FINAL PROJECT REPORT
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MAPPING BUSHFIRE HAZARD AND IMPACTS

Final project report

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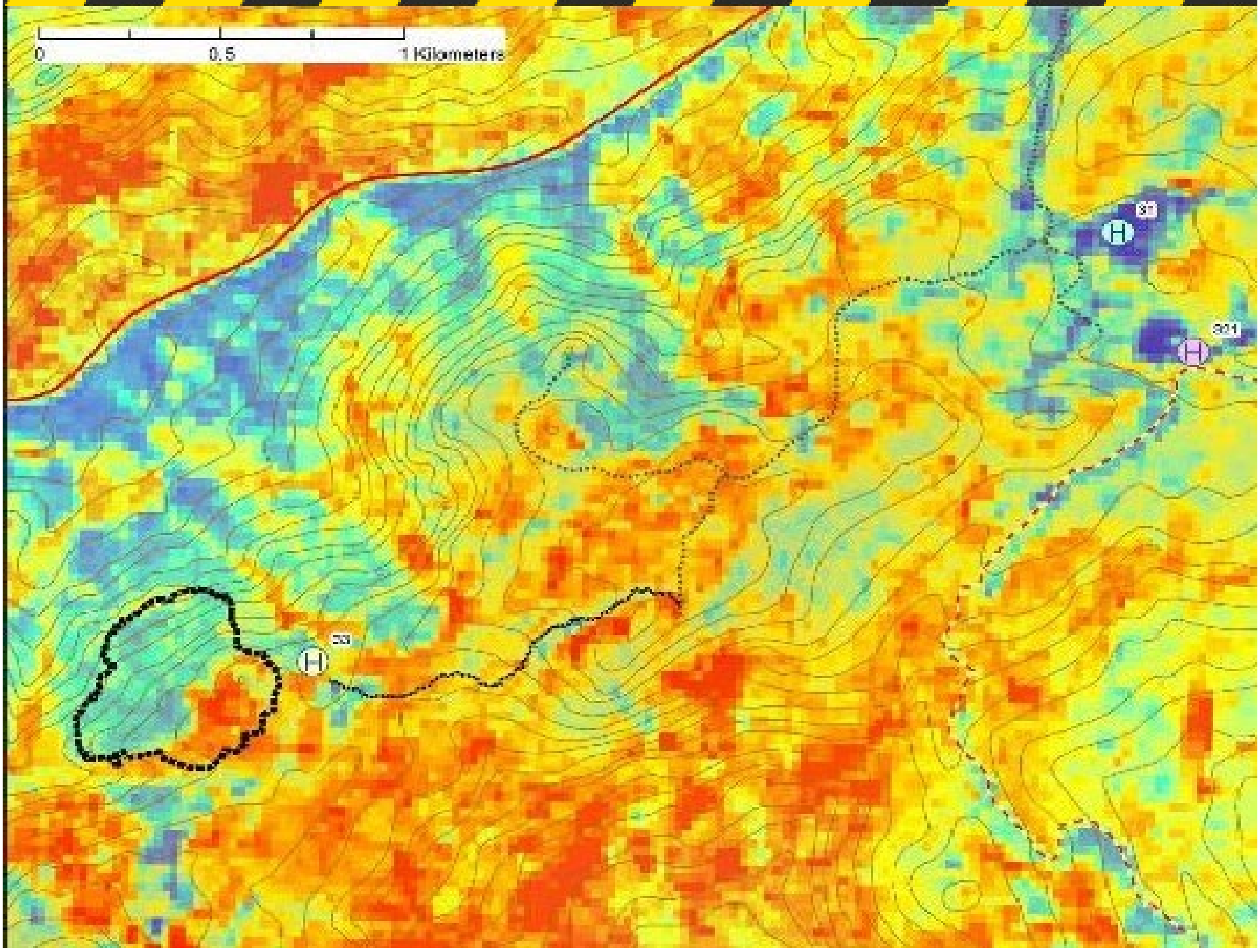
Australian National University & Bushfire and Natural Hazards CRC



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Cover: Examples of elevate fuel fraction of cover map used by ACT Parks and Conservation Service to plan suppression activities. Source: Adam Leavesley

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ACKNOWLEDGMENTS

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We thank our project end-users and their organisations for their continued enthusiastic engagement and valuable feedback over the seven years duration of this project.

EXECUTIVE SUMMARY

Fuel condition (e.g. moisture content, horizontal and vertical continuity and the quantity or load) affect flammability and therefore is a key determinant of the ease of ignition and the spread rate of a fire. Many research institutions and management services are investing an important amount of resources on field-based fuel condition monitoring to understand its dynamics and support operational fire management activities. However, field sampling is expensive and time-consuming, sometimes subjective and implies also a delay time until the data are processed and made available. The Bushfire & Natural Hazards CRC project '*Mapping Bushfire Hazards and Impacts*' used cutting-edge technology to produce near-real-time spatial information on fuel condition, fire hazard and impact to support a wide range of fire risk management and response activities such as hazard reduction burning and pre-positioning firefighting resources and, in the longer term, the new Australian Fire Danger Rating System (AFDRS) given it considers fuel condition as ne of the key factors required to determine fire danger and support other decision -making.

The first phase of this project (2014-2017) involved the parallel investigation of several promising data sources and methods that can be categorised as either 'in-field' (grassland curing on-ground sensors and ground-based LiDAR laser scanning for fuel structure characterisation) or 'national-scale' (the Australian Flammability Monitoring System-AFMS, and the High-resolution Fire Risk and Impact (HiFRI) model-data fusion framework) methods. Generally, information derived from the national-scale methods appeared to represent enough accuracy and better return on investment and generated greater interest among end-users.

Consequently, over 2017-2020, this research project focused on ensuring the continuity of the AFMS but further developing the algorithms to estimate fuel moisture content (FMC), and through this, its acceptance and adoption. The AFMS provides information on FMC and flammability across Australia at 500m resolution every four days. It also displays information on soil moisture content near the surface (0-10 cm) and shallow soils (10-35 cm) as research outcomes from the project "Improving land dryness measures and forecast". Our research project also improved estimates of litter FMC by incorporating the effect of soil moisture content in existing physics-based models, developed a methodology to map fuel loads using satellite data and an objective and observation-based approach to assess fire danger that considers spatial data on the occurrence of actual fires as well as on fire factors that are already routinely produced every day for Australia.

The improved litter FMC, fuel load and fire danger retrieval algorithms and products derived from this project are not yet included in the AFMS nor generated at near real-time and across Australia. Further research and development is needed to make that step and providing landscape scale, cost-effective way to comprehensively monitor fuel condition and fire danger at such a broad scale. Consequently, future research should focus on developing a multi-sensor system that will display daily information on fire danger and fuel condition from whatever satellite sensor has collected an image over Australia, including high-resolution satellite imagery. This will improve the temporal and

spatial resolution of the information we currently provide at the AFMS that will allow the identification of, for example, local fuel moisture gradients in the landscape that are currently not identifiable using the 500m pixel resolution of the product we currently serve in the AFMS.

The use of high-resolution satellite imagery will provide an unprecedented level of detail and accuracy when estimating fuel condition, bringing the system closer to use in operations. However, the data volumes and large compute resources required to store and generate these high-resolution products becomes a challenge. Consequently, future research should also focus on developing an alternative methodology for computing fuel condition that can provide up to date estimations by reducing the required storage and computing resources using state-of-the-art artificial intelligence algorithms.

END-USER PROJECT IMPACT STATEMENT

Stuart Matthews, *NSW Ryral Fire Service*

Monitoring the state of fuels across wide areas is an important challenge for several problems in fire management ranging from modelling the spread and severity of going fires through to long-term risk planning and land management. This challenge involves understanding complex biophysical processes and differences in vegetation, weather and climate that range from meters to the continental scale and hours to years.

Over the life of this project, the team have tackled difficult problems in monitoring and modelling fuels and made important progress. Key achievements from an end-user include development of routinely available live fuel moisture data, presented through an easy to use web site; integrated presentation of flammability, live moisture, and soil moisture; investigation of novel approaches to modelling flammability, fire occurrence, and fuel accumulation; improving our understanding of coupled soil-fuel moisture physics; and assessment of options for remote sensing of grass curing when the MODIS platform that has been used in Australia for 20 years is no longer available.

This project has also served as an excellent example of how to keep a long-running research project relevant to end-user needs. This has included lots of engagement from the project team and use tools like prototypes (leading to the development of the AFMS) and surveys to understand how science can support end-users.

PRODUCT USER TESTIMONIALS

Adam Leavesley, *ACT Parks and Conservation Service*

There is no silver bullet to the worldwide wildfire/bushfire problem, so the research strategy is aimed at achieving incremental advancements that deliver improvements to operational capability across a range of relevant fields. Two critical drivers of bushfire behaviour are fuels and fuel condition. Inadequate knowledge of the distribution of fuel and its condition were key factors in the two most serious prescribed burn escapes in the past decade – Margaret River in WA and Lancefield in Victoria. Also, fuel condition, specifically live fuel moisture content (FMC), is probably the single most critical factor determining the propensity of a landscape to burn and an important contributing factor to the behaviour of bushfires.

The '*Mapping Bushfire Hazards and Impact*' project has significantly advanced knowledge and operational capability of fuels and fuel condition. The main research effort aimed at deriving continent-wide spatially-explicit estimates of live FMC at near real-time has been achieved. The estimates returned at a resolution of 500m x 500m have been consistent with observed fire behaviour during bushfires and prescribed burns. Besides, the system has succeeded in capturing terrain-driven differences in fuel moisture content relevant to prescribed burning operations.

The next step in the operationalisation of the work is to develop mission-critical infrastructure which will acquire the satellite data, implement the required processing, apply the algorithms and then supply the output to users in an optimal format. An appropriate system may require high bandwidth connections, adequate processing power to cope with uneven demand for processing power, appropriate security to minimise the probability of service interruption, flexible output formats and redundant output sources. Additional utilisation work could use the live FMC data to derive secondary metrics aimed at meeting specific operational needs. This step is important because of the vast differences across the Australian continent in the biophysical systems associated with fire. Another driver for the development of secondary metrics is the regulatory differences between Australian jurisdictions which may require different specific metrics.

The project has delivered significant advancements in the operational capability to capture spatially-explicit information about the distribution of fuels and the effects of fire. The project developed a specification for deriving analogues of the Overall Fuel Hazard from LiDAR and then applied the method to an Australian Capital Territory-wide LiDAR dataset to produce spatially-explicit fuel maps at resolutions of 2m, 5m and 25m. The 25m maps were easiest to use in GIS systems and the resolution was suitable for operations. Qualitative validation of the fuel data showed good agreement between areas with a high cover of elevated fuels and the LiDAR-derived estimates. There was also good agreement between estimates of fire severity derived using the differential Normalised Burn Ratio ΔNBR procedure and the LiDAR-derived fuel maps. Furthermore, observed anomalies in fire behaviour during prescribed burns appeared to be correlated with higher coverage of elevated fuels. The next steps in the utilisation of LiDAR for fuel mapping would be to define appropriate metrics for different fuel types and fire behaviour models and then produce quantitative validations. A drawback in the use of LiDAR for fuel mapping is that some metrics such as the depth of the litter layer cannot be reliably obtained using remote-sensing. Ultimately, it makes little sense trying to use LiDAR for deriving fuel metrics that were devised for collection by a person in the field. A better approach may be to develop new fire behaviour models based on parameters that can be reliably obtained by remote-sensing.

The project has delivered significant technical assistance in the development of methods for assessing prescribed burn severity. The ∆NBR procedure developed by the United States Forest Service was trialled for assessment of prescribed burn severity using burns conducted in rugged sub-alpine terrain in the Australian Capital Territory. The results from the trials were then used to test methods for estimating for-fire hydrological risk and to produce a flammability map for planning future burns. The results from the flammability map showed good agreement with a sub-canopy climate model developed to estimate flammability. Future work should validate the use of ∆NBR or superior methods of estimating fire severity so that agencies can: 1) improve understanding of the effects of prescribed burns; 2) generate improved fire histories to support more sophisticated understanding of secondary effects of fire on ecological systems; 3) better manage hydrological resources, and 4) generate robust estimates of carbon emissions.

The overall outcome from the project has been to significantly advance knowledge and operational capability for fire managers in understanding the distribution of fuels and their condition. The bushfire sector is well-placed to rapidly take up these advances and deliver better advances for communities across Australia.

INTRODUCTION

Goverment agencies, individuals and businesses need accurate spatial information on fire hazard to prevent, avoid and manage impacts. Bushfire hazard depends not only on weather but also on landscape conditions. For example, fire hazard monitoring in Australia involves fire danger indices that consider mainly meteorological conditions, although a simple algorithm is used in the McArthur Forest Fire Danger Index to calculate the 'Drought Factor Value' from antecedent weather data, intended as a rough estimate of litter moisture content. To date, there has not been much emphasis on routinely providing and using spatial information on landscape-related hazard factors such as fuel condition in determining fire risk. Partly, this is because of a lack of reliable, consistent, accurate and long-term information. This situation is changing, however. Several relevant satellite, airborne and mapping derived products and prediction models are now readily available to estimate important landscape variables that determine fire hazard. Their applicability, added value and any adaptations required need to be assessed with direct reference to the data currently required for fire risk calculations and fire behaviour models, and how these might change soon due to current or upcoming research on fuel and fire behaviour.

This project developed methods to produce the spatial information on fuel condition and fire hazard needed by planners, land managers and emergency services. The relevance and added value represented by these new information sources were compared to the practical feasibility and costs of its use.

Together with the end-users, we developed worked case studies and guidelines to describe how each information source can be produced and/or used operationally and to determine research and development requirements and priorities.

The key research outputs of the project are:

1. A review of using LiDAR for forest and fuel structure mapping
2. Specification for deriving analogues of the Overall Fuel Hazard from LiDAR and then applied the method to an Australian Capital Territory-wide LiDAR dataset to produce spatially-explicit fuel maps at resolutions of 2m, 5m and 25m.
3. A methodology to estimate and map fuel moisture content (FMC) and flammability across Australia based on satellite imagery.
4. A preliminary assessment of a more objective and observation-based approach to fire danger assessment that considers spatial data on the occurrence of actual fires as well as on fire factors that are already routinely produced every day for Australia.
5. A preliminary assessment of the influence of soil moisture dynamics in litter FMC.
6. A methodology to map fuel loads using satellite data.
7. A high-resolution Fire Risk and Impact (HiFRI) model-data fusion framework.

8. A comprehensive analysis of the suitability of operational coarse resolution near-surface soil moisture data to improve the McArthur forest fire danger index.

The key utilisation output of the project is the Australian Flammability Monitoring System, a prototype website that provides near-real-time information on fuel condition and flammability across Australia.

RESEARCH APPROACH

The **first phase of this project (2014-2017)** involved the parallel investigation of several promising data sources and methods that can be categorised as either 'in-field' or 'national-scale' methods. Initially, we reviewed and analysed the potential added value of new data sources relating to fire danger and fuel condition. The utility and feasibility of using a new data source depended on such factors as spatial resolution, accuracy, operational availability and the resources required for data acquisition, processing and interpretation. In discussion with end-users, we assessed each of the available data sources against these criteria and determined where further research can help to overcome some of the constraints - this was then the focus of subsequent research efforts. Where possible, the spatial data derived was evaluated against ground-based measurements. Where appropriate, the information was developed to fit into the Fire Danger Rating system or fuel classification systems suitable for end-users.

In brief, in-field methods provide detailed information at the plot scale of metres to hectares. They provide more accurate and spatially concentrated measurements but can also be relatively costly - examples investigated in this project include on-ground networks of field sensors measuring grass curing or fuel moisture content (FMC) and automated ground-based LiDAR laser scanning for fuel characterisation. National-scale methods are generally derived from already available satellite imagery and other spatial data. Two such methods were successfully developed in this project: the Australian Flammability Monitoring System (AFMS), and the High-resolution Fire Risk and Impact (HiFRI) model-data fusion framework. The former was implemented at national-scale, whereas the latter was tested for a smaller region but can be applied anywhere in Australia.

Generally, information derived from the national-scale methods appear to represent a better return on investment and generated greater interest among end-users (Yebra, van Dijk et al. 2016). They, therefore, appear to have greater utilisation potential than in-field methods, which require careful consideration of the cost and the representativeness of the sample locations. However, end-users did recognise the importance of in-field methods as part of the verification, acceptance and tuning of large-scale methods. Moreover, the adoption of some in-field technologies was considered more likely to occur once data acquisition and analysis technologies become cheaper.

Among the national-scale options investigated, information on fuel moisture content (FMC) and flammability at a national-scale was judged to represent the best return on investment and generated the greatest interest among end-users. Consequently, it was recommended, and subsequently agreed by the BNHCRC, that development of that type of information, to be provided through a web service called the Australian Flammability Monitoring System (AFMS) would be the major focus for R&D over the next years (2017-2020).

Consequently, **over 2017-2020**, this research project focused on **ensuring the continuity of the AFMS**, and through this, its acceptance and adoption. The AFMS provides the first Australia-wide product of flammability from satellite estimates of live FMC (Yebra, Quan et al. 2018). The flammability index was adjusted using a continuous logistic probability model between fire occurrence and live FMC. We evaluated the feasibility and relative benefits of using different satellites to compute FMC (Yebra, van Dijk et al. 2018) to ensuring data continuity and redundancy as well as create the opportunity to increase the temporal and/or spatial resolution of the AFMS. The most promising candidate data sources to support AFMS continuity strategy are the geostationary Japanese Himawari-8 satellite, the European Sentinel-2 and the Landsat and VIIRS satellites. After conversations with Geoscience Australia, we adapted the FMC code for computing the FMC and Flammability maps visualised in the AFMS to run with Geoscience Australia high-resolution datasets in their cloud infrastructure. We have provided a proof-of-concept code that computes the products using Sentinel 2 data at a resolution of 20 metres.

Despite the importance of live FMC, it is only one of the variables that influence fire occurrence, and therefore the importance of other factors (e.g. fire weather, dead FMC, total fine live and dead fuel load, and ignition) should also be considered for a comprehensive characterisation of flammability, where possible. Consequently, we worked to develop a comprehensive characterisation of flammability (Van Dijk, Yebra et al. 2019). Such an approach provides a more observation-based and comprehensive assessment of flammability, where current national approaches (e.g. the McArthur-type methods) are conceptual and focused on meteorological variables.

Finally, we worked with the Department of Defence to develop a low-cost technology to monitor fuel loads on Defence Lands using Landsat and Sentinel-2 optical remote sensing data available at Digital Earth Australia and the National Computation Infrastructure (Massetti, Yebra et al. 2020). The fuel load maps were obtained by calculating the time series of the Vegetation Structure Perpendicular Index (Massetti, Rüdiger et al. 2019), an index that measures post-fire disturbance, and fitting these to fuel accumulation curves derived from literature.

KEY MILESTONES

The key achievements of the project are sumamrised below.

USING LIDAR FOR FOREST AND FUEL STRUCTURE MAPPING: OPTIONS, BENEFITS, REQUIREMENTS AND COST

Understanding fuel structure is important for assessing suppression difficulty, risk of damage from bushfires, monitoring fuel build up and planning hazard reduction programs. Technologies such as airborne Light Detection and Ranging (LiDAR) can provide precise information about fuel structure over larger areas. However, the use of LiDAR by fire managers is still in the early stages and has not been implemented through any routine operational program in Australia.

We addressed this situation by describing and evaluating the maturity and suitability of airborne LiDAR to derive the different types of information needed in forest fuel assessment by setting questions scoped in consultation with fire managers through the Bushfire and Natural Hazards CRC project 'Mapping bushfire hazard and impacts'. We first covered some of the basic principles on LiDAR and then focused on the analysis of the information content and accuracy of airborne LiDAR to retrieve the forest fuel attributes that are important for fire management.

The information that can be derived about the height, cover fraction and density of different over- and understorey layers was assessed, along with other useful information that may be derived. Additional measurements that help to make more optimal use of airborne LiDAR data was presented, including terrestrial laser scanning, UAV-borne LiDAR, and airborne imaging. Guidance was provided on discovering existing LiDAR data, factors determining the cost of new LiDAR data acquisition, and options for processing the data. Finally, the current and future development in the use of LiDAR for fire management were discussed.

Summarising, airborne LiDAR may be considered a mature data product that is commercially available, using established data standards. However, standardised data specifications and processing methods for applications in fuel mapping do not yet exist. Essential aspects to consider are the type of fuel information, accuracy and spatial detail desired. Greater data density can increase accuracy and spatial detail, but will also increase the cost of acquisition. In forests with a dense overstorey canopy high data density may be the only way to obtain information on the understorey. In small-scale applications, field or UAV-mounted LiDAR systems may be a suitable alternative for airborne LiDAR.

We identified the follow priority areas for research and development to achieve more cost-effective and successful use of LiDAR by the fire management community; the development of standardised methods to acquire and process airborne LiDAR data for fuel mapping, the validation of these methods using field measurements, and investigation of full-waveform airborne LiDAR as a promising alternative to current LiDAR data collection methods. The Bushfire and Natural Hazards CRC project 'Mapping bushfire hazard and impacts' is working with end-users to pursue each of these lines of enquiry.

This research project developed standardised methods to process airborne LiDAR data for fuel mapping that was applied in the ACT deriving fuel maps at resolutions of 2m, 5m and 25m that have been broadly used by ACT Parks and Conservation Service for both response and planning activities (Figure 1).

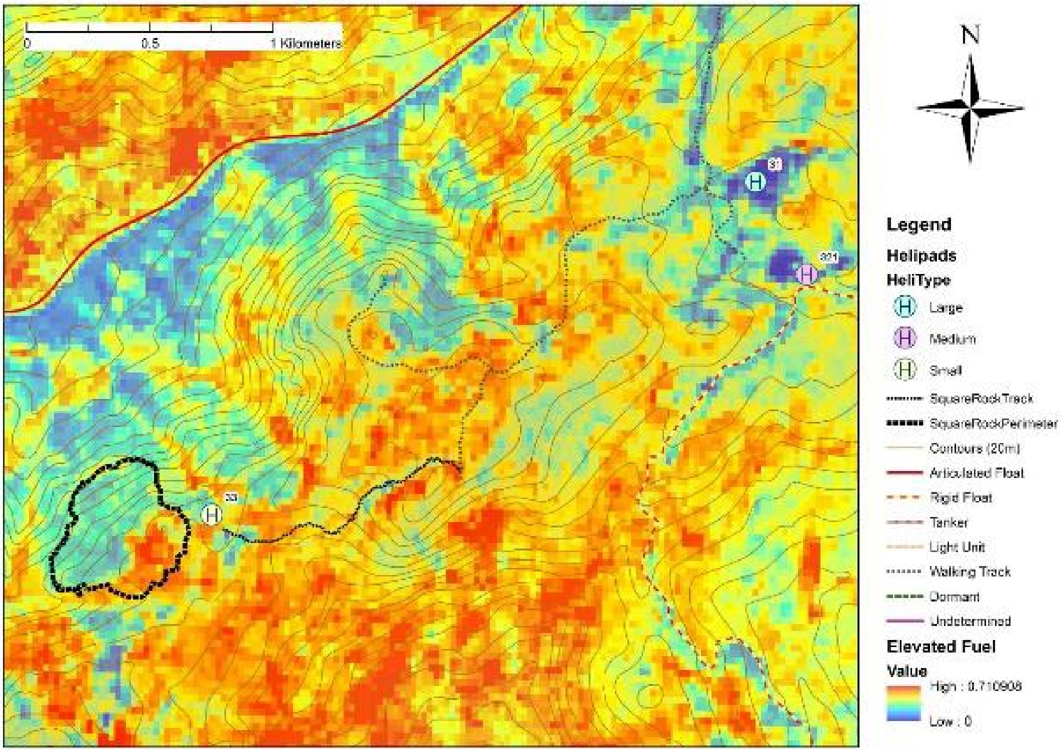

FIGURE 1 - EXAMPLES OF ELEVATE FUEL FRACTION OF COVER MAP (25M RESOLUTION) USED BY ACT PARKS AND CONSERVATIONS SERVICE TO PLAN SUPPRESSION ACTIVITIES; INLCUDING 1) LOCATE A SITE FREE OF TREES TO WINCH SPECIALIST FIREFIGHTERS IN. THEY THEN TRIMMED THE SHRUBS TO ALLOW HELICOPTERS TO BE LANDED (SAFER AND MORE STAFF ARE QUALIFIED TO LAND THAN WINCH); 2) UNDERSTAND THE EXTENT OF THE FUEL REDUCTION THAT TOOK PLACE IN 2013 (THE BLUE AREAS ON THE MAP FACING NORTH) FOR USE IN PLANNING THE SUPPRESSION STRATEGY (SEE THE FOLLOWING SLIDES SHOWING THE DIFFERENCE IN HEIGHT OF THE SHRUBS) AND 3) TRY TO PICK THE EASIEST LINE TO CONSTRUCT THE WALKING TRACK TO THE FIRE (THAT'S THE THICKER BLACK LINE THAT LEADS TO THE HELIPAD. THE OTHER THINNER BLACK LINE WAS AN EXISTING WALKING TRACK. SOURCE: ADAM LEAVESLEY, ACT PARKS AND CONSERVATION SERVICE

MAPPING LIVE FUEL MOISTURE CONTENT AND FLAMMABILITY

Fuel Moisture Content (FMC) is one of the primary drivers affecting fuel flammability that lead to fires. Satellite observations well-grounded with field data over the highly climatologically and ecologically diverse Australian region served to estimate FMC and flammability for the first time at a continental-scale (Figure 2). The methodology includes a physics-based retrieval model to estimate FMC from MODIS (Moderate Resolution Imaging Spectrometer) reflectance data using radiative transfer model inversion. The algorithm was evaluated using 360 observations at 32 locations around Australia with mean accuracy for the studied land cover classes (grassland, shrubland, and forest) close to those obtained elsewhere ($r^2=0.58$, RMSE=40%) but without site-specific calibration. Logistic regression models were developed to generate a flammability index, trained on fire events mapped in the MODIS burned area product and four predictor variables calculated from the FMC estimates. The selected predictor variables were: actual FMC corresponding to the 8-day and 16-day period before burning; the same but expressed as an anomaly from the long-term mean for that date; and the FMC change between the two successive 8-day periods before burning.

Separate logistic regression models were developed for grassland, shrubland and forest. The models obtained an "Area Under the Curve" calculated from the Receiver Operating Characteristic plot method of 0.70, 0.78 and 0.71, respectively, indicating reasonable skill in fire risk prediction. More details in Yebra (2018).

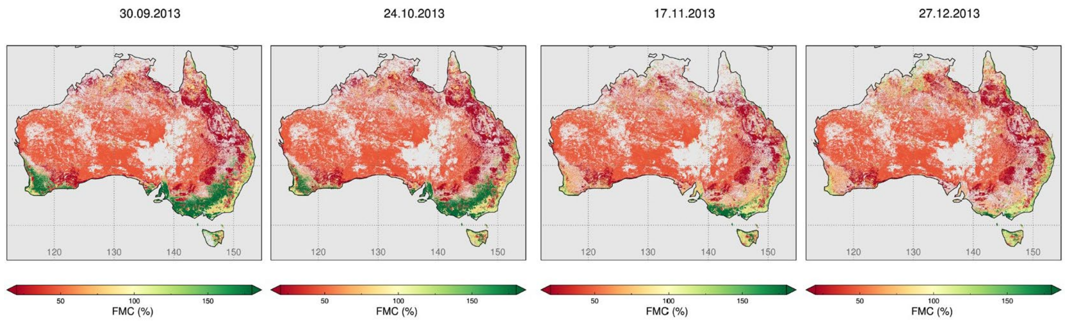

FIGURE 2 – EXAMPLES OF FUEL MOISTURE CONTENT MAPS

We evaluated the feasibility and relative benefits of using alternative remote sensing imagery to compute FMC at finer spatial or temporal resolutions. The evaluated data sources include the geostationary Japanese Himawari-8 satellite (10min, 2km), the European Sentinel-2 (5 days, 20 m), the Landsat (16 days, 30m) and VIIRS (daily, 750 m) satellites. We used Radiative Transfer Models to build a database of simulated spectra for the different studied sensors and corresponding to different FMC conditions. The database was then used to test the suitability of the different sensor to retrieve FMC based on their different spectral characteristics and goodness of retrieval (e.g. r2 and RMSE between retrieved and modelled). VIIRS obtained the highest accuracy retrieval (r2=0.8, RMSE=19%, n=6178) followed by Sentinel-2 (r2=0.8, RMSE=23, n=6178), Landsat-8 (r2=0.8, RMSE=24, n=6178) and Himawari-8 (r2=0.7, RMSE=24, n=6178). VIIRS, therefore, is likely the best candidate to ensure the continuity of data provision. Sentinel-2 and Himawari-8 are the best second and third candidates that obtain similar accuracies while increasing the spatial (Sentinel-2, 20m) and temporal (Himawari-8, 10 minutes) resolutions of the products displayed in the AFMS. More details in Yebra (2018).

Future work should focus on integrating estimates from these different data sources to better support a range of fire management activities such as prescribed burning and pre-positioning of firefighting resources and inform the future National Fire Danger Rating System.

IMPROVING DEAD FUEL MOISTURE CONTENT ESTIMATES (PHD PROJECT)

Fuel moisture content (FMC) of the litter or surface fine fuel layer is a critical factor determining fire ignition and spread and is an important input for most fire danger and fire behaviour prediction models. Several models have been developed to forecast litter FMC. Those models range from empirical regression functions against weather variables to physics-based models with water and energy continuity equations. Soil moisture below the litter layer has been shown to influence litter FMC, but few models explicitly consider its effect.

We evaluated how soil moisture content may affect litter FMC by coupling soil moisture as a boundary condition to the physics-based 'Koba' model, which simulates fuel radiation, energy and moisture fluxes in the surface and subsurface litter layer. The coupled model was tested at five sites in Victoria, Australia, where litter FMC values were recorded continuously during 2014-2015 using calibrated fuel stick sensors. Two versions of the model were compared against the observations: the uncoupled model and a model version accounting for the vapour flux from soil to litter. The potential of soil water flowing by capillary rise was assumed negligible during all but the wettest conditions. The simulation results showed that the influence of soil moisture depends on environmental conditions. Soil moisture appeared to have a minor influence on FMC when both soil and litter were dry, but a stronger influence when the soil was relatively wet. Correspondingly, the coupled model explained observed FMC better than the uncoupled model for the two wetter study sites. As expected, the subsurface litter layer in contact with the soil appeared more sensitive to soil moisture conditions than the surface litter layer. The influence of soil vapour flux on litter FMC can be considerable during the transition from wet to dry litter and soil conditions. This has implications for hazard reduction burning, which is typically planned to take advantage of transitional fuel moisture conditions. Further research is needed to understand the influence of the structure and thickness of litter on the importance of soil vapour flux. Additional, research should focus on applying the method spatially over broader scales as that would allow dead FMC maps be visualised in the AFMS and used as an input in the AFDR.

MAPPING FUEL LOADS USING SATELLITE DATA

Fuel loads are a main driver of fire rate of spread. Therefore, a spatially explicit estimation of fuel loads, coupled with their variation through time may improve wildland fuel management and contribute to the design of more efficient active fire response strategies. The high frequency of planned and unplanned fires in large wild areas linked to varying fire severity levels that affect the rate at which fuels re-accumulate, make the continuous monitoring of wildland fuels challenging with field-based survey methods. We used Landsat and Sentinel-2 satellite remote sensing data available at Digital Earth Australia and the National Computation Infrastructure to map fuel loads for five Defence Lands. The fuel load maps were obtained by calculating the time series of the Vegetation Structure Perpendicular Index (Massetti, Rüdiger et al. 2019), an index that measures post-fire disturbance, and fitting these to fuel accumulation curves derived from literature. More information is presented in Massetti (2020). Future research should focus on the validation of the obtained maps using field measurements and the upscale to a continental scale approach. In the longer term the maps could serve in the AFMS and be used as input in the AFDR.

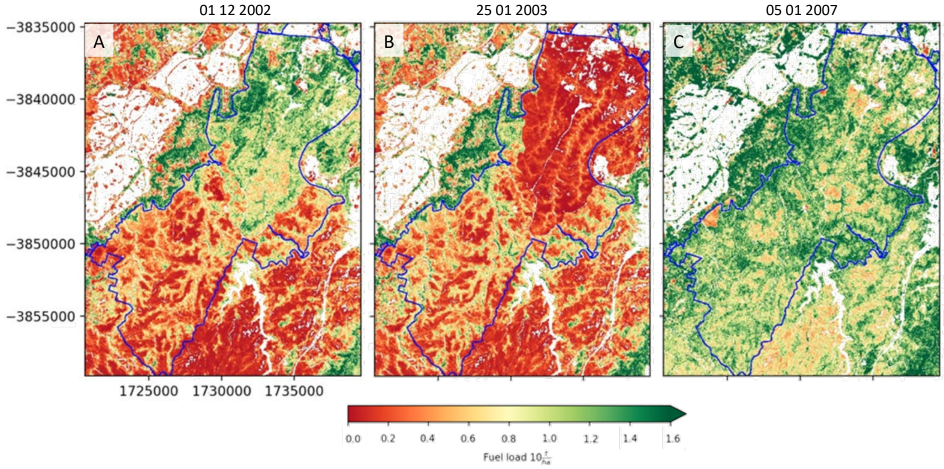

FIGURE 3 - FUEL LOAD MAPS AT HOLSWORTHY BARRACKS (A) JUST BEFORE, (B) SOON AFTER, AND (C) 4 YEARS AFTER THE 2003 FIRE. LOW FUEL LOADS ARE REPRESENTED IN RED, HIGH FUEL LOADS ARE REPRESENTED IN GREEN

A HIGH-RESOLUTION FIRE RISK AND IMPACT (HIFRI) MODEL-DATA FUSION FRAMEWORK

We developed a model-data fusion framework to provide estimates on historic fire impacts on landscape values, as well as potentially real-time estimates of current fuel load and flammability (Figure 4). A case study area was undertaken to analyse the value of alternative airborne and remote sensing observations in a model-data fusion framework. The data were used to set up a spatial forest growth, water use and carbon uptake model at high (25 m) spatial resolution and daily time step. The model shares a common heritage with the Australian Water Resources Assessment Landscape (AWRA-L) water balance model used by the Bureau of Meteorology and includes coupled models of water, carbon and biomass (fuel) dynamics that can be applied at high resolution. The model-data fusion framework is referred to here as the High-resolution Fire Risk and Impact (HiFRI) framework.

The case study comprised the period 2000-2010 for the western ACT, including native forests, plantation forests and grasslands. Much of the area was burnt in 2003. The data integrated within HiFRI included high-resolution Landsat imagery, a digital elevation model and daily weather grids. The case study demonstrated that it is feasible to produce estimates of the effects of fires on water and carbon balance variables. The results show strong slope effects associated with solar irradiance. Integrating satellite observations also showed the expected influence from vegetation regrowth after the fire.

A key priority for further development is to define one or more potential practical applications. However, the research in question was undertaken in the first phase of the life of the BNHCRC (2014-2017) and not continued thereafter in response to a project evaluation and prioritsation process. More info in van Dijk et al. (2015).

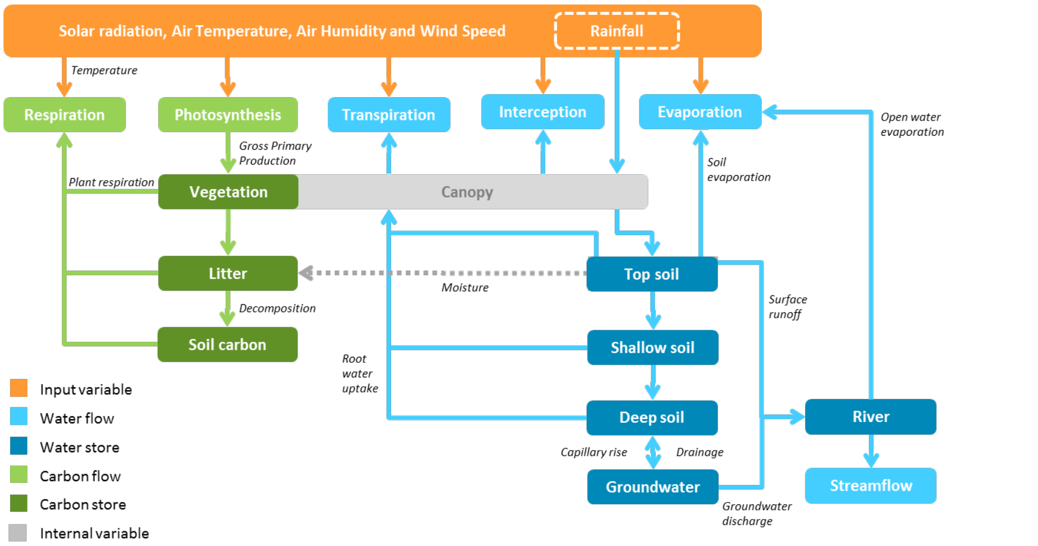

FIGURE 4 - ILLUSTRATION OF THE HIFRI MODEL. THE GREEN COMPONENTS ARE NOT CURRENTLY PART OF THE OPERATIONAL AWRA-L MODEL IN USE BY BUREAU OF METEOROLOGY.

ANALYSIS OF THE SUITABILITY OF OPERATIONAL COARSE RESOLUTION NEAR-SURFACE SOIL MOISTURE DATA TO IMPROVE THE MCARTHUR FFDI

For most of Australia, the McArthur Forest Fire Danger Index (FFDI) is currently calculated based on soil moisture deficit (SMD) estimated from the Keetch-Bryam Drought Index (KBDI). The KBDI is an empirical estimate of SMD, and relies on several assumptions regarding how precipitation can enter and exit the soil profile.

Information on SMD, or soil moisture more broadly, can be obtained from many other sources currently available and may have the potential to improve the estimation of FFDI. One advantage of using such soil moisture information in the calculation of the FFDI, compared to SMD information, is that soil moisture can be directly measured at a site and used as a reference for the comparison of spatially averaged data sets.

We investigated opportunities to better inform the FFDI through the consideration of alternative soil moisture data sources. Two alternative products that are known to predict soil moisture well are described and evaluated: (1) the model-based Antecedent Precipitation Index (API) and (2) the official Soil Moisture Ocean Salinity (SMOS) satellite mission soil moisture estimates. The alternative data sources were used to calculate the Drought Factor and subsequently the FFDI over a sample period of four years (2010-2013), covering the period available to both products. The utility of the alternative soil moisture data sets was compared to the currently used KBDI data set through sensitivity testing, to explore the suitability of the products in potentially informing calculation of FFDI.

The results showed that the KBDI is a relatively poor predictor of soil moisture content, and much better estimates can be obtained from the model, the satellite, or both. However, replacing the KBDI with more accurate soil moisture estimates is not straightforward, as it requires scaling of the soil moisture units. The conceptually most logical scaling approach was shown to lead to different temporal distribution and frequency of FFDI values, which is likely to create problems in operational use. This highlights the lack of physics basis and interpretation for the McArthur FFDI approach, which will need to be addressed before improved estimates of soil moisture (and fuel moisture) can be used productively to improve fire danger assessment. Further detail is presented in Holgate (2017).

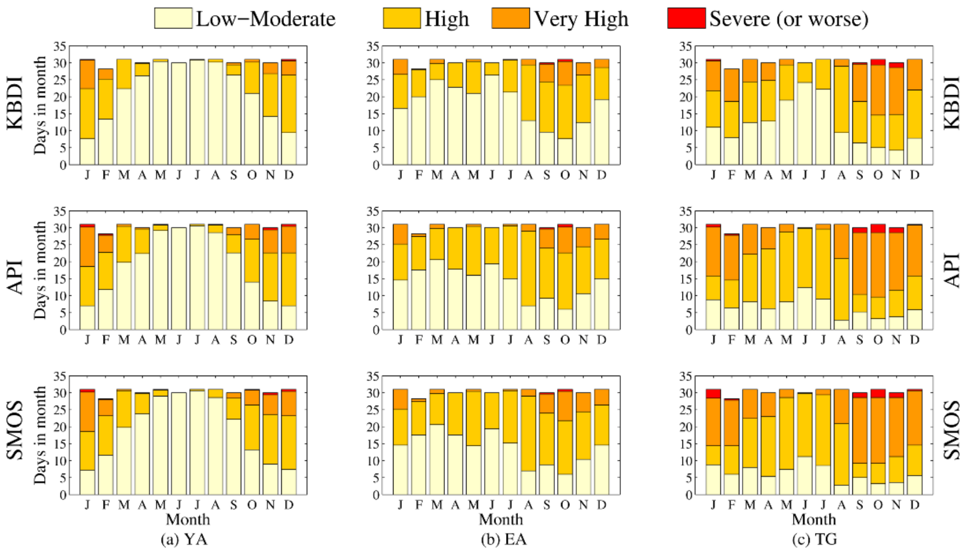

FIGURE 5 - FREQUENCY DISTRIBUTION OF FIRE DANGER RATING (FDR) BY MONTH (2010-14) AT SITES (A) YANCO AGRICULTURAL INSITUTE (YA); (B) EMERALD AIRPORT (EA); AND (C) TERRITORY GRAPE FARM (TG).

TOWARDS COMPREHENSIVE CHARACTERISATION OF FLAMMABILITY AND FIRE DANGER

Fire danger ratings inform the community and fire managing agencies of fire risk. Fire danger ratings are currently primarily based on fire danger indices (FDIs) calculated using methods that were developed many decades ago. The challenges and issues with these methods are well documented. We developed a more objective and observation-based approach to fire danger assessment that considers spatial data on the occurrence of actual fires as well as on fire factors that are already routinely produced every day for Australia. A preliminary assessment suggested a very good potential of the methodology to formally and objectively incorporate any new fire danger predictors (Figure 6). Further research should combine the method with forecasted rather than observed weather and fuel conditions to produce forward predictions of expected FDI. More details in Van Dijk et al. (2019). Our approach is complementary to the fire behaviour approach taken by AFDRS which is a work in progress.

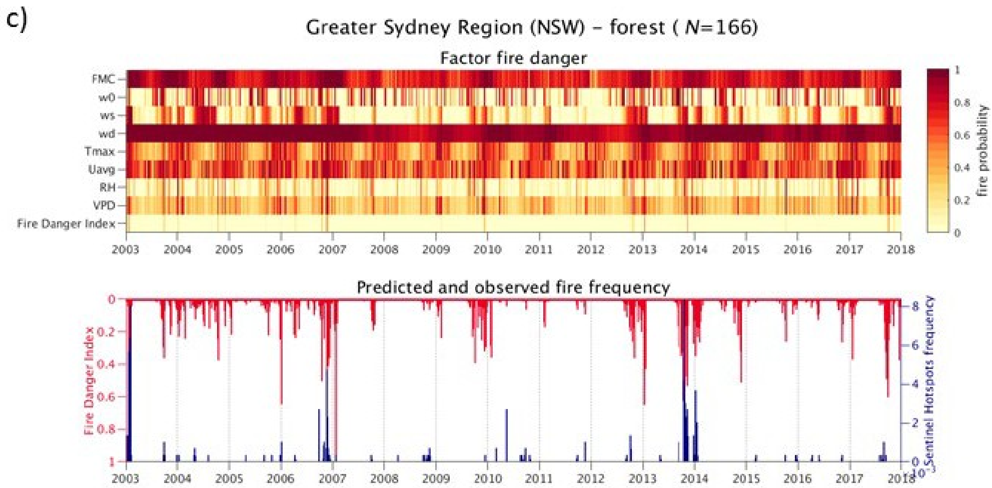

FIGURE 6 - EXAMPLE TIME SERIES OF FIRE PROBABILITY FOR INDEX COMPONENT AND OVERALL FIRE DANGER INDEX FOR GREATER SYDNEY REGION (TOP) AND COMPARISON OF OVERALL FIRE DANGER INDEX AND OBSERVED FIRE FREQUENCY (BOTTOM). TIME SERIES ARE ALL CALCULATED AS AVERAGE ACROSS THE VEGETATION TYPE AND FIRE WEATHER AREA. ALL EIGHT PREDICTORS (LFMC, W0, WS, WD, TMAX, UAVG, RH, AND VPD) WERE RESAMPLED FROM THEIR ORIGINAL RESOLUTION TO 0.025° AND DAILY RESOLUTION OF THE FIRE OBSERVATIONS. THE ANALYSIS PERIOD WAS 2003-2017.

FMC,FUEL MOISUTRE CONTENT; W0, WS, WD ARE THE RELATIVE MOISTURE AVAILABILITY IN THE TOPSOIL (0–10 CM), SHALLOW SOIL (0.1–1M) AND DEEP SOIL (1–6M), RESPECTIVELY; TMAX, MAXIMUM DAILY TEMPERATURE (°C); UAVG, MEAN DAILY WIND SPEED (M/S), RH, RELATIVE HUMIDITY (RH, %) AND VPD, VAPOUR PRESSURE DEFICIT (PA).

UTILISATION AND IMPACT

SUMMARY

In response to the information requirements expressed by end-users, we developed an experimental, operational, near-real-time flammability data service (The Australian Flammability Monitoring System, AFMS). Emergency services and land management agencies are using the system's different filters and settings to evaluate the risk of a bushfire occurring and spreading in certain parts of the country, based on the dryness of soil and fuels and the flammability of vegetation. The AFMS is starting to be part of preseason planning when fire agencies and land management departments formulate their seasonal outlook for fire and map at-risk areas.

THE AUSTRALIAN FLAMMABILITY MONITORING SYSTEM

Output description

The Australian Flammability Monitoring System (AFMS, http://anuwald.science/afms) is the first, continental-scale prototype web service providing spatial information on landscape flammability conditions.

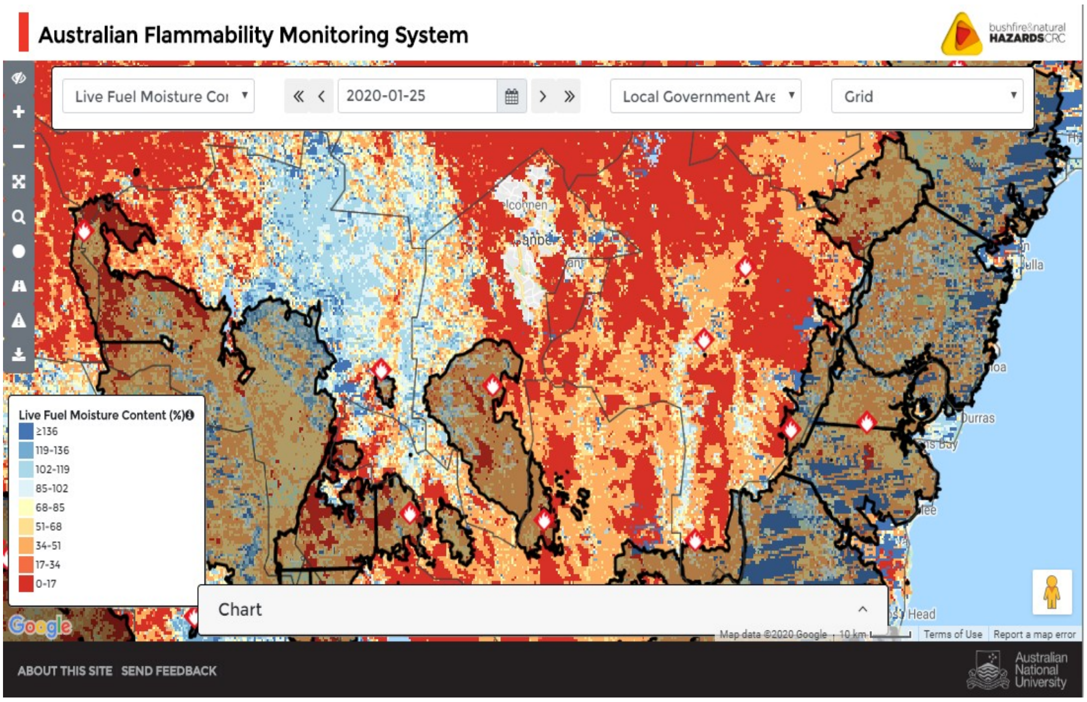

FIGURE 7 – MAP OF FMC AS DISPLAYED IN THE AFMS AT THE END OF JANUARY 2020. RED REPRESENT VERY DRY FUEL WHILE DARK BLUE THE OPPOSITE, ACTIVE FIRES AT THAT TIME AND THE FIRE PERIMETERS ARE ALSO DISPLAYED. THE MAP CLEARLY SHOWS HOW DRY THE FUEL WAS IN THE AREAS THAT WERE BURNING.

More specifically, the AFMS provides easier and faster access to spatial information on:

- Live FMC, in kg water per kg dry matter, expressed as a percentage
- Uncertainty in the FMC values, in the same units

- A Flammability Index (FI), providing a relative measure of fuel flammability between 0 and 1
- Soil moisture content near the surface (0-10 cm), in m3 water per m3 of soil volume
- Soil moisture content in the shallow soil (10-35 cm), in the same units.

All the information visualised at the AFMS, except the soil moisture values, are research outputs of this project. The soil moisture content values are research outcomes from the project “Improving land dryness measures and forecast” led by Dr Imtiaz Dharssi (Bureau of Meteorology).

The AFMS allows users to visualise and interpret information on all these variables as maps or graphs for any part of Australia. Data can be compared to preceding years or downloaded for further analysis and also be summarised per regional areas.

GIS layers showing the outlines of Fire Weather Areas, Local Government Areas, States and Territories, National Parks, and Natural Resources Management regions can be selected to combine with the map and assist in spatial orientation. The map can also be made semitransparent to discern underlying a road map or satellite imagery.

The AFMS provides information on fuel condition and flammability across Australia at 500 m resolution providing a clearer picture of the landscape where there are high levels of vegetation and soil dryness, which are the perfect conditions for a severe bushfire. However, end-users also highlighted the need of a higher spatial resolution version of the AFMS to allow the identification of local FMC gradients in the landscape that are currently not identifiable using the 500 m pixel resolution of the MODIS product currently underpinning AFMS. Consequently, we have adapted the FMC code for computing the FMC and Flammability maps visualised in the AFMS to run with Geoscience Australia high-resolution datasets in their cloud infrastructure. We have provided a proof-of-concept code that computes the products using Sentinel 2 data at a resolution of 20 m and GA is currently working on the operational implementation.

Extent of use

The AFMS has been used to make informed decisions about where a fire may ignite and spread, and what areas should be prioritised when sending resources and equipment. It has also been used in prescribed burn planning, particularly in mountainous locations where flammability changes depending on terrain aspect.

The AFMS has been demonstrated in operations centres and media commentary.

Since we released the AFMS version 1.0, we have invited end-users to provide comments and suggestions through seminars and workshops as to the website design and features, or on what might be required to improve and make the website optimally useful. For example, on 23 March 2018, the AFAC Predictive Services Systems Working Group sponsored a webinar where the AFMS was demonstrated and followed by a facilitated discussion on priorities for further development. The system was also presented in a Fire Management Workshop organised by the Fire and Incident Management Branch of NSW National Parks and Wildlife Service on the 15th of May 2018 in Sydney and demonstrated at the NSW Rural Fire Service headquarters in Sydney on the 12-13 Nov 2019 2019-2020 fire season. These types of educational events are helping to inform fire and land managers of the benefits of using the AFMS in their organisation to assist them with resource allocation for fire protection and response improved awareness of fire hazard to people and property, as well as to assist on scheduling planning and prevention activities (Fig. 7). At the same time, the feedback received during these events helped us to meet the end-user requirements better and guide developments for the release of subsequent versions.

Utilisation potential

For now, the core audience for the system is fire managers. All end-users involved in the project, and participating in several seminars and presentations featuring the AFMS, recognised the value of the system to improve fire management in Australia. Fire managers across Australia can use the AFMS to understand when our landscape is in a position that is either not going to burn, burn in a way that will allow them to control a fire, or when conditions are so dry that if a fire starts it will be very dangerous and difficult to control.

However, they also identified some significant barriers to adoption by the Australian bushfire sector. Firstly, neither FMC nor FI are presently used in any models or systems. This means that the sector needs to explore the information and develop work processes for using it. A clear example woud be to use the FMC as inputs in the AFDR which highlights "Fuel Condition" as one of the key drivers. Until that happends, some suggestions for use are indicated in figure 7.

In the future use of the AFMS could expand to individual community members, such as farmers. Those on the land could use the mapping to assess how dry their landholding is when preparing for the fire season. While there has been interested from community groups on how the mapping can be used at a local level, people will always take time to trust and use a new information system.

The team is testing the AFMS in its present state before identifying where it can be further used by fire managers and the community. We have shared our findings with key stakeholders through education events that have helped inform fire and land managers of the benefits of using a tool such as the AFMS in their organisation. The AFMS has also been included in teaching advanced fire science at tertiary institutions.

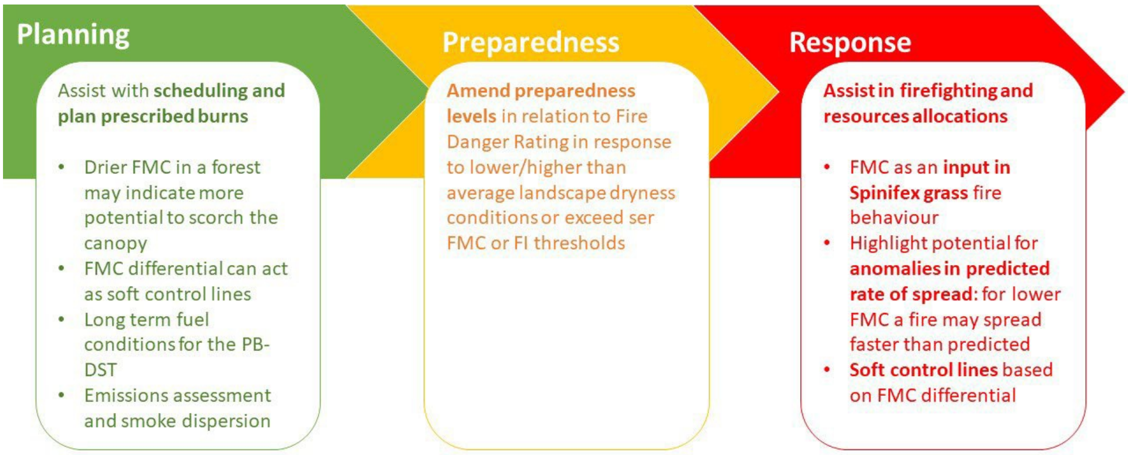

FIGURE 8 – CURRENT AND POTENTIAL USES OF THE AUSTRALIAN FLAMMABILITY MONITORING SYSTEMS IN FIRE MANAGEMENT

Impact

The AFMS is the first web application in the world to disseminate satellite-derived FMC, flammability, and other fire risk-related products at such a continental scale. The spatial maps provided on the website are used by land and fire managers to plan fuel-reduction activities, such as prescribed burning. The AFMS is also attracting great interest from insurance companies, which can use the data to price fire risk into their policies. Also, several private landowners have mentioned their interest in using our spatial data to inform their bushfire plans and help them prepare for the bushfire season.

The AFMS's algorithm to calculate satellite-derived FMC has also been implemented in the emissions assessment and smoke-dispersion module of the European Commission's Forest Fire Information System, which provides the European Commission and the European Parliament with updated and reliable information about wildland fires on the continent. The product has also been evaluated and used in South Africa, Argentina, Italy, the United States, and China.

Utilisation and impact evidence

We provide a summary of the use of the AFMS over the 2019/2020 fire season. The AFMS received around 1,500 visits between November 2019 and February 2020, which averages around 15 sessions per day in that time, with sessions averaging 6 minutes. There was a spike of users around the new year / early January peak in the fire season. From March to 26 April, the AFMS had over 1,400 users (50 per day). The top cities accessing the website were Sydney (20%), Melbourne (20%), Brisbane (10%), Canberra (7.5%), Perth, Adelaide and other places. Most users hit the site directly rather than search or referrals. NSW RFS and NSW OEH are both in the top 10 service providers, suggestion people connecting from within their office network but the majority were reporting via public telecommunication, suggesting people accessing the site from home/mobile.

Some selected Testimonials on the use and impact of project outcomes:

- **Laurance McCoy, NSW Rural Fire Service.** From our [NSW-RFS] perspective, statewide there has been recent patchy rainfall and it is sites like Marta's that help us to actually detect the risk, or give us more detailed analysis in terms of the effect of that rainfall"
- **Stuart Matthews, NSW Rural Fire Service.** Over the past year, this project has demonstrated the value of researchers working closely with end-users to bring research to utilisation. The Australian Flammability Monitoring System has been useful not only in sharing research outputs with operational users but also allowed users to provide feedback during the project, leading to an improved interface to the data. The project team have also been doing excellent work to expand the impact of their research and ensure the longevity of the work. This includes reviewing potential alternatives to the ageing MODIS remote sensing platform, revising the flammability index to include dead fuel moisture effects, and coupling dead fuel moisture models with soil moisture products. These efforts are building an integrated suite of observational and modelling tools that will enable users to better understand and predict potential fire occurrence and behaviour.
- **Adam Leavesley, ACT Parks and Conservation Service.** The ACT Parks research partnership with the Mapping Bushfire Hazards and Impacts research group has yielded some exciting operational advancements in the past 12 months. These are 1) Improved estimates of the extent of flammable land in mountainous terrain; 2) application of LiDAR-derived fuel maps to bushfire suppression, and 3) greater experience in the use of LiDAR-derived fuel maps in prescribed burning operations. Also, the usability of the Australian Flammability Monitoring System (AFMS) has greatly advanced the following additional utilisation investment by the CRC during the last financial year. At a national level, fuel moisture information has been identified as a key gap in available inputs for bushfire risk assessment.
    - Analysis of fire severity mapping. The research group has provided expert advice to ANU to ACT Park's analysis of prescribed burning patterns from five years of data collection. The analysis yielded important information about the relative flammability of different topographic aspects during the prescribed burning season. The information was used to produce the next 10-year burn plan for the ACT, improving the reliability of the risk reduction analyses and the benefit-cost analyses conducted for the plan.
    - Operational experience of LiDAR-derived fuel maps for fire suppression. The 2018-2019 bushfire season was the first opportunity for ACT Parks to evaluate the use of LiDAR-derived fuel maps for fire suppression. The maps clearly indicated where fuel had been reduced by prescribed burns conducted in 2013 and this

supported decision-making in the IMT. A poster demonstrating the example was on display at BNHCRC/AFAC conference in Melbourne in August.

  - Use of LiDAR-derived fuel maps for prescribed burn planning. The maps are a valuable tool for prescribed burn planning in forested mountainous terrain and the trials have shown that the data can be useful for more than five years. It is intended to acquire more LiDAR to update the maps.
  - Australian Flammability Monitoring System (AFMS). The usability of the AFMS has greatly increased following utilisation investment by the CRC. It is becoming clear that at a national level fuel moisture is a key missing component of inputs for estimating bushfire risk. New work will ensure the continuity of the system when MODIS is decommissioned. Having identified the need for this information, the bushfire sector must now develop a robust and efficient way to apply it.

- **Simeon Telfer, Fire Management Officer, Department for Environment and Water (DEW).** DEW in South Australia is certainly interested in utilising AFMS, particularly the higher spatial resolution. As an example, we had a particularly tricky burning season last autumn due to fuel moisture deficits, with the majority being far too dry to safely burn, but some pockets being very suitable. The spatial resolution of AFMS was too a bit too coarse to identify these pockets easily, however, the suggested resolution would be a very useful tool. In the longer term, we would like to incorporate this data as one component of a burning window decision support tool. Obviously, the addition of a live fuel moisture component may also help explain unexpected fire behaviour of bushfires, which is currently a gap in our analysis of fire behaviour.
- **David Taylor, Fire Planning Officer, Tasmania Parks and Wildlife Service.** I have developed several tools for our Fire Duty Officer to use. One is the Bushfire Operational Hazard Model (BOHM) I display base data, fuel group(13), fuel age, fuel load (100m resolution updated yearly). I import forecasted NetCDF grids from the BOM so they have access to 15:00 forecasted weather values(Temp, RH, Wind, Curing). I am now downloading Water Landscape Water Balance – Root Zone, your Flammability Index and JASMIN soil moisture data from the AFMS. [...] With the flammability index I will have to read to get an understanding of it and how it is calculated to determine the best way in which we could use it. Offhand probably the same as the HFI grid I produce (if you were to drop a match how hot fire would get) we use that in prepositioning fire crews and patrols.
- **Phill McKenna, Senior Research Officer, Centre for Mined Land Rehabilitation.** Thanks very much for sending your paper [about the AFMS]

through. It is great to see that this work has been completed and I would love to look further into how this can be applied to the recent fires in Central QLD using high res imagery. [...] The recent fires in central QLD have got me thinking about incorporating this data into our workflow. The most obvious option is to use some areas as analogues for our controlled burns at mine sites in Central QLD. However, there are a number of broader related questions that I would include in the study, including looking at the FMC and flammability of various fuels (including rainforest areas) in the lead up to the fires in November. [...]

- **James Bondio, Manager Portfolio Data Analytics at Energy Queensland** contacted us as he is establishing a bushfire planning committee at Energy Queensland and was interested in connecting to our research.
- **Adam Kiil, Senior Data Scientist at Western Power (WA)** contacted us because he would like to include the information displayed in the AFMS into his fire risk and vegetation management modelling.
- **Dr Senani Karunaratne, Senior Research Scientist at the Agriculture Victoria Research Department of Economic Development, Jobs, Transport and Resources** contacted us requesting more information on the AFMS as they would like to use it to model productivity at a farm scale.
- **AON and Willis, (re)insurance brokers** have contacted us to request more information about the AFMS as they would like to use the information to map fire risk and price their policies.

Please see reference to publications, articles and media evidence that have been used to communicate utilisation and/or research impact in the publication list at the end of the document.

CONCLUSION

The Bushfire & Natural Hazards CRC project '*Mapping Bushfire Hazards and Impacts*' used cutting-edge technology to produce near-real-time spatial information on fuel condition, fire hazard and impact to support a wide range of fire risk management and response. After exploring different data sources and modelling and in response to the end-users' priorities, this project mainly focused on the development of accurate algorithms to retrieve life and FMC, fuel load and flammability. Live FMC and flammability was make easily accessible via the Australian Flammability Monitoring System (AFMS) prototype. Further research is need to further validate and upscale the dead FMC and fuel load methodologies at a continental scale before been able to serve those maps via the AFMS.

The AFMS is in test-use in many organisations and has attracted a lot of national and international interest. However, the main priority to facilitate adoption in the Australian bushfire sector is to further work on developing specific, operational applications and integrate the information displayed in the AFMS into agencies' current and future decision processes and tools.

Future research should also focus on developing a multi-sensor system that will display daily information on fire danger and fuel condition from whatever satellite sensor has collected an image over Australia, including high-resolution satellite imagery. The use of high-resolution satellite imagery will provide an unprecedented level of detail and accuracy when estimating fuel condition bringing the system closer to use in operations. However, the data volumes and large computing resources required to store and generate these high-resolution products become a challenge. Consequently, future research should also focus on developing an alternative methodology for computing fuel condition that can provide up to date estimations by reducing the required storage and computing resources using state-of-the-art artificial intelligence algorithms.

Finally, and in the longer term, there is a need for a bespoke high-resolution space-based fuel monitoring sensor tuned to the Australian landscape, with spectral wavelengths designed specifically to look at live FMC and fuel load, thus informing at the highest possible accuracy, when and where forests are approaching critical dryness levels and fuel loads. This is because the all the data explored in this project to retrieve fuel condition is collected by sensors onboard of foreign-owned satellites that do not fully fit-for-purpose in terms of readiness, spatial resolution and signal sensitivity in Australia's Eucalypt-dominant forests.

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TEAM MEMBERS

RESEARCH TEAM

Marta Yebra

Senior Lecturer in Environment and Engineering at the Fenner School of Environment & Society and Research School of Aerospace, Mechanical, and Environmental Engineering, Mission Specialist of the ANU Institute for Space. Her research focuses on using remote sensing data to monitor, quantify and forecast natural resources, natural hazards, and landscape function and health at local, regional and global scales.

Albert van Dijk

Professor in Water Science and Management at the Fenner School of Environment & Society. He has expertise in retrieving vegetation structure and density information from optical and passive microwave remote sensing, and in the application of remote sensing observations and biophysical models into downstream operational environmental monitoring and forecasting methods.

Geoff Cary

Associate professor in Bushfire Science at the Fenner School of Environment & Society (ANU). Geoff's research interests include evaluating fire management and climate change impacts on fire regimes using landscape-scale simulation and statistical modelling, ecological investigation of interactions between fire and biota from genes to communities, empirical analysis of house loss in wildland fire, and laboratory experimentation of fire behaviour.

OTHER CONTRIBUTING STUDENTS AND COLLABORATORS

1. **Li Zhao** PhD student at ANU under the supervision of Dr Marta Yebra, Prof Albert van Dijk and A/Prof Geoff Cary and BNHCRC Student, looking at improving estimates of litter FMC by incorporating the effect of soil moisture content in existing physics-based models.

2. **Sami Shah** PhD student at ANU under the supervision of Dr Marta Yebra, Prof Albert van Dijk and A/Prof Geoff Cary and BNHCRC Associated Student, is working on an integrated fire risk index for Australia.
3. **Gianluca Scortechini** PhD candidate at ANU under the supervision of Dr Marta Yebra, Prof Albert Van Dijk and Dr Pablo Rozas-Larraondo (ANU) is developing a global FMC algorithm.
4. **Matthew Gale** PhD candidate at ANU under the supervision of A/Prof Geoff Cary, Prof Albert van Dijk and Dr Marta Yebra is using remote sensing to characterise variables relevant for fire behaviour.
5. **Dr Yang Chen** was PhD candidate from Monash University and BNHCRC Associated Student completed her thesis on "Modelling forest fuel hazard change over time using LiDAR technology". She has since secured a postdoctoral research position at CSIRO Perth.
6. **Dr Andrea Massetti** was a PhD candidate from Monash University UNSW and BNHCRC Associated Student completed his thesis on mapping fire severity and vegetation recovery using remote sensing data.
7. **Dr David Riaño** Senior researcher at the University California Davis (California), is an ongoing collaborator on estimating fuel properties from satellite data.
8. **Dr Xingwen Quan** a lecturer at the University of Electronic Science and Technology of China. He is supporting the validation of the Australian Flammability System at a global scale.
9. **Dr Samsung Lim** (UNSW) an expert on full-waveform LiDAR, is providing expert advice on the full-waveform LiDAR processing.
10. **Dr. Philip Frost** (Council of Scientific and Industrial Research, South Africa) has collected field live fuel content measurements to validate our satellite product over South Africa and validated and implemented the AFMS in South Africa. Other international researchers have contacted us for a similar objective, this includes Dr Florent Mouillot (UMR CEFE CNRS, University of Montpellier), Dr Carlos Di Bella (Instituto de Agua y Clima, Argentina), Dr Mariano Garcia (Center of landscape and climate research, University of Leicester, UK), Prof Emilio Chuvieco (University of Alcala, Spain) and Prof Susan Ustin (UC-Davis).
11. **Lois Padgham** was an undergraduate student at ANU as well as operational bushfire firefighter of ACT Parks and Conservation Service and undertook a special topic project under Dr Marta Yebra's supervision to validate satellite-based fuel moisture estimates for the forest in Namadgi NP as well as observations from the CosmOz sensor to monitor fuel moisture content.

12. **Nicola McPherson** was an Engineering Honours student at ANU that carried out a project entitled "Grassland curing and moisture content monitoring with passive microwave remote sensing".
13. **Honghao Zeng** was a master student enrolled in the Fenner School of Environment and Society (ANU) who carried out a multivariable analysis of fire occurrence in Australia under the supervision of Dr Marta Yebra.
14. **Zhaoyu Zhang** was an undergraduate student that carried out an independent research project on characterising and assessing the spectral signature of grasslands with different degree of curing.
15. **Emilie Morscheck** ANU College of Engineering and Computer Science was an undergraduate student that carried out a project on Risk assessment for wildfire occurrence in high-voltage power line corridors by using remote-sensing techniques. Role: Primary Supervisor.
16. **Sheng Xuan** was an honours student at Fenner School of Environment and Society, ANU comparing the influence of fuel moisture content and curing on fire behaviour of grassland-based. Role: Primary supervisor
17. **Ivan Kotzur** was an honours student at Fenner School of Environment and Society, ANU looking at remotely sensing primary production recovery following a bushfire.
18. **Liam Robin Steel** undertook a special topic project at Fenner School of Environment and Society, on the evaluation of fire severity algorithms with grown truth data.
19. **Lauren De Waal** (Honours student, Research School of Engineering, ANU) Grassland curing and moisture content monitoring with automated sensing systems.

END-USERS

The table below lists the project's key end-users that have shown more constant support. The project team recognises that other stakeholders have approached the research team.

End-user organisation	End-user representative	Extent of engagement (Describe the type of engagement)
NSW Rural Fire Service	Stuart Matthews	Intellectual input into methods developed Support facilitating access to and understanding of internal operational systems and data Facilitate meetings with end-users in his organisation to understand their needs

		Reviewing and adding testimonials to most of our milestone reports
ACT Parks and Conservation	Adam Leavesley	Intellectual input into methods developed Support facilitating access to and understanding of internal operational systems and data Facilitate meetings with end-users in his organisation to understand their needs Reviewing and adding testimonials to all of our milestone reports Supporting fieldwork by providing staff members and vehicles Leading the writing of conference manuscripts with our team as co-authors
Department of Defence	Frederick Ford	Intellectual input into methods developed Support facilitating access to and understanding of internal operational systems and data Facilitate meetings with end-users in his organisation to understand their needs Reviewing and adding testimonials to one of our milestone reports
QLD Fire and Emergency	Andrew Sturgess	Intellectual input into methods developed Support facilitating access to and understanding of internal operational systems and data Facilitate meetings with end-users in his organisation to understand their needs
Department of Environment, Water and Natural Resources, SA	Simeon Telfer	Intellectual input into methods developed Support facilitating access to and understanding of internal operational systems and data Facilitate meetings with end-users in his organisation to understand their needs
NSW National Parks and Wildfire Service	Felipe Aires	Intellectual input into methods developed Facilitate meetings with end-users in his organisation to understand their needs

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