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A MODEL-DATA FUSION FRAMEWORK FOR ESTIMATING FUEL PROPERTIES, VEGETATION GROWTH, CARBON STORAGE AND THE WATER BALANCE AT HILLSLOPE SCALE

FEASIBILITY STUDY IN NAMADGI NATIONAL PARK, ACT

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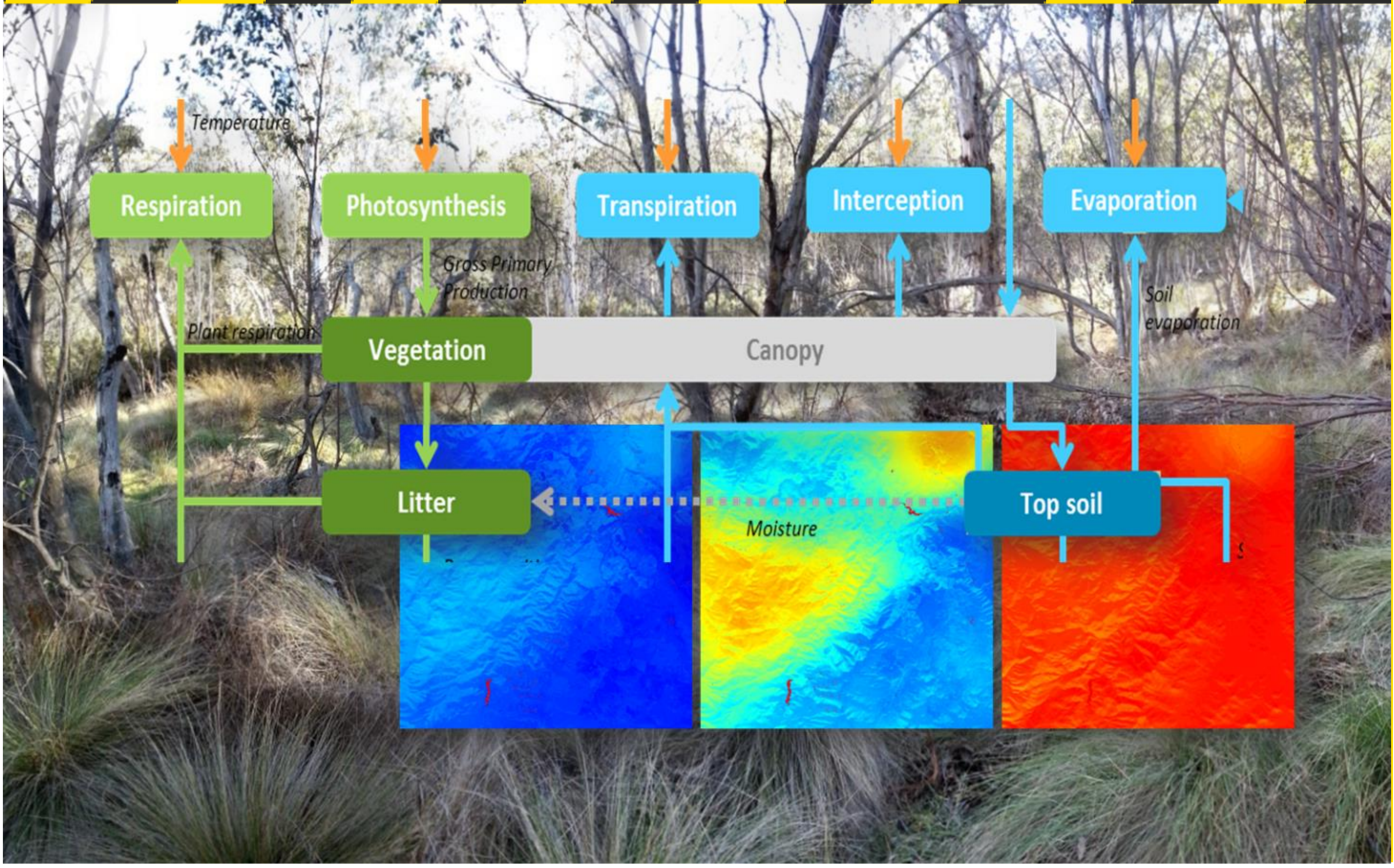

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Cover: Illustration of the model-data fusion. Credit Albert van Dijk.

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EXECUTIVE SUMMARY

This progress report is an output from the Bushfire and National Hazards CRC, Project A1 'Mapping Bushfire Hazard and Impacts'. It documents the first steps in the development of 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. Model-data fusion refers to the blending of observations with model predictions by considering the error in both.

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 provisionally 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 climate grids. The case study demonstrated that it is feasible to produce estimates of 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. Possible applications discussed are as follows:

- **Quantifying changes in fuel load, water resources and carbon storage**. The results show that it is feasible to estimate the spatial and temporal impacts of burning on landscape values. Previous model applications support the predicted impact on streamflow generation, but further research would be required to calibrate the coupled carbon/fuel model for specific species, ecosystems and environments. Existing empirical fuel accumulation curves, field measurements and terrestrial and airborne LiDAR provide opportunities to do so.
- **Real-time fuel moisture mapping**. Information on spatial gradients in fuel moisture content is useful for fire managers planning prescribed burning. This would require modest further development and, if absolute moisture content values are required, model calibration. A key uncertainty is related to the gridded precipitation estimates and therefore the assimilation of additional field station weather and soil measurements may be advisable.
- **Fire spread modelling**. Fuel load and moisture content for different strata can partly be derived from the framework and may be of use for fire spread modelling. Further discussion is required to establish and prioritise such opportunities.

- **Real-time fire risk forecasting at high resolution**. The HiFRI framework would be readily combined with numerical weather forecasts available from Bureau of Meteorology. However, the effect of local topography and vegetation on wind speed may require further consideration and model development. It needs to be established whether real-time fire risk forecasts at high resolution would be of greater practical use to fire managers than the currently available forecast information.

It is intended that this progress report serve as a basis for further discussion with project end users and other stakeholders in the Bushfire and Natural Hazards CRC, with the goal of defining concrete applications, and based on this, further development and the establishment of application pilots.

ACKNOWLEDGEMENTS

This report was made possible through funding from the Bushfire and Natural Hazards CRC through the project 'Mapping bushfire hazard and impacts' (project A1, Milestone 2a – Case study for ACT forest analysing usefulness and reliability of LiDAR, Landsat and SRTM derived remote sensing information for spatial estimation of fire impacts on landscape values).

We thank John Gallant and Jen Austen of CSIRO for their assistance with the SRTM derived data and Juan Pablo Guerschman of CSIRO for his assistance with the Landsat data cube. We also thank Philip Zylstra of University of Wollongong and Jason Sharples and Rachael Griffith of UNSW for discussion of ideas, and Gary Featherston of the Australasian Fire and Emergency Services Authorities Council (AFAC) for his comments on an earlier draft.

Last but not least, we thank our lead end user Dr Adam Leavesley and his colleagues of the ACT Parks and Conservation Service, for their continued enthusiastic engagement and valuable feedback.

END USER STATEMENT

In this report, the project team has demonstrated a strong grasp of the issues and the scientific literature and this is an attractive feature of the project. It is a strength of the report that the limiting weaknesses is the present data availability and knowledge have been flagged because it provides the opportunity for the industry to advocate for improvement.

Adam Leavesley, *ACT Parks and Conservation Service, ACT*

INTRODUCTION

Government 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 MacArthur Forest Fire Danger Index to calculate a 'Drought Factor' from antecedent weather data, intended as a rough estimate of fuel availability and moisture content. To date, there has not been much emphasis on routinely providing and using spatial information on landscape-related hazard factors 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 in the near future due to current or upcoming research on fuel and fire behaviour.

In 2013, the Bushfires and National Hazards Cooperative Research Centre initiated the project **"Mapping Bushfire Hazard and Impacts"** (project code A1 – Van Dijk). The project aims to develop methods to produce the spatial information on fire hazard and impacts needed by planners, land managers and emergency services. The relevance and added value represented by these new information sources will be compared to the practical feasibility and costs of its use. The two research priorities are to produce spatial information on:

1. **Fuel and flammability**: mapping fuel load, structure and moisture and interpretation methods that can be used to support fire management and response activities. The outcome sought is better fire management and preparedness.

2. **Fire impacts**: spatial data and methods to determine the impact of unplanned and prescribed burning on fuel accumulation as well as landscape values (habitat, water resources and carbon storage) over time, in support of fire management. The objective is more effective and efficient fire and landscape management and through this, greater overall landscape value.

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

Land managers need spatial information on historic fire impacts, as well as on current fuel load and flammability, and landscape values such as water resource generation, carbon storage, and habitat. Relevant applications include the spread and impact of unplanned or prescribed fires and subsequent recovery on catchment water yield and the carbon lost and subsequently sequestered again after burning. Current prediction methods are crude and make bold assumptions; for example, about the similarity of the water use patterns between (well-studied) recovering mountain ash forests and (unstudied) other forest types.

The roadmap for this research activity sketches the pathway from research to industry solution (Figure 1). A high degree of adaptive management is implicit; each step will involve extensive discussion with end-users.

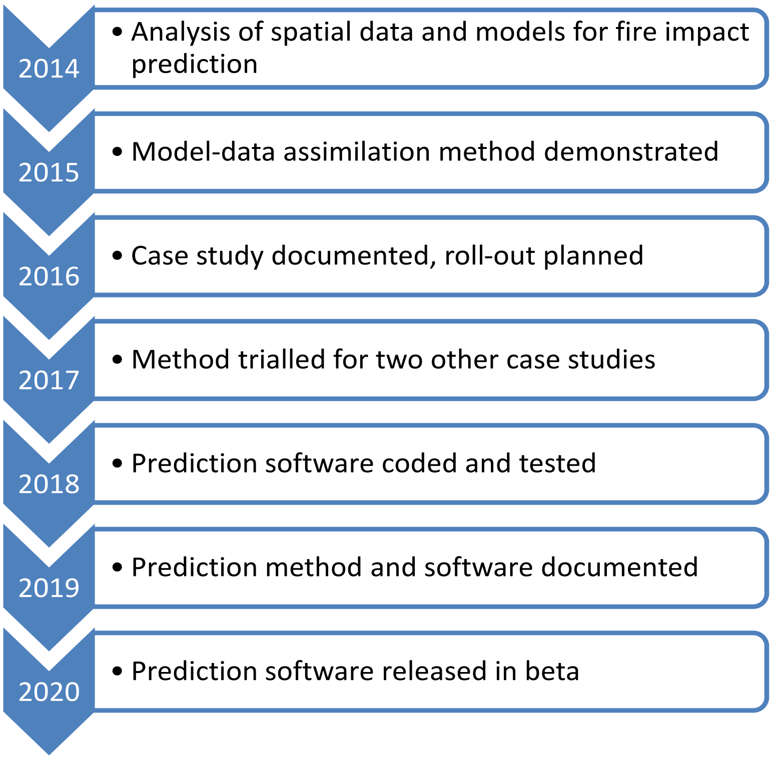

FIGURE 1. INDICATIVE ROADMAP FOR MODEL-DATA SYSTEM DEVELOPMENT

OBJECTIVE

This report documents the first step in the development of a model-data fusion framework that can provide best possible estimates on historic fire impacts, as well as on current fuel load and flammability and landscape values such as water resource generation, carbon storage, and habitat, as expressed in vegetation structure and composition. Model-data fusion refers to blending observations with model predictions by considering the error in both. In terms of biophysical variables, the overall objective can be translated into the goal of providing historic and current spatial information on:

- Vegetation biomass and carbon storage
- Vegetation height and structure
- Moisture content of living, suspended and surface fuel
- Water use and streamflow generation

The characteristics of the framework should be as follows:

- Spatial mapping is produced at the highest resolution feasible, so that the usefulness of the information for land and fire managers on the ground is maximised.
- Where possible, the information is up to date so that current conditions can be assessed.
- All essential input data used should be available anywhere in Australia.
- Additional local data sets can be used to further enhance estimates, or to calibrate or verify predictions.
- The resulting system can be made operational for any part of Australia.

CASE STUDY

The case study area is the western ACT including most of Namadgi National Park and plantation forests to the north of it, and includes adjacent areas of NSW. The area is bounded by longitudes 148.750° and 149.000° East and latitudes 35.250° and 35.625° South (see Figure 2). This represents an area of 28 by 42 km or 1,176 km2.

The period for which analysis was undertaken covered the full calendar years 2000 through to 2010.

The goal of this exercise was to analyse the usefulness of airborne and remote sensing observations in a model-data fusion framework, including using these data to set up a spatial forest growth, water use and carbon uptake model.

The area was chosen because it contains both native and plantation forest, contains several of ACT's water catchments, and experienced major fires in January 2003, meaning that there are recent satellite and field observations during several years before the fires as well as for the recovery phase.

Once fully tested and deemed sufficiently accurate for the purpose, the resulting time series and mapping can be combined with data of past fire events and severity, from ACT and NSW agencies or derived from remote sensing burned area mapping to analyse fire impacts on water, carbon and fuel as a function of fire severity and time since burning.

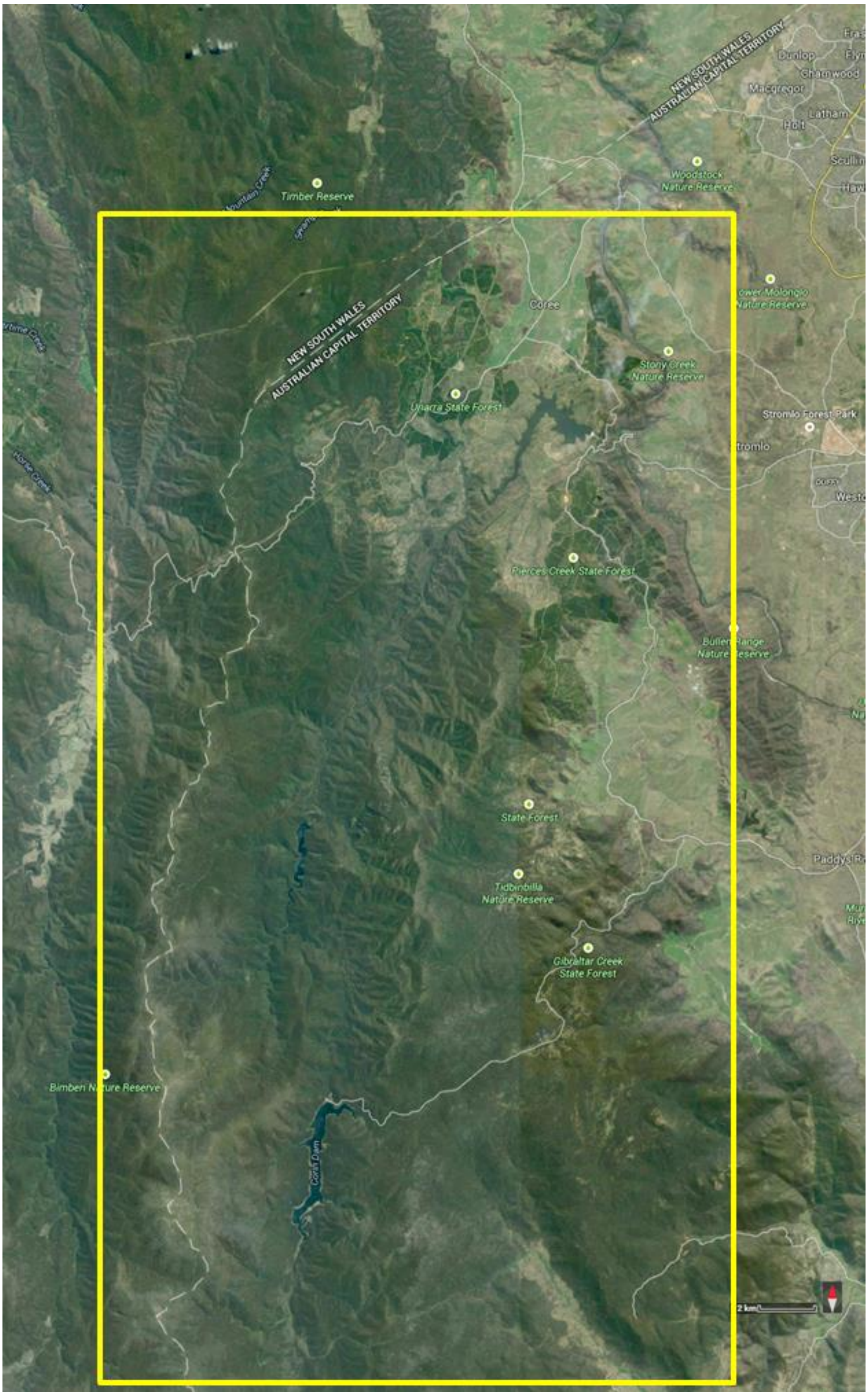

FIGURE 2. SATELLITE IMAGERY OF THE WESTERN ACT, AND ADJACENT AREAS IN NSW, SHOWING THE CASE STUDY AREA (YELLOW OUTLINE). (SOURCE: GOOGLE MAPS)

DATA

LANDSAT SATELLITE IMAGERY

Geoscience Australia (GA) has been collecting and archiving Landsat satellite imagery directly from a Landsat satellite downlink at Alice Springs since 1979. Until recently, it was costly and slow to retrieve and processing these imagery from the archive, moreover, the data were not atmospherically corrected (that is, the effect of the atmosphere on measurements was not removed, making data harder to work with).

This changed recently with the development of the Australian Geoscience Data Cube ('the data cube') – a set of data structures and tools that has been used to organise and analyse imagery for the years 1998-2012 of the Landsat collection across Australia. The data is hosted on the National Computational Infrastructure (NCI) in Canberra and amounts to 110 Terabytes of data derived from more than half a million images. Instead of the original images, the data are atmospherically corrected, and subsequently stacked into tiles of one degree (ca. 100 km) square, with a resolution of 4000 grid cells along both sides of the tile, equivalent to ca. 25 m on the ground (Figure 3).

As an example, the maps of the Normalized Difference Vegetation Index (NDVI) calculated from Landsat imagery acquired in the month before (December 2002) and after (February 2003) the 2003 fires are presented in Figure 4. The impacts of the fires are clearly present on the post-fire image through a dramatic reduction in the NDVI (brighter colours in the post-fire image in comparison to the pre-fire image).

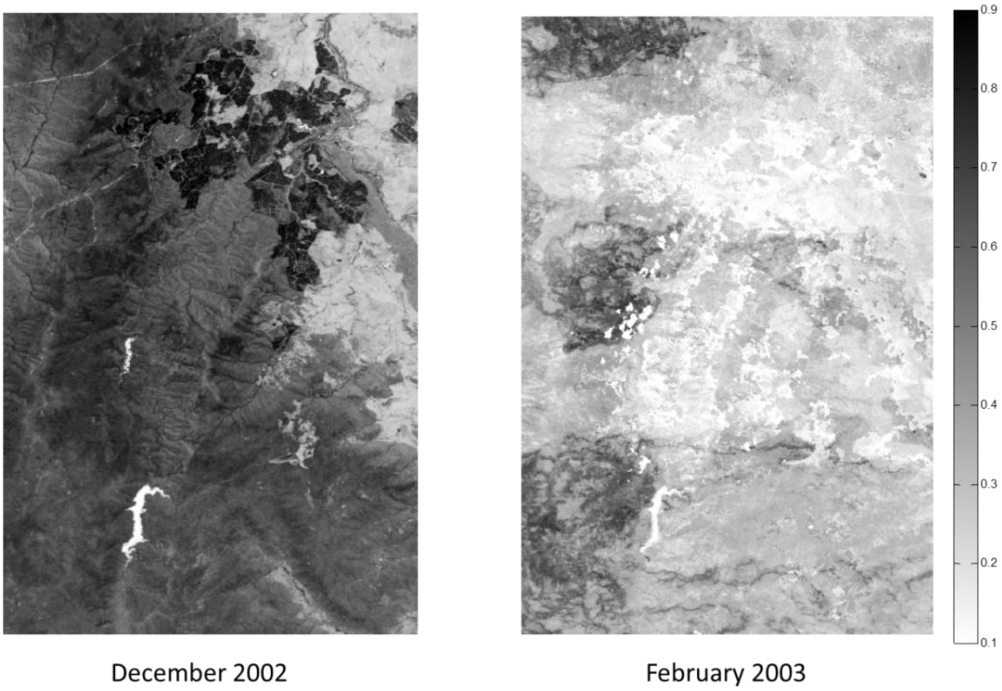

FIGURE 2. MAPS OF NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI) CALCULATED FROM LANDSAT IMAGERY THE MONTH BEFORE (LEFT) AND AFTER (RIGHT) THE JANUARY 2003 FIRES. DARK COLOURS REPRESENT HIGH GREENNESS.

SHUTTLE RADAR TOPOGRAPHY MISSION DERIVED DATA

The Shuttle Radar Topography Mission (SRTM) was an international research effort that obtained digital elevation models (DEMs) for almost the entire globe (between 60° N and 56° S). For many regions, it generated the highest-resolution elevation data available. The mission used a specially modified radar system that flew on board the Space Shuttle Endeavour during an 11-day mission in February 2000 (Farr et al., 2007). For Australia, a digital elevation model (with trees and other non-terrain features removed) was developed at 1 arc second resolution (ca. 30 m) (Gallant et al., 2011) and is available through Geoscience Australia.

Gallant and Austen (in prep.) used these data to calculate relative illumination for each month of the year. Relative illumination expresses the radiation that a grid cell will receive relative to that received on a horizontal surface, as a function of direct and diffusive radiation, slope steepness and aspect, and shading. These data were kindly made available by the authors for the purposes of this project; an example is shown in Figure 5.

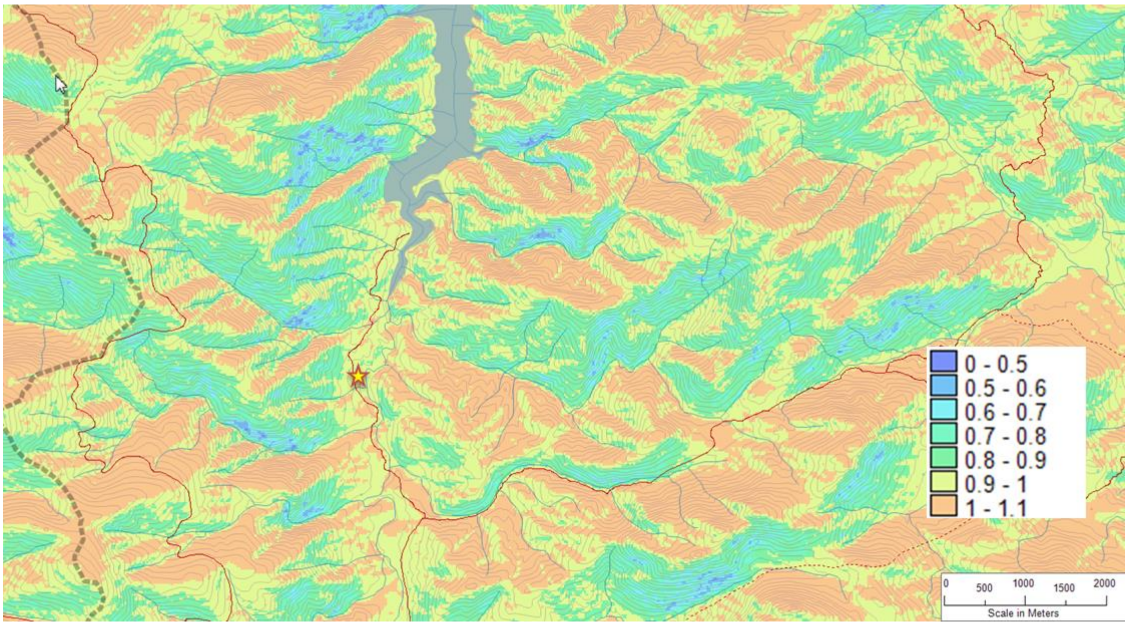

FIGURE 3. RELATIVE ILLUMINATION FOR OCTOBER FOR AN AREA SOUTH OF CORIN DAM, ACT. THE STAR DENOTES THE LOCATION OF THE NAMADGI NP COSMIC RAY SENSOR DISCUSSED ON PAGE 28.

DAILY CLIMATE GRIDS FOR AUSTRALIA

At present, there are two sources of daily climate data for Australia at 0.05° (ca. 5 km) resolution.

The Queensland Government maintains the SILO (Scientific Information for Land Owners) data base of historical climate records for Australia1. SILO includes interpolated surfaces of daily climate variables that have been derived either by splining or kriging station data. Daily maps for 1889 to present are available

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[1] www.longpaddock.qld.gov.au

for maximum and minimum air temperature; rainfall; pan evaporation; solar radiation; vapour pressure; and mean sea level pressure.

The Bureau of Meteorology provides a generally similar dataset free of charge2 The methods followed to generate these data are documented in Jones et al. (2009). Daily total rainfall grids are available for 1900 onwards, daily minimum and maximum temperature for 1910 onwards, vapour pressure is available for 1971 onwards, and solar exposure for 1990 onwards. The resulting data are generally similar to those available from SILO data, the main differences being that the interpolation of solar exposure data is enhanced with satellite observations where available; and that daily rainfall estimates are not provided where the station density is considered too low for credible interpolation.

In addition to these two data sets, the Terrestrial Ecosystem Research Network (TERN) has recently started producing daily climate grids at 0.01° (ca. 1km) resolution (Figure 6). The analysis method make full use of the historical Bureau of Meteorology data and uses a new regression-based procedure for obtaining standard period means for stations with short records (Hutchinson et al., publication forthcoming). The analyses have also incorporated the impacts of proximity to the coast on temperature and have refined the impacts of topography on precipitation. Finally, the analyses incorporate comprehensive semi-automated error checking and quality assurance processes on all data sets. Daily grids of precipitation, temperature and vapour pressure are currently available for 1970-2012 via the National Computing Infrastructure3.

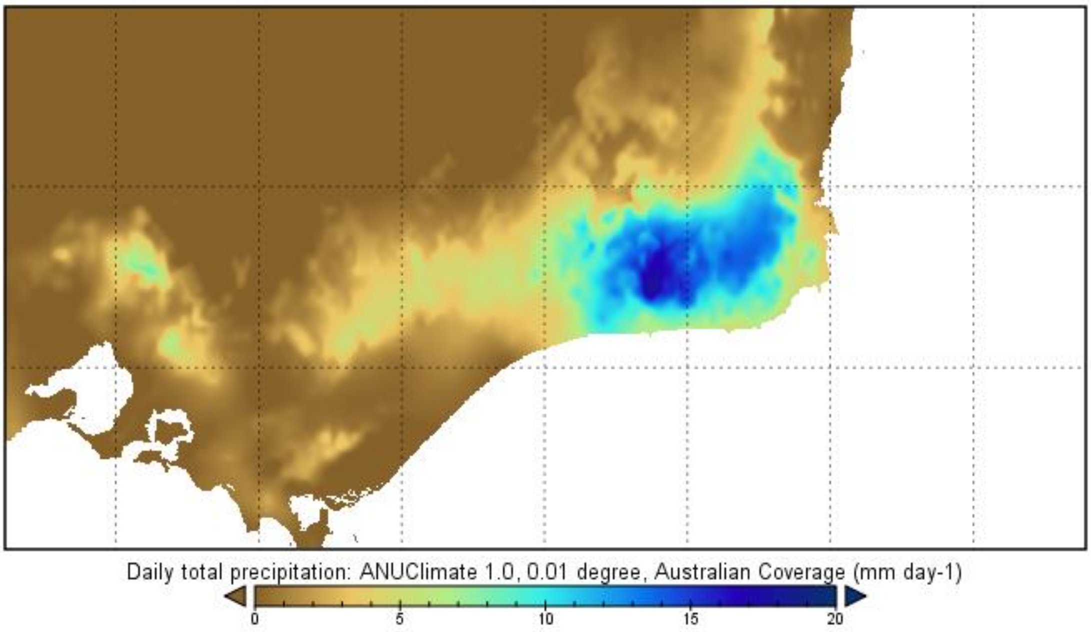

FIGURE 4. EXAMPLE OF A DAILY RAINFALL GRID AT 0.01° RESOLUTION (CA. 1KM) FROM THE TERN ECOSYSTEM MODELLING AND SCALING INFRASTRUCTURE FACILITY (E-MAST)

Wind can be an important factor determining drying rate before the risk of fire occurs, as well as in creating fire weather itself. It may be possible to use interpolated wind speed in future. Specifically, McVicar et al. (2008) developed a method to convert daily wind-run (km/day) from low-set anemometers (< 3

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[2] http://www.bom.gov.au/climate/maps/

[3] http://dap.nci.org.au/thredds/remoteCatalogService?catalog=http://dapds00.nci.org.au/thredds/catalog/rr9/Climate/eMAST/ANUClimate/0_01deg/v1m0_aus/day/land/catalog.xml

m) to daily average wind-speed (m/s), and then interpolate these spatially using ANUSPLIN Version 4.3 (Hutchinson, 2004). Currently, this method has been used to produce daily near-surface wind speed grids across Australia at 0.01° resolution for 1975-2014, by interpolating station measurements from the Bureau of Meteorology (Australian Daily Wind Data Product IDCJC06.200706). These data can be accessed via the CSIRO Data Access Portal[4]. A challenge at high resolution would be to account for the influence on local wind speed from (a) local hillslope topography, and (b) forest height and denseness, which are not accounted for in these gridded data. Both simple and complex methods exist to predict these effects (e.g., Forthofer et al., 2014). However, it is not clear how important such wind exposure effects are for determining spatial patterns in fuel, water and carbon dynamics, as opposed to fire behaviour.

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[4] http://dx.doi.org/10.4225/08/54C6F946C3AE8

MODEL SYSTEM

INTRODUCTION

The model used here to estimate vegetation growth, carbon uptake and water use shares the same heritage as the landscape water balance model (AWRA-L) in the Australian Water Resources Assessment system (Van Dijk, 2010; van Dijk and Renzullo, 2011).

AWRA was developed for the Bureau of Meteorology, who currently uses the model at 0.05° (~5 km) resolution to support production of the National Water Account and Australian Water Resource Assessment reports. The system combines a comprehensive spatial hydrological model with meteorological forcing data and remotely-sensed land surface properties, and produces estimates of water stored in the soil, surface water and ground water.

The Landscape hydrology model (AWRA-L) is part of AWRA and describes the spatial water balance. AWRA-L is intermediate between a simplified 'tiled' land surface model and a lumped catchment model. The water balance of a top soil, shallow soil, and deep soil groundwater and surface water dynamics are simulated. Actual evaporation is estimated using the Penman-Monteith model (Monteith, 1964) with the exception of the rainfall interception component. The model also includes a representation of vegetation and the way in which it responds to water availability. Model output spatial resolution is dictated by the meteorological forcing which is based on a combination of station network observations and geostationary cloud cover observations interpolated on a 0.05° regular grid. Full technical detail on AWRA-L can be found in Van Dijk (2010).

AWRA water balance estimates have received extensive evaluation, using streamflow and deep drainage observations from several hundreds of catchments and sites, respectively; evapotranspiration measurements at four flux tower sites; satellite radar and microwave radiometer estimates of surface soil moisture content; and vegetation canopy cover and density estimated from optical satellite observations (e.g., Bauer-Marschallinger et al., 2013; Doubkova et al., 2014; Doubkova et al., 2012; Liu et al., 2010; Renzullo et al., 2014; Tregoning et al., 2012; van Dijk et al., 2013; Van Dijk et al., 2012; Van Dijk et al., 2011; Van Dijk and Warren, 2010; Viney et al., 2014; Wallace et al., 2013).

NEW MODEL DEVELOPMENTS

Partly in support of the Bushfire Natural Hazards CRC, more recent developments of the model are focused on including the following enhancements:

1. The main components of the **carbon balance**: the dynamics of vegetation biomass, soil litter and soil carbon, and the fluxes between these stores as well as the photosynthesis and respiration exchanges with the atmosphere. The modifications also include water-carbon linkages given vegetation growth and photosynthesis require water for transpiration, and the breakdown of litter and soil carbon depends on moisture.
2. **Fuel load and moisture content**: live fuel load is calculated from estimated vegetation leaf and woody biomass, whereas dead fuel load

is estimated from biomass turnover. Their moisture content is estimated from soil water availability and top soil wetness, respectively, while the moisture content of fine dead fuel is more closely related to atmospheric humidity.

3. **Produce high resolution outputs**: the model has been developed to use input data with high spatial resolution of 1/4000th degree (~25 m), to be more informative to land and fire managers, especially in areas with complex terrain. Specifically, the following enhancements have been made:
    - Multi-spectral Landsat TM data can be used to replace model-simulated vegetation canopy properties (cover fraction, canopy conductance and photosynthetic capacity) using the theory developed by Yebra et al. (submitted);
    - Because of the higher resolution, slope illumination effects are accounted for using a Digital Elevation Model; and
    - Where available, higher resolution climate data can be used.
    - Where available, field or remotely sensed information on soil or vegetation properties (e.g., from LiDAR) can be used to improve model assumptions.

The resulting model is referred to here as the High-resolution Fire Risk and Impact (HiFRI) model for ease of reference and is illustrated in Figure 5. The additional model components have been implemented, requiring some changes in the model logic, input data and hydrological equations. The model requires further testing, calibration and validation. All modifications compared to AWRA-L will be documented in a forthcoming publication.

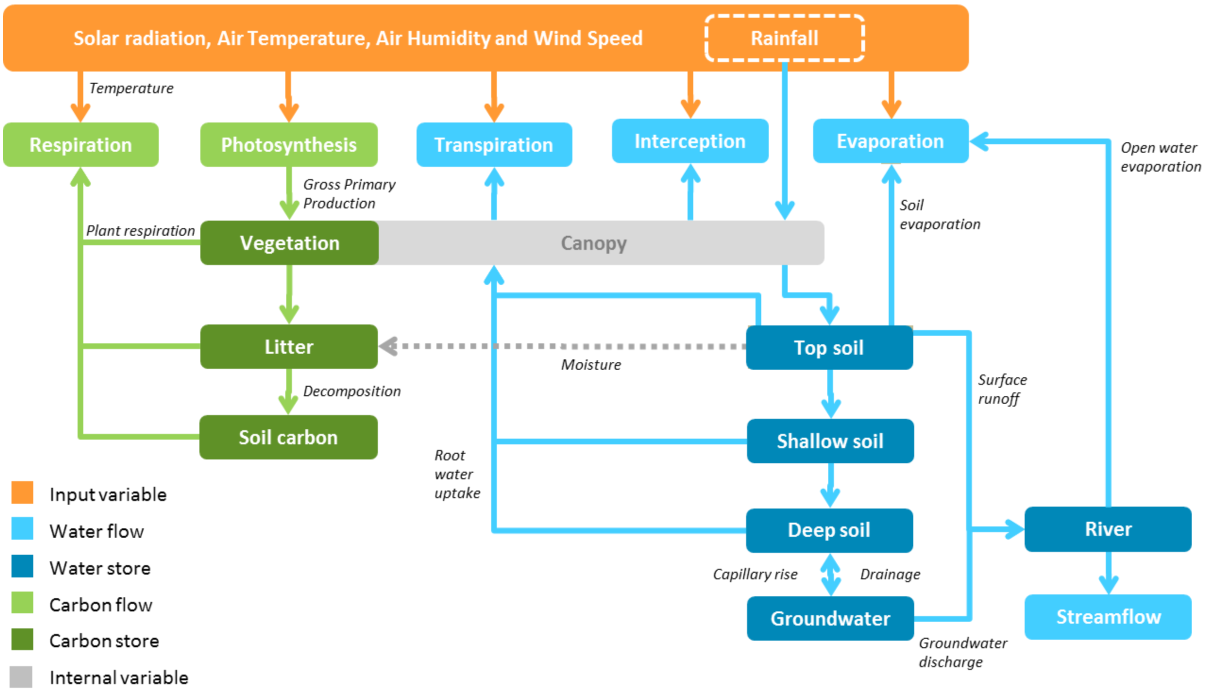

FIGURE 5. ILLUSTRATION OF THE HIFRI MODEL. THE GREEN COMPONENTS ARE NOT CURRENTLY PART OF THE OPERATIONAL AWRA-L MODEL IN USE BY BUREAU OF METEOROLOGY.

MODEL-DATA FUSION FRAMEWORK

Below follows a description of how the new input data sets were incorporated as part of this feasibility study.

LANDSAT SATELLITE IMAGERY

From the data cube Landsat composite images we calculated monthly maps of the so-called greenness indices: the Normalised Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI). Example images from before and after the 2003 Canberra fires are shown in Figure 2. From these indices, the following metrics were calculated:

- Vegetation **canopy cover** (cf. Donohue et al., 2008).
- **Canopy conductance** for water (Yebra et al., 2013) and CO2 (Yebra et al., submitted).

Where available, these estimates replace the model-simulated values. Moreover, model variables that are directly related to vegetation canopy cover (leaf area index and leaf biomass) were adjusted accordingly.

SRTM-DERIVED DATA AND GRIDDED CLIMATE DATA

The version of the HiFRI model used in this feasibility study requires estimates of the following variables:

- Daily total **precipitation**, derived from the TERN data base (~1 km resolution).
- Daytime average and 24-hour average **air temperature**, which were estimated from the minimum and maximum daily temperature from the TERN data base (~1 km resolution).
- Daytime average **vapour pressure deficit**, which was estimated from minimum temperature, by assuming that air humidity reached 100% when this temperature occurred. This essentially assumes that boundary layer moisture content is limited by condensation (Van Dijk, 2010). This assumption has been made to minimise the number of essential inputs and has been shown a good assumption in most environments. Alternatively, vapour pressure estimates based on station observations are available from Bureau of Meteorology and SILO and may be considered in future.
- Daily incoming short-wave solar **radiation**, derived from the SILO data base (~5 km resolution), and multiplied by the monthly relative illumination grids (~30 m resolution) derived from SRTM data that were described in the section ‘Data’ (p. 13).

RESULTS AND DISCUSSION

The model was evaluated for the period 2000–2010. The three years 2000–2002 were used to initialise the water and carbon stores (a so-called 'spin-up') after which the full period 2000–2010 was evaluated and the outputs recorded. Model run-time was about 6 hours on a laptop PC with standard processor (Intel Core i7 vPro), or ~5 seconds per day (not including spin-up and decompression of model outputs). The recorded outputs included:

- vegetation properties and carbon balance terms (cf. Figure 5):
- vegetation canopy cover; and
- gross primary production (GPP), i.e. carbon uptake for photosynthesis;

water balance terms:

- moisture content of top soil and shallow soil;
- streamflow; and
- evapotranspiration (ET), as the sum of transpiration, interception and evaporation

Various other outputs could also have been recorded (see Figure 5).

Cursory analysis of maps and analysis of area- average time series suggested that the model produced the correct outputs, that is, the magnitudes and temporal patterns were consistent with outputs from previous model applications at national scale with at 0.05° resolution (e.g., as used in the Bureau of Meteorology water assessment reports).

However, some important differences were also found. In particular, accounting for hillslope illumination at this finer scale produced clear spatial patterns in variables such as GPP, ET and soil moisture.

Examples for top soil moisture content are shown in Figure 6 for three times leading up to the 2003 fires. The resulting maps show clear hillslope scale patterning. This is due to different drying rates (ET) which are in turn a function of solar illumination, as predicted using the SRTM DEM. Furthermore the second map shows large-scale patterns associated with the 1-km interpolated rainfall estimates. Given the sparseness of the rainfall gauge network, this is likely to be an important source of uncertainty in the days following spatially varying rainfall.

A possible application of these data could be in assessing the spatial variability in surface fuel wetness in support of prescribed burning activities and national fire danger rating systems. To illustrate this, Figure 7 shows the temporal and spatial variability in estimated top soil moisture for a region of interest around Corin Dam (cf. Figure 6). This suggests that the spatial variation in soil moisture may be greatest in spring and autumn, some days to weeks after a large rainfall event. Such knowledge can be useful for planning backburning activities.

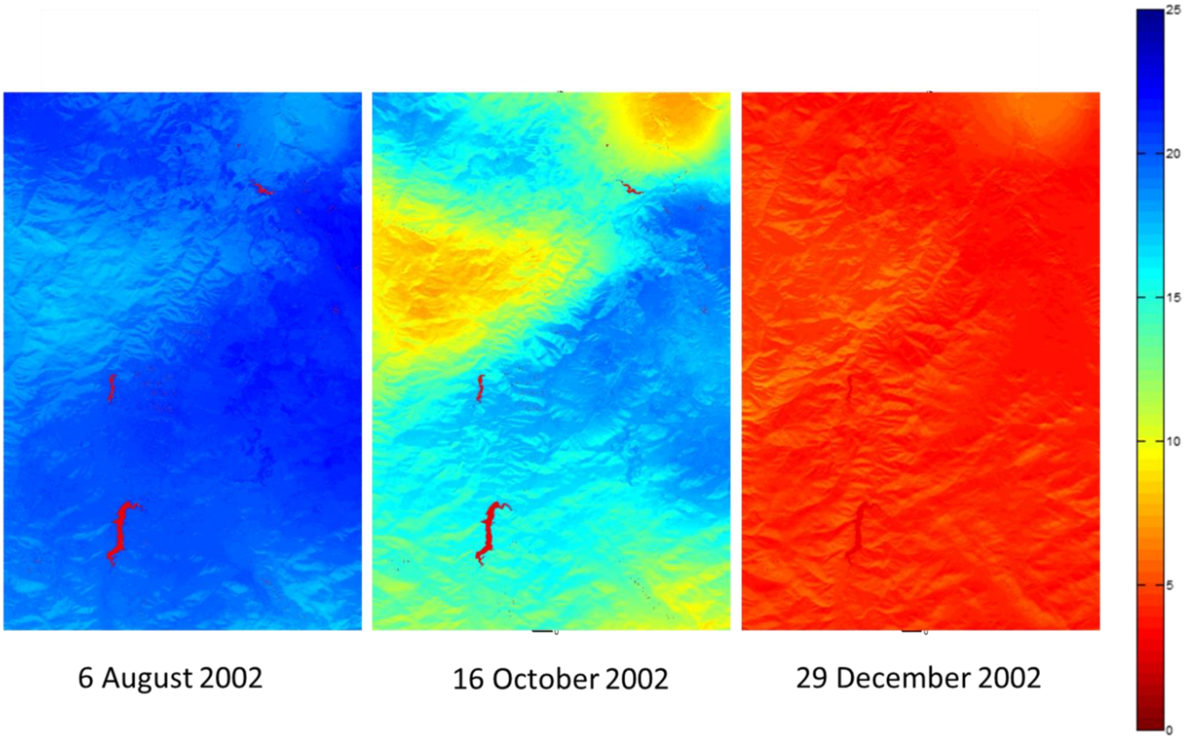

FIGURE 6. PREDICTED SOIL MOISTURE CONTENT (VOLUME (%) IN TOP 10CM MINERAL SOIL) FOR THREE TIMES LEADING UP TO THE 2003 BUSHFIRES, REPRESENTING WET WINTER CONDITIONS (LEFT); SPRING CONDITIONS AFTER RAINFALL OVER PART OF THE CASE STUDY AREA (MIDDLE); AND DRY SOIL CONDITIONS A FEW WEEKS BEFORE THE FIRES (RIGHT).

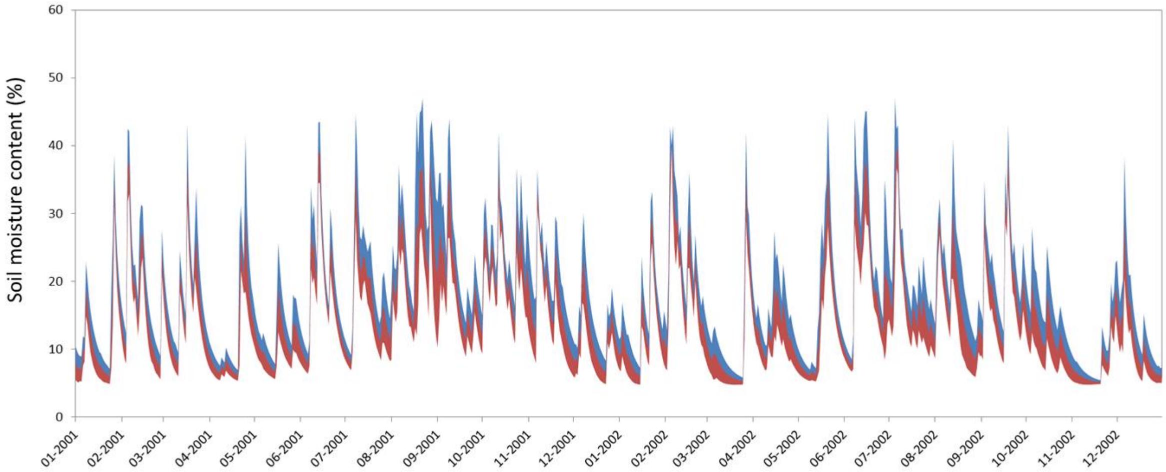

FIGURE 7. TIME SERIES OF TOP SOIL MOISTURE FOR THE AREA INDICATED BY THE YELLOW OUTLINE IN FIGURE 6, SHOWING THE AVERAGE VALUE PLUS (BLUE) AND MINUS (RED) THE STANDARD DEVIATION IN MODELLED VALUES SPATIALLY (A MEASURE SPATIAL VARIABILITY) CALCULATED FOR EACH TIME STEP.

The potential use of the model-data fusion framework for fuel build-up and carbon storage estimation is illustrated in Figure 8, showing the accumulated total GPP estimated for the year 2010. Again the influence of slope illumination is clear, combined with the vegetation cover and canopy conductance estimates derived from the Landsat imagery.

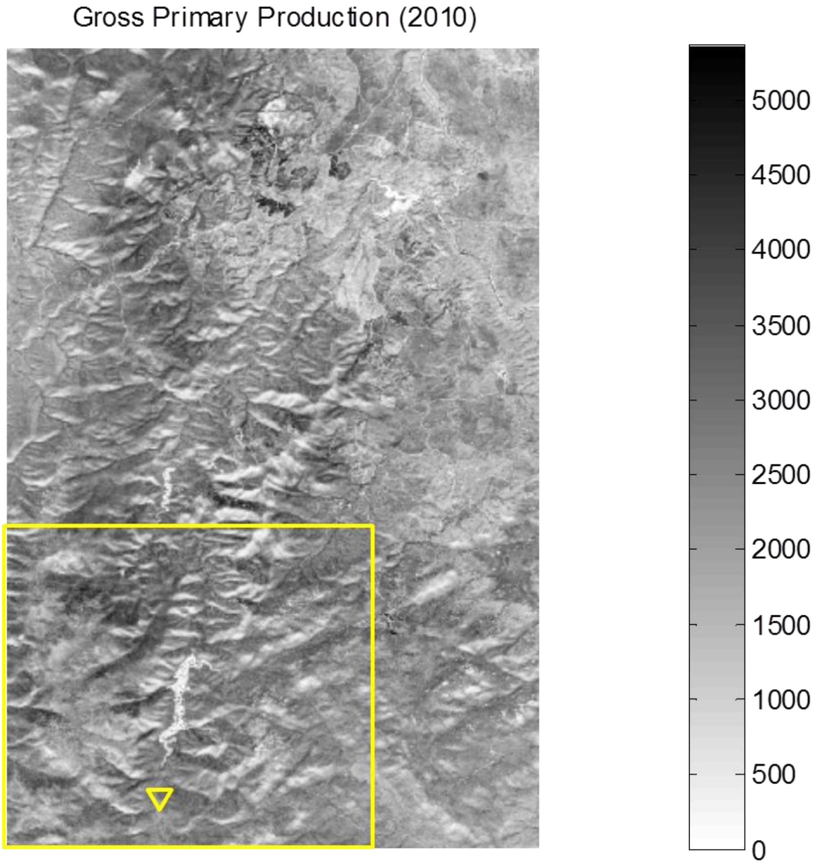

FIGURE 8. ESTIMATED VEGETATION CARBON UPTAKE (GPP, GC M^{-2} Y^{-1}) FOR THE CASE STUDY IN 2010.

Such information cannot be directly translated into carbon storage and the build-up of living and dead fuel; to do this, additional modelling and assumptions are needed to estimate how much of GPP is converted into biomass, how the rate at which biomass turnover produces dead fuel (Roxburgh et al., 2006). Unfortunately this varies between species and ecosystems in a way that cannot currently be derived from satellite remote sensing.

Much knowledge about forest growth and dead fuel production is however contained in empirical methods developed for fire management and forestry applications, such as timber/biomass/fuel accumulation curves (Gould et al., 2011; Olson, 1963; Raison et al., 1986). A promising way forward would involve merging the dynamic GPP estimation with such observation-based empirical methods, such that the spatial and temporal detail in model-data fusion estimates can be combined with the empirical strength of observation-based methods. This is illustrated in Figure 9.

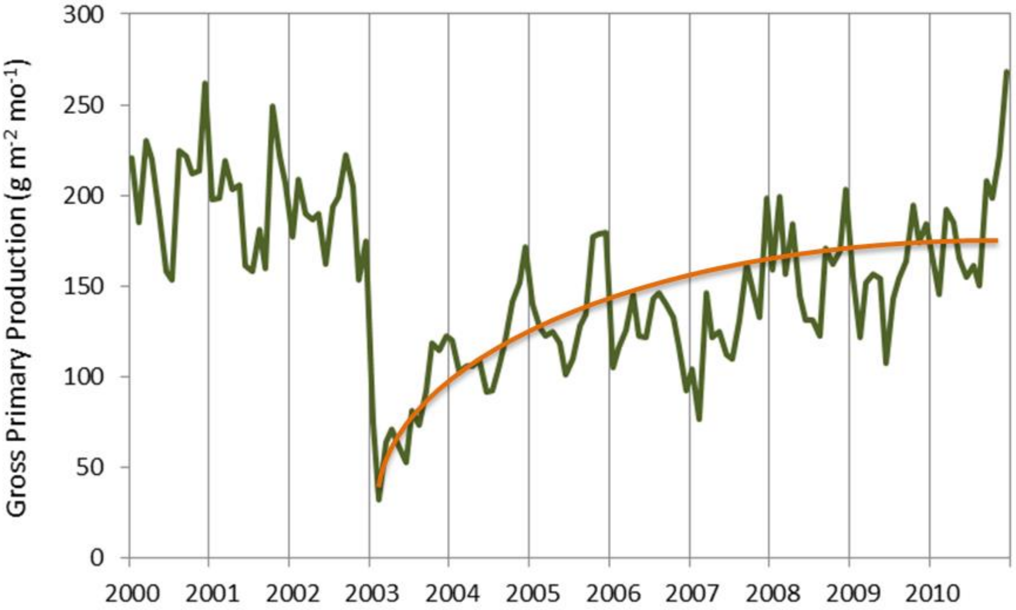

FIGURE 9. AREA-AVERAGE MONTHLY CARBON UPTAKE (GPP, GREEN LINE) FOR THE AREA OUTLINED BY THE YELLOW OUTLINE IN THE PREVIOUS FIGURE. THE BROWN CURVE IS ADDED TO ILLUSTRATE THE USE OF GPP ESTIMATES TO ENHANCE THE FUEL ACCUMULATION GROWTH CURVE APPROACH.

NEXT STEPS TOWARDS PRACTICAL APPLICATIONS

Having demonstrated the feasibility of high resolution fuel, water and carbon modelling, a key priority for further development is to define one or more potential practical applications. This can then provide a clear context and guide further development into operational solutions. Below a number of possible applications is presented with an initial discussion of possible opportunities, challenges and development needs.

QUANTIFYING CHANGES IN FUEL LOAD, WATER RESOURCES AND CARBON STORAGE

One of the initially intended applications of the framework is to estimate the spatial and temporal impacts of burning (both planned and unplanned) on landscape values, such as water resources generation, carbon storage and habitat dynamics.

Based on previous evaluation studies, there is a reasonable degree of confidence that the current system allows fire impacts on streamflow generation to be estimated with a useful accuracy (Van Dijk et al., 2012). This is also true for the uptake of atmospheric carbon by photosynthesis (GPP) (Yebra et al., submitted).

However uncertainty is greater in critical processes that need to be captured to estimate net carbon structure and, closely related, fuel accumulation:

- How much of GPP is converted into biomass – net primary production, calculated as GPP minus plant respiration – and how this is influenced by climate conditions.
- The partitioning of NPP into new leaf, wood and root biomass.
- The rate of leaf, wood and root biomass turnover (litter production).
- The rate of decomposition of litter, and the partitioning of this into soil organic matter and CO2.

Modelling approaches exist to describe these processes and these are used in carbon cycle and forest growth models (Roxburgh et al., 2006). However the parameters describing the various rates and fractionations are specific to species, ecosystems and environments and this means local data are required for calibration and/or validation.

There are some good opportunities to derive some of the information required for model calibration by making use of the following data:

- **Field measurements** of fuel load (or forest inventories, or carbon storage surveys) are critical to achieve accurate model predictions. These may be available from the literature (e.g., Thomas et al., 2014), from research projects, or from routine assessments made by land or fire managers.
- **Terrestrial laser scanning** (LiDAR) provides an objective and highly precise technology to map the structure of a small (e.g., <1 ha) area of forest. This technology is particularly suitable to (a) collect data for validation larger scale estimates from mapping or airborne or satellite

remote sensing; and (b) obtain detailed information on surface and understory fuel (Figure 10).

- **Airborne LiDAR** provides a cost effective method for LiDAR collection over large areas. It is particularly suitable to obtain accurate information about forest height and canopy cover over large areas, and also provides reasonably accurate information about the structure and density of the understory (Figure 11). As a side benefit, it also produces a highly accurate DEM that can be used in modelling. LiDAR was collected for some parts of the ACT in 2014, and further data collection to cover the entire territory is planned in autumn 2015.

These data are not suitable as direct inputs for the model, as they lack full coverage in space and/or are changeable over time. However, they can be used to calibrate, validate and extend modelling, for example to calibrate biomass accumulation curve methods where (near-) complete removal of the forest occurred at a known time in the past.

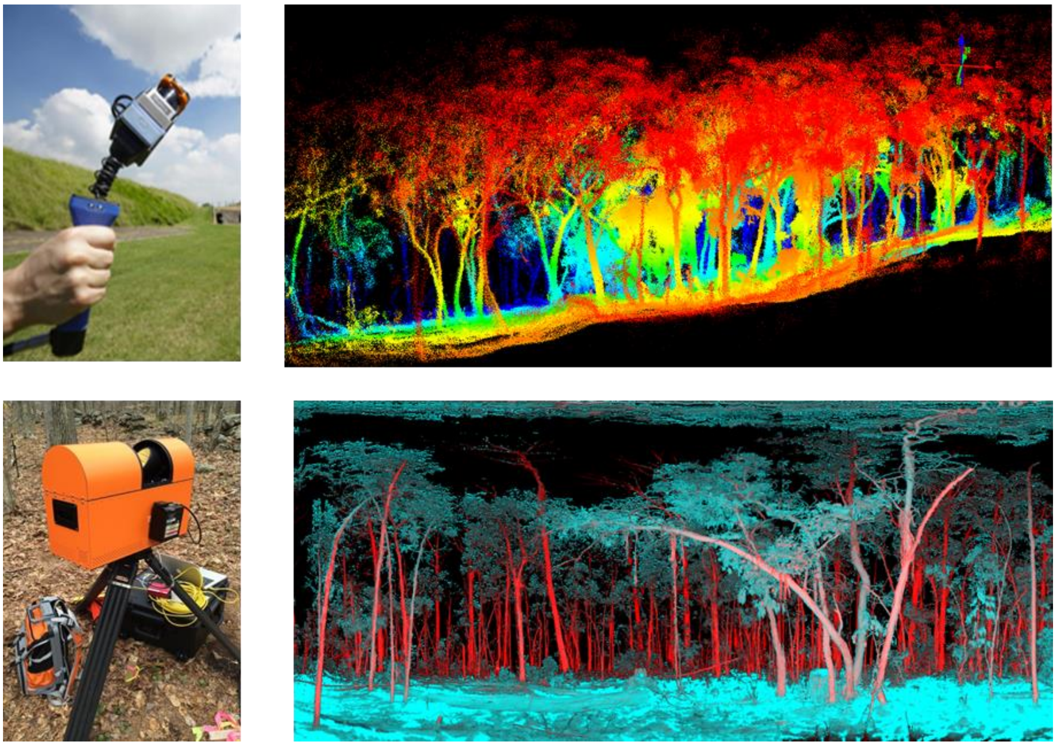

FIGURE 10. EXAMPLES OF TERRESTRIAL LASER SCANNING DATA: (TOP LEFT) THE ZEBEDEE LASER SCANNER AND (TOP RIGHT) SIDE VIEW OF THE POINT CLOUD COLLECTED FOR A FOREST PLOT ON BLACK MOUNTAIN RESERVE, ACT (COLOURS INDICATE THE DISTANCE FROM THE VIEWPOINT); (BOTTOM LEFT) THE FIXED-POINT DUAL WAVELENGTH ECHIDNA LIDAR (DWEL) SCANNER AND (BOTTOM RIGHT) SIDE VIEW OF POINT CLOUD FOR AN AREA OF FOREST IN TUMBARUMBA IN NSW (COLOURS INDICATE LEAF MATTER AND SNOW IN BLUE AND BARK IN RED).

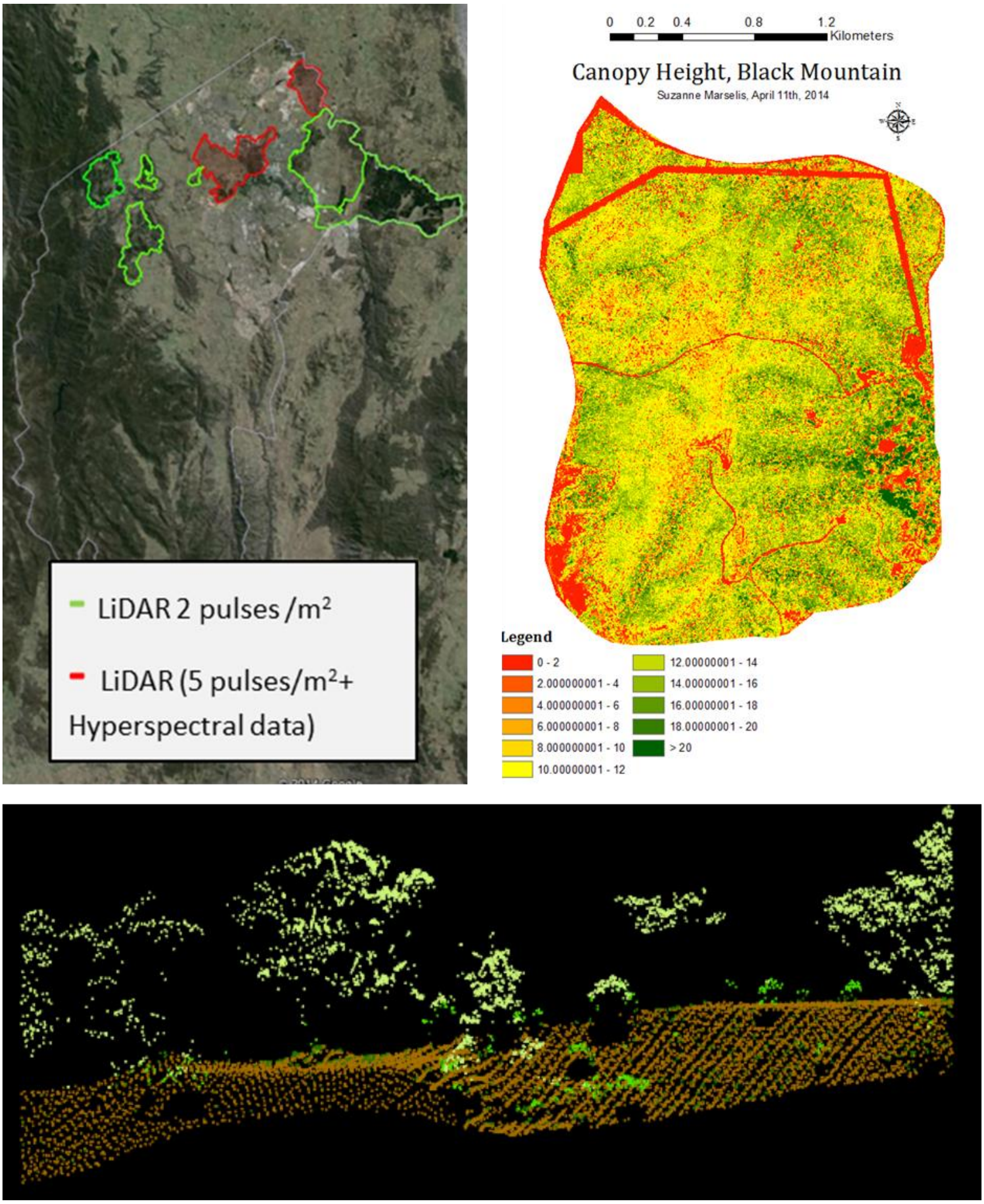

FIGURE 11. ILLUSTRATION OF LIDAR COLLECTED OVER THE ACT IN 2014: (TOP LEFT); (TOP RIGHT) MAP OF CANOPY HEIGHT DERIVED FROM THE DATA FOR THE BLACK MOUNTAIN RESERVE, AUSTRALIAN CAPITAL TERRITORY; (BOTTOM) VISUALIZATION OF MULTIPLE LIDAR RETURNS AT BLACK MOUNTAIN RESERVE. BROWN = GROUND RETURNS, PALE GREEN = TREES, LIGHT AND DARK GREEN = LOW VEGETATION/SHRUBS (MARSELIS, 2014).

REAL-TIME FUEL MOISTURE MAPPING

In principle, the same model-data fusion framework could be developed to provide up-to-date information on the spatial patterns in fuel moisture. Discussions with ACT Fire Management Officers have suggested that information on spatial gradients in fuel moisture content could potentially be very useful for fire managers planning prescribed burning. The HiFRI model-data framework can provide estimates of fuel moisture as follows:

- **Surface fuel and soil moisture**. Top soil moisture is currently one of the model outputs, and the simulations show clear hillslope aspect patters that may be useful in identifying the extent of moisture differentials. Surface fuel is not explicitly estimated, but can be estimated based on the assumption that it is in equilibrium with top soil moisture or air humidity.
- **Living fuel moisture**. This is not currently estimated but could probably be estimated with good accuracy by assuming that it has a simple relationship with root zone soil water availability. Moreover, overstorey fuel moisture content can be retrieved from Landsat imagery (Yebra and Chuvieco, 2009; Yebra et al., 2008). These method are currently being tested for the ACT (Figure 14) and once validated can be integrated into the model.
- **Dead fuel moisture**. The moisture content of dead fuel that is not in contact with the soil is not currently estimated. This could be predicted from air humidity with relative ease using methods developed by Sharples and colleagues (Sharples and McRae, 2011; Sharples et al., 2009).

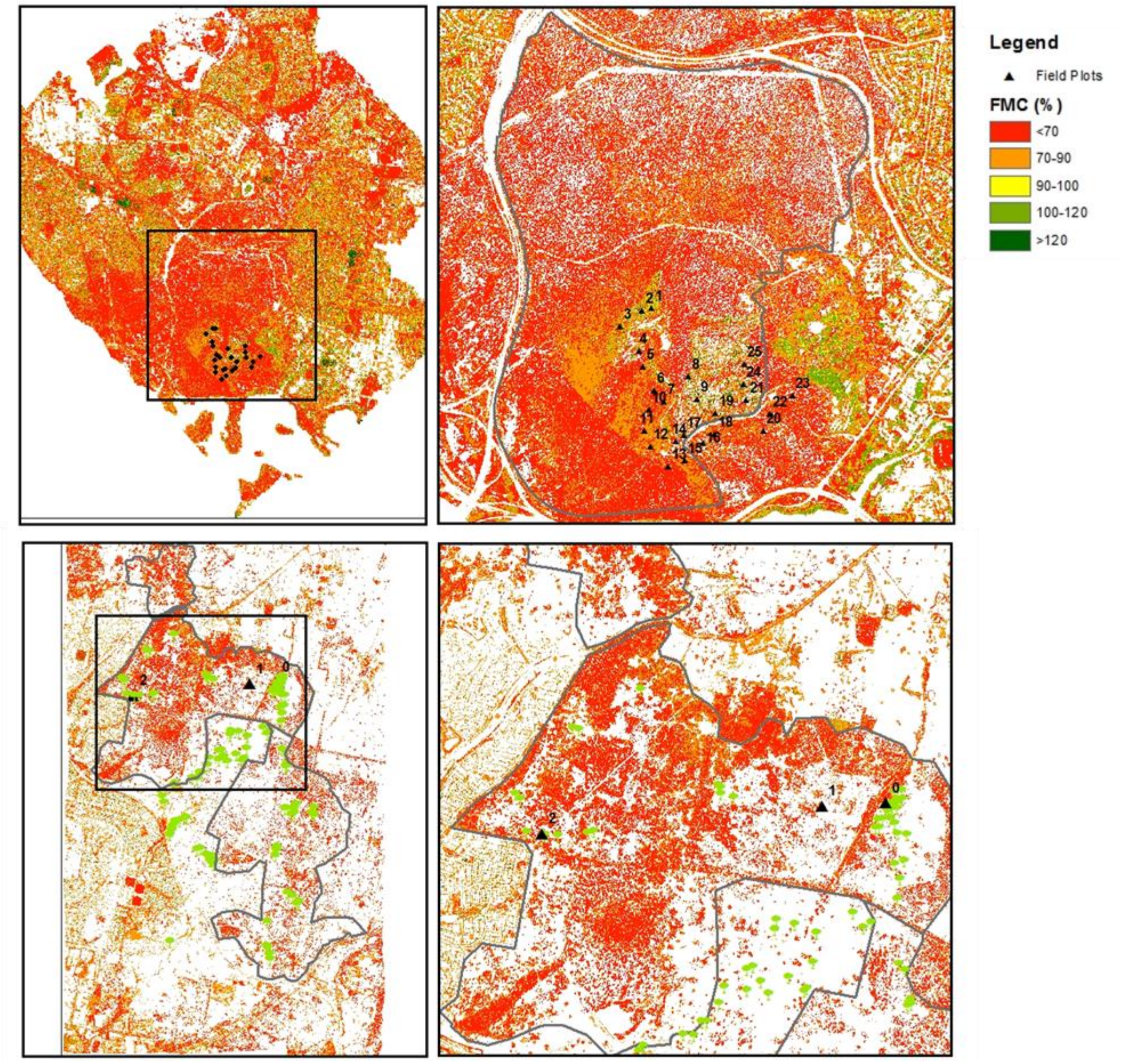

FIGURE 12. OVERSSTOREY FUEL MOISTURE CONTENT ESTIMATION AT THE BLACK MOUNTAIN NATURE RESERVE (UP), THE MULLIGAN'S FLAT AND GOOROOYAROO RESERVE (DOWN) AND SURROUNDINGS USING HYMAP HYPERSPECTRAL DATA COLLECTED AT THE ACT AND RADIATIVE TRANSFER MODELLING (JURDAO ET AL., 2011; YEBRA ET AL., 2008). FIELD PLOTS SAMPLED FOR VALIDATION ARE ALSO DISPLAYED.

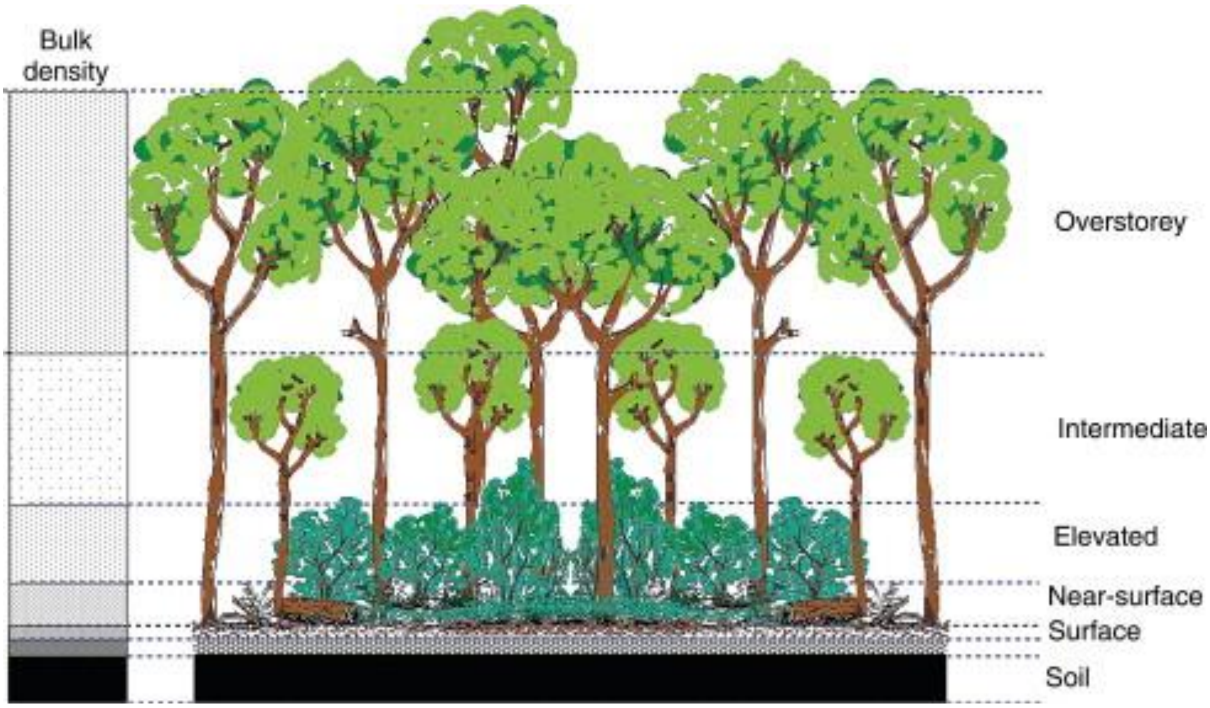

FIGURE 13. INDICATION OF DIFFERENT FOREST LAYERS USED IN FOREST FUEL ASSESSMENTS (GOULD ET AL., 2011).

In all cases, the estimates would be expressed in relative terms. Providing estimates in absolute terms (e.g., gravimetric water content) would require calibration with field measurements of moisture in the different forest layers (Figure 15).

A critical uncertainty in moisture monitoring is to obtain accurate observations of rainfall across space. The BoM rainfall network is not sufficiently dense to provide such information for high resolution modelling in most parts of Australia. Addressing this issue, ACT government has invested in deploying a number of supplementary weather stations across the ACT. For these observations to be incorporated in the 1-km gridded rainfall data, they would need to be supplied to the Bureau of Meteorology in a routine and standardised manner.

An alternative solution would be to develop a separate interpolation method that includes these observations. A further sophistication for high resolution modelling would be to incorporate point measurements of other weather variables and fuel and soil moisture estimates currently being collected by ACT government. This can be done through a technique called data assimilation, an advanced model-data fusion technique that uses a statistical method to adjust model predictions with point observations. For this approach to produce operational information, the data collection and data assimilation software both would need to be done in an automated (e.g., daily) fashion, such that up to date predictions can be produced. This could result in a customized software system that is not easily transferred to another region, however.

To develop more generic and flexible operational monitoring systems, the collection of data would need to occur in a standardised and automated way. One approach to this is being trialled in collaboration with CSIRO through the Australian National Cosmic Ray Soil Moisture (CosmOz) network, a network of remote area stations that produce standardised data on weather and soil moisture across Australia. The stations are built around a soil moisture sensor that uses an entirely new technology that relies on the interaction of intergalactic cosmic rays with water in the proximity of the sensor, providing a reliable integrated average estimate of vegetation and soil moisture content down to a depth of a few decimetres over an area 600 m in diameter; far larger than any existing methods. One of the sensors is installed in the Namadgi National Park, where its use for fire and flood risk monitoring is being evaluated (Figure 14). The system is extremely durable and low maintenance, helped by the fact that (i) all sensors are non-contact (apart from TDR moisture probes attached for research purposes); (ii) the system is powered by a solar panel; and (iii) measurements are telemetered in near real-time and in a standardised manner via the Iridium communication satellite. This means that field maintenance costs are extremely low. A network of such stations can help generate more spatially detailed information on rainfall, weather and moisture in the landscape. Research is currently ongoing to develop methods to derive information on vegetation and soil moisture separately.

FIGURE 14. (LEFT) LOCATION OF THE NAMADGI COSMOZ STATION, AND (RIGHT) THE STATION COMPONENTS.

FIRE SPREAD MODELLING

Fire spread modelling requires information on fuel load, structure and moisture content, along with fine resolution meteorological and terrain data (Cruz et al., 2015). Partly, this information can be derived from the HiFRI model-framework. Further discussion with fire modelling researchers would be required to investigate how the two modelling approaches can be integrated. However, even without considering a fully integrated modelling approach, key elements available from HiFRI may provide improved inputs into operational fire spread modelling during planned and unplanned fire events. For example, the latest generation of forest fire spread models (Cheney et al., 2012) requires inputs on the structure of surface and near-surface fuel layers for predicting rate of spread, and these might potentially be available from an enhanced HiFRI approach, as up-to-date estimates across large areas.

REAL-TIME FIRE RISK FORECASTING AT HIGH RESOLUTION

Finally, the HIFRI model framework can in principle also be used to produce near-real time (e.g., daily or weekly) fire risk monitoring and forecast information.

The main challenge in doing so would be to obtain up-to-date estimates and forecasts of rainfall and weather conditions of sufficient quality and spatial detail. At present, weather forecasts are available from the Bureau of Meteorology's ACCESS-R system, providing a larger number of variables including precipitation, radiation, temperature, vapour pressure and wind speed at 0.11° resolution (~11 km) and 3-hour interval (see example in Figure 15). Higher spatial resolution forecasts are available around the major population centres. It is noted that the ACCESS-R forecasts are not identical to the official forecasts, using these forecasts might be possible in negotiation with the Bureau.

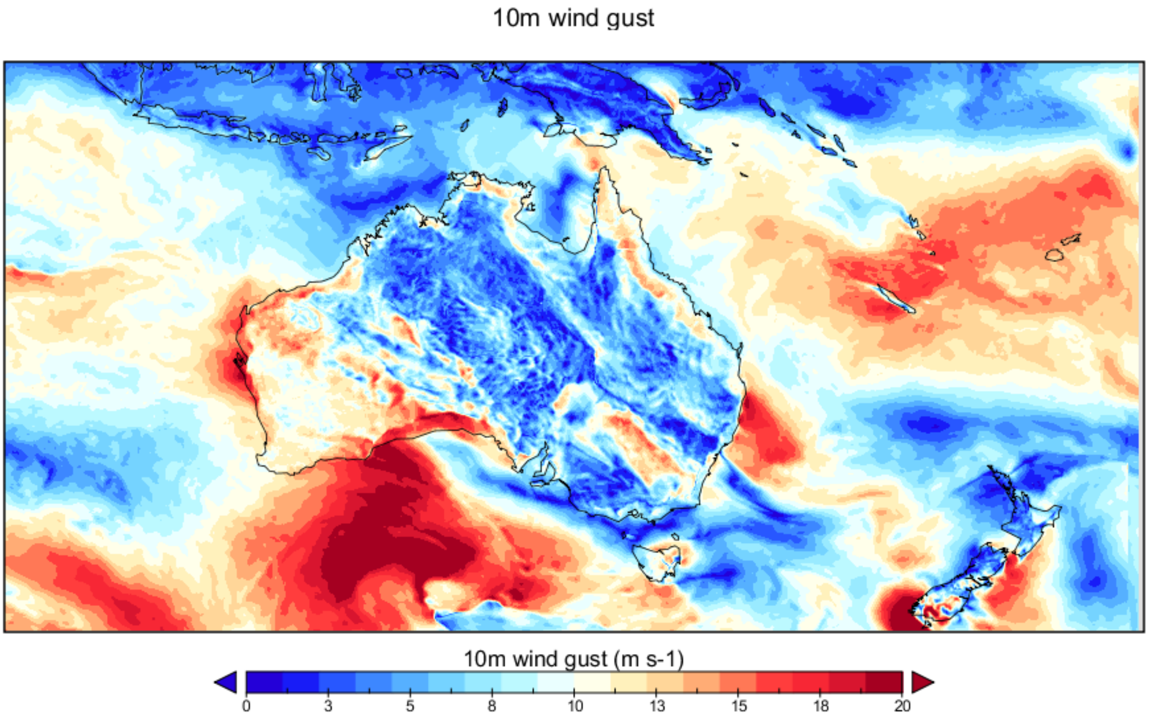

FIGURE 15. ILLUSTRATION OF BUREAU OF METEOROLOGY ACCESS-R FORECASTS: 10 M HEIGHT WIND GUST FOR THE 27 HOUR FORECAST ON 6:00 UTC 22 NOVEMBER 2014.

An important challenge would be to account for the effect of vegetation and topography on wind fields. Research is ongoing to better predict this effect, particularly on the leeside of slopes, where unexpected changes in wind speed and direction can occur (Sharples et al., 2012).

Most importantly, it would first need to be established if there is a practical mechanism through which fire managers could use such detailed fire risk predictions, should it be produced.

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