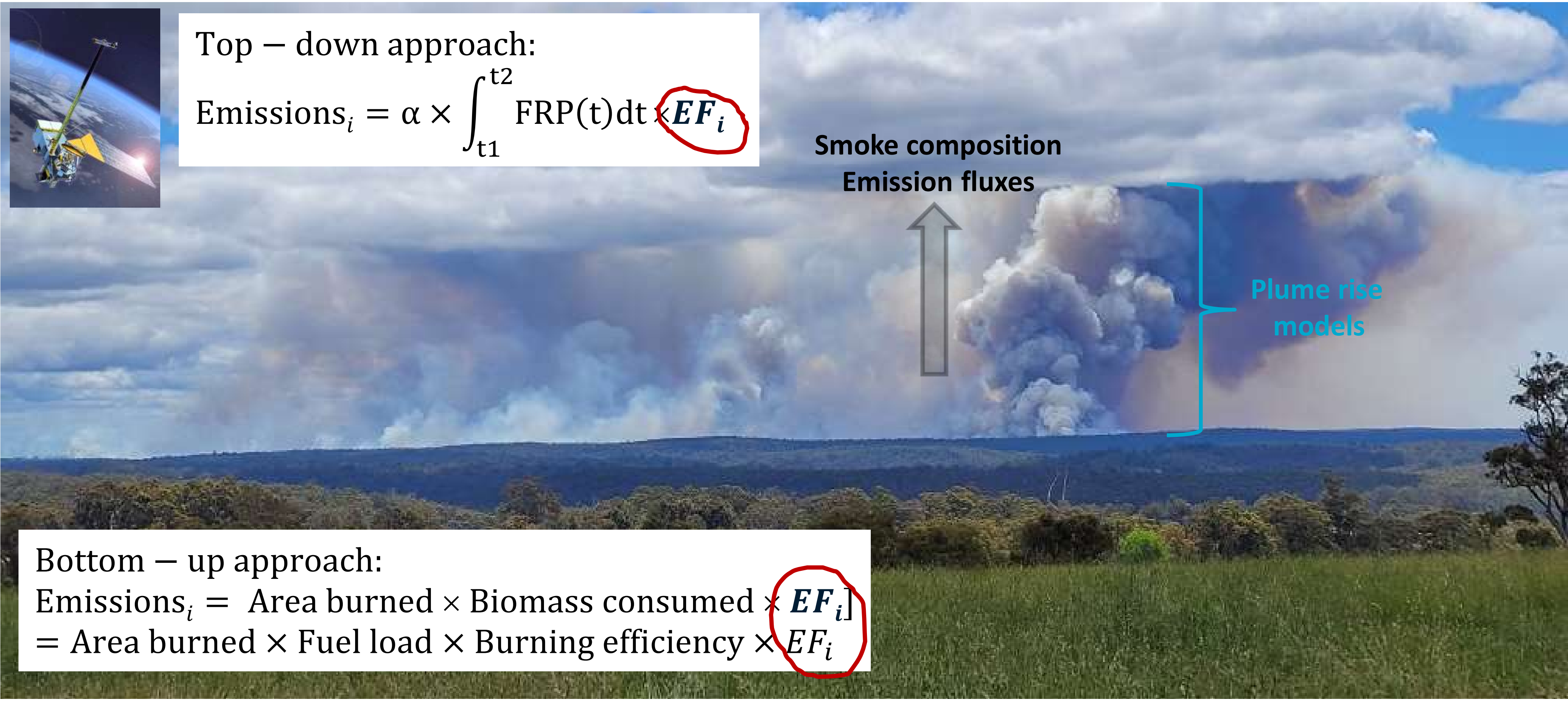


Active fire hotspot locations using MODIS and VIIRS satellite observations between 1-5 April 2023

Emission factors required for both approaches

Top – down approach:

$$\text{Emissions}_i = \alpha \times \int_{t1}^{t2} \text{FRP}(t)\,dt \times \boldsymbol{EF_i}$$



Bottom – up approach:

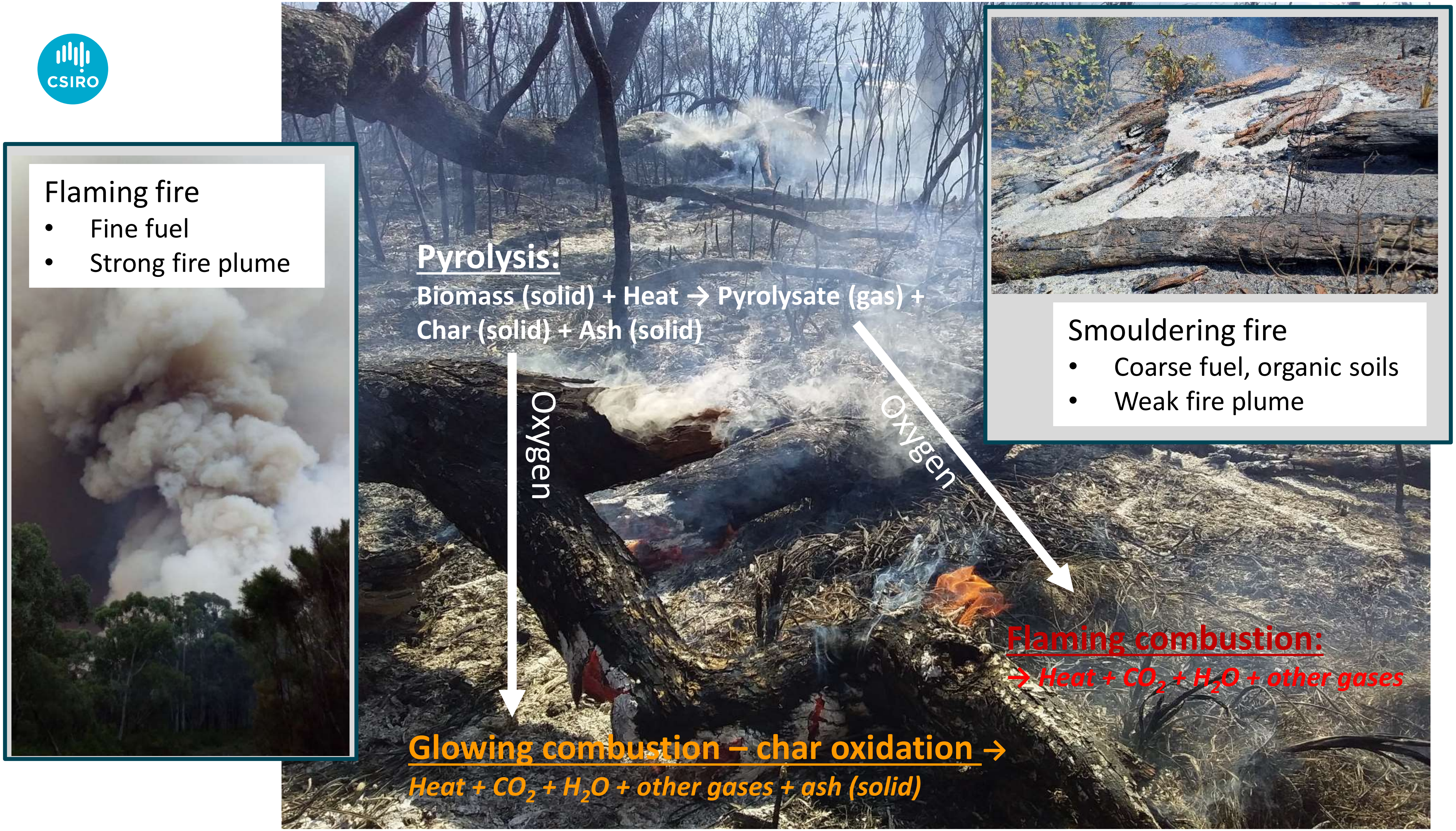
$$\text{Emissions}_i = \text{Area burned} \times \text{Biomass consumed} \times \boldsymbol{EF_i}]$$
$$= \text{Area burned} \times \text{Fuel load} \times \text{Burning efficiency} \times EF_i$$

Deriving emission factors

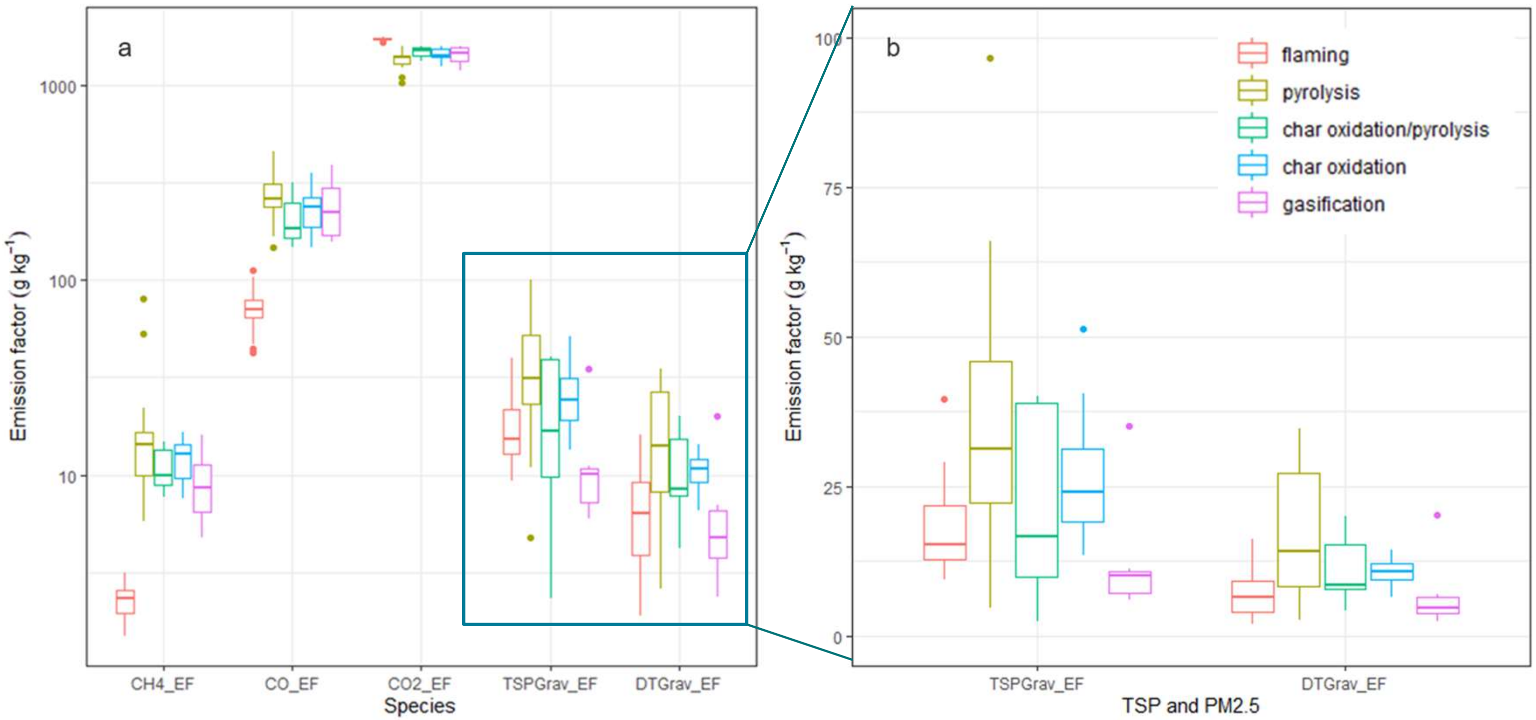
Laboratory experiments in Pyrotron

Field measurements using backpack sampler

Open path FTIR (University of Wollongong)


Flaming fire
• Fine fuel
• Strong fire plume
Pyrolysis:
Biomass (solid) + Heat → Pyrolysate (gas) + Char (solid) + Ash (solid)
Oxygen
Oxygen
Smouldering fire
• Coarse fuel, organic soils
• Weak fire plume
Flaming combustion:
→ Heat + CO_2 + H_2O + other gases
Glowing combustion – char oxidation →
Heat + CO_2 + H_2O + other gases + ash (solid)

Emissions as a function of combustion process



Finding an explanatory variable to explain observed variation in particle EF – Combustion efficiency?

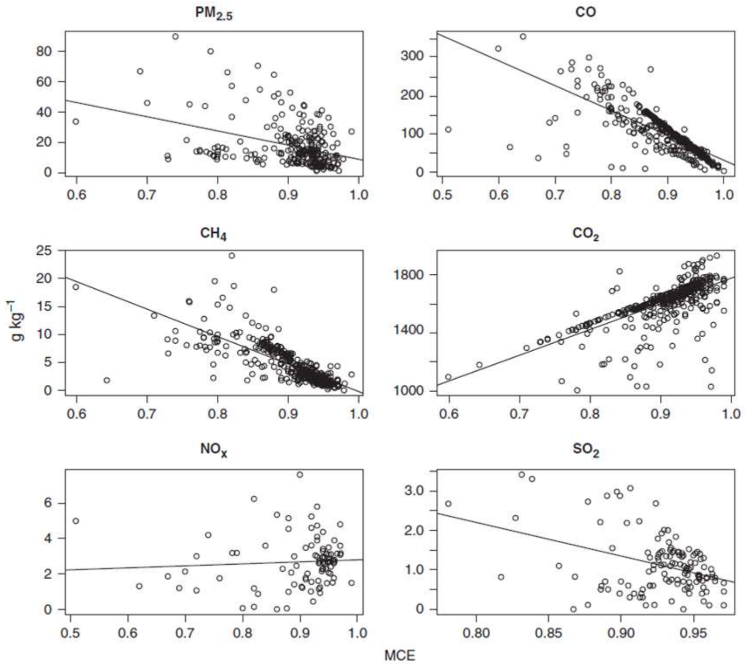
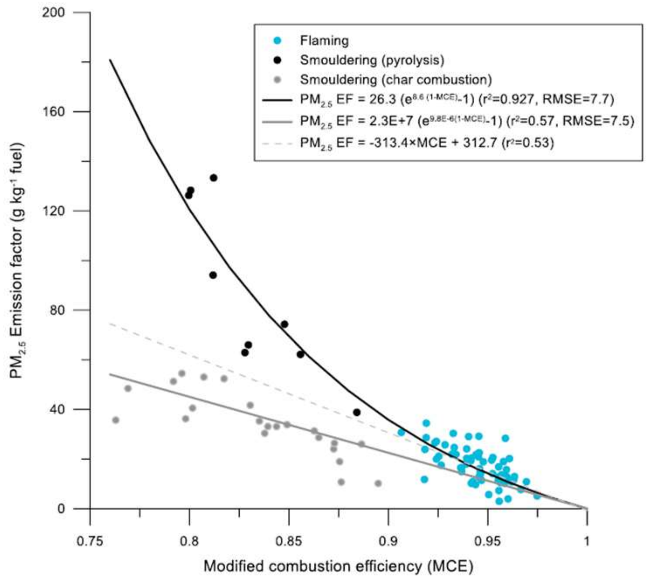
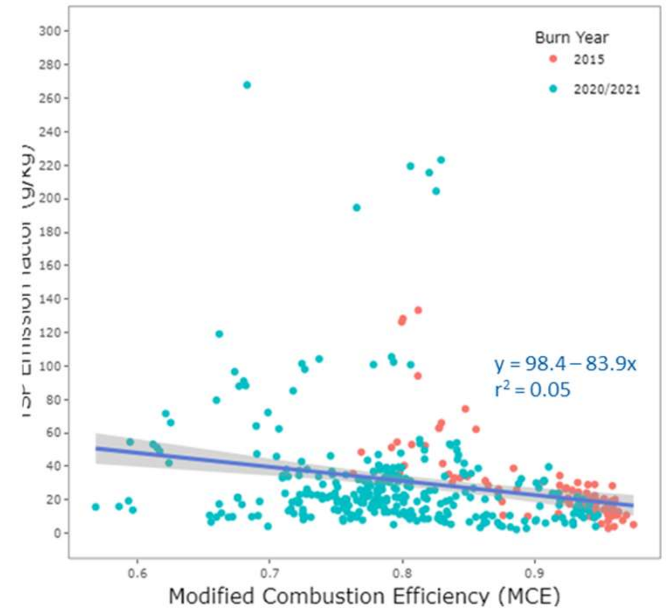


Fig. 2. Correlation plots between modified combustion efficiency and emission factor of major pollutants including $PM_{2.5}$, CO, CH_4, CO_2, NO_x and SO_2.

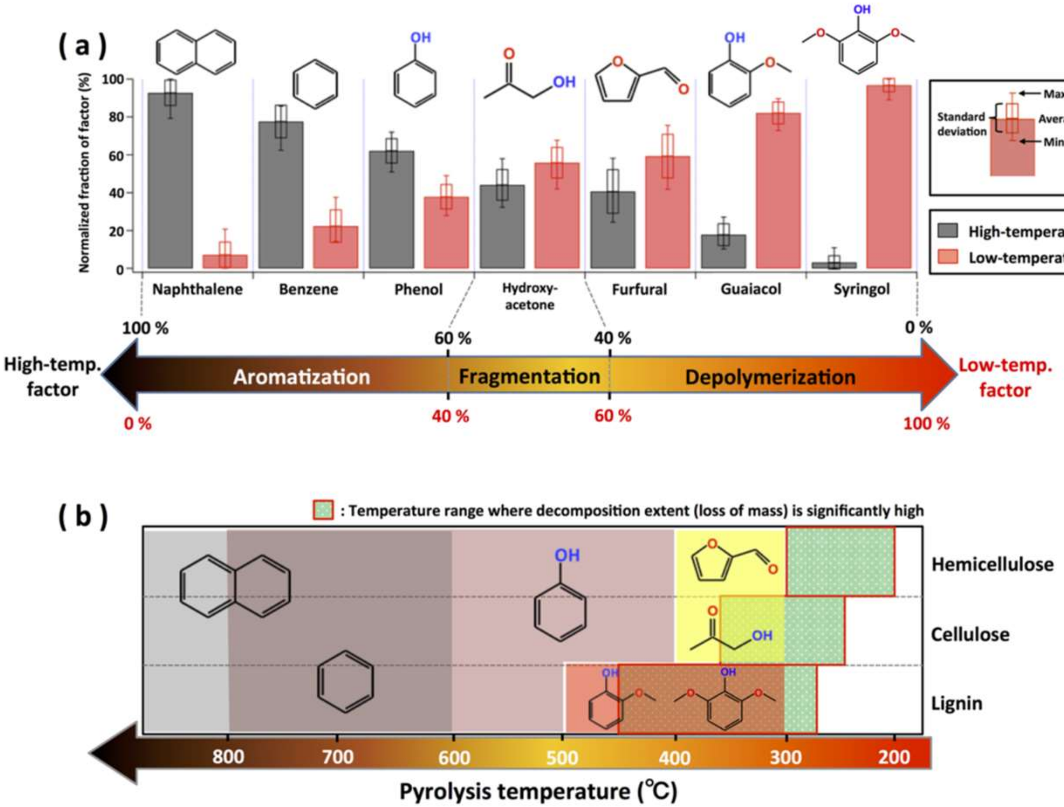
Prichard et al (2020) International Journal of Wildland Fire, 29, 132–147, https://doi.org/10.1071/WF19066



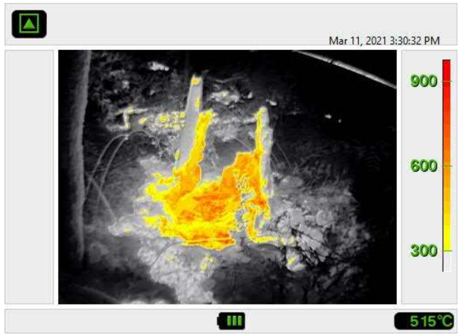
Reisen et al. (2018). Journal of Geophysical Research: Atmospheres, 123, 8301–8314. https://doi.org/10.1029/2018JD028488

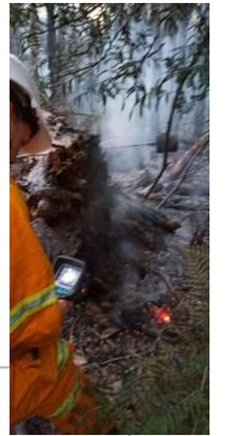


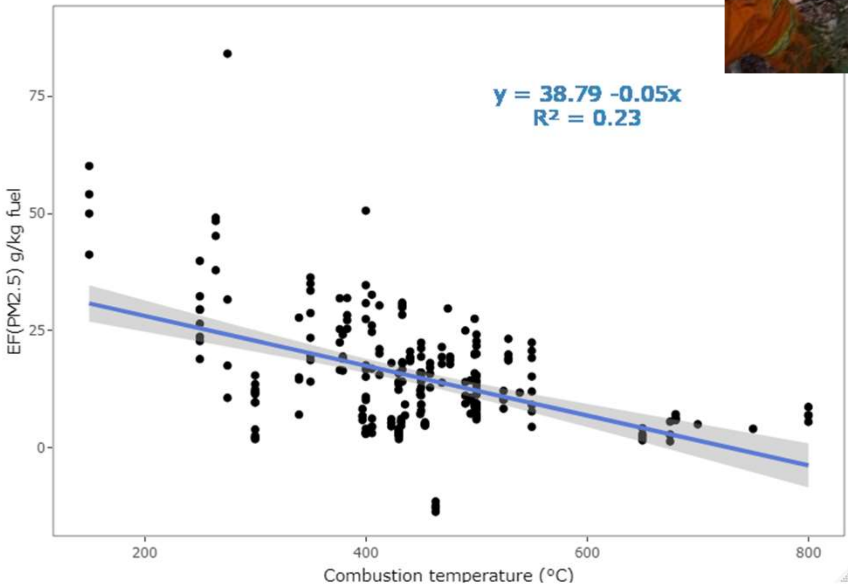
Finding an explanatory variable to explain observed variation in particle EF – Combustion temperature?



K. Sekimoto et al. (2018) Atmos. Chem. Phys., 18, 9263–9281
https://doi.org/10.5194/acp-18-9263-2018







Upscaling from individual log to burn area

Develop a distribution of combustion temperatures from smouldering CWD

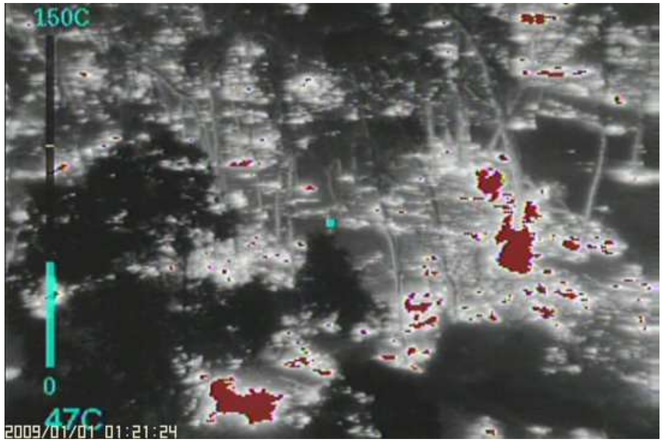
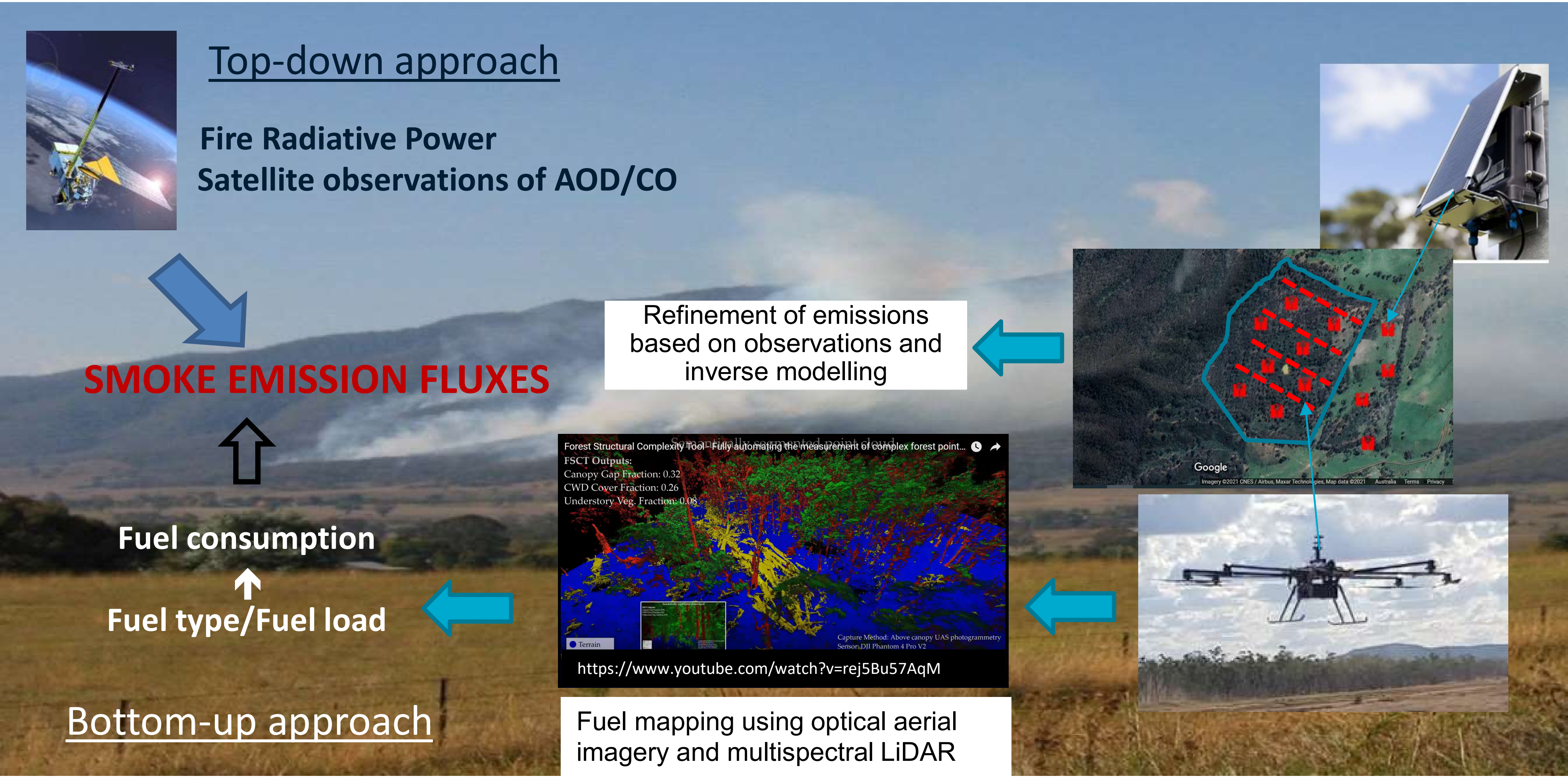


Photo: Aaron van Winden and Will Johnston
from DELWP Barwon South West

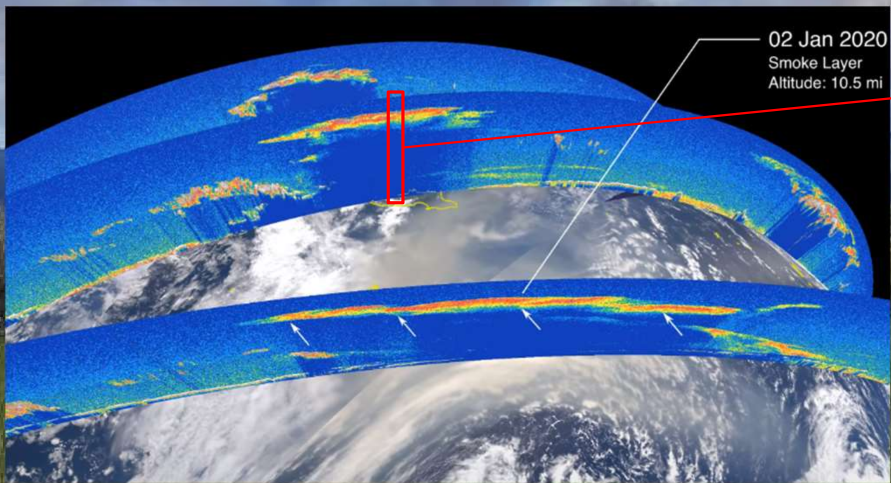
Combination of approaches to give us the most robust short-term smoke forecasting

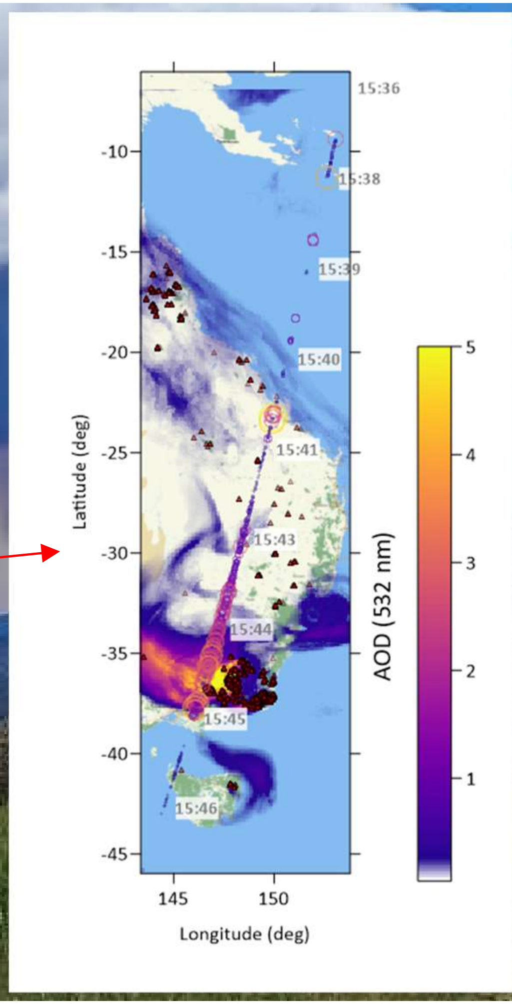


Derive emissions from satellite AOD or CO observations

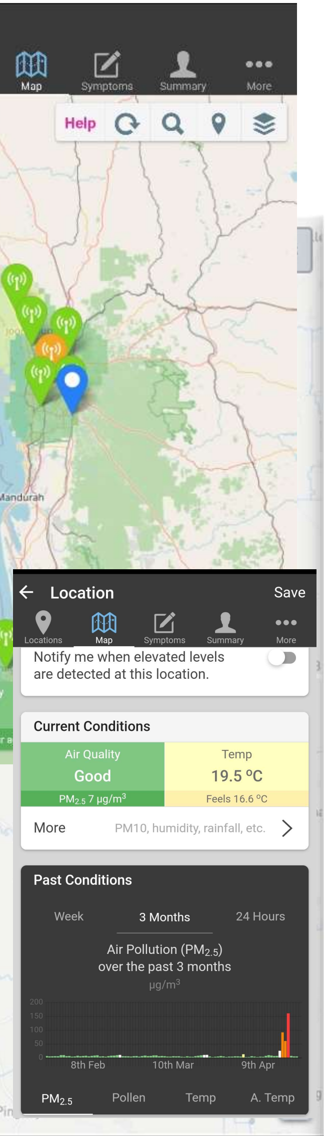
Top – down approach:

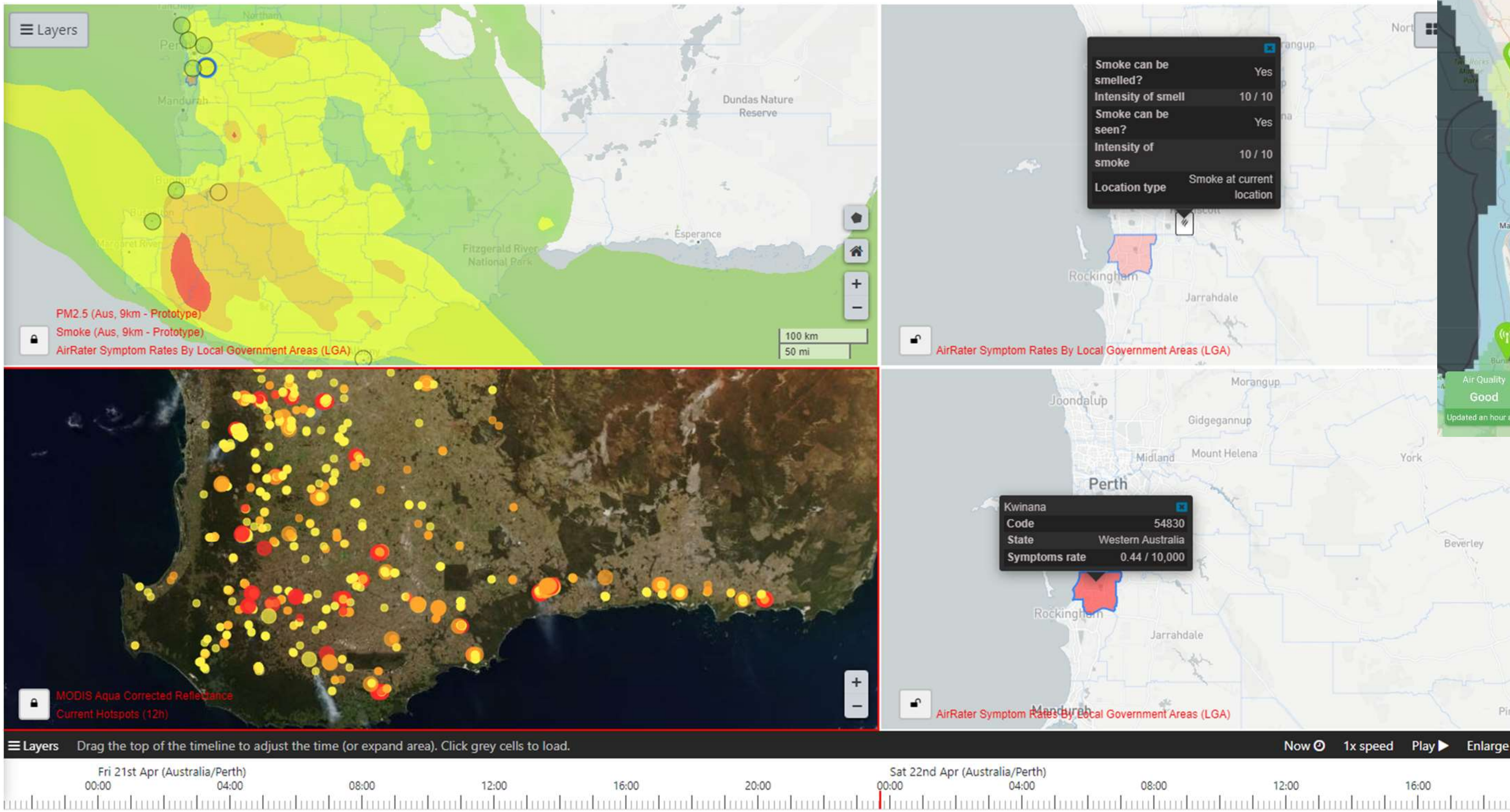
1. Derive emissions using FRP, which is related to the rate of biomass combustion
2. Derive particle emissions using satellite AOD observations (MODIS, Himawari)
3. Derive emission rates of trace gases (e.g. CO, NO_2) using the TROPOspheric Monitoring Instrument (TROPOMI) observations.





From forecast to exposure





Thank you

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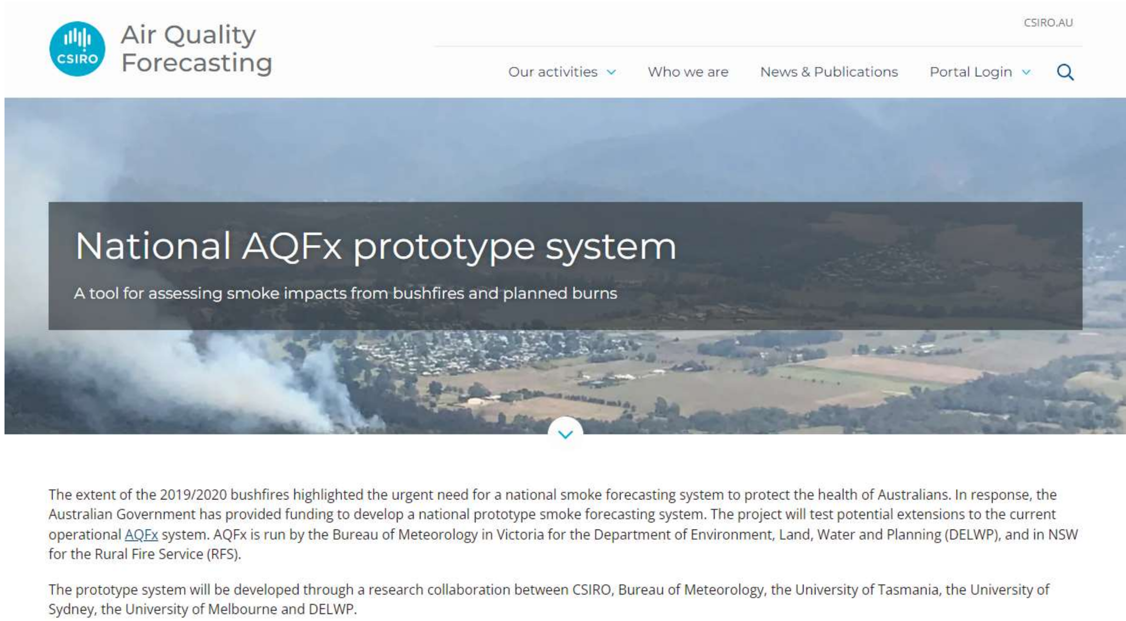

https://research.csiro.au/aqfx/