University of Southern Queensland

Faculty of Health, Engineering and Sciences

A review of smoke dispersion models for smoke pollution hazard mitigation associated with controlled, forest fuel reduction burns

A dissertation submitted by

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Abstract

Fuel load reduction burns are an established method for reducing wild-fire hazard in Australia but smoke from controlled fires can be hazardous. There are demonstrated linkages between air pollution from controlled fires and hospitalizations and death in people with existing pulmonary and cardio-vascular conditions. Land managers will need to demonstrate that they have considered smoke hazards by modelling plumes from proposed fires.

Accurately modelling smoke emission from hazard reduction fires in forested areas is complex. Model inputs include fuel load and type, topography, weather and atmospheric conditions. Modern modelling includes chemical transformations and deposition.

This research explores the various types of models that have been created for modelling smoke from open fires, their history and development. The reader will gain an understanding of the breadth of this field and the principals of plume modelling from open fires.

A project model was created as part of this research for the purposes of:

1. Explaining model development and use. The model uses a Gaussian plume model with receptors in a dynamic georeferenced grid; and

2. The model will also be used as a template for further development of simple web-based tool for the researcher and departmental colleagues who have an interest in modelling small fire plumes with simple inputs.

The research explores AQFx and the modular template for AQFx, BlueSky. AQFx is a set of models developed by the Bureau of Meteorology and CSIRO to assist land managers predict air pollution dispersal from controlled fires. While some components of the model are well tested, others require refinement. This research looks at how the model might be improved using data from controlled fires in Queensland. A methodology for gathering data required by the CSIRO research team has been developed as part of this project.

The research reviews newer satellite imagery technology and its potential use in calibration and validation of smoke plume modelling. The results of this component of the research are of interest to other researchers. This project concludes that Planet Labs daily high-resolution imagery provides clear images of plumes across Australia. These images can be used for reviewing advection and dissipation formula.

Finally, this research proposes some achievable steps that can be taken to

1. Assist the researcher's employer help staff and landholders model plumes from small, hazard reduction burns; and

2. Gather data required by CSIRO to improve the function of AQFx.

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Nomenclature and Anacronyms

ACCESS - The Australian Community Climate and Earth System Simulator.

AQVx – (Air Quality Visualization X) a web based interactive visual display system for air pollution based on the AQFx model.

AQFx – (Air Quality Forecasting X) an Australian smoke and air quality forecasting system developed by CSIRO and the BoM.

CSIRO – The Commonwealth Scientific and Industrial Research Organization.

DEA – Digital Earth Australia (Hotspot mapping)

DES – Queensland Department of Environment and Science.

DoR – Queensland Department of Resources.

HYSPLIT - Hybrid Single-Particle Lagrangian Integrated Trajectory model

MODIS – Moderate Resolution Imaging Spectroradiometer.

SPARK – An Australian wildfire behavior simulator.

Chapter 1 Introduction

'*It's important not to kill more people with smoke from prescribed burns than would be at risk from the bushfires we are trying to prevent*'. James Haig, Superintendent and Manager, Bushfire Mitigation Queensland Fire and Emergency Services.

1.1 Outline of Study

The above statement outlines the balance of risks that land managers must consider in carrying out controlled or prescribed burns. It is well accepted that controlled burns can reduce the risk of catastrophic fire but land managers must ensure the cure is not worse than the disease.

There has been growing interest around the world in both the hazard associated with bushfire smoke and in modelling dispersal of the smoke.

In both moral and economic terms, land managers must consider the probability, proportion and magnitude of their liability and find the best balance between hazards associated with deliberate, controlled burns and accidental, catastrophic fires.

The federal government as well as a number of state governments have identified the need for accurately predicting smoke hazard from controlled burns. CSIRO and the BoM in Australia have been developing the AQFx model over several years. The AQFx model has been successful in Victoria and NSW. CSIRO and the BoM have been provided with funding to roll the model out on a national basis.

This study will assist in understanding and explaining the model and test the model's effectiveness in Queensland. The study hopes to assist in calibrating the model for Queensland and demonstrating the model's usefulness for land managers.

1.2 Introduction

Prescribed burns are carried out in Australia for a range of purposes. They are used to reduce hazardous fuel loads, control weeds, clear rank grass and for ecological purposes.

Factors that influence fire behavior include rainfall, relative humidity, air temperature, wind speed, slope and fuel load (QLD Dept National Parks Recreation Sport and Racing, 2012). The only component of these hazard variables that can be influenced by forest managers and firefighters is the fuel load. Mechanical removal of fuel (slashing or mulching) has successfully been used in relatively small areas of green space, but mechanical methods are unaffordable on a larger scale (anything more than a few hectares) even within a peri-urban context.

Hazard reduction burns remain the most viable alternative for fuel reduction. Prescribed or hazard reduction burns are the most effective method of reducing wildfire hazard in most areas of Australia.

Hazard reduction burns carry a number of risks. Land managers in Australia, particularly government land managers have historically been reluctant to conduct prescribed burns (The Inspector General, Emergency Management, The State of Queensland, 2020). This is primarily due to the hazards associated with prescribed burns. Hazards include fires 'escaping' and causing injury or damage, visibility issues from smoke (and associated traffic hazards) and smoke inhalation (particularly for high-risk people and personnel carrying out the controlled burns).

Fire behavior in forests has been well researched. Methods for maintaining control of fires are well developed. Risk can be managed though preparation (construction of fire management lines and fire breaks), planning (planning optimum ignition patterns) and mop-up (patrolling the fire and putting out smouldering logs).

A focal point of recent research has been in identifying the effect smoke from prescribed burns has on health. There is a growing body of evidence that smoke from wildfires and controlled burns can significantly affect health. Government as well as private landholders are seeking ways to manage smoke hazard and balance the risk smoke poses with the risk of catastrophic fire events.

The visual hazard smoke has on transport infrastructure is also of significant interest to land managers. Mr Julian Gregson from the Department of Resources stated that his interest in this study was primarily in managing visual hazard on the Bruce Highway.

More recent research and funding has been targeted at smoke hazards. Smoke hazard modelling for prescribed burns and wildfires is a complex and interesting topic explored through this dissertation.

Smoke hazard modelling ranges from simple box models through to complex full physical model sets that combine fuel load models, fire behaviour models, climate models and atmospheric chemistry models for a full air quality model.

A detailed set of objectives for this study are provided in section 1.4

1.3 The Problem

Land managers need to demonstrate that they have managed significant risks to neighboring populations posed by their land parcels. Democratic governments, in particular, are sensitive to public perception and criticism about their land management practices.

Government agencies will use smoke modelling to optimize controlled burn timing if the model is demonstrably useful in managing risk.

This study seeks to increase understanding of smoke modelling, test the AQFx model and demonstrate how the model can become more precise through agency input and field calibration.

1.4 Research Objectives

This study will:

1. Compare satellite images of visible smoke plumes from prescribed burns in Queensland with output from the CSIRO/BoM AQFx model.

2. Describe the satellite images of visible smoke plumes from prescribed burns using a model built for the project. This description will include model inputs such as fuel load, fuel conversion rates, wind, buoyancy, and dispersal.

3. Detail the inputs used by AQFx and the methods used to calibrate and validate the model. The original project specification aimed to assist CSIRO calibrate the AQFx model for Queensland by gathering air quality data in the field during prescribed burns. Due to CSIRO having problems rolling the model out in Queensland and problems sending equipment, the CSIRO research team instead asked for a methodology for gathering Fire Radiated Power data using drones. The methodology will be used in the next fire season.

4. Support the National rollout of AQFx by reviewing the relative accuracy of using live fire data from Government agencies versus using the Digital Earth Australia Hotspots mapping. The study will seek to understand how to optimize collection, collation and input of fire data.

1.5 Conclusions

This dissertation aims to explain how smoke from bushfires and prescribed burns is modelled. This will be achieved by

1. leading the reader through the development of various models and explaining the engineering science behind them. Emphasis is placed on the various inputs and operation of AQFx; and

2. Creating a model to demonstrate how smoke models work, and how they can be georeferenced, comparing the georeferenced model to real plumes visible in Planet Labs imagery and commenting on the comparison.

The dissertation aims to demonstrate the effectiveness of the AQFx model in predicting smoke behavior. This will be achieved primarily through visual demonstration of satellite images of the

plumes compared to AQFx outputs (via the AQVx visualization tool). Variance in plume structures will be explained using simple models created as part of this dissertation.

This research is expected to increase take-up of the AQFx model by land managers in Queensland as well as encouraging Queensland government agencies to coordinate and contribute burn data to AQFx.

The initial proposal for this research included a more detailed analysis if AQFx and gathering some field data to support AQFx calibration. CSIRO researchers have collaborated with the author. AQFx rollout was delayed, and the CSIRO team proposed that a better alternative at this point would be to develop a method for improving the accuracy of the smouldering plume function in AQFx.

The plume model developed as part of this project will be used by DoR staff as a stopgap measure until AQFx becomes available. The model has been developed with Mr Gregson's particular requirements in mind (relatively small fires, in QLD and with a focus on ground level smoke).

A review of literature will explain:

a) the requirement for smoke modelling,
b) the background of smoke modelling
c) the inputs required for modern modelling
d) how plumes can be interpreted from satellite imagery

The outcomes of this study will be used to demonstrate the usefulness of smoke modelling in planning prescribed burns. The study will demonstrate the importance, capacity and processes agencies can use to supply data to AQFx and make the model more accurate. The study will engage key stakeholders and future users of AQFx and smoke modelling.

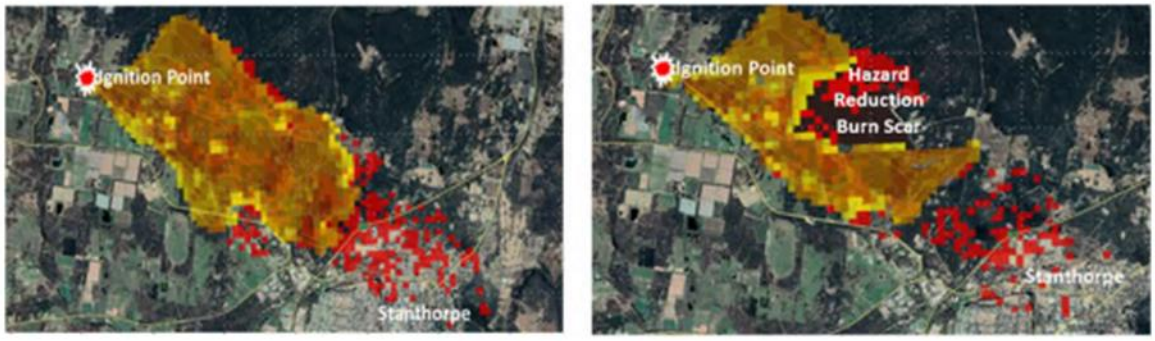
Chapter 2 Literature Review

Plume modeling from fires (prescribed and unplanned) is a novel area for the researcher. It was necessary to gain an understanding of the problem, the science and math, the technology, and techniques. The literature review moves through the requirement for modelling, the background to modelling and techniques used. The review addresses the inputs required for smoke modelling which are significantly complex in contemporary models.

2.1 Introduction

There is little credible dispute that controlled burns are effective in reducing forest fuel load and consequentially, the hazards associated with bushfire. The Victorian Royal Commission into Bushfires (Victorian Parliament, 2010) proposes more research into hazard reduction burns. Queensland's 2019/2020 Bushfires review (The Inspector General, Emergency Management, The State of Queensland, 2020) is persuasive in the evidence supporting hazard reduction burns as a bushfire hazard mitigation tool.

The below map on the left, models where the September fire could have spread from the ignition point, assuming there was no hazard reduction burn. In comparison, the below map on the right shows the actual hazard reduction burn scar significantly reduced the magnitude of the 6 September fire and very likely saved a significant number of houses[16].



(Source: QPWS)

Figure 2-1 Extract from the Queensland Bushfire Review 2019/2020, pg. 21

Planned burns are not without risk. The obvious risk if fires escaping and becoming wildfires, this is managed through planning resources, constructing fire breaks, back-burning and picking a climatically suitable day to burn. The less obvious risk is from smoke. Smoke carries a number of hazards including reducing visibility on roads, triggering asthma and exacerbating other respiratory as well as cardiovascular disorders.

Clear linkages have been demonstrated between both increased pollutant levels, particularly $PM_{2.5}$ and hazard reduction burns and between hazard reduction burns and hospitalisations and death related to poor air quality (Broome et al 2016) (Desservettaz et al 2019).

A review of literature about the health effects of bushfire smoke reveals that catastrophic fires have a more pronounced affect on the health of populations than planned burns (Arriagada, 2020). Smoke pollution from wildfires can be more severe and last longer than that of controlled burns.

The statement at the beginning of Chapter 1 takes on a new meaning when consideration is given to the idea that the best way to control smoke pollution may be to choose when to release the smoke (by use of controlled burns).

2.2 Background and Development of Smoke Modelling

2.2.1 Box Models and Eulerian grid models:

(Goodrick et.al 2012) provides a simple explanation of the various smoke models in use. A simple box model is a volume of air. The smoke is the emission from a fire in the box. The simple model assumes complete and instantaneous mixing of smoke with the air. The concentration of pollutants such as fine particulate matter and Carbon Monoxide are calculated and evenly distributed through the box. For this equation, the variables would be the amount of

fuel available for combustion, the amount of fuel consumed and the conversion of fuel to pollutants.

Operational box models incorporate at least some level of complexity – the model will have at least an inflow of pollutant rate, an emission rate from a source, a deposition rate and an outflow rate and may incorporate chemical transformations as well.

Simple box models have been used historically to describe simple physical processes such as a fire in a valley. The ultimate mixing height (ceiling of the box) in this case is the height of the hills or mountains surrounding the valley and the length and breadth of the valley describe the base of the box.

Box models become more complex as more boxes are added and as more influences on smoke transport are explored in the model:

Adding boxes is the first step in increasing the complexity and accuracy of a box model. If you divide the valley into two boxes, one box above and one below, the emissions enter the lower box directly from the fire and enter the second box from the first box. At this stage, the relative buoyancy of the smoke from the first box should be considered in calculating inflow of pollutants to the second box. Inflow of pollutants from the lower box to the upper box will depend on the concentration of pollutants in the lower box, the wind speed and direction, buoyancy of air entering from the first box (which in turn will depend on ambient air temperature in the upper box) and there will also be a rate of movement of pollutant from the upper box back to the lower box.

A complex box model will divide the lower box into hundreds of smaller boxes (a grid), application of a fire behaviour model will describe the timing of when and for how long fire is present in each box and the amount of pollutant released into the box. The atmosphere is gridded above the ground layer boxes and each atmospheric box is influenced by (generally) six neighbouring boxes. Significant computing power is required for complex Eulerian grids, where the grid is fine, and the time intervals are small.

Most systems for mapping smoke transport thought a Eulerian grid rely on some form of the Navier-Stokes equations. Jos Stam (Stam, 1999) writes an interesting article about modifying

the Navier-Stokes equation to provide stability to smoke simulations. It's interesting that the modifications created for computer animation purposes have been picked up by engineers and other modelers.

Equation 2-1

$$\nabla \cdot u = 0$$

and

Equation 2-2

$$\frac{\partial u}{\partial t} = -(u \cdot \nabla)u - \frac{1}{\rho}\nabla p + \upsilon \nabla^2 u + f$$

Where u is the velocity field and p is a pressure field (both must be initialized), f is an external force (wind, convection), ρ is the density of the smoke, ν is the kinematic viscosity and ∇ is the vector of the spatial partial derivatives:

Equation 2-3

$$\nabla - \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$$

Joe provides equations for stable diffusion as well which are not included here. There are a number of variations that include evolution of temperature and density.

Equation 2-4

$$\frac{\partial T}{\partial t} = -(u \cdot \nabla)T \; and \; \frac{\partial \rho}{\partial t} = -(u \cdot \nabla)\rho$$

which affect buoyancy force:

Equation 2-5

$$f_{buoy} = -\alpha\rho z + \beta(T - T_{amb})z$$

Where z = (0,0,1) (positive upward), and α and β are positive constants.

Smaller scale details to flow are added via a number or means such as semi Lagrangian paths.

2.2.2 Gaussian Plume, Puff Models and Lagrangian Flow:

Gaussian models follow the general form (Davis & Cornwell, 2012):

Equation 2-6

$$C(x,y,z) = [\frac{Q}{(2\pi u\sigma_y\sigma_z)}]\exp\,[\frac{-(y-y_0)^2}{2\sigma_y^2}]\exp\,[\frac{(z-z_0)^2}{2\sigma_z^2}]$$

Where C is the concentration at the specified point (in g/m^2) σ_y and σ_z are standard deviations for the axis, these terms vary depending on whether conditions are stable or unstable, Q is the emission rate in g/s of the species of interest from the fire, x is the centerline of the plume and always is in the direction of the wind. z_o is a vertical centerline and is best represented by a function such as Briggs plume rise but can be considered linear by adding the height of the smoke stack or discharge (for a fire, it could be 1-3 metres) to a simple plume rise equations such as Carson and Moses:

Equation 2-7

$$\Delta h = 0.29\left(\frac{V_s d_s}{u_s}\right) + 2.62(\frac{Q_h^{\frac{1}{2}}}{u_s})$$

Where Q_h is the heat emission in kW, u_s is the windspeed at the smoke exit height in m/s, V_s is the stack gas exit velocity (could be approximated at 1 or 2 m/s for a fire, and d_s is the stack exit diameter, this could be several square metres for a fire and many modelers use multiple cores or stacks to represent a fire.

Achtemeier, 2005 explains modifications to the Briggs equations for industrial stacks that will help match the puff model Daysmoke to the Equations.

Equation 2-8

$$h = \left(\frac{3}{2\beta^2}\right)^{1/3} F^{1/3} x^{2/3} / U$$

Where:

Equation 2-9

$$F = \frac{g\Delta T w d^2}{4T_s}$$

in this case h is the height of the plume axis above the source, x is the horizontal distance along the plume centerline, U is the mean horizontal wind speed through the profile of the atmosphere containing the plume, w is the stack ejection speed, d is the diameter of the stack at the exit, ΔT is the temperature difference between the smoke and the air at the stack and T_s is the temperature of the smoke at the stack. β is the entrainment coefficient, Briggs normally uses 0.6.

There are a number of variations used in Gaussian modelling such as incorporating reflectance for near ground concentrations (to account for the smoke sitting at the surface rather than penetrating the ground)

Puff models and Lagrangian models focus on the movement of the smoke or smoke particles rather than using a grid of boxes.

Puff models use cylindrical or spherical puffs of smoke to represent a plume.

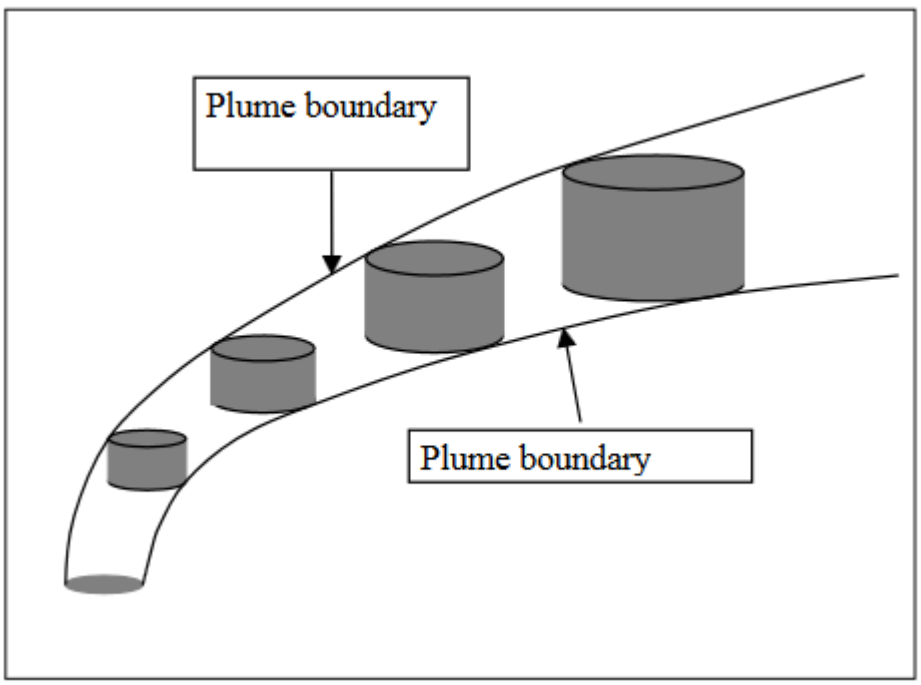


Figure 2-2 Daysmoke puff from Achtemeier 2005

The puffs expand and become more diffuse as they move away from the fire. Puff models generally use a Gaussian equation for the expansion of the puffs. Gary Achtemeier provides an explanation of the Daysmoke model. The Daysmoke model uses the Entraining Turret Model. This model describes the plume as a series of rising cylinders (or turrets). The cylindrical puffs of smoke are surrounded by entraining air (an annulus).

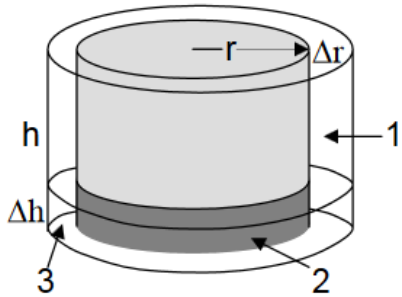


Figure 2. A breakdown of an expanding cylinder into three components: (1) an annulus around the original cylinder, (2) a cylinder added to the original cylinder, and (3) an annulus around the added cylinder.

Figure 2-3 Turret Puff Achtemeier 2005

Each cylinder is increased in volume from it's last position by a second cylinder added to the bottom of the main cylinder and a second annulus added to the bottom of the main annulus. Composition of the cylinder is modified by the wind. No wind means that the second cylinder is composed entirely of plume gasses. A wind that bends the plume over to 45° will change the composition of the lower cylinder to half ambient air and half plume air.

2.3 Inputs required for modern modelling:

Modelling smoke requires inputs relating to the amount of biomass per hectare, the consumption rate of this biomass, the effect of wind on smoke dispersal and a mixing height (which is influenced by atmospheric stratification and buoyancy of the plume). Consumption rate of fuel

is tied to short- and long-term weather (how hot it is, the relative humidity, how dry the fuel is and how dry the soil is) The Queensland Parks and Wildlife Service Planned Burn Guidelines provide an overview of the inputs required to determine fire severity (Queensland Department of National Parks, Recreation, Sport and Racing, 2012). As evident in this document, historical inputs for smoke modelling were derived from manual observations of weather, fuel load and other factors such as a drought index

Modern smoke models derive inputs from other models. Fuel load is often modelled across a landscape. LiDAR is now used to help model fuel load. Eusuf et al, 2020 explain a process of mapping forest fuel loads with LiDAR and stratifying the fuel load in the forest profile using the Voxel approach. Many of the stakeholders interviewed referred to LiDAR fuel load mapping.

Fire behavior modelling is the next input for smoke hazard mapping. PHOENIX RapidFire is a fire behavior simulator currently used extensively by land managers, emergency services and planners in Australia. Tolhurst et.al 2008 discusses the inception of the model and in general, what it does. The model has advanced since the article written in 2008. There is a significant body of work about PHOENIX. Other literature discusses the model's ability to accurately predict problem fires.

Meteorological data and modelling are required inputs of the fire behavior model and the smoke model. The Bureau of Meteorology (BoM) provides the data for PHOENIX and AQFx. The BoM provide a description of the process in their 2018 Operations Bulletin (Bureau of Meteorology, 2018).

2.3.1 Emissions - Fuel Load estimation

Current Methods for Estimating Fuel Load:

The Queensland Parks and Wildlife Service (2012) provide a fuel estimation method for tons/hectare of fuel based on ground cover. This method is still widely used by Queensland land managers. The method is site specific, and the fuel load is estimated via physical on-site measurements.

CSIRO 2017, provided the State of Queensland with a model for fuel load estimation based on Olsen's (1963) fuel accumulation model. The CSIRO model:

Equation 2-10

$$x = x_{ss}(1 - e^{-k(t+tx)})$$

Where x is the fuel load at time t, k is the fuel decomposition rate and x_{ss} is the maximum potential fuel load. CSIRO estimates k and x_{ss} based on empirical data for each vegetation structure class and general ecosystem. These values are tabulated in CSIRO's 2017 document. Ecosystem data is provided by the QLD Herbarium.

Table 3. Summary of *k* values for each of the structural classes

Structure Class	Decomposition Rate (k)
1. Tree Closed – Mid Dense	0.65
2. Tree Sparse – Very Sparse	0.35
3. Shrubland	0.26
4. Grassland	0.8
5. Sedgeland	0.8
6. Nil vegetation	n/a

Table 2-1 k values from CSIRO 2017

As well as vegetation structural class mapping, fuel estimation requires input of burn scars from previous fires. The term t_x refers to the time at which a proportion of fuel which remains following a fire, with consideration for the decay constant.

Equation 2-11

$$t_x = \frac{-\ln(1-p)}{k}$$

The proportion of fuel remaining, p is estimated using the burn scar mapping derived using LandSat imagery by The Queensland Government Remote Sensing Centre (Goodwin & Collett 2014) and the fire intensity at the time of the burn derived from McArthur's 1967 equations for forest fire danger index (FFDI). Proportions remaining following a fire have also been estimated from empirical data, related to vegetation structure classes and tabulated:

Table 2. Assumed percentage of fuel remaining after bushfire by Vegetation Structure Class and 1:20 year FDR

Vegetation Structure Class	1:20 year Fire Danger Rating					
	Catastro-phic	Extreme	Severe	Very High	High	Low–Moderate
	FFDI 100+	FFDI 75-99	FFDI 50-74	FFDI 25-49	FFDI 12-24	FFDI 9-11
1. Trees closed - mid dense	0%	0%	10%	20%	40%	70%
2. Trees sparse - very sparse	0%	0%	10%	10%	20%	50%
3. Shrubland	0%	0%	10%	20%	40%	70%
4. Grassland	0%	0%	10%	10%	20%	50%
5. Sedgeland	0%	0%	10%	10%	20%	50%
6. Nil veg	0%	0%	10%	10%	20%	50%

Table 2-2 Proportion of fuel remaining from CSIRO 2017

Recent Research in Fuel Load Estimation:

Use of LiDAR to map forest fuel loads has been studied extensively. Advances have been made and this area of research and the method of modelling fuel load is promising. Chen et al. studied a three step multiple regression analysis to predict fuel load in Victorian Eucalypt forests. Using findings from other studies related to the effective canopy cover, years since the last burn, aspect and several other variables, Chen et al. produced significant advances in LiDAR modeling of fuel load. Stefanidou et al. confirm and adds to the work of Chen et al. Stefanidou et al. discusses remote sensing data in the visible range as another data source which could be used in

the LiDAR analysis. Another LiDAR approach where significant investment has been made is in the Voxel method of analyzing a point cloud within the forest. Eusuf et al. write a recent and contemporaneous article on use of the Voxel method in Australian ecosystems.

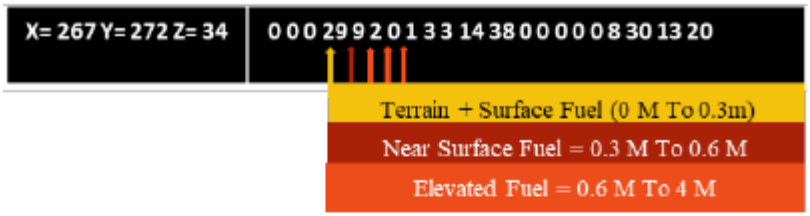


Figure 10: A sample of point clouds in a column in the voxel space at coordinate x = 267, y= 272 & z= 34

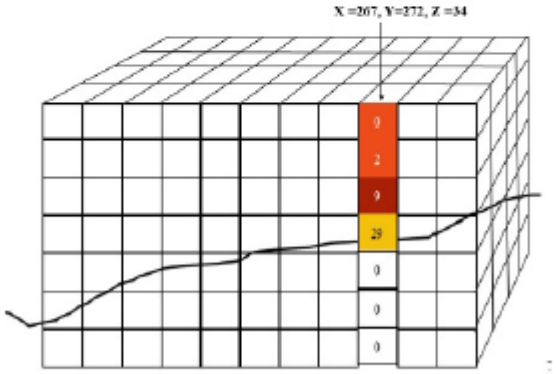


Figure 11: Representation of figure 10 at x= 267, y= 272 & z= 34 in a voxel space of 534 x 543 x 67

Figure 2-4 Eusuf et al 2020, Voxel space LiDAR cloud interpretation

2.3.2 Emissions – Fire Behavior

Fire behavior, the fire energy and the proportion of the fuel burnt directly affects emissions.

AG McArthur pioneered fire behavior modelling in Australia in the 1960's. His 1967 leaflet on fire behavior in Eucalypt forests describes fire behavior in terms of air temperature, relative humidity, wind velocity, drought (6-8 weeks or more without rain) and the stability of atmospheric conditions. McArthur produced a forest fire danger meter (a simple model) which is still in use in a modified form today (as per the above section on fuel load mapping).

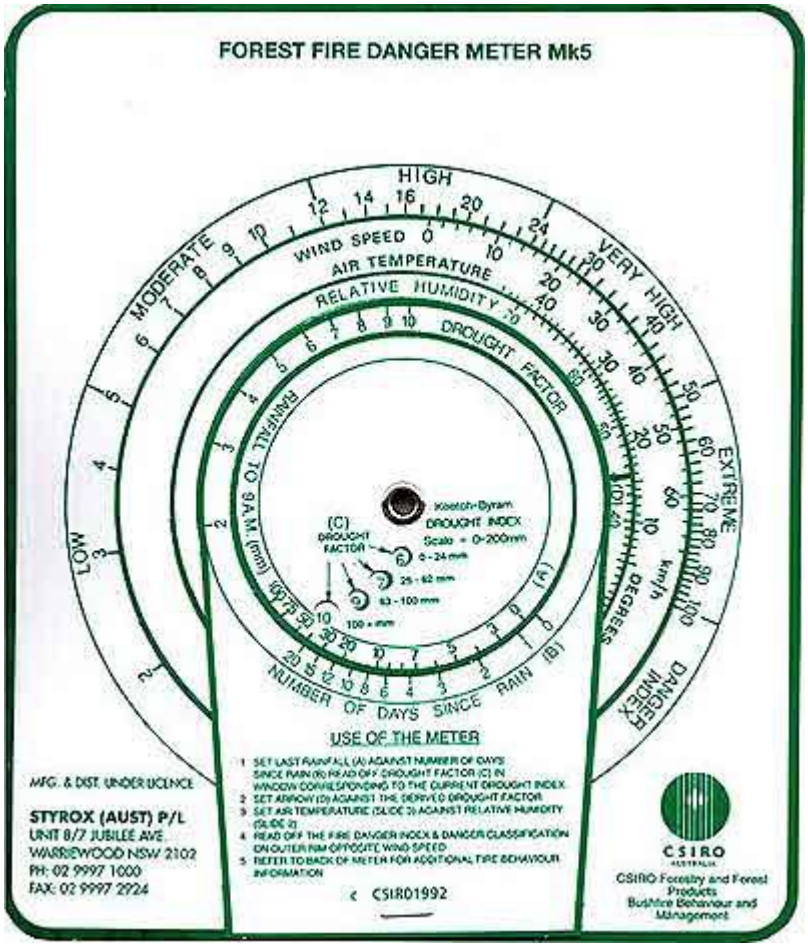


Figure 2-5 Picture of a McArthur Forest Fire Danger Meter CSIRO

Tolhurst et al. 2008 created the next generation of fire behavior modelling in Australia with the PHOENIX suite of models. SPARK is the latest model being used in Australia, Miller et al. 2015.

2.3.3 Weather forecasts and real-time weather data

Basic models take manual input from directly observed and/or predicted weather. Many agencies still use psychrometers and anemometers on the day of the proposed burn along three-day forecasts. Modern air pollution models use gridded climatic data derived directly from the relevant agency (normally a national weather data provider). The imported data often requires gridding and/or conversion (Cope et al. 2020) (BoM 2018). Data will include projected (and/or real-time) wind speed, precipitation, relative humidity and solar radiation, often at a range of altitudes.

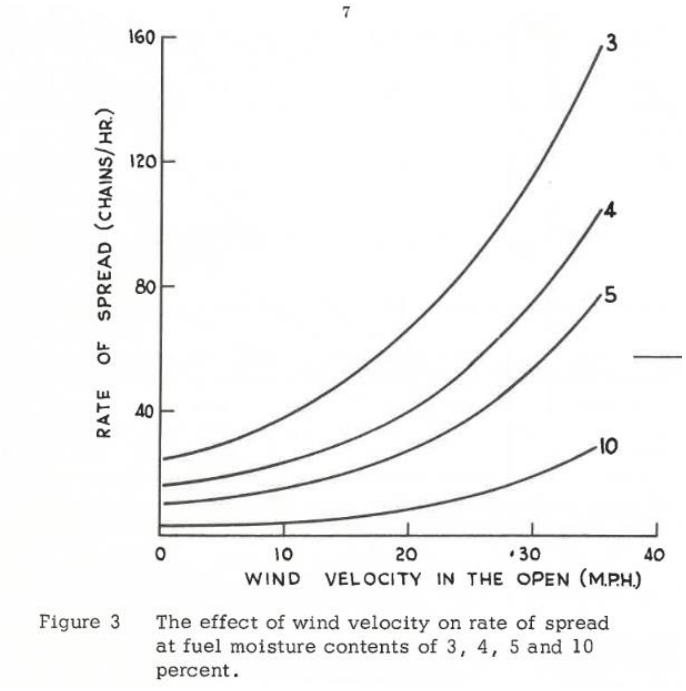


Figure 2-6 From McArthur 1967

2.4 Detecting and analyzing plumes and fires using remote sensing

Williamson et.al 2013 encountered issues with visual interpretation of plumes due to controlled burns being for short durations. The satellite has to pass within a smaller time window and there needs to be clear skies over the fire at the time of the pass. Initial reviews of Planet Labs images of fires for this research has encountered the same issue.

Li et.al 2015 demonstrates that work is continuing in the attempt to delineate smoke plumes automatically through remote sensing. There are significant issues relating to the varying temperature of smoke plumes (both internally as well as with respect to the ambient temperature), chemical composition of the smoke, which varies from fire to fire as well as over time. These researchers met with some success but were unable to generate good results unless the sky was almost devoid of cloud.

Ellicote and Vermote 2012 is an important work in not only understanding the scope of how the MODIS platform aboard the Terra and Aqua NASA satellites might be used to find and quantify aspects of fires but the University of Maryland team have provided some critical research findings in regards to determining FRP using remote sensing methods including satellite and UAV. The formula provided by the team:

Equation 2-12

$$FRP = A_{sample}\varepsilon\sigma \sum A_n T_n^4$$

Where A_{sample} is the satellite pixel in m^2 , ε is the fire emissivity, σ is the Stefan Boltzmann constant ($5.67x10^{-8J}$-$1m^{-2}K^{-4}$), A_n is the fractional area of the ith thermal component and T_n^4 is the temperature of the ith thermal component (K). Ellicote and Vermote discuss the issues

with atmospheric interference but prove a theory that could likely be used successfully by UAV.

The Himawari satellite is a geostationary satellite which has proved useful in both finding fires and comparing visible plumes with modelled plumes Cope et al. 2019.

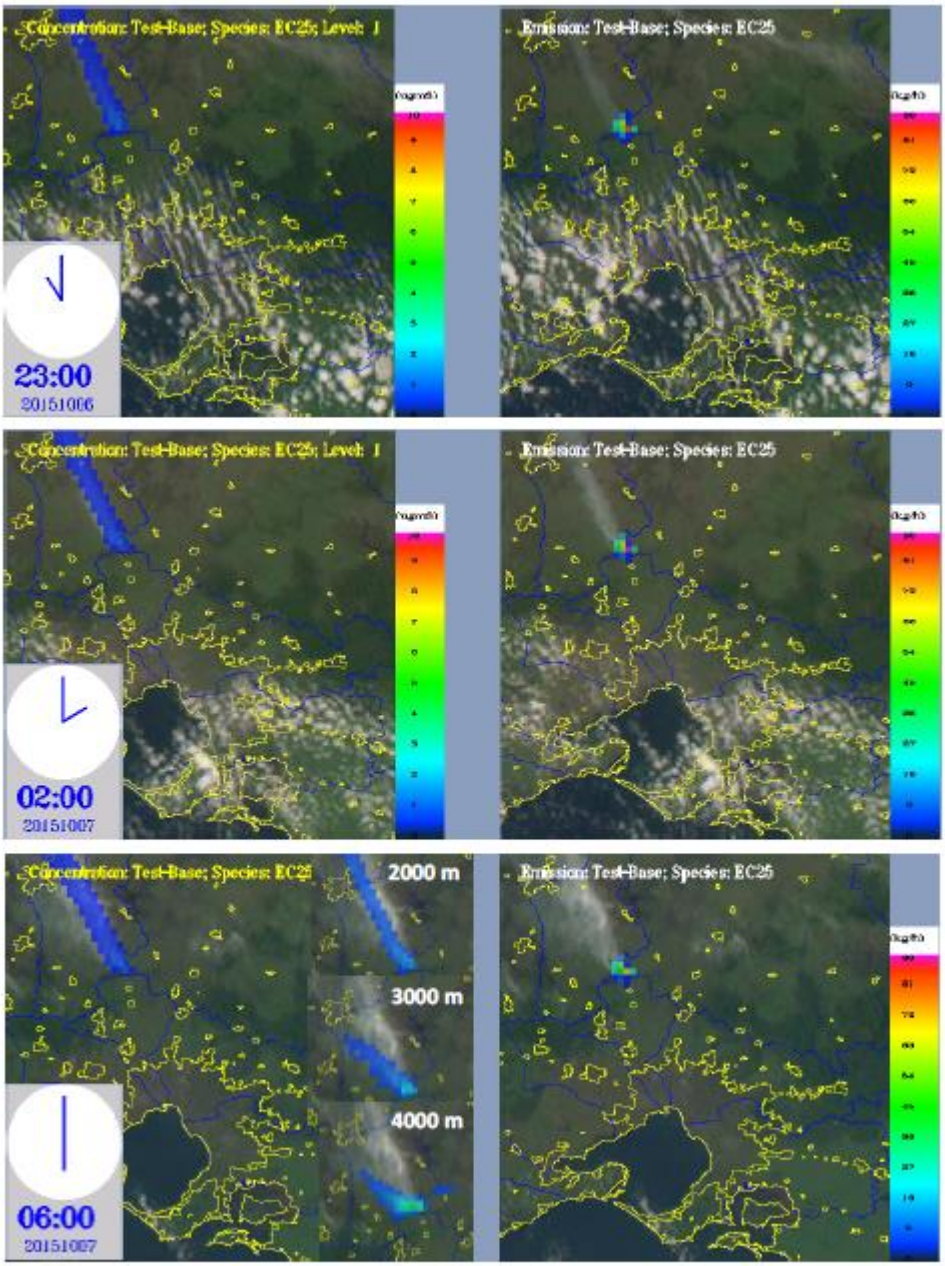


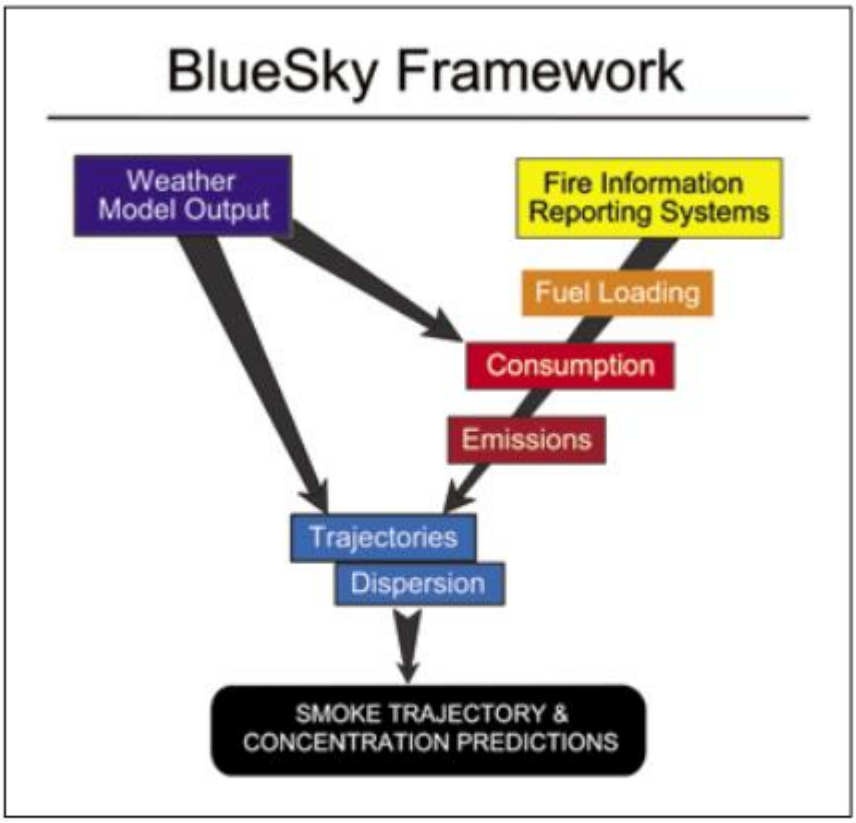
Figure 31 Comparison of forecasts and observed (Himawari satellite) smoke plume positions- 7th October 2015. The modelled model plume is shown in the left column. The observed smoke plume is shown in the right column. Also shown are the modelled Lancefield-Cobaw emissions (right). Note that the times are in UTC.

Figure 2-7 Cope et al. 2019 – Himawari satellite image overlain with modelled plumes.

2.5 Models used in AQFx

2.5.1 Plume rise and dispersal modelling

AQFx uses a range of models for inputs and plume modelling. AQFx uses a modular approach based on the United States BlueSky framework.



The BlueSky framework uses data on weather, fires and fuels, emissions, and terrain. BlueSky calculates smoke plume rise, particulate matter concentrations, visibility, and chemistry. Its final outputs are forecasts of smoke trajectories and concentrations, with Web displays.

Figure 2-8 From BlueSky U.S Forest Service 2006

The BlueSky framework uses an emission model based on forest types within the United States and uses the United States Weather Service data for climatic input. The BlueSky framework is

modular in it's inputs and produces a web based display. AQFx has taken similar modular elements and combined them. AQFx uses BoM weather models (BoM 2018), fuel loads for Australian ecosystems as described in the sections above, emission inputs were previously derived from a modified version of the fire simulator PHOENIX RapidFire called FireFlux (Cope et al. 2019) (which stores data from the burnt area for emission data processing). Very recent literature indicates that the SPARK fire behavior model replaces FireFlux as the fire simulation/emission model. Plume rise and dispersion models from BlueSky use CALPUFF. CALPUFF has a complex dispersion model (Scire et al. 2000). The dispersion model has a range of functions which incorporate terrain, including buildings, chemical transformations and processes above lakes and oceans. The basic plume dispersion equations are a hybrid Gaussian puff and slug (elongated puff) model. Equations are taken directly from the CALPUFF User Manual (Version 5). Note that these are the basic equations and represent a very small portion of the dispersion modelling.

Equation 2-13

$$C = \frac{Q}{2\pi\sigma_y\sigma_z} g \exp\left[-\frac{d_a^2}{2\sigma_x^2}\right] \exp\left[-\frac{d_c^2}{2\sigma_y^2}\right]$$

and

Equation 2-14

$$g = \frac{2}{2\pi^{\frac{1}{2}}\sigma_z} \sum_{n=\infty}^{\infty} \exp\left[-\frac{(H_e + 2nh)^2}{2\sigma_z^2}\right]$$

Puffs follow Gaussian form, C is the concentration in g/m^2 of smoke at the receptor, Q is the mass of smoke in the plume, $\sigma_{x,y,z}$ are the standard deviations (note the x standard deviation is used in the puff unlike the constant emission model normally associated with Gaussian Plumes). d_a represents the distance to the puff center in the along-wind direction, and d_c represents the distance from the puff center to the receptor in the crosswind direction, g is the vertical term and

this represents reflectance from both the top of the mixing height and the ground. H_e is the effective height above the ground of the puff center and h is the height of the mixed layer.

For the horizontally symmetrical puffs, the equations can be reduced to

Equation 2-15

$$C(s) = \left[\frac{Q(s)}{2\pi\sigma_y^2(s)}\right] g(s)\exp\left[-\frac{R^2(s)}{2\sigma_y^2(s)}\right]$$

Where R is the distance from the center of the puff to the receptor and s is the distance travelled by the puff.

The slug models are elongated Gaussian puffs stretched in the along-wind direction

Equation 2-16

$$C(t) = \frac{Fq}{(2\pi)^{\frac{1}{2}}\acute{u}\sigma_y} g \exp\left[-\frac{d_c^2}{2\sigma_y^2}\frac{u^2}{\acute{u}^2}\right]$$

And

Equation 2-17

$$F = \frac{1}{2}\left\{\mathrm{erf}\left[\frac{d_{a2}}{\sqrt{2\sigma_{y2}}}\right] - \mathrm{erf}\left[\frac{-d_{a1}}{\sqrt{2\sigma_{y1}}}\right]\right\}$$

Where u is the vector mean wind speed and ú is the scalar wind speed ($\acute{u} = (u^2 + \sigma_v^2)^{1/2}$ and σ_v = wind speed variance), q is the source emission rate (g/s), F is the causality function and g is the vertical coupling factor as above. The terms d_{a2} and d_{a1} refer to the distances from slug end 1

and slug end 2 to the receptor. The subscripts 1 and 2 on the dispersion coefficients refer to the oldest and youngest ends of the slug respectively.

The CSIRO team advised that AQFx uses a different set of dispersion models. **Lower resolution** modelling (broadscale) uses the Chemical Transport Model.

The Chemical Transport Model is a Eulerian modelling framework. It uses a semi-empirical advection-diffusion equation for reactive species as the governing equation. The governing equation for a single pollutant species from Cope et al. 2009 is:

Equation 2-18

$$\frac{\partial \dot{C}}{\partial t} + \frac{\partial U\dot{C}}{\partial X} + \frac{\partial V\dot{C}}{\partial Y} + \frac{\partial W\dot{C}}{\partial \sigma} = \frac{\partial}{\partial X}\dot{\rho}K_1\frac{\partial \dot{C}/\dot{\rho}}{\partial X} + \frac{\partial}{\partial Y}\dot{\rho}K_2\frac{\partial \dot{C}/\dot{\rho}}{\partial Y} + \frac{\partial}{\partial \sigma}\dot{\rho}K_3\frac{\partial \dot{C}/\dot{\rho}}{\partial \sigma} + (P-L)V_m M_1 M_2$$

Where $V_m, M_1 \; and \; M_2$ are horizontal and vertical scale factors chosen to match the meteorological model the equation is being used in. $\dot{C}$ is the scaled concentration ($\dot{C} = C/V_m M_1 M_2$) and C is the mass density eg g/m^3. $\dot{\rho}$ is the scaled atmospheric density ($\dot{\rho} = \rho/V_m M_1 M_2$). $U, V \,\&\, W$ are scaled velocities in the X, Y and σ directions, $U = u/M_1, V = v/M_2 \,\&\, W = w/V_m$ where $u, v \,\&\, w$ are the corresponding cartesian velocity components. $K_{1,2}$ are the scaled horizontal components of the eddy diffusivities and K_h is the vertical eddy diffusivity so $K_1 = \frac{K_h}{M_1^2}, K_2 = \frac{K_h}{M_2^2} \; and \; K_3 = \frac{K_z}{V_m^2}$. P is the chemical rate of change from chemical production and emission and L is the loss rate through wet and dry deposition and chemical transformation.

Table 1 Coordinate scaling factors used by the CTM.

Host Model	Horizontal coordinate system	Scaling Factors			Vertical coordinate system	Scaling Factor
		M_1	M_2	M_3		$V_m = \partial z / \partial \sigma$
LAPS	Spherical	$\cos(\theta)$	1.0	R_e	p/p_s	$p_s/\rho_a g$
CCAM	Spherical	$\cos(\theta)$	1.0	R_e	p/p_s	$p_s/\rho_a g$
TAPM	Rectangular	1.0	1.0	1.0	$(z-z_s)/(z_t-z_s)\times z_t$	$z_t/(z_t-z_s)$

R_e=earth radius; p=pressure; p_s=surface pressure; z = height above sea level; z_s = ground height; z_t = top of model domain; g = gravity; ρ_a = air density

Figure 2-9 Coordinate scaling factors from Cope et al. 2009

The governing equation is solved using a set of one-dimensional solutions. Advection, horizontal and vertical diffusion are solved using partial differential equations. The wind components and mass flux is solved conventionally at the interface of the cells.

Higher resolution (near field) dispersion modelling uses (or will use) HYSPLIT. HYSPLIT stands for Hybrid Single-Particle Lagrangian Integrated Trajectory model. The model uses a Langrangian approach for advection and diffusion which has a moving frame of reference. This is coupled with a fixed Eulerian grid to provide a frame of reference for the user. The frame of reference is also the input grid (and source for the Lagrangian component) for the gridded weather data. HYSPLIT has a long history of development and refinement. The model began with hand drawn trajectories in the 1940's through Gaussian, Gaussian Puff, Puff/Trajectory hybrid and through to the global gridded hybrid. Mr Cope explained that HYSPLIT would be used for near field species concentrations in the near future, it was unclear which formula iteration would be used.

The governing advection (transport/trajectory) equation for HYSPLIT uses a particulate change in position formula for particles and puffs (from Stein et al. 2015):

Equation 2-19

$$P_{mean}(t+\Delta t) = P_{mean}(t) + \frac{1}{2}[V(P_{mean}, t) + V([P_{mean}(t) + [V(P_{mean}, t)\Delta t]\}, t+\Delta t)]\Delta t$$

P_{mean} is the position vector, V is the average of the three dimensional velocity vectors at initial and first guess positions.

Dispersal (diffusion) is governed by turbulence equations and added after the advection term:

Equation 2-20

$$X_{final}(t+\Delta t) = X_{mean}(t+\Delta t) + \acute{U}\ (t+\Delta t)\Delta t$$

And

Equation 2-21

$$Z_{final}(t+\Delta t) = Z_{mean}(t+\Delta t) + \acute{W}\ (t+\Delta t)\Delta t$$

Where $\acute{U}$ and $\acute{W}$ correspond to turbulent velocity components which are derived through the modified discreet-time Langevin equation from weather data. The mean and final particle positions X and Z are horizontal and vertical respectively.

HYSPLIT is a complex, global model containing deposition and chemical transformation functions, the degree to which these advanced functions will be used in near field AQFx modelling is not known by the researcher (this aspect is possible not clear yet to the developers either).

The CSIRO team explained to the researcher that the plume rise equation (at least for the smoldering plume) is based on the equations used in Luhar et al. 2020 to effectively model a smoldering open-cut coal mine fire at Hazlewood:

For a free burning fire of Diameter L (m):

Equation 2-22

$$\Delta h = 4.2 \frac{[(1-E)Q_H]^{0.26} L^{0.63}}{u^{0.5}}$$

Where E is the fraction of heat released in the environment as thermal radiation (=0.3). Q_H is the total heat rate (kcal/s) and u is the wind speed in m/s.

Luhar et at. 2020 assumes that when L is 90% of the source is burning, this represents the maximum possible output, furthermore, the model took hourly data on the burn rate of the coal and made L a function of that so $L_{new} = 0.9L*(Q_{hourly}/Q_{max})$. This function in AQFx uses output from PHOENIX/SPARK.

The spread of the plume around it's centerline is modelled by the equation $r_p = \beta\Delta h$ where β, the entrainment constant is 2/3 and r_p is the plume radius.

2.5.2 Fire behavior and emissions modelling

Cope et al. 2019 explains that the base fire behavior model used in AQFx is PHOENIX RapidFire. PHOENIX RapidFire is a well-established fire behavior model in Australia. The model takes weather, slope and fuel load inputs (as well as assets and firebreaks). The intensity calculated from fuel load, humidity and temperature along with wind and slope forces inform rate of spread vectors. These vectors are fitted to elliptical templates of spread to define the fire front. The computational model provides a relatively complex fire front (as complex as the fuel load mapping, topography and changes in wind speed and direction). PHOENIX is able to define "hotspots" which are important in generating multicore plumes. PHOENIX uses these to inform ember spread modelling. PHOENIX is not designed for plume modelling but in generating the

fire spread modeling it is necessary to calculate fuel usage for the heat transfer functions required by the spread vectors. PHEONIX RapidFire was modified to capture the burnt fuel and feed that data into AQFx. The modified program is called PHOENIX FireFlux. PHEONIX is not ideal for modelling prescribed burns. The model has been calibrated for 'worst case scenario' fires. The objective of the model is to assist with disaster planning and also to help firefighters target break construction and other firefighting efforts during a disaster. Th model does not work well for small, controlled burns.

SPARK is likely to replace PHOENIX as the fire behavior model used in AQFx. SPARK is a Raster based model rather than a vector based model. SPARK layers the inputs over a grid:

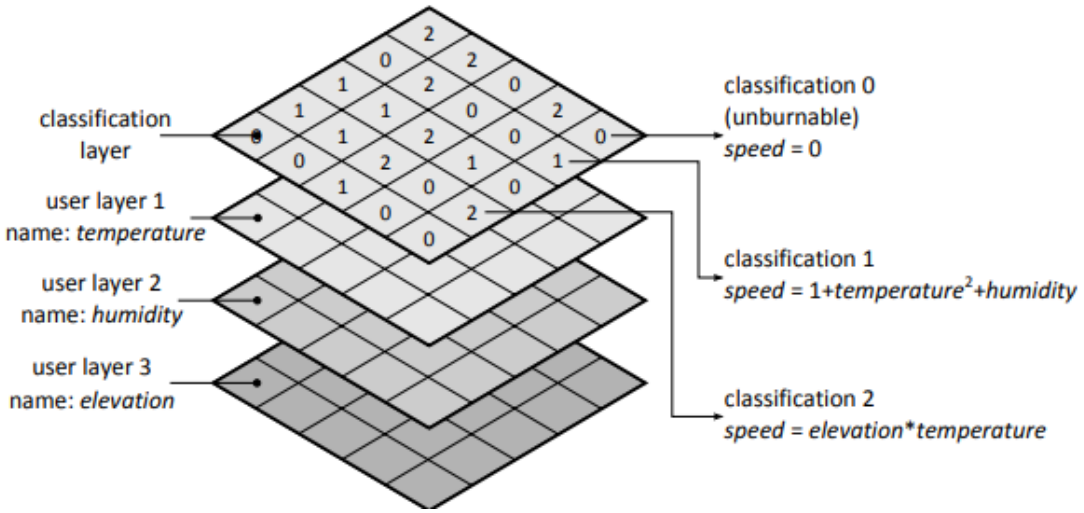


Figure 2-10 From Hilton et al. 2015

The program creates and populates grid tiles around each "burning" tile. Each burnt tile of the grid can provide data on emissions from that tile. QFES have been rolling this model out through Queensland and it is likely to be used more extensively in controlled burn modelling.

Both fire behavior models use a set of models for different ecosystems. The McAurthur model is used for Eucalypt forests while other models such as CSIRO's GRASS is used for grassland areas.

2.6 Conclusions

Smoke Modeling and AQFx:

There are a large number of smoke models available for agencies to use directly or to use as a template for custom models. The project uses the Hysplit and Korean forest service Gaussian models as a base for the project model. The simple Gaussian models are relatively easy to use and accurate to the degree required for small, controlled burns. From the starting point of the a simple box model, where instantaneous mixing is assumed over a large airspace, smoke modelling has become a well-researched and complex field of study. AQFx is a complex model with gridded inputs for fuel, weather, air quality and topography. The model uses a modified version of the BlueSky framework, with a modified version of CALPUff, a complex dispersion model with a long history of up refinements. The model incorporates other complexities including chemical transformations, multiple plumes and multiple fires as well as anthropogenic pollution sources of pollution such as industrial and traffic and natural sources such as dust. AQFx requires significant computing power and constant input feeds from the BoM. AQFx is built on a tested set of models that will provide a life saving air quality forecasting service.

Satellite Imagery and Smoke Plumes:

Monitoring and measurement of smoke plumes using satellites is not well advanced. Most literature the researcher discovered where satellite data has been used to research fire plumes has focused on the NASA MODIS sensors aboard Terra and Aqua. All satellite data is impacted by cloud cover and both the NASA satellites and Himawari offer relatively low resolution. Use of Planet Labs daily imagery and speculation about future real-time video have not been well researched.

Chapter 3 Research Design and Methodology

3.1 Finding Plumes to Compare

There are a number of agencies across Queensland that carry out prescribed burns, these include the Department of Resources (DoR), Queensland Parks and Wildlife Service (Department of Environment and Science), (DES), and Forestry Plantations Queensland (HQ Plantations).

Access was obtained to the Queensland Department of Resources burn schedule for prescribed burns. The burns were proposed from June through to October. Data from DoR includes fuel load estimates. Mr Julian Gregson, Team Leader, State Land Management, DoR is collaborating with the author. An example of the collaboration and subsequent study plume is provided in Appendix E.

HQ Plantations has a public website listing proposed, active and completed burns.

The other primary Department responsible for conducting burns is the Queensland Parks and Wildlife unit of the Department of Environment and Science. DES has a publicly available public dataset spatial dataset.

Another valuable tool for finding fires is the DEA Hotspot mapping. Preliminary work on the study used DoR advice as well as Hotspot mapping to identify suitable plumes for comparison.

3.2 Access to Modelling

Access to AQVx was delayed due to ITC issues. Access to AQVx was provided on 30 September rather than 30 June as expected. There is not currently capability to input projected controlled burns, however this should be available in 2022. AQVx shows plumes in Queensland with the capability launched in September 2021. Comparisons between Planet Labs images and AQVx output are made but limited numbers of these were available due to the timeframes.

In leu of model availability, the author has prepared a Gaussian model in order to better explain commercial modern model behaviour. These descriptions compare simple Gaussian outputs with

Planet Labs imagery to explain how models operate and what advances have been made, particularly with AQFx and AQVx.

3.3 Access to Planet Earth

Access to Planet Earth is arranged through the QLD Department of Resources. Testing of the system to locate plumes was conducted with about half of the fire locations provided by the Department of Resources located. A third of the fires provided satisfactory plumes.

Plumes were located using DoR information and Hotspot mapping. Planet Labs images over a period of several days around the event were inspected. Images that contained plumes were downloaded. Images with Cloud or other interference were not used.

3.4 Describing Plumes with Simple Models

A model has been created in Microsoft Excel for this research. The model is a Gaussian model with a dynamic geographic grid. This model uses a common Gaussian equation found in many smoke models such as South Korea's Forestry Department smoke model. As the primary interest is in pollutant at ground level as this affects health and traffic, the model incorporates a reflectance term as described in Chapter 2:

Equation 3-1

$$C(x,y,z) = \left[\frac{Q}{(2\pi u \sigma_y \sigma_z)}\right] \exp - \left[\frac{y^2}{2\sigma_y^2}\right] \{\exp\left[\frac{-(z-z_0)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+z_0)^2}{2\sigma_z^2}\right]\}$$

σ_y & σ_z are calculated using the formula $\sigma_y = ax^{0.894}$ and $\sigma_z = cx^d + f$ where a,c,d, and f correspond to stability class. The algorithm for the dispersion coefficients matches the charts displayed in Appendix C. Stability classes are derived using the tables shown in Appendix C

and then matched to the variables shown in the Tables in Appendix C. These are taken from the Cornwall and Davis 2012 text on Environmental Engineering.

The model uses the plume rise equation provided in Luhar et al. 2020 as described in Chapter 2.

The model has a dynamic receptor grid with 200 points along the plume centreline and 50 points each side of the centreline. This aspect of the model has likely been used in spatial science but has not been noted in any literature. The dynamic receptor grid solves a problem of being able to model the plume of a prescribed burn anywhere in Queensland and allows the plume from a proposed fire to be modelled several days in advance with some basic weather predictions. It is particularly suited to prescribed burns.

The grid uses the Australian Mapping Grid, a metric Universal Traverse Mercator. The user defines the length of the centreline and its endpoint coordinates to generate the grid. The grid is optimally designed for a 20km long centreline. 10 to 50 km long centrelines were tested in the testing phase and will work well.

The model uses "IF" statements to test if the centreline has an Eastern or Western bearing and a Northern or Southern bearing. Sin and Cos functions are then used to project the grid off the centreline.

The model is a point source model, using the model for multicore fires and layering of plumes will be discussed in Chapter 4.

The user inputs fuel load and other parameters effecting burn efficiency and burn time such as relative humidity, wind speed and days since last rain in accordance with the McAurthur Forest Fire Danger Index.

As the model projects the plume onto a mapping grid, the output can be imported into ArcGis (GQIS will also provide excellent results). Concentrations of the target species are attributed to each point in the grid. The data can be rasterized in ArcGis for ease of use by operators if required.

Plumes to be modelled were captured from Planet Earth imagery and then georeferenced in ArcGis using the georeferencing toolkit. The plume images were georeferenced using Earth-I

imagery as a base. Three common points were used to georeference (stretch) the Planet Earth image. Earth-I georeferencing is checked by DoR spatial Science unit. This is an accepted method for georeferencing and this method of georeferencing is accurate to the degree required for this study.

The Woodgate plume is used as a demonstration of multicore plume modelling where 4 modelled cores (or plumes) are overlain on the plume image.

The Maryborough plume is used as a demonstration of 3 dimensional modelling where four vertical strata at 2, 5, 10 and 20 metres height are modelled.

Weather observations for the day of the plumes were downloaded from BoM.

3.5 Inputs into AQFx

AQFx inputs are complex. The inputs include fuel load modelling, fire behaviour modelling, atmospheric modelling and terrain as well as measured data for those parameters. The study describes these inputs and how they interact in more detail in Chapter 4.

Comparing the project model to Planet Labs plumes is a method used in Chapter 4 to explain and understand AQFx inputs and how they work with the model. Examples of AQFx output (via AQVx are provided).

Chapter 4 Research Results and Discussion

Introduction

The overall themes of this research project were to:

1. Develop an understanding of plume modelling for prescribed burns, in particular, the contemporary Australian model AQFx.

2. Provide some useful data/or service in support of the rollout of AQFx in Queensland.

The first component of the results chapter discusses the discovery of intelligence and the network of information required by CSIRO to assist in rolling AQFx out in Queensland.

The second part of this chapter deals with identifying plumes using Planet Labs and commenting on the usefulness of this product for calibrating and verifying models.

The third part of this chapter focusses on the model constructed for this project. Discusses input and outputs and compares output to imagery. This part of the project seeks to improve and validate the constructed model as well as explain the more complex processes used in AQFx.

The fourth part of this chapter reviews AQVx output and compares Planet Labs Imagery to AQVx output.

The fifth part of the chapter discusses development of the smoldering plume methodology for sampling FRP and plume height.

4.1 Prescribed burns in QLD

An important component of this project was identifying the various agencies/corporations with significant interest in prescribed burns. The author met with representatives from QFES, HQ Plantations and DoR to discuss access to planned burn data, particularly in relation to up-coming burns. AQFx relies on proposed burns being entered into the database for air quality predictions. The author found that there is a significant amount of data available. QFES is beginning to take

a role in gathering and coordinating this data, QFES has an interest in reporting the total area burnt. There is significant scope for QFES to collate data from a range of agencies to feed into the AQFx model.

Information gathered, as well as contact details for relevant stakeholders will be passed on to the CSIRO team as part of this project. A summary of data is provided below.

Department of Resources:

The Department of Resources manages approximately 17,000 parcels of Unallocated State Land in Queensland. DoR is responsible for managing fire fuel risks on the parcels. Many of the parcels are small and urban, mechanical means such as slashing are used in these areas. There are many larger areas of land where prescribed burns are used to reduce fuel load. The Department of Resources maintains a database of proposed burns. The database is not a public facing database and access to the information will be through DoR staff.

2	FCRC	East of Dundathu	FCA98	Resources	0	518	Wildfire 03.08.2021	
2	FCRC	Maryborough Showgrounds	FCA81	Resources	0		Wildfire 08.08.2021	
3	BRC	Bingera	L37 - AP22917	QPWS	0	345	Completed 13.08.2021	
3	FCRC	Booral Road	FCA57	Resources	Contractor support - $1500. Or local RFB.	1.8	May - August 2021	
2	FCRC	Boonooroo Estate	FCA42	Resources	Contractor support - $1500. Or local RFB	7.5	May - August 2021	

Table 4-1 Sample from DoR database, green means completed burns, less than 50% of the proposed burns have been completed, this is fairly normal across the agencies/corporations.

It is likely that Julian Gregson from DoR will be the contact for this database in 2022. Mr Gregson will assist in providing details of up-coming burns.

Department of Environment and Science:

The Department of Environment and Science has responsibility for managing National Parks and State Forests. DES maintain a geographical database of a prescribed burn schedule which is available in .kml format from the QLD Government's open data portal: https://www.data.qld.gov.au/dataset/queensland-parks-and-wildlife-service-fire-advisories/resource/db74c713-a1cf-4109-be1f-b78130ec65d5?truncate=30&inner_span=True

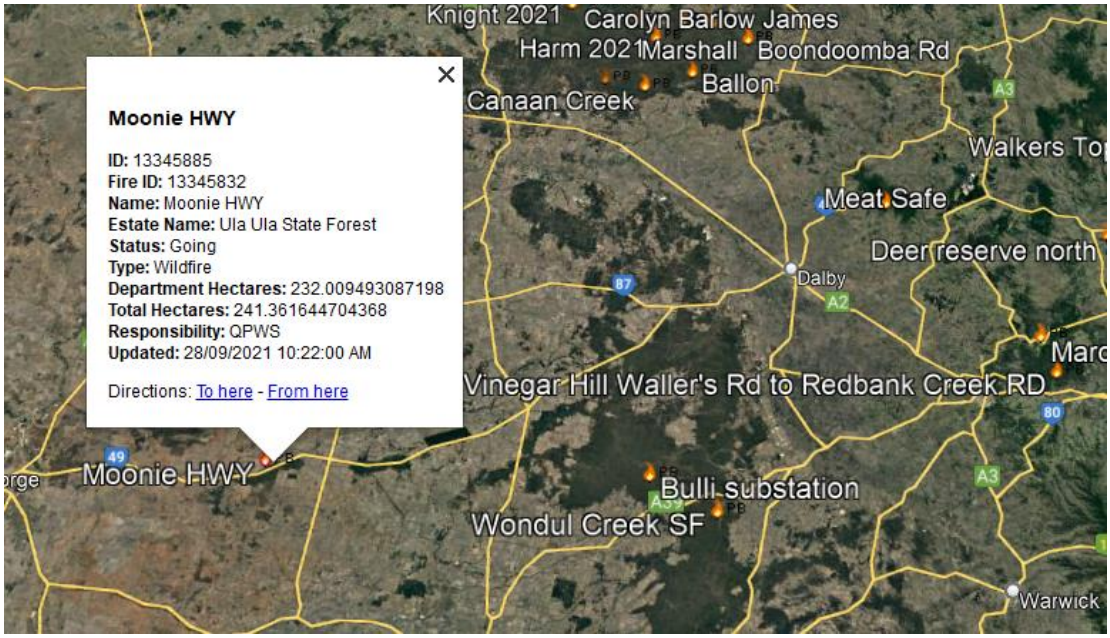


Figure 4-1 QPWS planned burn information displayed as a .kml on Google Earth

Queensland Fire and Emergency Services:

QFES provide a Hazard Reduction Burn update via their website:

https://www.qfes.qld.gov.au/safety-education/hazard-reduction-burn-notifications

SEQ Water planned burn website:

https://www.seqwater.com.au/project/planned-burns

HQ Plantations:

HQ Plantations have a detailed geographical data set for planned burns available at:

https://www.hqplantations.com.au/our-plantations/fire-protection#fire-map

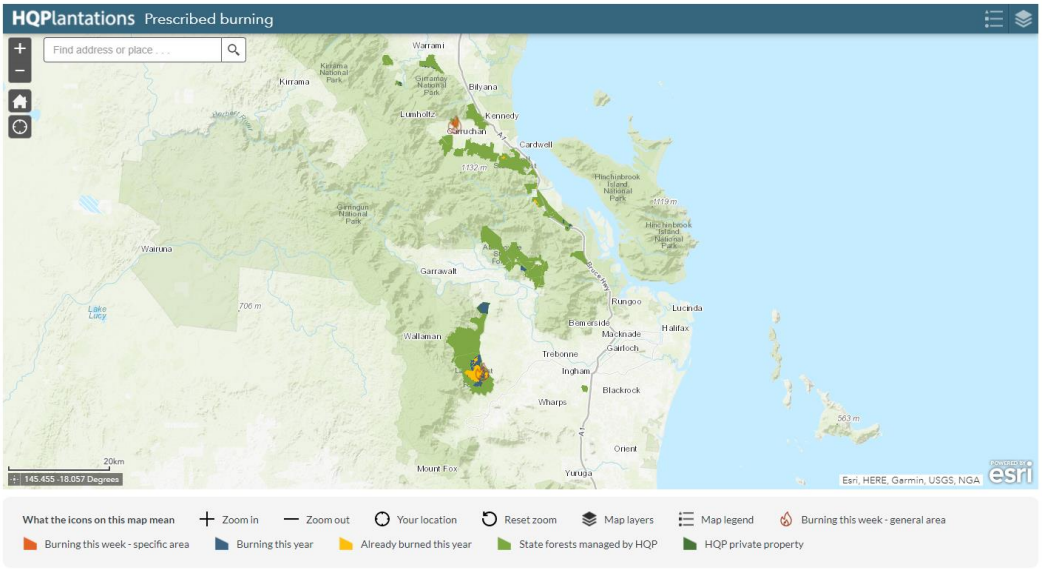


Figure 4-2 HQ Plantations uses an ESRI platform to map planned burn data for public use.

4.2 Identifying plumes using Planet Labs

Dept Resources Planned Burns:

This research investigates modelling plumes from prescribed burns. The primary focus of reviewing plume detection focused on reviewing plumes from known prescribed burns. Mr Gresgson from Department of Resources supplied six prescribed burns as examples:

Date	Location	Lot on Plan	Observable/Notes
31/05/2021	Woodgate	118/CK3572	Yes – Good
15/06/2021	Howard	59/AP15500	No – cloudy – Fire scar clearly evident in images taken 2 days before burn and 2 days after burn.
21/06/2021	Maryborough	1/AP6551	Yes – Appears to be near the end of the burn – small distinct plume.
29/06/2021	Eidsvold	2/AP13797	No – Image available for 29 June but no smoke visible, Clear image from 04/07/2021 shown no burn scar.
30/06/2021	Allies Ck	23/NT202	No – No imagery available on the day.
18/07/2021	Torbanlea Primary School	9/AP22166	No – Clear imagery but no plume

Table 4-2 Department of Resources burns that were reviewed.

Other Fires:

Plumes were located using DEA hotspot with relative ease. Plumes located using hotspot data are useful for calibration and validation of AQFx in that weather data and fuel data is likely to be available for them. These plumes are less suited to calibration and validation of the AQFx model than planned burns conducted by the various government agencies as information about them, including the ignition pattern may not be available.

A sample of DOA hotspot data located plumes demonstrates that a significant number of plumes can be located. There is such a significant number of plumes available that a filtering process could be used; for example, the plumes could be categorized into classes where there is accurate fuel load data and accurate weather data (close to a BoM station).

Figure 4-3 a 2 hour test run for plume locations found 10 plumes with high quality imagery in 1 week of Planet Labs archives (September 30 2021 to October 5 2021).

4.3 AQFx and AQVx Output

The next stage in this research involved comparing plumes located from Planet Labs imagery with plumes modelled by AQFx. The AQVx (AQFx web based viewer) was used for this task. AQFx (and AQVx) was set to become available from 30 June 2021, however due to delays in rollout of the product, the researcher only gained access to the product on 30 September 2021. Initial testing of the AQFx system for modelled plumes versus real plumes failed. The model is very much in a testing phase. Modelled plumes were in very different locations to real plumes, to the degree that no real comparison could be made in this study. Fire locations in National Parks in South West and Central Queensland were confirmed with Mr Nathan Morgan, Senior Ranger. These areas were reviewed in AQVx. Screenshots were saved of the fire areas and then compared a few days later to Planet Labs imagery. Planet Labs clearly shows the plumes but these plumes are a significant distance from the modelled plumes. There were also modelled plumes but no fires were detected.

Figure 4-4 Available images from Planet Labs on the 5th October 2021. The red cross in this image indicates the center of the main plume circled red in the next image.

The source is missing from Planet Images but plumes should be visible near Taroom. There could be smoke in the Western areas but it looks more like cloud. The issues found were discussed with the CSIRO team. There were several server outages over the testing period, also, AQFx has a function of modelling smoldering plumes over several days based on hotspot data. This means that there may be no DEA hotspot where there is a plume shown in AQVx. The CSIRO team is currently working on cluster analysis of hotspots to refine this function.

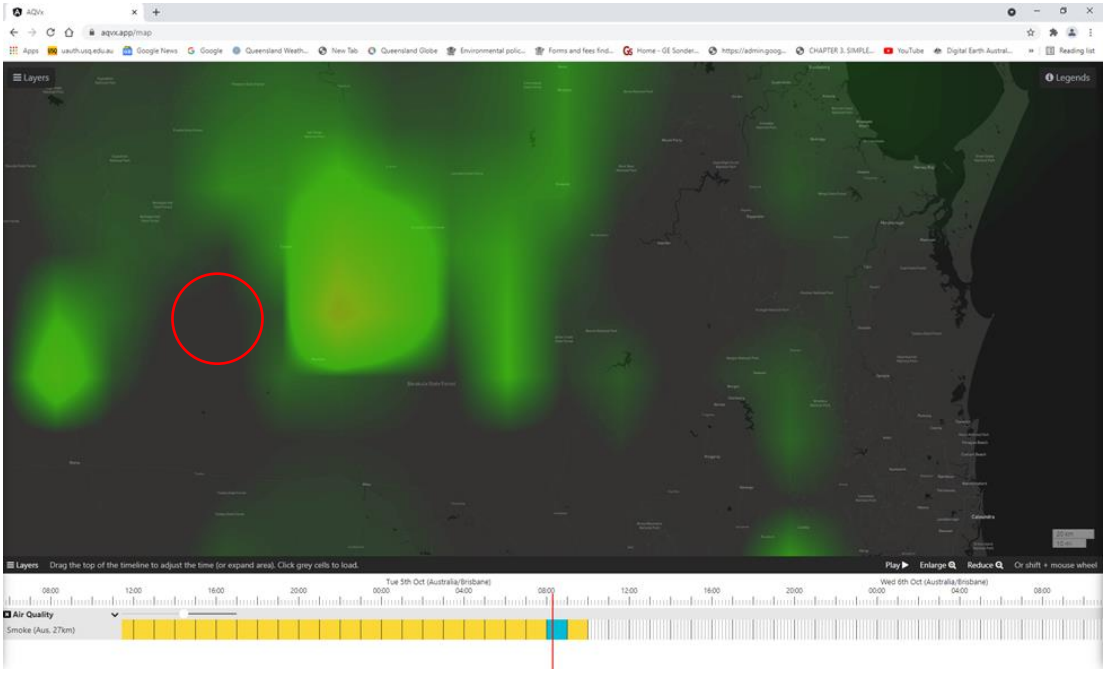


Figure 4-5 October 5 AQVx output. The red circle is an area where there was a significant plume in Planet Labs – but none shown in AQVx.

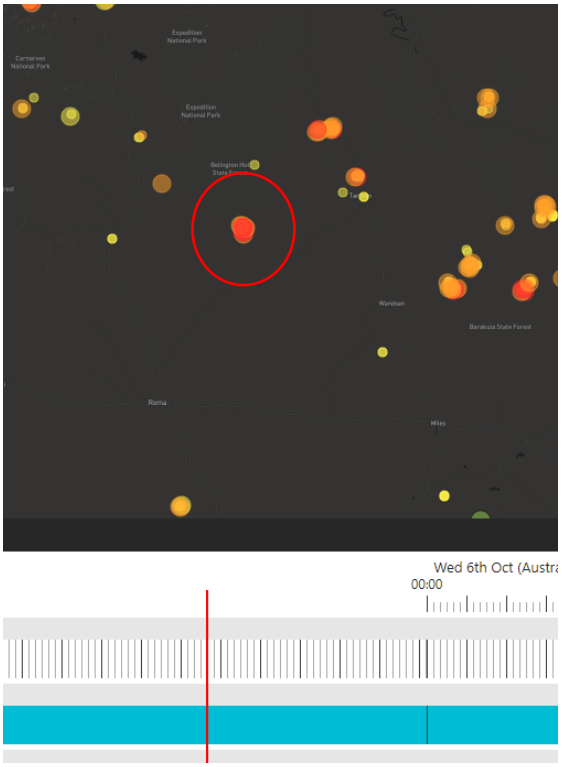


Figure 4-6 The red circle shows the relevant fire.

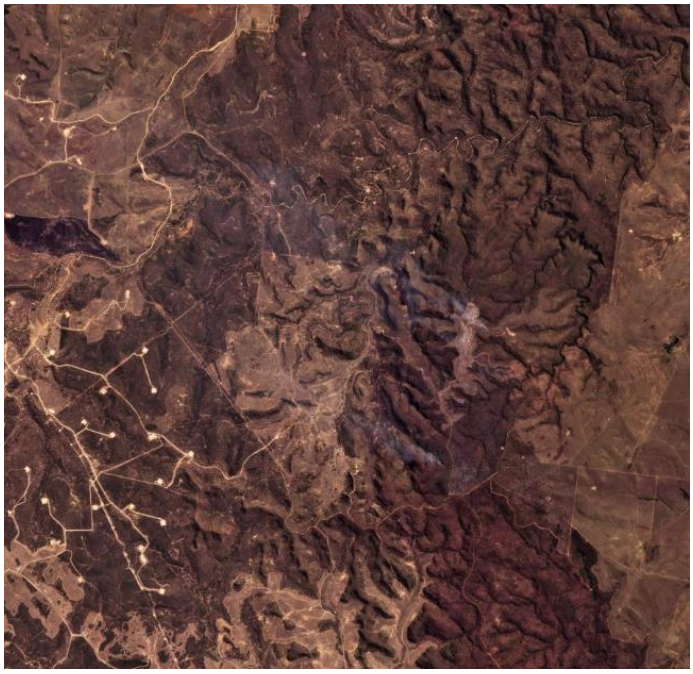


Figure 4-7 Capture of the fire on the 5th October.

Figure 4-8 Capture from Planet Labs of the same fire plume on the 4th October.

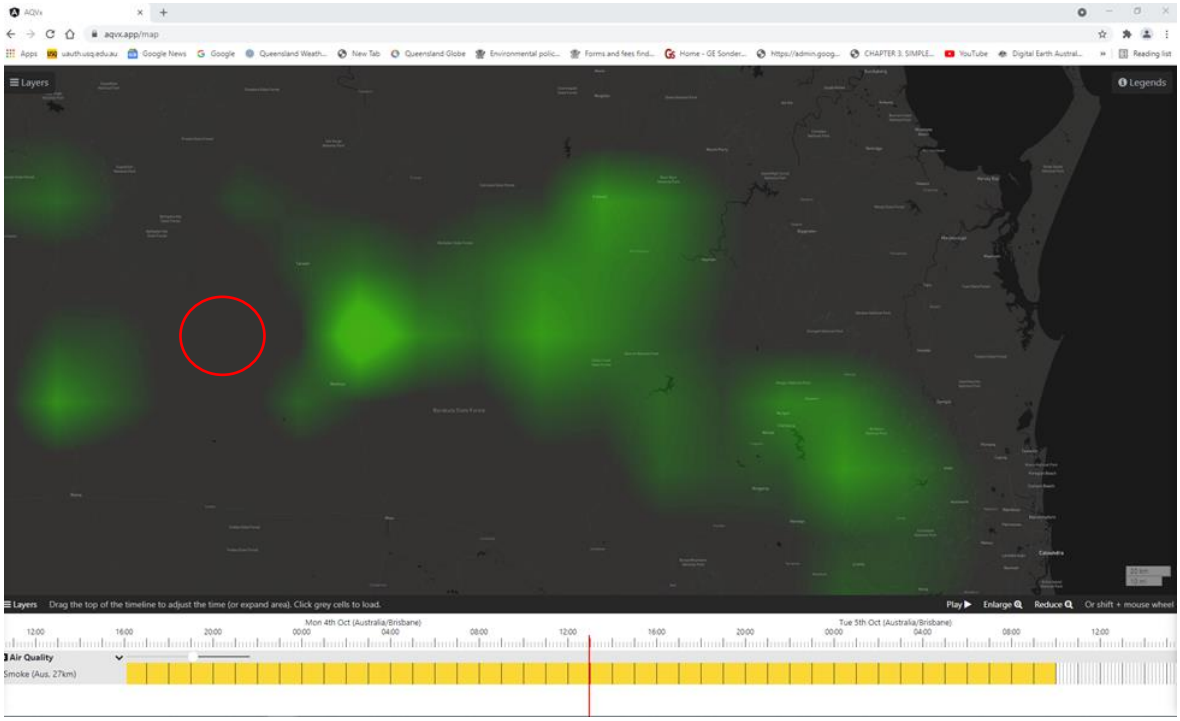


Figure 4-9 AQVx output from October 4, red circle indicates where the plume in the above image should be.

4.4 Project Model Development and Use

A Gaussian model has been designed to assist in understanding inputs and processes of prescribed burn plume modelling and to assist the Department of Resources by providing a model until a suitable alternative becomes available.

Model inputs include:

- Fuel Load in tons/ha
- Wind speed in km/hr
- Burn time in hours (how long the burn is expected to take
- Flame height (calculated from the McAurthur Forest Fire Danger Index). Table included in model.
- Atmospheric stability class and related coefficients. Tables included in model.

Other variables that can be adjusted include:

- Burn efficiency in %.
- Rate of spread in m/hr.
- Heat released into the environment in %.
- Target species g/kg fuel burnt.

All the above variables are set to an average prescribed burn fire, or a best estimate derived from research in Cope et al. except for windspeed and estimated burn time.

The user can draw a line in a GIS program to determine the start and end points of the plume model. The line is drawn from the start of the fire in the direction of the predicted wind.

The model assumes a constant plume, based on the average fire output over the burn time.

The model outputs a grid half the width of it's length with 20,000 receptors. Each receptor has a calculated g/m^3 of species concentration.

The receptor output is exported to a table with X and Y coordinates and a concentration of target species at each of the 20,000 coordinates in g/m^3 and µg/m^3.

This table is ready to import into ArcGis or QGIS. Output from the model is found in Appendices D and E.

Woodgate:

Following testing on mock fires, the Woodgate fire was modelled first:

The fire was modelled with a 1 hectare fire area, 10 tons of fuel per hectare, a windspeed of 20 km/hr (from BoM). Moderate solar radiation is assumed to give a stability class of B. A stability class of C could be tested too as the average wind speed was 5.5 m/s for the burn, perhaps a little low. 50 to 100 µg/m^3 would be unpleasant and noticeable, 100 to 600 would affect health and over 600 would be cloying.

Tests mapping the whole fire in one plume had an expected result. The plume was much larger with greater inaccuracy close to the fire.

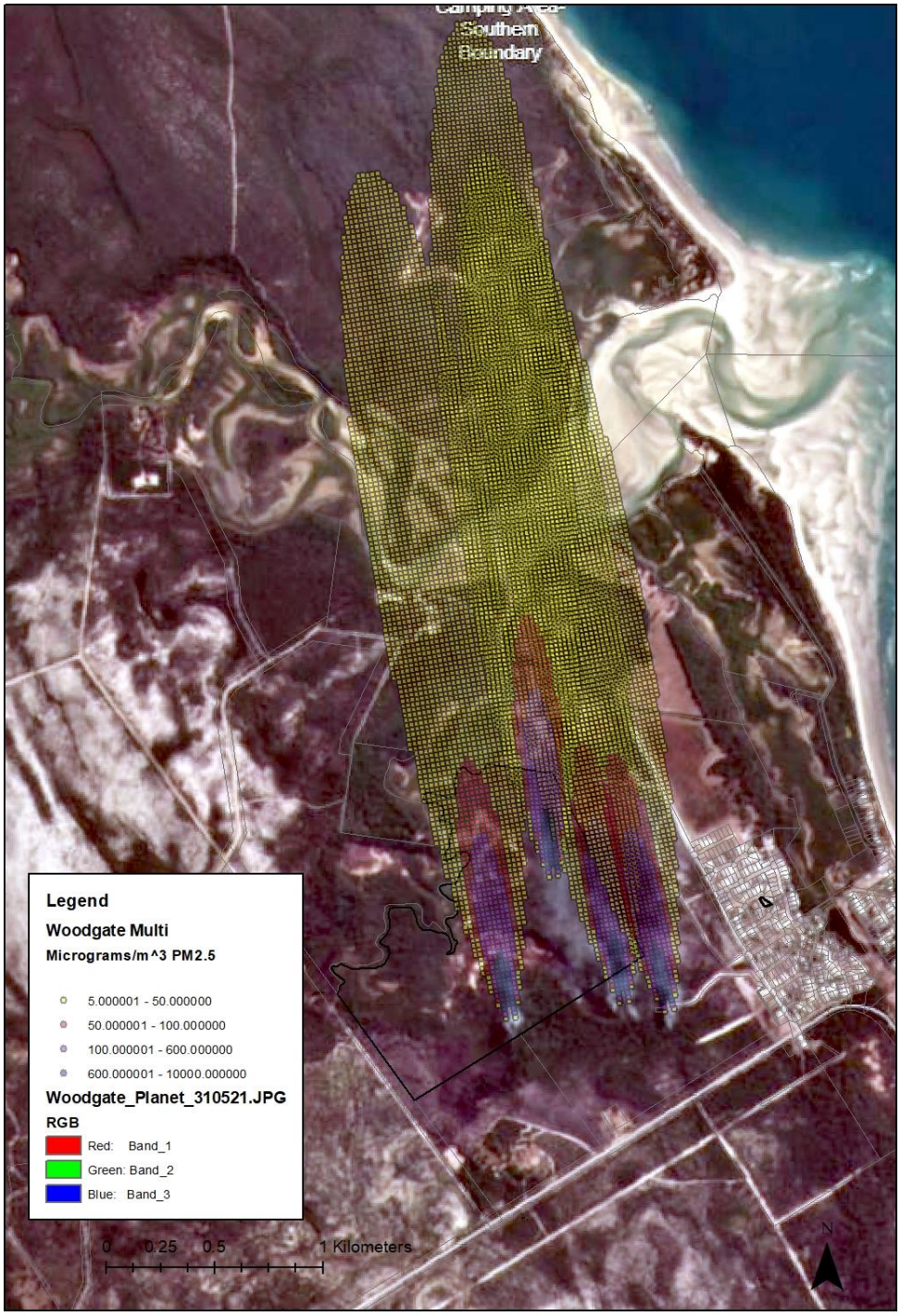


Figure 4-10 Project model output of multicore plume at Woodgate

Gaussian models are not accurate for near fire concentrations. The point model will overestimate concentrations close to the source. Model outputs are generally fairly good for the single core (plume) fire and match expected ranges of concentration for a fairly small fire.

Mapping with multiple cores increases the accuracy of the plume map. AQFx uses fire behavior modelling which produces multiple cores. BlueSky, CALPUFF, and AQFx models are designed to take multicore input.

The behavior of prescribed burns is influenced by the ignition pattern. The ignition pattern in this case is how the fire has taken on the distinct cores present in the image above. The researchers at CSIRO have noted that ignition patterns and their effects on plumes are an area where more research is required.

In this case the researcher has modelled 4 plumes and the limitations of the simple model are obvious. The dynamic grid means that each plume has a distinct grid that can't be easily integrated with the grids from other plumes. The operator can't simply add all concentrations in a grid space together.

AQFx Chemical Transport Model uses a set grid, breaking the atmosphere up into a Eulerian Grid similar to HYSPLIT and CALPUFF. Smoke moves in puffs through the grid. The set grid allows for a number of other features. AQFx takes a gridded atmospheric input from the BoM. Each grid then has forces for wind and accommodates temperature changes with altitude.

The model developed for this project could be made more effective by running a fire behavior model like SPARK, noting cores and then modelling and adding the cores. The plumes can be integrated by rasterizing the vector data and projecting the rasters onto a third, coarser grid which calculates totals.

There is looping motion observed in the Planet Labs imagery that can't be replicated with a Gaussian Plume. From a review of the literature, this looping behavior should be captured by CALPUFF and the Chemical Transport Model.

Maryborough Fire:

The Maryborough fire was a simple, single plume at the time Planet Labs captured it. The imagery showed that a larger area had burnt earlier in the day (a distinct reddish hue in the burnt vegetation).

This plume was modelled at 4 heights, 2, 5, 10 and 20 meters. The 20-meter plume height produced some very high concentrations close to the fire, which indicates an issue with the model. The plumes were not particularly different apart from the aforementioned, which may also indicates an issue in using this model at higher altitudes.

The issue of very high concentrations close to the fire (in the x direction) at higher altitudes is caused by the reflectance term at the end of the Gaussian equation used in this model. The model is designed to help understand where there will be smoke inhalation and visibility issues. A model used to visualize a plume will need to reduce or remove the reflectance term above a relative height. This feature is common in more sophisticated models where terrain is also an input. In the student's model, the issue could be solved using an (IF) function and a non-reflectance formula if the Z value is over 2 metres.

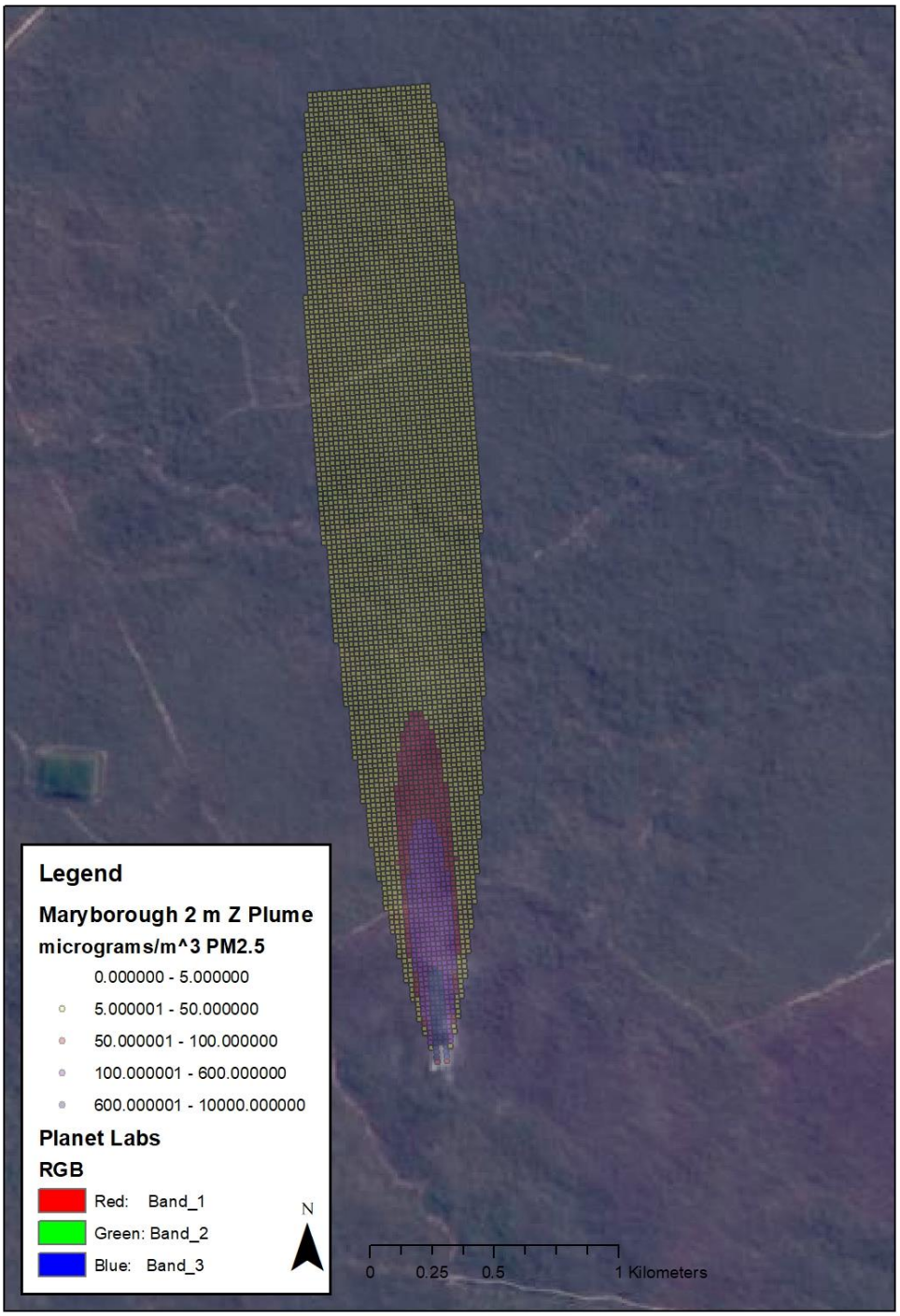


Figure 4-11 Project model output of Maryborough Plume at 2 metre vertical layer.

4.5 Proposed smoldering plume methodology

Introduction:

There are three primary issues with the AQFx plume model that have been identified to the researcher by the CSIRO team. The first is that there are problems with the plume rise equation for the smoldering component of the fires. The second is the course woody fuel load estimation and the third is the volume of pollutant released in the smoldering plumes. The methodology proposed aims to provide data to improve the smoldering plume rise and volume of pollutant models.

The CSIRO team identified that the preferred areas of focus are fire radiated power measurement from the smoldering component of the fire and direct measurement of plume heights. The CSIRO team suggests the use of UAV's equipped with thermal imaging cameras and possibly other sensors as a way of measuring fire radiated power and potentially plume height.

This methodology proposes a method of gathering thermal data and plume heights using a combination of UAV's equipped with thermal cameras and measurement of plume heights with an inclinometer.

Background:

The smoldering plume rise equation used in AQFx and described in Chapter 2 has a number of assumptions that will benefit from empirical data. Particular issues will include the entrainment constant and the area of the fire, L may be a more complex function and/or some adjustment to the percentage burning. Heat released and patterns in how it is released from smoldering over a larger area will be of interest. The combination of patterns of heat release and patterns of plume rise over the fire will better inform the equation.

Method Concept:

UAV's are equipped with a thermal imaging cameras and air quality monitors to provide temperature and plume altitude over a smoldering fire.

Problems:

Calibration and georeferencing thermal images:

Georeferencing will likely require a set of three hotplates or potentially signal fires. The hotplates or fires will be used in stitching for automated georeferencing programs for a sweeping UAV or as a steady signal for a stationary UAV.

1. The preferred option is to use a UAV capable of remaining at approximately 200 metres altitude for an hour. This option would allow constant surveillance of a fire and detailed data to be collected for the duration of interest. This option would require an expensive UAV and an expensive camera.

2. The most likely option will be to use a standard UAV ($2,500) capable of 30 minutes flying time with a $6000 camera such as the FLIR Vue Pro R.

Either UAV will have GPS/GLONASS receivers and an altimeter. Most altimeters are barometric and may not be reliable while working in convection currents. Use of hotplates for georeferencing lessens the requirements for this data to be accurate. The hotplates can be precisely georeferenced with a DGPS unit.

Calibration is less limiting with modern thermal cameras than has been detailed in historic studies. Modern thermal cameras have better calibration equipment and software than those used in the studies discovered in the literature review. Manufacturers propose a ±5ºC error, although that claim may not have considered this particular use.

Plume height:

Plume height can be measured in the daytime with an inclinometer. Sites to measure the plume from would need to be located before the fire, based on weather predictions so that the sites are located approximately perpendicular to wind from the fire. CSIRO are keen to take the smoldering plume heights over an extended period (24 hours if possible). The inclinometer is an optical device and will not work at night.

Another method for determining plume height is to fly a sensor equipped UAV (Plantower PM2.5 sensor) up and down through the vertical profile of the plume. This method does not consider the flaming fire plume and there is less risk of overheating the drone with smoldering plumes. This component of the method would rely on the UAV altimeter.

CSIRO preferred method:

Options were discussed with the CSIRO team and the preference is to use the cheaper UAV platforms.

Fire radiated power component: The FLIR or similar camera is georeferenced and calibration validated with the set of three hotplates. More information is required about the optical bands available on the cameras as georeferencing initial images may be able to use optical methods (painting a DGPS positioned cross on the ground). The UAV will fly a pattern over the non-flaming area of the fire at approximately 40 metres altitude every 20 to 30 minutes (depending on the size of the fire). UAV batteries are changed out each flight and recharged. The camera has a field of view angle of 35º x 27 º which gives tan(35/2)*40m = 25 m x tan(27/2)*40m = 19m over a resolution of 336 x 256 pixels or 13*13 pixels/m^2 or approximately 80 mm resolution. Each pixel will have a calibrated temperature attribute. The full smoldering fire sweep will be georeferenced and stitched using an off the shelf product such as Trimble. There are some concerns about smoke interference with the stitching program's feature recognition however the camera manufacturers claim excellent smoke penetration and the heat signatures should provide adequate patterning.

The plume measurements are best taken at regular time and height intervals. Similar to the FRP measurements, plume height can be measured every 30 minutes. In this case the UAV's internal GPS receiver and altimeter will be used. Some assistance will be required in determining the best option for parallel logging of the UAV x,y,z position and the PM2.5 reading.

Due to the flight plan of the air quality UAV being a vertical zigzag and flight time being 30 minutes, there will need to be two drones.

Design of BBQ plates:

Due to the pixel size being approximately 80 mm, the georeferencing heat plates do not need to be particularly big. Off the shelf BBQ's of ¼ square meter will suffice. If they are to be used for calibration, it would be ideal to equip at least one of the plates with temperature sensors and a better quality heat switch activated gas valve. It would be relatively simple to set this to 400ºC – 500ºC.

Setting up the BBQ plates would require that they are in a large triangle with sides about 15 metres long. This will ensure they can be captured in the effective area of the image and suited to georeferencing.

Testing:

1. If the BBQ plates are used for calibration, test with thermometer to ensure the plate can be maintained at a constant temperature.

2. Ensure that the plates temperature can be captured by the UAV at the desired altitude. It would also be ideal to image the plate at a range of altitudes to test limits.

3. Test to ensure that the BBQ plates can be seen in the presence of a nearby fire. This test would be conducted in an open, cultivated paddock or claypan, a fire < 2*2 metres is lit in the middle of the BBQ plate triangle. It would be ideal to add green leaves at some point during the test to see how the camera performs with mid-dense smoke.

4. Test the automatic stitching program to ensure it works.

5. Validate the PM2.5 meter with known particulate concentrations.

Expected output:

Output provided to the CSIRO team will be georeferenced thermal images of the whole prescribed burn area taken every 20 to 30 minutes for 24 hours if possible. Pixel size will be below 100mm and each pixel will contain a temperature attribute, accurate to within approximately ±10ºC. PM2.5 data is provided at the same timestep with x,y,z data over the fire.

Chapter 5 Conclusions

Introduction

This research familiarized the researcher with the topic of modelling plumes from open fires, particularly plume modelling for prescribed burns. The researcher has been welcomed into a community of air quality scientists and has made valuable, and mutually beneficial connections throughout Queensland and Australia. Access to models, equipment and fires has been difficult with pandemic related lockdowns and related pressure on information, technology and communications contractors and suppliers. Despite these setbacks, the researcher has been able to determine what assistance can be provided for the rollout of AQFx in Queensland and has made some significant inroads in providing that assistance, particularly relating to data feeds from relevant State agencies. The researcher discovered interesting results from Planet Labs imagery and has provided the CSIRO team with intelligence about data they had not explored.

Conclusions about using Planet Labs to Calibrate and Validate plume models:

Planet Labs offers an ability to calibrate and validate a prescribed burn plume model with limitations. It is easy to find plumes with Planet Labs but the data is only in the visual radiation range. Modelling plumes from Planet Labs will need to look at the full depth of the plume (a three dimensional model), the researcher is not aware of a way to stratify observations so any observations must model the plume through three dimensions and then convert this to a two

dimensional concentration through the plume for comparison. Comparisons will be able to be made but will be limited in how much can be validated about plume height and concentrations at different height stratums.

This research found that plumes are able to be discovered in Planet Labs relatively easily although the number of planned burns able to be modelled in advance of a burn and then quality imagery discovered in Planet Labs is 20%. There are problems with timing of burns. Land managers will cancel or change burn plans due to unfavorable climatic conditions on the day of a planned burn. Planned burns often only take a few hours and the satellite must be over the burn at the right time. The reason for achieving 20% good quality results is that Planet Labs often has several scenes for an area in 1 day.

The research looked at proposed burn data from one agency, Department of Resources. Department of Resources has a limited proposed burning plan. Agencies including HQ Plantations and DES have much larger burning programs. These agencies could provide significant number of fires, greatly increasing the number of burns that can be modelled in advance and then validated with imagery.

In terms of finding plumes without pre-planning, Planet Labs offers a large number of these. When combined with fuel load data and climatic conditions data, these plumes offer a range of calibration and verification options.

The CSIRO team expressed an interest in Planet Labs when the results from this research were discussed with them. Planet Labs maintains an archive of imagery that can be accessed for historic fires that are of interest to the research team

Conclusions regarding the use of AQFx in modelling smoke pollution from prescribed burns.

The focus on AQFx plume modelling from prescribed burns in Australia deals with air quality, particularly as it affects major cities. The scale of the modelling has been developed to show concentration loads over large areas. The AQFx model will be effective in planning burns in

peri-urban areas and areas near to populated areas. Agencies responsible for managing prescribed burns will find the model useful for this purpose. An example would be the Department of Environment and Science considering a prescribed burn of a large area of forest in the Brisbane valley. AQFx will take current atmospheric pollution loads, fuel loads and atmospheric predictions. The output will provide information about whether the burn should go ahead and which day is optimal for carrying out the burn in the coming week to minimize air pollution impact in Brisbane.

An agency such as Department of Resources will have limited use for the AQFx model. DoR should contribute planned burn data to AQFx to assist with the broader air quality modelling effort, however, a small model such as the one created for this project will suit DoR's needs more effectively. DoR frequently burns areas under 100 hectares. The smaller scale and focus on smoke at ground level are important for smaller prescribed burns where warnings need to be issued to close neighbors and nearby traffic hazards identified. The burn can be planned well in advance and modelling outputs provided in map form to neighbors on the day or the day proceeding the burn.

Timing of the research was not ideal for testing AQFx, the model is in preliminary stages of rollout in Queensland. Plumes were modelled where there were no fires and there were significant plumes visible in Planet Labs that were not modelled in AQFx. The model was not operating reliably through the 10 days of review, it's likely that significant testing of systems and calibration was occurring in this time.

AQFX relies on accurate data about proposed burns for the forward air quality modelling function. Data on proposed burns is dispersed across a number of agencies in Queensland. Some agencies have are interested in better modelling of air quality as it relates to prescribed burns while other agencies are not interests. There will be issues accessing planned burn data from agencies. This study will assist CSIRO identify and coordinate burn data entry as key stakeholders, their mode of operation in this area of business was reviewed and key personnel identified.

Fuel load data is also a problem area for AQFx. Fuel load data has the potential to be damagingly inaccurate. There is a particular issue with the methodology for mapping fuel load where a disturbed area will produce a much lower modelled fuel load than an area that has not been

disturbed for some time. This is generally a good rule, however, in drier areas observations are that many undisturbed areas have little or no fine fuel load to carry a fire and a high proportion of large course woody debris and green shrubs. Many of the disturbed areas have a higher proportion of fine fuel capable of carrying a fire. The resultant emission output in these cases with be the reverse of the modelling, where the undisturbed area will not carry a fire.

In the final meeting with the CSIRO team prior to lodgment of this document, the team discussed improvements currently being made including addition of the SPARK module and HYSPLIT for the near field plumes. AQFx is still under development and will be a significant tool for land managers across Australia in the near future.

Chapter 6 Recommendations and Further Work

Further work with AQFx

AQFx requires input from all agencies who conduct significant prescribed burn programs. A focal area for the CSIRO air quality community must be to coordinate input of prescribed burn data and plans. There are a number of agencies in Queensland that could take a lead role in this function for Queensland agencies. DoR is the custodian of much of Queensland's spatial information and could be considered a leader if the data is a spatial set. DES is the lead environmental agency in Queensland, responsible for air quality monitoring. QFES is the lead agency for fire related issues in Queensland and could also lead this effort. Alternatively, the Commonwealth can lead this initiative and produce a method of entering the data that is relatively easy, accurate and editable to accommodate changes to plans.

Fuel load mapping is a concern and this area requires more work. LiDAR will be a viable option for mapping fuel load in peri-urban areas but it is unlikely to be cost effective in the near future for large areas of State Forest and National Parks. There is a large body of research and a growing feed of spatial data to assist in this problem area. QFES are undertaking research in this area and DoR has begun to assist in that as a result of this project. DoR officers are now collecting data relating to fuel loads in grassland ecosystems. It's likely that concerted research effort in identifying methods of quantifying and classifying fuel loads remotely will yield results.

Further work in refining the smoldering plume function in AQFx has been discussed in Chapter 4. The challenge will be to test and use the proposed methodology through the 2022 prescribed burn season.

Further Work for the Department of Resources

Findings from this research suggest that DoR should create a basic model for use in small prescribed burns. The model should attach to current offerings in QLD Globe. A Gaussian model specifically targeted at the 2 metre height above ground will provide the agency with required data on potentially impacted residences and roads. A similar model to the one created for this project would be ideal. An input box for the basic inputs such as fuel load and expected

wind speed and direction and a feature to input the fire area polygon are fairly simple to create. Observations of the DoR plumes in this study indicate that greater sophistication such as terrain inputs are unnecessary. The ability to export the plume as a .kml and send to neighbors and other stakeholders would be useful.

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Appendix A – Project Specification & Schedule

A-1 – Project Specification

ENG4111/4112 Research Project

Project Specification

For: Seamus Batstone

Title: A review of smoke dispersion models for smoke pollution hazard mitigation associated with controlled, forest fuel reduction burns.

Major: Environmental Engineering

Supervisor: Ian Craig

Enrolment: ENG4111 – ONL S1 – 2021

ENG4112 – ONL S2 – 2021

Project Aim: To critically review the CSIRO AQFx air pollution model prior to adoption by the Queensland Fire and Emergency Services and to gain significant skills in air pollution modelling.

Programme: Version 1, 14/03/2021

1. Review bushfire smoke modelling developed by CSIRO for Australia (AQFx - the air quality forecasting system).
2. Describe the model inputs and calculations made by the model.
3. Review the BlueSky model developed by the Unites States Forest Service.
4. Review industrial pollution plume modelling and contrast this with bushfire smoke modelling.
5. Compare AQFx model outputs with visible smoke plumes for historic fires. This will require acquisition or estimation of historic fuel loads (QFES often have this data) and access to Planet Labs daily imagery.

If time and resources permit:

6. If possible (dependant on appropriate data and time) attempt to compare BlueSky model outputs with historic fires using Planet Labs daily imagery.
7. Dependant on QFES cooperation, test AQFx model predicted output in the field during prescribed burns.

Resources:

1. Access to Planet Labs daily imagery.
2. Access to AQFx model.
3. Access to BlueSky model.

And if possible, dependant on the third party:

4. If QFES are willing and able to participate in the study, access to air quality monitoring equipment will be required (the student will organise acquisition or hire of a SMOG or similar air quality measurement device).

A-2 – Project Schedule

Project Specification Schedule:

Appendix B – Risk Assessment

The field work component was not progressed

University of Southern Queensland **Offline Version**

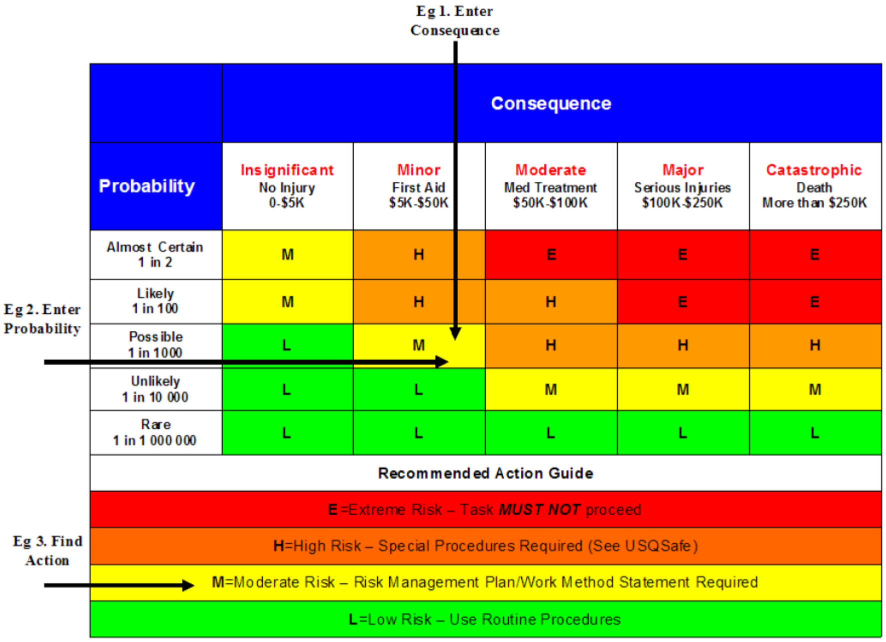
USQ Safety Risk Management System

Note: This is the offline version of the Safety Risk Management System (SRMS) Risk Management Plan (RMP) and is only to be used for planning and drafting sessions, and when working in remote areas or on field activities. It must be transferred to the online SRMS at the first opportunity.

Safety Risk Management Plan – Offline Version			
Assessment Title:	Air Quality Monitoring of Planned Hazard Reduction Burns	Assessment Date:	3/06/2021
Workplace (Division/Faculty/Section):	Academic/Health Engineering and Sciences/Engineering	Review Date:(5 Years Max)	30/09/2021

Context			
Description:			
What is the task/event/purchase/project/procedure?	Monitoring air quality during planned hazard reduction burns		
Why is it being conducted?	To support research work as part of a final year dissertation		
Where is it being conducted?	Mutliple parcels of State owned land in South East Queensland		
Course code (if applicable)	ERP2021	Chemical name (if applicable)	N/A
What other nominal conditions?			
Personnel involved	Seamus Batstone		
Equipment	N/A		
Environment	Forested areas		
Other			
Briefly explain the procedure/process	A portable air quality monitor will be used to collect air samples in areas near where a planned hazard reduction burn is taking place.		

Assessment Team - who is conducting the assessment?	
Assessor(s)	
Others consulted:	



Eg 1. Enter Consequence

Eg 2. Enter Probability

Eg 3. Find Action

Probability	Consequence				
	Insignificant No Injury 0-$5K	**Minor** First Aid $5K-$50K	**Moderate** Med Treatment $50K-$100K	**Major** Serious Injuries $100K-$250K	**Catastrophic** Death More than $250K
Almost Certain 1 in 2	M	H	E	E	E
Likely 1 in 100	M	H	H	E	E
Possible 1 in 1000	L	M	H	H	H
Unlikely 1 in 10 000	L	L	M	M	M
Rare 1 in 1 000 000	L	L	L	L	L

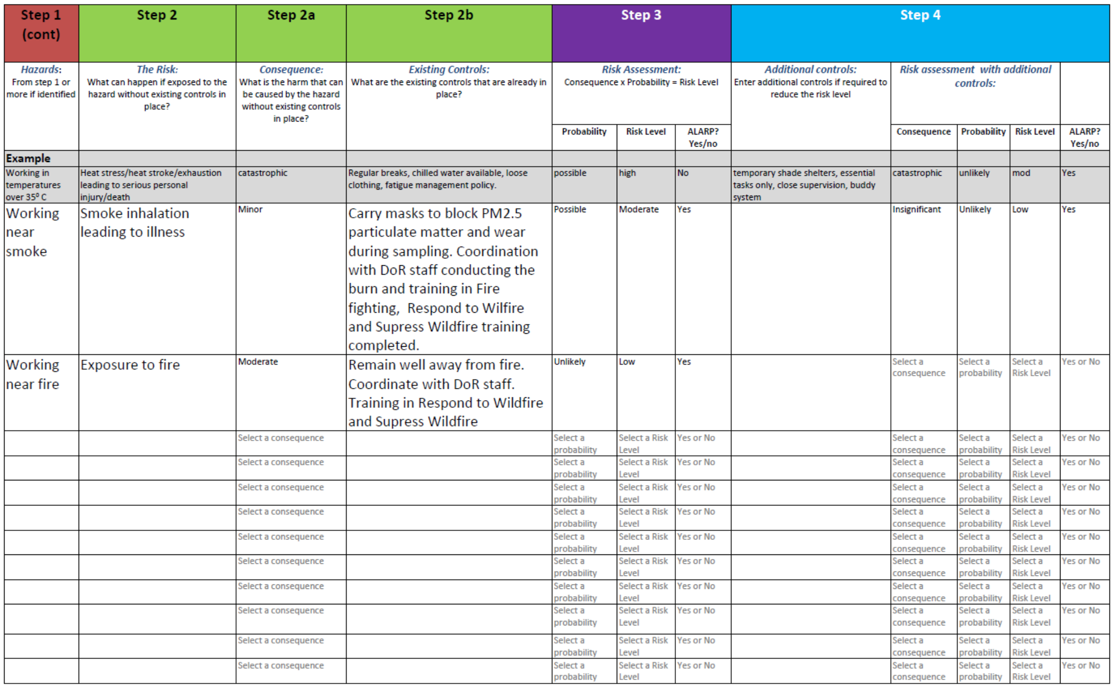
Recommended Action Guide

E=Extreme Risk – Task ***MUST NOT*** proceed

H=High Risk – Special Procedures Required (See USQSafe)

M=Moderate Risk – Risk Management Plan/Work Method Statement Required

L=Low Risk – Use Routine Procedures



Step 1 (cont)	**Step 2**	**Step 2a**	**Step 2b**	**Step 3**			**Step 4**				
Hazards: From step 1 or more if identified	*The Risk:* What can happen if exposed to the hazard without existing controls in place?	*Consequence:* What is the harm that can be caused by the hazard without existing controls in place?	*Existing Controls:* What are the existing controls that are already in place?	*Risk Assessment:* Consequence x Probability = Risk Level			*Additional controls:* Enter additional controls if required to reduce the risk level	*Risk assessment with additional controls:*			
				Probability	Risk Level	ALARP? Yes/no		Consequence	Probability	Risk Level	ALARP? Yes/no
Example											
Working in temperatures over 35⁰ C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	catastrophic	Regular breaks, chilled water available, loose clothing, fatigue management policy.	possible	high	No	temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	mod	Yes
Working near smoke	Smoke inhalation leading to illness	Minor	Carry masks to block PM2.5 particulate matter and wear during sampling. Coordination with DoR staff conducting the burn and training in Fire fighting, Respond to Wilfire and Supress Wildfire training completed.	Possible	Moderate	Yes		Insignificant	Unlikely	Low	Yes
Working near fire	Exposure to fire	Moderate	Remain well away from fire. Coordinate with DoR staff. Training in Respond to Wildfire and Supress Wildfire	Unlikely	Low	Yes		Select a consequence	Select a probability	Select a Risk Level	Yes or No
		Select a consequence		Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
		Select a consequence		Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
		Select a consequence		Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
		Select a consequence		Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
		Select a consequence		Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
		Select a consequence		Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
		Select a consequence		Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
		Select a consequence		Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
		Select a consequence		Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
		Select a consequence		Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No

Step 1 (cont)	Step 2	Step 2a	Step 2b	Step 3			Step 4				
Hazards: From step 1 or more if identified	*The Risk:* What can happen if exposed to the hazard without existing controls in place?	*Consequence:* What is the harm that can be caused by the hazard without existing controls in place?	*Existing Controls:* What are the existing controls that are already in place?	*Risk Assessment:* Consequence x Probability = Risk Level			*Additional controls:* Enter additional controls if required to reduce the risk level	*Risk assessment with additional controls:*			
				Probability	Risk Level	ALARP? Yes/no		Consequence	Probability	Risk Level	ALARP? Yes/no
Example											
Working in temperatures over 35° C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	catastrophic	Regular breaks, chilled water available, loose clothing, fatigue management policy.	possible	high	No	temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	mod	Yes
		Select a consequence		Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
				Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
				Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
				Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
				Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No
				Select a probability	Select a Risk Level	Yes or No		Select a consequence	Select a probability	Select a Risk Level	Yes or No

Step 5 - Action Plan (for controls not already in place)			
Additional controls:	*Resources:*	*Persons responsible:*	*Proposed implementation date:*
			Click here to enter a date.
			Click here to enter a date.
			Click here to enter a date.
			Click here to enter a date.
			Click here to enter a date.
			Click here to enter a date.
			Click here to enter a date.
			Click here to enter a date.
			Click here to enter a date.
			Click here to enter a date.
			Click here to enter a date.
			Click here to enter a date.

Step 6 - Approval			
Drafter's name:	Seamus Batstone	Draft date:	3/06/2021
Drafter's comments:	Please note that the person undertaking the duties is experienced in managing planned burns and trained in fire suppression. The person undertaking the duties will also remain well away from hazards and coordinate activites with Department of Resources staff		
Approver's name:		Approver's title/position:	
Approver's comments:			
I am satisfied that the risks are as low as reasonably practicable and that the resources required will be provided.			
Approver's signature:		Approval date:	Click here to enter a date.

Appendix C – Project Model Charts

C-1 – Horizontal Dispersion Coefficients Chart

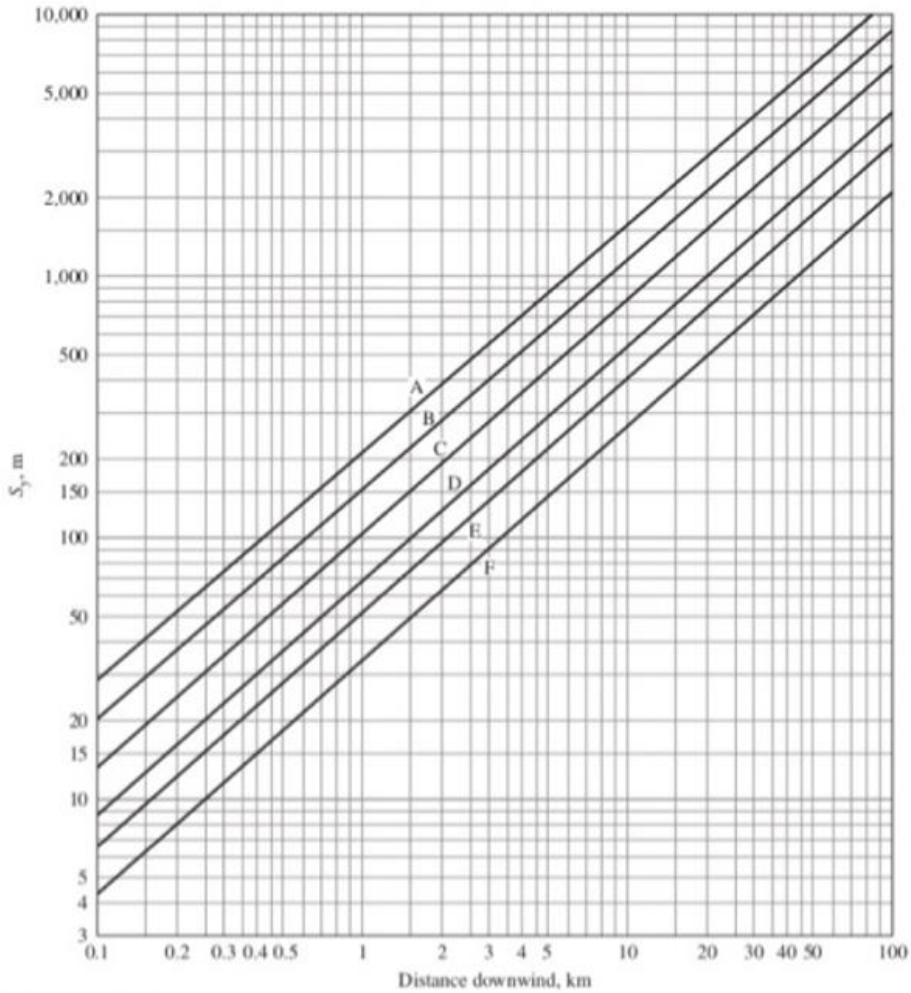


FIGURE 9-24
Horizontal dispersion coefficient. (*Source:* Turner, 1967).

C-2 – Pasquill Stability Classes Table

Estimation of Pasquill Stability Classes*

Surface (10m) Windspeed (m/s)	Daytime			Nighttime	
	Incoming solar radiation**			Cloud cover fraction	
	High	Moderate	Low	≥4/8	≤3/8
<2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	D
5-6	C	C	D	D	D
>6	D	D	D	D	D

C-3 – Vertical Dispersion Coefficients

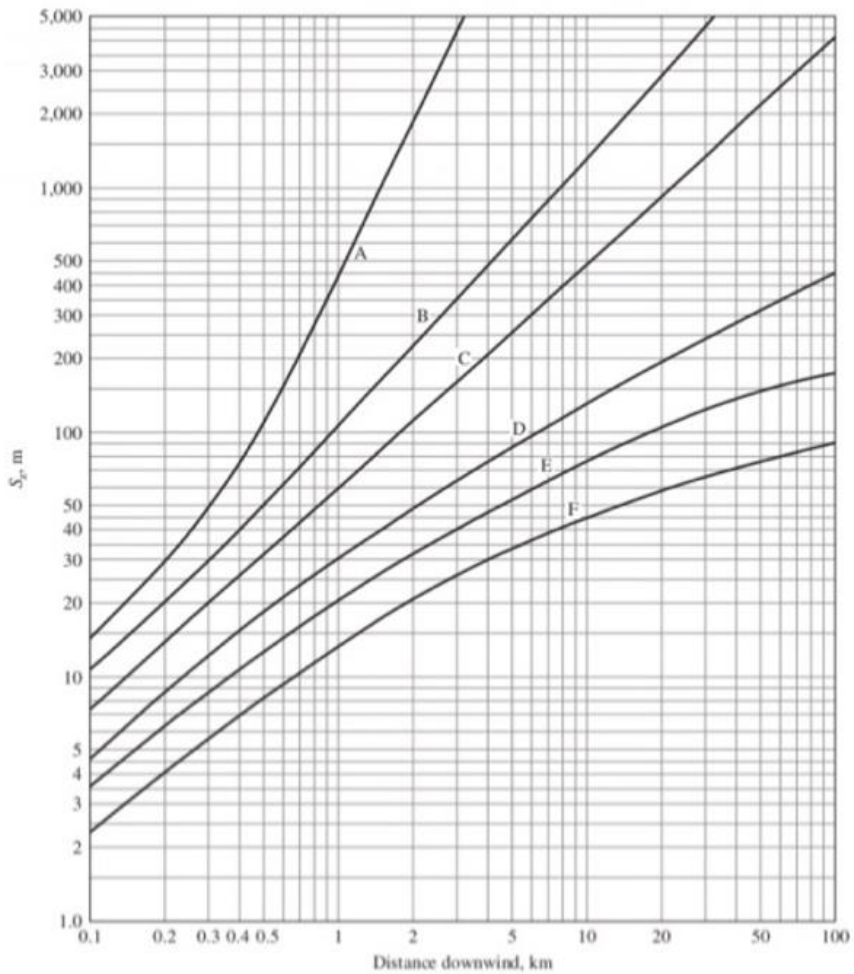


FIGURE 9-25
Vertical dispersion coefficient. (*Source:* Turner, 1967.)

C-4 – Dispersion Coefficient Variables

	x less than 1 km				x greater than 1 km		
Stability	**a**	**c**	**d**	**f**	**c**	**d**	**f**
A	213	440.8	1.941	9.27	459.7	2.094	-9.6
B	156	106.6	1.149	3.3	108.2	1.098	2.0
C	104	61.0	0.911	0	61.0	0.911	0
D	68	33.2	0.725	-1.7	44.5	0.516	-13.0
E	50.5	22.8	0.678	-1.3	55.4	0.305	-34.0
F	34	14.35	0.740	-0.35	62.6	0.18	-48.6

Appendix D – Project Model Screenshots

D-1 – Sheet 1 Formula and Inputs

Fuel					
Fuel Load (t/ha)	10				
Fire size (ha)	1			<1000m	>1000m
Burn efficiency %	60		a	156	156
Rate of spread m/hr	30		c	100.6	108.2
E - heat released	0.3		d	1.149	1.098
Energy (Qh) Kcal/s	1.195029		f	3.3	2
Burn time (hrs)	6	L SQRT((A	23.03294		
Q (g PM2.5/s)	13888.89				
Flame ht (m)	1.5				
Wind Speed (km/hr)	15	4.166667	m/s		
Relative humidity					
Temperature					
Days since last rain					
PM2.5 g/kg fuel burnt	50				
Plume Centreline			Coords		
Start E	468413		E	298	0.075206
Start N	7185473		N	3955	0.075206
End E	468115		Length	3966.211	19.83105
End N	7189428		Flank	991.5527	19.83105
Z	50				
Plume height (H)	8.443597				
Day lookup	Sunlight		Overcast/late eveningn or early morning		
	Strong	Moderate	Slight		
<2	A	A	B		
2 to 3	A	B	C		
3 to 5	B	B	C		
5 to 6	C	C	D		
>6	C	D	D		

$$\Delta h = 4.2\frac{[(1-E)Q_H]^{0.26}L^{0.63}}{u^{0.5}}$$

sy & sz & p lookup table

	X=<1000m				X>1000m			
	a	c	d	f	c	d	f	p
A	213	440.8	1.941	9.27	459.7	2.094	-9.6	0.07
B	156	100.6	1.149	3.3	108.2	1.089	2	0.07
C	104	61	0.911	0	61	0.911	0	0.1
D	68	33.2	0.725	-1.7	44.5	0.516	-13	0.15
E	50.5	22.8	0.678	-1.3	55.4	0.305	-34	0.35
F	34	14.35	0.74	-0.35	62.6	0.18	-48.6	0.55

0	468413	7185473	467424.2	7185398	469401.8	7185548
1	468411.5	7185493				
2	468410	7185513				
3	468408.5	7185532				
4	468407	7185552				
5	468405.6	7185572				
6	468404.1	7185592				
7	468402.6	7185611				
8	468401.1	7185631				
9	468399.6	7185651				
10	468398.1	7185671				
11	468396.6	7185691				
12	468395.1	7185710				
13	468393.6	7185730				
14	468392.1	7185750				
15	468390.7	7185770				
16	468389.2	7185789				
17	468387.7	7185809				
18	468386.2	7185829				
19	468384.7	7185849				
20	468383.2	7185869				
21	468381.7	7185888				
22	468380.2	7185908				
23	468378.7	7185928				
24	468377.2	7185948				
25	468375.8	7185967				
26	468374.3	7185987				
27	468372.8	7186007				
28	468371.3	7186027				
29	468369.8	7186046				
30	468368.3	7186066				
31	468366.8	7186086				
32	468365.3	7186106				
33	468363.8	7186126				
34	468362.3	7186145				
35	468360.9	7186165				
36	468359.4	7186185				
37	468357.9	7186205				
38	468356.4	7186224				
39	468354.9	7186244				
40	468353.4	7186264				
41	468351.9	7186284				

```
=IF(($B$22-$B$20)>0, L4+(SIN($F$20)*($E$22/200)),L4-(SIN($F$20)*($E$22/200)))
```

D	E	F	G	H	I	J	K	L	M
								Centre	
								E	N
							0	468413	7185473
							1	468411.5	7185493
	<1000m	>1000m					2	468410	7185513
a	156	156					3	468408.5	7185532
c	100.6	108.2					4	468407	7185552
d	1.149	1.098					5	468405.6	7185572

Clipboard Font Alignment

B10 =((B6*B5*1000*(B7/100)*18000)/(B11*60*60))/4184

	A	B	C	D	E	F	G	H	I	J
	Fuel									
	Fuel Load (t/ha)	10								
	Fire size (ha)	1			<1000m	>1000m				
	Burn efficiency %	60		a	156	156				
	Rate of spread m/hr	30		c	100.6	108.2				
	E - heat released	0.3		d	1.149	1.098				
	Energy (Qh) Kcal/s	1.195029		f	3.3	2				
	Burn time (hrs)	6	L SQRT((A	23.03294						
	Q (g PM2.5/s)	13888.89								

Clipboard Font

D11 =SQRT((B6*10000/B11)/PI())

	A	B	C	D	E	F	G	H
	Fuel							
	Fuel Load (t/ha)	10						
	Fire size (ha)	1			<1000m	>1000m		
	Burn efficiency %	60		a	156	156		
	Rate of spread m/hr	30		c	100.6	108.2		
	E - heat released	0.3		d	1.149	1.098		
	Energy (Qh) Kcal/s	1.195029		f	3.3	2		
	Burn time (hrs)	6	L SQRT((A	23.03294				
	Q (g PM2.5/s)	13888.89						

D-2 – Sheet 2 Distance, Coordinates and Concentration Calculations:

			X distance	1	2	3
Sz	Sy			E	N	991.552728
3.806522	1.488173	0	10	467424.2	7185398.496	0
4.412368	2.744609	1	19.83105	467422.8	7185418.271	0
5.766788	5.100366	2	39.66211	467421.3	7185438.046	0
7.230616	7.3287	3	59.49316	467419.8	7185457.821	0
8.770352	9.478119	4	79.32422	467418.3	7185477.596	0
10.36911	11.5707	5	99.15527	467416.8	7185497.371	0
12.01654	13.61908	6	118.9863	467415.3	7185517.146	0
13.70557	15.63141	7	138.8174	467413.8	7185536.921	0
15.43106	17.61339	8	158.6484	467412.3	7185556.696	0
17.18906	19.56921	9	178.4795	467410.8	7185576.471	0
18.97647	21.50208	10	198.3105	467409.3	7185596.246	0
20.79075	23.41454	11	218.1416	467407.9	7185616.021	0
22.62981	25.30863	12	237.9727	467406.4	7185635.796	0
24.49187	27.18604	13	257.8037	467404.9	7185655.571	2.3356E-288
26.37541	29.04819	14	277.6348	467403.4	7185675.346	1.0082E-252
28.27912	30.89628	15	297.4658	467401.9	7185695.121	1.5417E-223
30.20185	32.73134	16	317.2969	467400.4	7185714.896	2.572E-199

=IF(E6<1000, (Sheet1!$E$8*(E6/1000)^Sheet1!$E$9)+Sheet1!$E$10, (Sheet1!$F$8*(E6/1000)^Sheet1!$F$9)+Sheet1!$F$10)

A	B	C	D	E	F	G	H	I	J	K	L	M	N
				X distance	1	2	3	4	5	6	7	8	9
	Sz	Sy			E	N	991.552728			971.7216735			951.8906
	3.806522	1.488173	0	10	467424.2	7185398.496	0	467444	7185400	0	467463.8	7185401.477	0
	4.412368	2.744609	1	19.83105	467422.8	7185418.271	0	467442.5	7185420	0	467462.3	7185421.252	0
	5.766788	5.100366	2	39.66211	467421.3	7185438.046	0	467441	7185440	0	467460.8	7185441.027	0
	7.230616	7.3287	3	59.49316	467419.8	7185457.821	0	467439.6	7185459	0	467459.3	7185460.802	0
	8.770352	9.478119	4	79.32422	467418.3	7185477.596	0	467438.1	7185479	0	467457.8	7185480.577	0

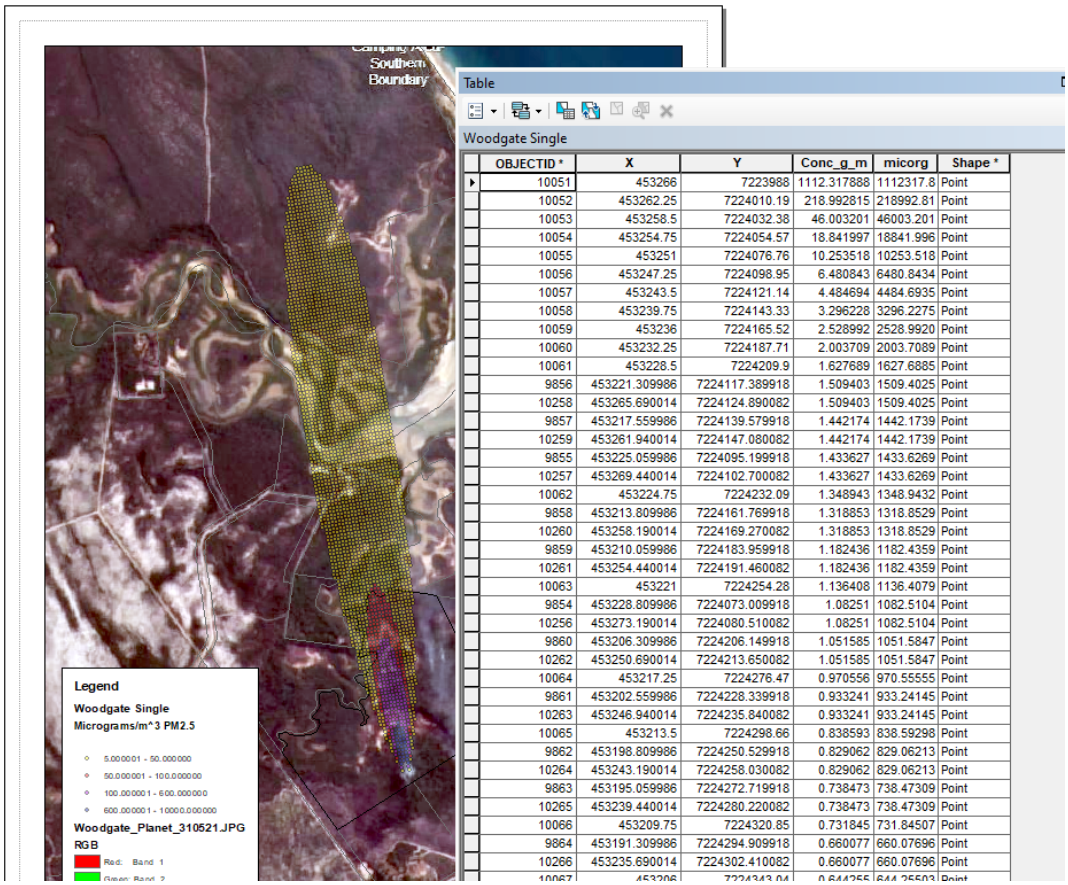
=(Sheet1!$B$12/(2*PI()*Sheet1!$C$14*$C19*$B19))*(EXP(-(H$5^2)/(2*($C19^2))))*(EXP((-(Sheet1!$B$24-Sheet1!$B$25)^2)/(2*($B19^2)))+EXP((-(Sheet1!$B$24+Sheet1!$B$25)^2)/(2*($B19^2))))

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
				X distance	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Sz	Sy			E	N	991.552728			971.7216735			951.8906			932.0596			912.2285	
	3.806522	1.488173	0	10	467424.2	7185398.496	0	467444	7185400	0	467463.8	7185401.477	0	467483.6	7185403	0	467503.3	7185404	0	467523.1
	4.412368	2.744609	1	19.83105	467422.8	7185418.271	0	467442.5	7185420	0	467462.3	7185421.252	0	467482.1	7185423	0	467501.9	7185424	0	467521.6
	5.766788	5.100366	2	39.66211	467421.3	7185438.046	0	467441	7185440	0	467460.8	7185441.027	0	467480.6	7185443	0	467500.4	7185444	0	467520.1
	7.230616	7.3287	3	59.49316	467419.8	7185457.821	0	467439.6	7185459	0	467459.3	7185460.802	0	467479.1	7185462	0	467498.9	7185464	0	467518.7
	8.770352	9.478119	4	79.32422	467418.3	7185477.596	0	467438.1	7185479	0	467457.8	7185480.577	0	467477.6	7185482	0	467497.4	7185484	0	467517.2
	10.36911	11.5707	5	99.15527	467416.8	7185497.371	0	467436.6	7185499	0	467456.3	7185500.352	0	467476.1	7185502	0	467495.9	7185503	0	467515.7
	12.01654	13.61908	6	118.9863	467415.3	7185517.146	0	467435.1	7185519	0	467454.9	7185520.127	0	467474.6	7185522	0	467494.4	7185523	0	467514.2
	13.70557	15.63141	7	138.8174	467413.8	7185536.921	0	467433.6	7185538	0	467453.4	7185539.902	0	467473.1	7185541	0	467492.9	7185543	0	467512.7
	15.43106	17.61339	8	158.6484	467412.3	7185556.696	0	467432.1	7185558	0	467451.9	7185559.677	0	467471.7	7185561	0	467491.4	7185563	0	467511.2
	17.18906	19.56921	9	178.4795	467410.8	7185576.471	0	467430.6	7185578	0	467450.4	7185579.452	0	467470.2	7185581	0	467489.9	7185582	0	467509.7
	18.97647	21.50208	10	198.3105	467409.3	7185596.246	0	467429.1	7185598	0	467448.9	7185599.227	0	467468.7	7185601	0	467488.4	7185602	0	467508.2
	20.79075	23.41454	11	218.1416	467407.9	7185616.021	0	467427.6	7185618	0	467447.4	7185619.002	0	467467.2	7185620	0	467487	7185622	0	467506.7
	22.62981	25.30863	12	237.9727	467406.4	7185635.796	0	467426.1	7185637	0	467445.9	7185638.777	2.1E-306	467465.7	7185640	9.5E-294	467485.5	7185642	2.4E-281	467505.2
	24.49187	27.18604	13	257.8037	467404.9	7185655.571	2.3356E-288	467424.7	7185657	6.4185E-277	467444.4	7185658.552	1E-265	467464.2	7185660	9.8E-255	467484	7185662	5.5E-244	467503.8
	26.37541	29.04819	14	277.6348	467403.4	7185675.346	1.0082E-252	467423.2	7185677	1.0544E-242	467442.9	7185678.327	6.9E-233	467462.7	7185680	2.8E-223	467482.5	7185681	7.4E-214	467502.3

D-3 – Sheet 3 Georeferenced Output

	A	B	C	D	E	F
1	X	Y	Z	Conc_g_m	micorg	
2	467424.2	7185398	50	0	0	
3	467422.8	7185418	50	0	0	
4	467421.3	7185438	50	0	0	
5	467419.8	7185458	50	0	0	
6	467418.3	7185478	50	0	0	
7	467416.8	7185497	50	0	0	
8	467415.3	7185517	50	0	0	
9	467413.8	7185537	50	0	0	
10	467412.3	7185557	50	0	0	
11	467410.8	7185576	50	0	0	
12	467409.3	7185596	50	0	0	
13	467407.9	7185616	50	0	0	
14	467406.4	7185636	50	0	0	
15	467404.9	7185656	50	2.3E-288	2.3356E-285	
16	467403.4	7185675	50	1E-252	1.0082E-249	
17	467401.9	7185695	50	1.5E-223	1.5417E-220	
18	467400.4	7185715	50	2.6E-199	2.572E-196	
19	467398.9	7185735	50	5.6E-179	5.6213E-176	
20	467397.4	7185754	50	1E-161	1.0127E-158	
21	467395.9	7185774	50	6E-147	6.0123E-144	

D-4 – Attributes Output to ESRI:



OBJECTID *	X	Y	Conc_g_m	micorg	Shape *
10051	453266	7223988	1112.317888	1112317.8	Point
10052	453262.25	7224010.19	218.992815	218992.81	Point
10053	453258.5	7224032.38	46.003201	46003.201	Point
10054	453254.75	7224054.57	18.841997	18841.996	Point
10055	453251	7224076.76	10.253518	10253.518	Point
10056	453247.25	7224098.95	6.480843	6480.8434	Point
10057	453243.5	7224121.14	4.484694	4484.6935	Point
10058	453239.75	7224143.33	3.296228	3296.2275	Point
10059	453236	7224165.52	2.528992	2528.9920	Point
10060	453232.25	7224187.71	2.003709	2003.7089	Point
10061	453228.5	7224209.9	1.627689	1627.6885	Point
9856	453221.309986	7224117.389918	1.509403	1509.4025	Point
10258	453265.690014	7224124.890082	1.509403	1509.4025	Point
9857	453217.559986	7224139.579918	1.442174	1442.1739	Point
10259	453261.940014	7224147.080082	1.442174	1442.1739	Point
9855	453225.059986	7224095.199918	1.433627	1433.6269	Point
10257	453269.440014	7224102.700082	1.433627	1433.6269	Point
10062	453224.75	7224232.09	1.348943	1348.9432	Point
9858	453213.809986	7224161.769918	1.318853	1318.8529	Point
10260	453258.190014	7224169.270082	1.318853	1318.8529	Point
9859	453210.059986	7224183.959918	1.182436	1182.4359	Point
10261	453254.440014	7224191.460082	1.182436	1182.4359	Point
10063	453221	7224254.28	1.136408	1136.4079	Point
9854	453228.809986	7224073.009918	1.08251	1082.5104	Point
10256	453273.190014	7224080.510082	1.08251	1082.5104	Point
9860	453206.309986	7224206.149918	1.051585	1051.5847	Point
10262	453250.690014	7224213.650082	1.051585	1051.5847	Point
10064	453217.25	7224276.47	0.970556	970.55555	Point
9861	453202.559986	7224228.339918	0.933241	933.24145	Point
10263	453246.940014	7224235.840082	0.933241	933.24145	Point
10065	453213.5	7224298.66	0.838593	838.59298	Point
9862	453198.809986	7224250.529918	0.829062	829.06213	Point
10264	453243.190014	7224258.030082	0.829062	829.06213	Point
9863	453195.059986	7224272.719918	0.738473	738.47309	Point
10265	453239.440014	7224280.220082	0.738473	738.47309	Point
10066	453209.75	7224320.85	0.731845	731.84507	Point
9864	453191.309986	7224294.909918	0.660077	660.07696	Point
10266	453235.690014	7224302.410082	0.660077	660.07696	Point
10067	453206	7224343.04	0.644255	644.25503	Point

Appendix E – Project Model Output:

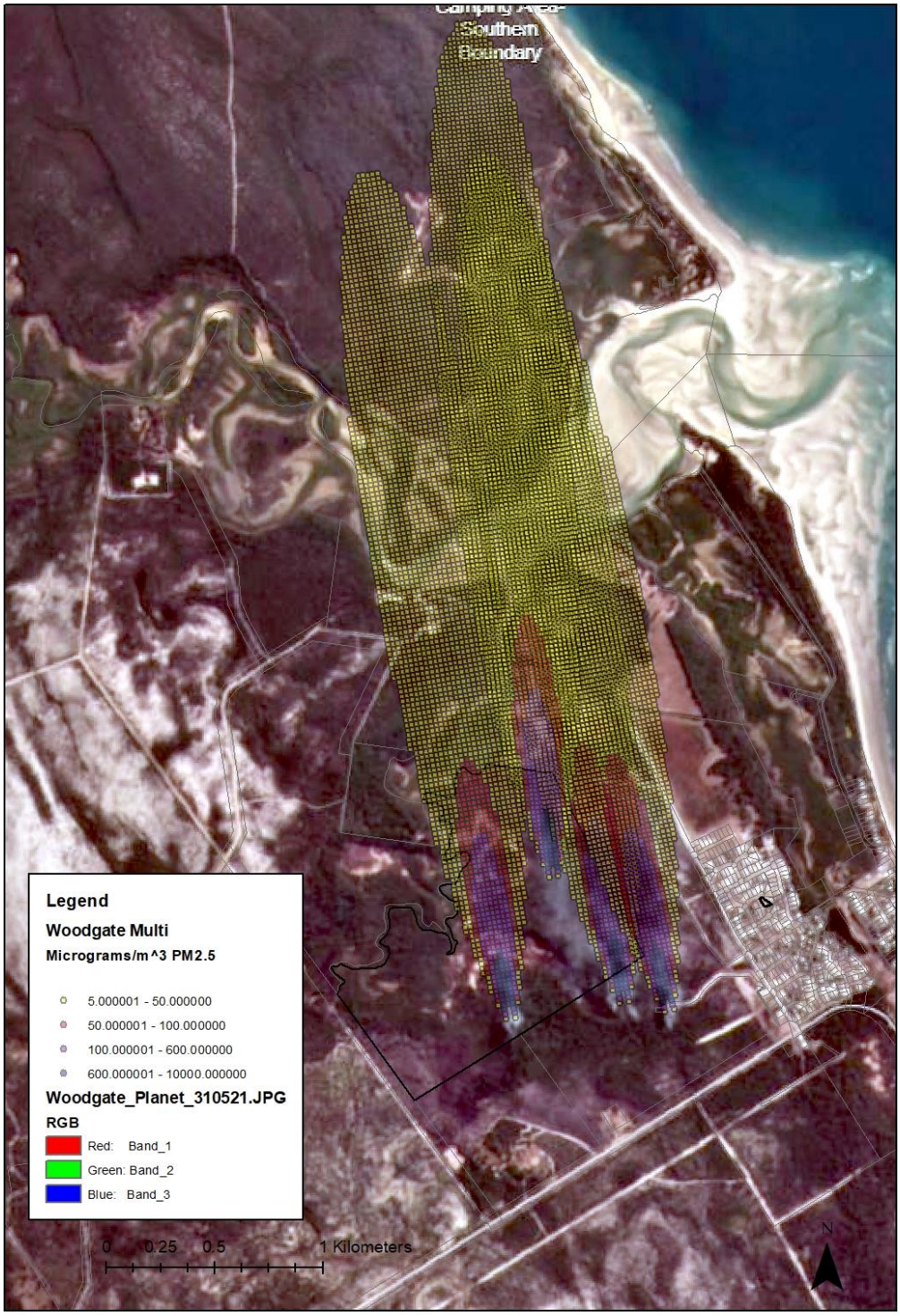
E-1 – Woodgate Fire

Plume only on Planet Labs base image:

Modelled Single Plume:


Southern
Boundary
Legend
Woodgate Single
Micrograms/m^3 PM2.5
5.000001 - 50.000000
50.000001 - 100.000000
100.000001 - 600.000000
600.000001 - 10000.000000
Woodgate_Planet_310521.JPG
RGB
Red: Band_1
Green: Band_2
Blue: Band_3
0 0.25 0.5 1 Kilometers
N

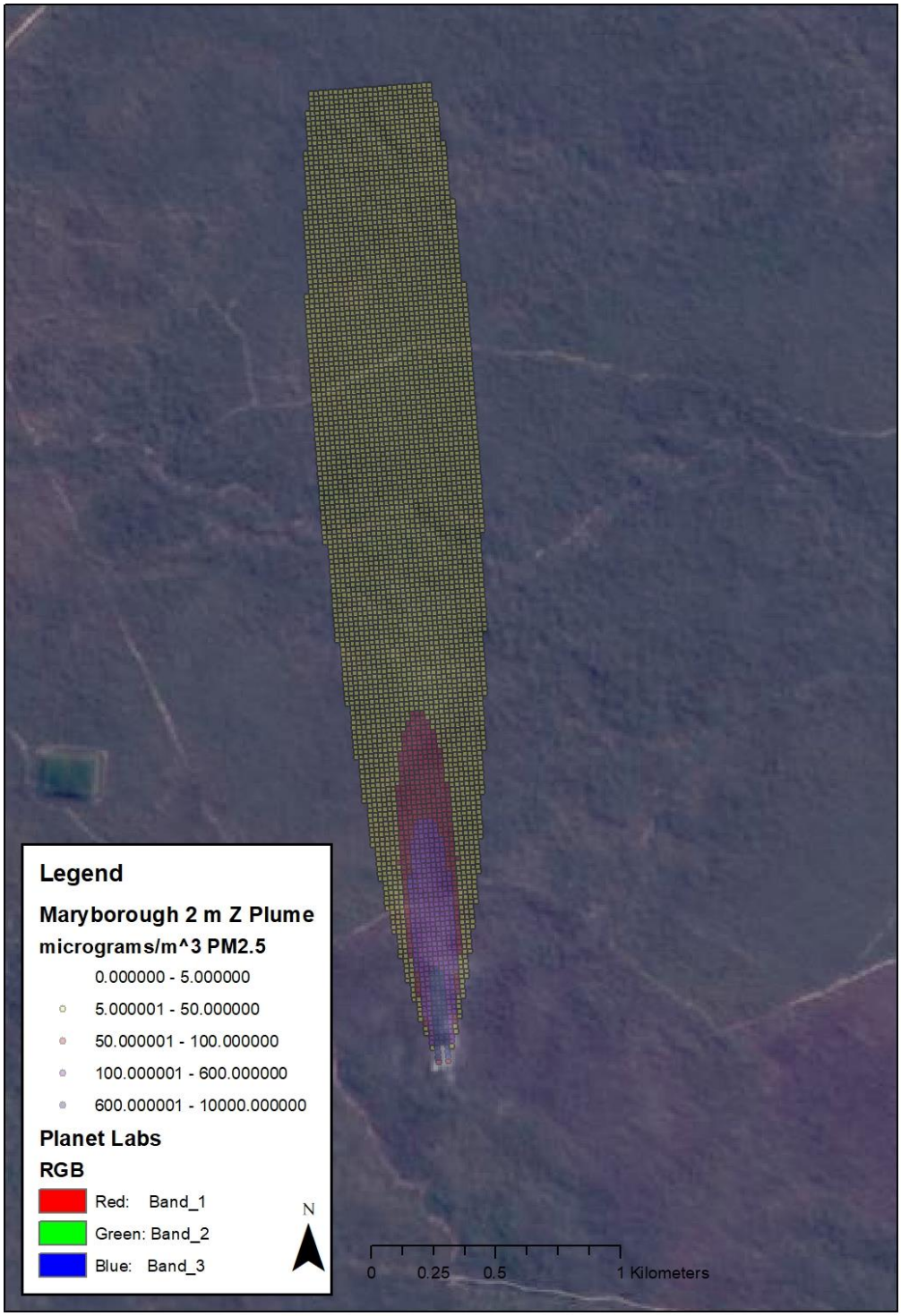
Multicore Plume:


Southern
Boundary
Legend
Woodgate Multi
Micrograms/m^3 PM2.5
5.000001 - 50.000000
50.000001 - 100.000000
100.000001 - 600.000000
600.000001 - 10000.000000
Woodgate_Planet_310521.JPG
RGB
Red: Band_1
Green: Band_2
Blue: Band_3
0 0.25 0.5 1 Kilometers
N

E-2 – Maryborough Fire

Plume only on Planet Labs base image:

Maryborough plume modelled at 2m above ground:


Legend
Maryborough 2 m Z Plume
micrograms/m^3 PM2.5
0.000000 - 5.000000
5.000001 - 50.000000
50.000001 - 100.000000
100.000001 - 600.000000
600.000001 - 10000.000000
Planet Labs
RGB
Red: Band_1
Green: Band_2
Blue: Band_3
N
0
0.25
0.5
1 Kilometers

Appendix F – Collaboration:

F-1 Department of Resources Typical Communication

RE: Smoke distribution modelling project

GREGSON Julian
To BATSTONE Seamus

BAS2 Woodgate Dump Burn Map.pdf
7 MB

Reply | Reply All | Forward
Mon 31/05/2021

Morning Seamus,

We are carrying out our first hazard reduction burn of the year at Woodgate from around 11am today - Burn area map is attached.

I estimate Woodgate KBDI is sitting around 140, at least 10 points lower than QFES estimation for Bundaberg, due to receiving more frequent coastal showers.

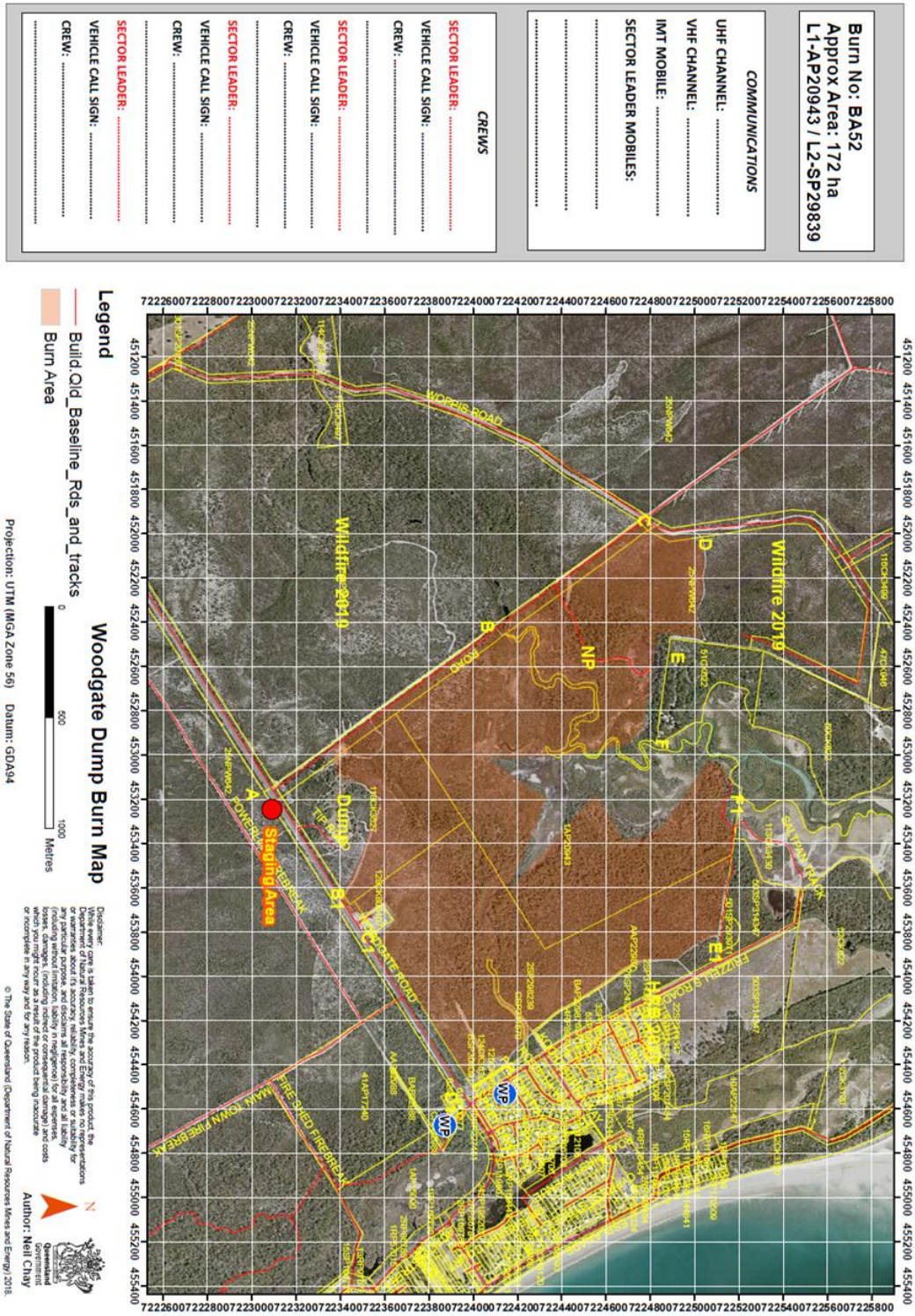
Winds today should be from the SSE gusting to around 15kmph, taking smoke away from the town and main roads with RH around 45% by midday. I'm hoping the majority of smoke will be cleared by midday tomorrow.

Regards,

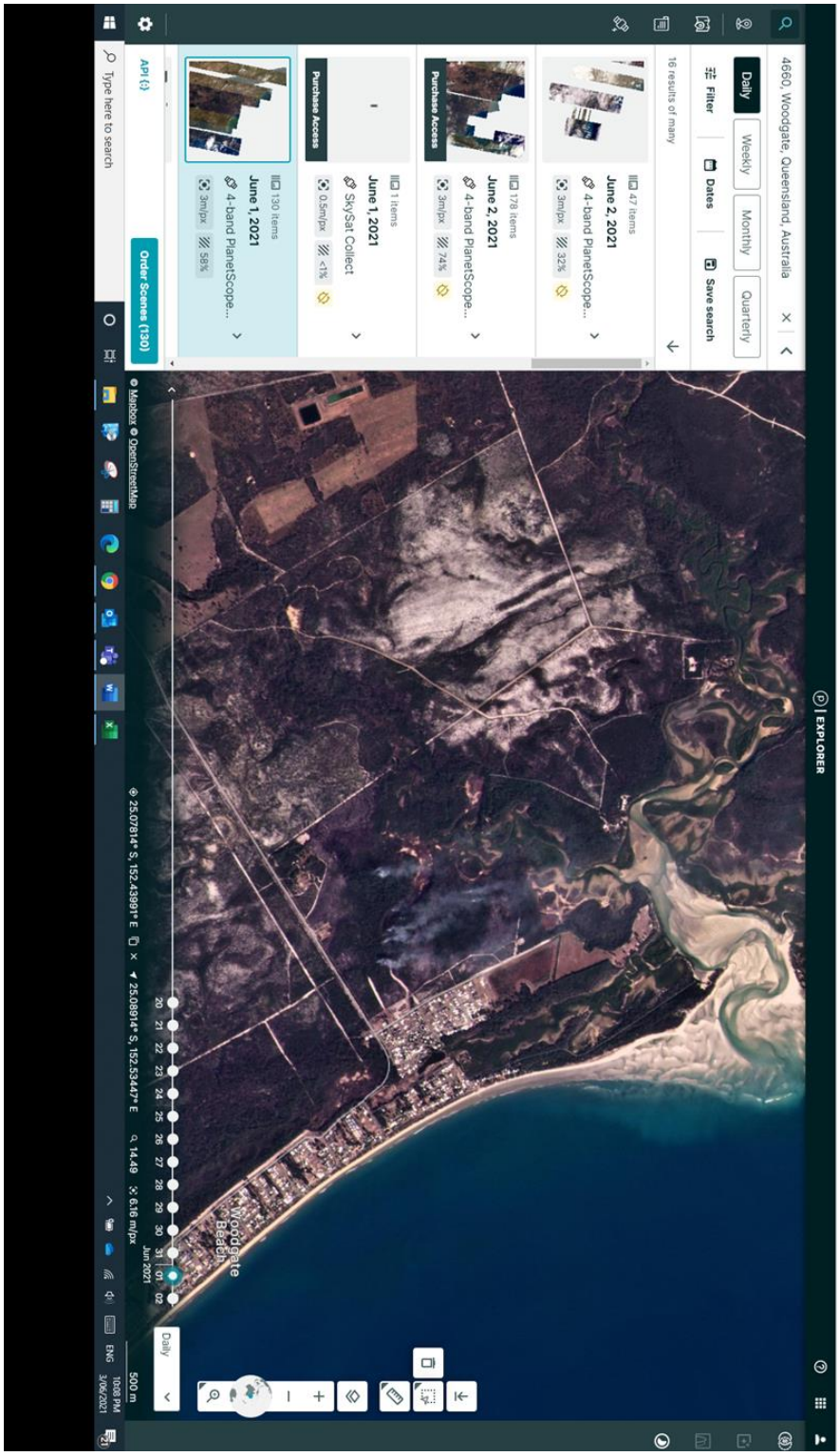
Julian Gregson
Team Leader
State Land Management
Department of Resources
Queensland Government
[redacted]

I work flexibly, generally between 7.30am and 3.30pm. I have sent this message at a convenient time for me. I don't expect you to read, action or respond outside of your preferred working hours.

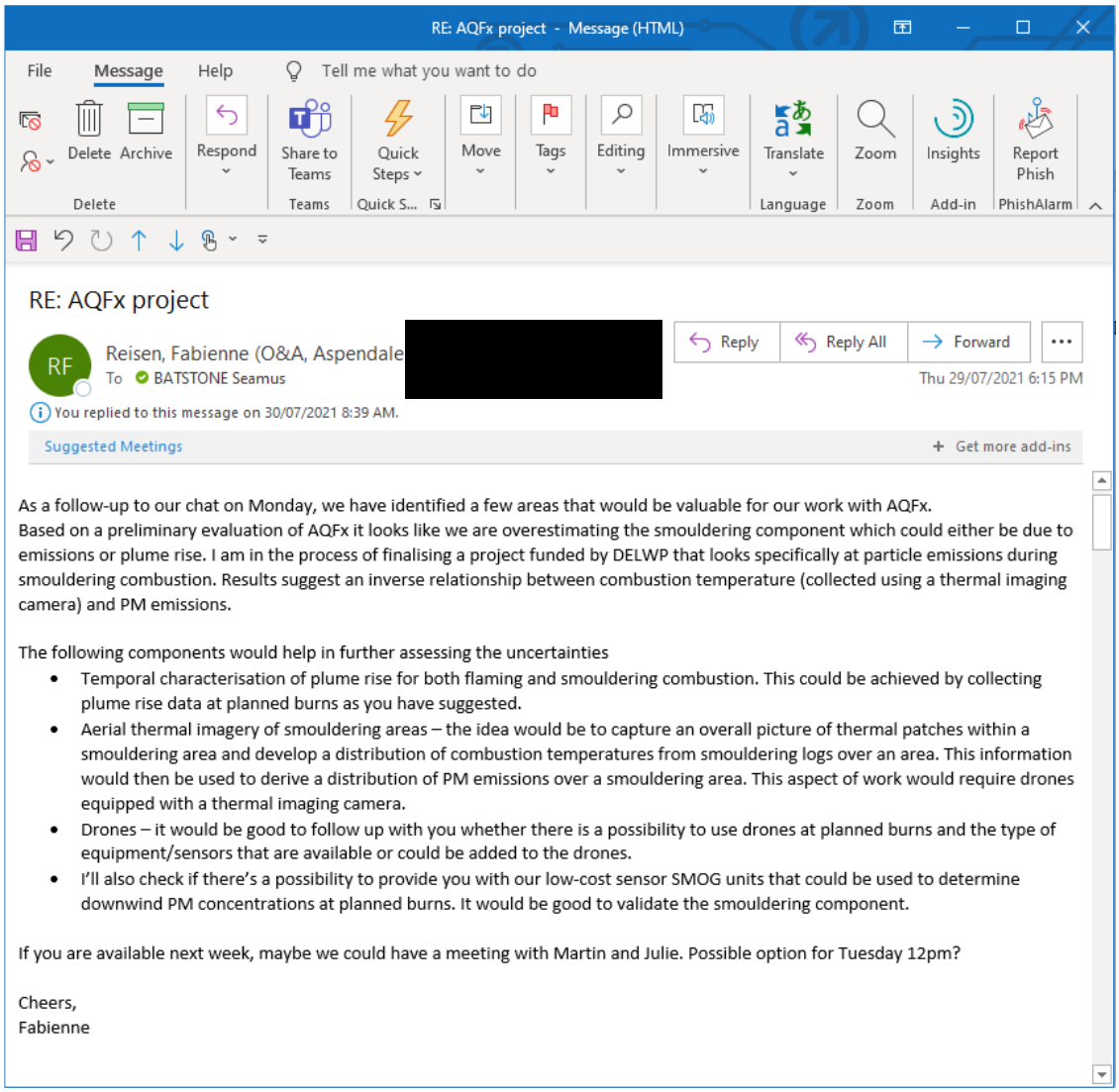
Burn Plan Provided



Corresponding Image Found in Planet Labs



F-2 – CSIRO collaboration occurred by meetings, email and MS Teams:



RE: AQFx project - Message (HTML)

File Message Help Tell me what you want to do

Delete Archive Respond Share to Teams Quick Steps Move Tags Editing Immersive Translate Zoom Insights Report Phish

Delete Teams Quick S... Language Zoom Add-in PhishAlarm

RE: AQFx project

RF Reisen, Fabienne (O&A, Aspendale [redacted]

To BATSTONE Seamus

Reply Reply All Forward

Thu 29/07/2021 6:15 PM

You replied to this message on 30/07/2021 8:39 AM.

Suggested Meetings + Get more add-ins

As a follow-up to our chat on Monday, we have identified a few areas that would be valuable for our work with AQFx.
Based on a preliminary evaluation of AQFx it looks like we are overestimating the smouldering component which could either be due to emissions or plume rise. I am in the process of finalising a project funded by DELWP that looks specifically at particle emissions during smouldering combustion. Results suggest an inverse relationship between combustion temperature (collected using a thermal imaging camera) and PM emissions.

The following components would help in further assessing the uncertainties

- Temporal characterisation of plume rise for both flaming and smouldering combustion. This could be achieved by collecting plume rise data at planned burns as you have suggested.
- Aerial thermal imagery of smouldering areas – the idea would be to capture an overall picture of thermal patches within a smouldering area and develop a distribution of combustion temperatures from smouldering logs over an area. This information would then be used to derive a distribution of PM emissions over a smouldering area. This aspect of work would require drones equipped with a thermal imaging camera.
- Drones – it would be good to follow up with you whether there is a possibility to use drones at planned burns and the type of equipment/sensors that are available or could be added to the drones.
- I'll also check if there's a possibility to provide you with our low-cost sensor SMOG units that could be used to determine downwind PM concentrations at planned burns. It would be good to validate the smouldering component.

If you are available next week, maybe we could have a meeting with Martin and Julie. Possible option for Tuesday 12pm?

Cheers,
Fabienne