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Research article

A data - Model fusion methodology for mapping bushfire fuels for smoke emissions forecasting in forested landscapes of south-eastern Australia

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ABSTRACT

The increasing regional and global impact of wildfires on the environment, and particularly on the human population, is becoming a focus of the research community. Both fire behaviour and smoke dispersion models are now underpinning strategic and tactical fire management by many government agencies and therefore model accuracy at regional and local scales is increasingly important. This demands accuracy of all the components of the model systems, biomass fuel loads being among the more significant. Validation of spatial fuels maps at a regional scale is uncommon; in part due to the limited availability of independent observations of fuel loads, and in part due to a focus on the impact of model outputs.

In this study we evaluate two approaches for estimating fuel loads at a regional scale and test their accuracy against an extensive set of field observations for the State of Victoria, Australia. The first approach, which assumes that fuel accumulation is an attribute of the vegetation class, was developed for the fire behaviour model Phoenix Rapid-Fire, with apparent success; the second approach applies the Community Atmosphere Biosphere Land Exchange (CABLE) process-based terrestrial biosphere model, implemented at high resolution across the Australian continent. We show that while neither model is accurate over the full range of fine and coarse fuel loads, CABLE biases can be corrected for the full regional domain with a single linear correction, however the classification based Phoenix requires a matrix of factors to correct its bias. We conclude that these examples illustrate that the benefits of simplicity and resolution inherent in classification-based models do not compensate for their lack of accuracy, and that lower resolution but inherently more accurate carbon-cycle models may be preferable for estimating fuel loads for input into smoke dispersion models.

1. Introduction

Globally, the burning of vegetation is a major source of trace gases and particulates to the atmosphere and a major pathway for returning carbon from organic combination to the atmosphere, mainly as carbon dioxide. The smoke emitted in vegetation fires has extensive health and economic impacts with fine particles ($PM_{2.5}$) in particular becoming a pollutant of concern for the health of regional populations (Dymond et al., 2004; Haikerwal et al., 2015). Other smoke pollutants harmful to human health include carbon monoxide (CO), organic compounds, ozone (O_3) and secondary organic aerosols (Kochi et al., 2010). The smoke from vegetation fires contributes to regional haze, reduces visibility and can disperse over long distances impacting human populations far from the smoke source (Koe et al., 2001).

Since the year 2000 the scale of burning in southern Australia has been large, with more than 1.2 M ha of *Eucalyptus* open forests treated with planned fire and 3.6 M ha burnt in wildfires (ABARES, 2013). The policy to increase the current rate of planned burning poses significant challenges for regional managers if smoke and pollutant impacts on population health are to be mitigated (Meyer et al., 2013). Smoke dispersion models are required to forecast medium to long distance transport of smoke constituents and their potential surface impacts on community and industry (Wain et al., 2008).

Both the type and amount of fuels affect smoke and emission during forest fires (Russell-Smith et al., 2009; Weise and Wright, 2014). Fine fuels (leaf litter, bark and small twigs with diameter < 6 mm) are usually burnt in flaming combustion and affect progression of the flaming front of a surface fire. Therefore fine fuels are inappropriate for estimating fire effects associated with post-frontal, smouldering combustion, a characteristic of heavier fuels such as coarse woody debris [CWD] (Cook and Meyer, 2009). In North America, fuels are grouped in complex fuel beds and include duff, fine litter fuels, coarse woody fuels

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of various diameter classes, grass, shrubs, understorey and canopy fuels (e.g. Fuel Characteristic Classification System, Ottmar et al., 2007). After selecting appropriate fuel bed characterization, such as amount (loading, kg m^2), density, and surface area to volume ratio, land managers apply a suite of models, including the emission model CONSUME (Ottmar and Prichard, 2008) to predict the smoke emissions, and the dispersion models available in the Bluesky framework (https://www.airfire.org/bluesky) to predict the smoke dispersion. In south-eastern Australia, fuel characterization research has focused on providing inputs for predicting fire spread (e.g. McArthur Meter and Phoenix fire spread model) and as such has focused on fine fuel components (Cruz et al., 2015; McArthur, 1967).

In contrast to fine fuels, the contribution of CWD, especially large woody fuels, to surface fire intensity in Australia is commonly ignored in fire behaviour models. Yet combustion of CWD contributes to total energy release, fire-line intensity, burn severity, burn depth, difficulty of suppression, total radiant heat flux and firefighter safety (Sullivan et al., 2002). CWD can smoulder for days and weeks releasing a complex mixture of gases and particulate matter (Reisen et al., in submission) and greatly contributing to the total fire emission (Volkova et al., 2014). Despite this, the quantification and mapping of CWD fuels in south-eastern Australia remains understudied. Nevertheless, the emerging requirement for accurate emission and dispersion prediction requires a system for mapping both fine and CWD fuels.

The most common approach for describing fuel loads has been association, in which fuel information is assigned to existing vegetation classifications and subsequently mapped (Keane, 2013). Depending on the design and intended application of the vegetation classes, for example the relative emphasis on floristic and structural characteristics, secondary attributes of the classes can sometimes be derived from a relatively small number of field measurements in each class. The accuracy of the association depends on correlation strength between the fuel attribute and the vegetation class (Keane et al., 2006). Classifications based on vegetation properties can be specifically designed to optimise the correlation between an attribute and the vegetation class (Keane, 2013). There are many examples from around the world where this has been done at multiple scales, including for the major vegetation types of Greece (Dimitrakopoulos, 2002), Canada (Hawkes et al., 1995) and the United States (Reinhardt et al., 1997). In south-eastern Australia, a vegetation association approach was applied in the Phoenix Rapid Fire model (Tolhurst et al., 2008). Thirty eight fuel groups, including all the categories of native grasslands, shrublands, forests and plantations, were derived from the aggregation of over 600 Ecological Vegetation Classes (DELWP, 2016) – using vegetation composition, vegetation structure and physiographic location (Tolhurst, 2005 unpublished; Table S1). These fuel groups were then assigned a fuel load including values for surface, elevated and bark fuels, based on limited field sampling and literature review.

A separate approach to fuel-load mapping is based on ecological processes (biogeochemical modelling), rather than solely on correlation with vegetation types. Biogeochemical modelling relates fuel load to the balance between primary production of live biomass and its removal through mortality to form dead organic matter (DOM), the incorporation of the DOM into soil and litter pools, and removal of DOM by decomposition. For example, the CABLE terrestrial biosphere model that has been used to assess Australian continental (Haverd et al., 2013a; Trudinger et al., 2016) and global carbon budget dynamics (Le Quéré et al., 2016), generates two structural fuel pools (fine litter and CWD) that approximate the fine and coarse fuel loads required for modelling of smoke dispersion.

The classification and biogeochemical modelling approaches for fuel load mapping each have strengths and weaknesses. The strength of classification based mapping is that the fuel map resolution is limited only by the resolution of the vegetation mapping, and in many cases, vegetation maps are produced at very high spatial resolution. If the fuel map is to be accurate then the correlation between the attribute (fuel load) and the class must be strong and stable. However, these attributes can be evaluated from field monitoring of well-defined sites, and updated as necessary, and therefore a relatively small field measurement program can produce a high resolution fuel load map. Further, when land use change and the impacts of natural events (e.g. fire, storms, floods) change the vegetation patterns, fuel load maps are automatically revised in line with the vegetation maps. This is a routine exercise for land-use and vegetation mapping based on remote sensing. The weakness is that fuel load dynamics measured in the field programme are fixed in time and therefore do not reflect climate variability. In the case of the Phoenix model, the fuel attribute linked to vegetation classes is fuel accession rate (defined by the rates of litterfall and fuel decay). Fuel load is calculated from the accession rate and the local fire history. The strength of the biogeochemical modelling approach is that it is based on known and verified ecological processes driven by measurable inputs, and is fully dynamic and consequently has a fine time resolution; for most processes the appropriate temporal resolution should be hours to days. However, the spatial resolution of the model is limited by both the resolution of the input data, and the computational demands. In most cases the practical resolution is $0.05^\circ \times 0.05^\circ$. Whether this resolution is suitable for smoke emission and dispersion modelling will depend on the application; for example, it may not be adequate for fine scale impact modelling to predict plume strike on individual facilities (e.g. hospitals). The lower spatial resolution of biogeochemical models may be sufficient for assessing regional carbon dynamics, smoke scenarios and biogeochemical cycles (Fleming et al., 2015; Running et al., 1989). However, the biggest weakness of both types of Australian fuel load mapping models described above is that most of the assumptions establishing the Phoenix fuel groups and their parameters, and the CABLE estimates, have not been tested at the regional spatial scale, principally because there are few datasets of reliable fuel load measurements at the required spatial scale.

The need for accurate smoke dispersion forecasting in southern Australia, based on best available fuel load mapping of fine and CWD fuels, has assumed a high priority due to the catastrophic fire regimes of the last decade (Keywood et al., 2015). The development of a prototype smoke forecast modelling framework became a highest priority for the land management agency of Victoria (Cope et al., 2016). The smoke forecasting model builds upon a number of components, with bushfire fuel load maps of fundamental importance. In the absence of CWD fuel load maps for the Phoenix Rapid fire predictions, and because of the limitations of Phoenix fuel maps described above, we were assigned the task of developing fuel load maps for operational use in smoke dispersion models from forest fires in Victoria. Here we describe a hybrid methodology that combines the vegetation association approach of the Phoenix model with continuous modelling of fuel load (CABLE), which we calibrate against a geographically extensive field dataset. This methodology provides fine and CWD fuel load estimates to a smoke emissions model now being applied by Victoria's Emergency Services to forecast the dispersion of smoke from fuel reduction burning and bushfires.

2. Experimental design and methods

2.1. The study area

All data were collected from forest sites across the 7.12 M ha of public forests and parks, extending from latitude 39°–36° S and longitude 142°–144° E, in the State of Victoria, Australia. These forests are dominated by the genus *Eucalyptus,* of which there are about 100 species in the State, and occur over 400–1500 mm per annum rainfall range and average winter and summer temperatures between 8° and 20 °C.