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MODEL PREDICTIONS FOR FUEL REDUCTION BURNING OF EUCALYPT OPEN FOREST IN THE GREATER BLUE MOUNTAINS REGION

Milestone 3.3.1 Model predictions for fuel reduction burning

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Cover: A field example of ecosystem components considered in modelling carbon accounting in response to a single prescribed burn. Source: David Pepper.

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ABSTRACT

Prescribed burns are a land management tool used for reducing fuel loads in terrestrial ecosystems. Under extended drier, hotter weather conditions they might be used increasingly and more widely to help manage risk of wildfire and subsequent damage to life, property and natural assets. They also represent a form of disturbance to ecosystems, including their biodiversity and biogeochemistry. From a biogeochemistry perspective, we apply the FullCAM carbon accounting model to eucalypt open forest sites in the greater Blue Mountains region that underwent prescribed burns and fieldwork campaigns in 2019. Field data were used to derive values and estimates that guided model calibration and helped to explore the suitability of FullCAM for simulating the effect of prescribed burning on this ecosystem type. The diameter at breast height of overstorey and understorey trees, leaf area index and surface litter fractions were key measurements for estimating production, allocation, turnover (litter input to surface debris) and breakdown (output from surface debris) of carbon pools of forest components and hence, for calibrating FullCAM. Measurements for paired burnt/unburnt plots were key to estimating loss of carbon from forest component pools to the atmosphere due to prescribed fire. Simulation of unburnt forest component pools were reasonable as a calibration, although improvements in simulating fractions of surface litter would probably improve simulations of the effect of prescribed fire on forest component pools. Recommendations related to collection of field data and to model structure are made to improve alignment between model-data comparisons.

END USER STATEMENT

Dr Felipe Aires, New South Wales National Parks and Wildlife Service, NSW

The application of FullCAM to sites that have accompanying field data specifically for evaluating the effect of prescribed burn effect on carbon (C) stocks and flows (including C emissions) highlights limitations and constrains in modelling and the dataset.

While the framework of FullCAM is suited to C accounting, both the model and the field data used for calibration need to be better aligned. Without the right configuration, the bulk of simulated effects and C emissions from prescribed burning will rely heavily on expert assumptions about twig litter fraction as an important feedstock to surface litter and understorey fraction as an important ecosystem component mostly affected by prescribed burn-scale fires.

The study concludes with recommendations to better align FullCAM and field data for the purpose of evaluating prescribed burning effects on C stocks and flows including C emissions. Such alignment would make it easier to apply FullCAM and the C accounting more robustly, yielding better estimates of C emitted and therefore better effectiveness of FullCAM as a suitable tool in planning prescribed burning.

INTRODUCTION

In practice, the risk and nature of fire, including its ignition, depends on sufficient and continuous dry fuel and prevailing weather conditions (Bradstock and Nolan, 2019). Fuel loads frequently determine whether ignitions can spread, how intense a fire burns and its severity (i.e. the impact it has, the damage done), as well as the quantities of biomass combusted and carbon (C) emitted. Prescribed burns are a land management tool used for reducing fuel loads in terrestrial ecosystems. Under extended drier, hotter weather conditions (Jones and Bettio, 2019), prescribed burning might be used increasingly and more widely to help manage risk of wildfire and subsequent damage to life, property and natural assets. In theory, under dry, hot conditions the risk of ignition of forest fuels typically escalates. Because prescribed burns reduce fuel loads, in practice, they can reduce risk but are also a type of ecological disturbance of terrestrial ecosystems, on their inherent biodiversity [i.e. species richness and abundances in both flora and fauna (e.g. Burrows, 2008; Hope, 2012; Sitters *et al*., 2015)] and on their underlying biogeochemistry. The latter inevitably involves alterations in stocks and flows of C (including C emissions), nitrogen and other elements and in the water balance between land and atmosphere [e.g. Butler *et al*., 2017; Department of Energy and Environment (DEE), 2019)].

Risk analysis is outside the scope of this study (see e.g. Howard *et al*., 2020). This study was confined to a biogeochemical perspective, deploying a model framework for ecosystem and landscape (spatial) scales. The FullCAM model for national C accounting can incorporate prescribed fire events, can be applied at the site level and is driven by local meteorology (e.g. Richards and Evans, 2004). Moreover, under increased likelihood of C accounting to meet national targets [United Nations Framework Convention on Climate Change (UNFCCC), 2016; 2020], FullCAM might be suitable for accounting for C associated with prescribed burns, and in planning prescribed burns to achieve strategic goals (Norris *et al*., 2010; Haslem *et al*., 2011; King *et al*., 2011).

In this study, we examine the suitability of the FullCAM framework for simulating the effect of prescribed burning on eucalypt open forest (as defined in FullCAM) at four sites in the greater Blue Mountains region that underwent prescribed burns in April-May 2019. The focus was on this type of forest structure rather than on a diversity of forest or mixed grass/woody systems. We make use of empirical data collected from field sites to derive and estimate forest components, some of which are suitable for comparing to simulated values. Other objectives were to explore the alignment of the FullCAM framework with these field data collections and test the suitability of FullCAM for simulating the effect of prescribed burning on these eucalypt open forest sites.

METHODS

FIELD SITES AND FOREST STRUCTURE

Four eucalypt open forest sites in the greater Blue Mountains region, west of Sydney, Australia, were used in this study: Belmore Crossing (BC), Lawson Ridge (LR), Oak Range (OR), and Rocky Waterholes (RW) (Figure 1). These sites were prescribed burned by NSW National Parks and Wildlife Service in April and May 2019 and fieldwork campaigns were done in May and June 2019; approximately 4-6 weeks after prescribed fires had extinguished. In this report, these sites are referred to as 'eucalypt open forest' to correspond with the terminology used in FullCAM. Sites were sampled using paired plots located in burnt and nearby unburnt forest (Figure 2).

The components of eucalypt open forest (e.g. see Figure 3) can be generalised as per Figure 4A, where the overstorey comprises dominant and mid-storey tree species; the understorey comprises smaller tree saplings, shrubs, ferns and grasses; aboveground dead organic material includes surface litter and coarse woody debris (CWD); and belowground soil organic matter (SOM) includes plant debris from coarse and fine roots as well as surface material that has been broken down and incorporated into topsoil. Field data (described below) for most of these components or their key attributes were sampled based on the plot sample scheme shown in Figure 4B. However, site photos (Figure 3) show the variability in the generalised ecosystem components (Figure 4A) across sites for burnt and unburnt plots. In particular, the understorey was variable from site-to-site (Figure 3A, B, H, I) and was majorly affected by the prescribed burn-scale of fire (Figure 3C, D, J, K). At the site-scale there was also variability in productivity (Figures 1, 2) and vegetation type (Figure 5), which can be an important consideration in planning prescribed burns (e.g. Marsden-Smedley, 2011; Office of Environment and Heritage (OEH), 2013). Fuel accumulation and fuel type and variability in climate and management practices also have the potential to affect fire behaviour and the impact of prescribed burning on C cycling (Bradstock *et al*., 2002).

FIELD DATA

Key ecosystem variables and their methods of measurement are outlined here, briefly but see Gharun *et al*. (2015) for further description of methods. A comprehensive description of the field sites is given in Bell *et al*. (2020). The sampling scheme (Figure 4B) was followed for three paired burnt/unburnt plots per site for each of the four sites (Figure 2).

Overstorey

Trees comprising the overstorey and mid-storey of the forest were subsampled in a central 20 × 20 m quadrat in each of three circular paired burnt/unburnt plots (n = 3 paired plots) within each site (BC, LR, OR, RW) in the Greater Blue Mountains region, NSW Australia (Figures 1, 2). Diameter at breast height (DBH) of trees was measured with a flexible tape measure and tree height (Ht) was estimated with a clinometer. These measurements of DBH and tree height were used, where applicable, in all three of the following allometric equations for tree biomass. The average of the three values was taken as an estimate biomass (M) per unit area for each of the paired plots.

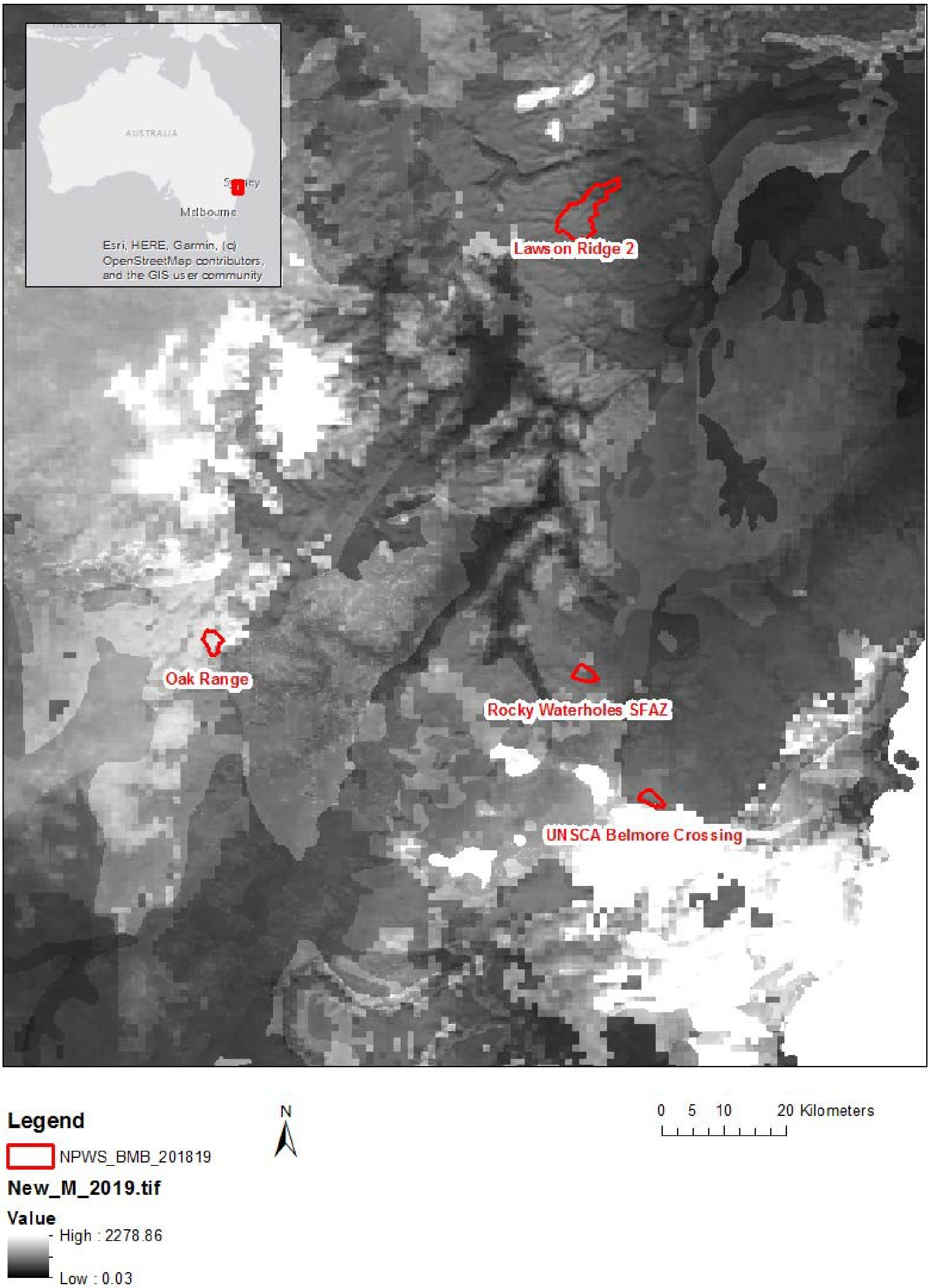

Figure 1. Location of four field sites in the greater Blue Mountains area that underwent prescribed burning by NSW National Parks and Wildlife Service (NPWS_BMB_201819) superimposed on the new maximum aboveground biomass image from Department of Industry, Science, Energy and Resources (March 2020).

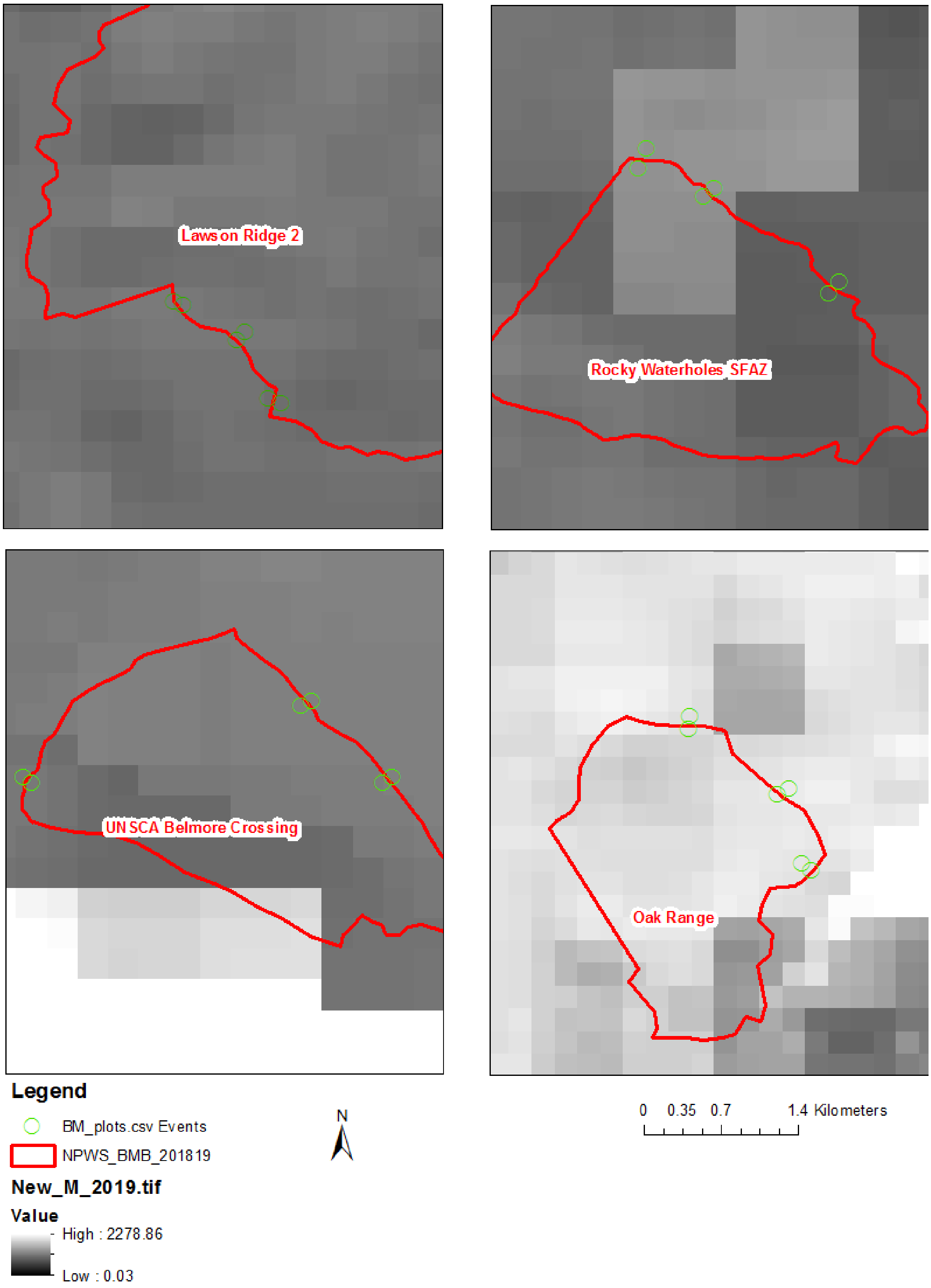

Figure 2. Location of paired plots (circles) at each of the four field sites in the greater Blue Mountains area superimposed on maximum aboveground biomass (grey scale); based on Site potential (M) and FPI average versions 2.0, Department of Industry, Science, Energy and Resources (March 2020).

Figure 3. Examples of unburnt and burnt eucalypt open forest. Sites include (A, C) Belmore Crossing (BC), (B) Lawson Ridge (LR), (H, J) Rocky Waterholes (RW), and (I, K) Oak Range (OR) taken 4-6 weeks after prescribed burning; Photos of overstorey canopy scorching and associated new litterfall (D and E, respectively), and resprouting of near surface vegetation and burnt surface litter and topsoil (F and G).

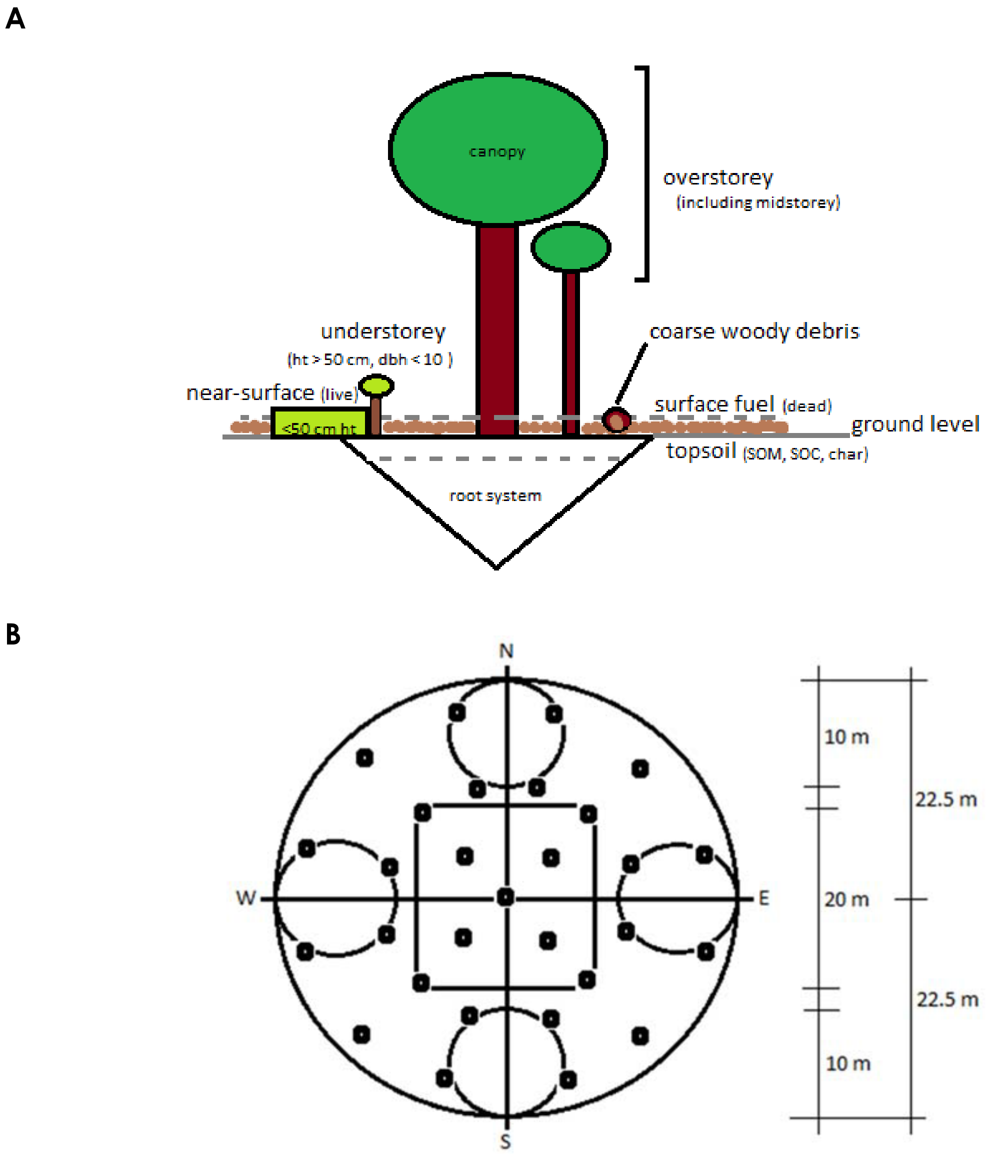

Figure 4. Forest ecosystem structure relating to measurements taken. (A) From top to bottom: overstorey was derived using measurements of diameter at breast height (taken at 1.3 m above ground level, denoted ‘dbh’) and height (denoted ‘ht’) for trees within the one central square subplot with length 20 m; understorey was derived using dbh and ht estimates within the four circular subplots with radius 5 m at the cardinal points); near-surface and surface fuels were sampled with a 0.1 m^2 ring within the circular subplot with radius 5 m at the north cardinal point; topsoil samples were collected for further analyses in the laboratory including bulk density, pH, electrical conductivity and elemental carbon and nitrogen; coarse woody debris (deadwood stems and branches >2.5 cm in diameter). SOM = soil organic matter, SOC = soil organic carbon.
(B) Sampling plot design showing one circular plot with radius 22.5 m, north-south and east-west transects, four circular subplots with radius 5 m at the cardinal points, one central square subplot with length 20 m and the 25 points approximately where digital images where taken across the plot to estimate leaf area index.

Allometric equations:

$LnM\ (kg) = -2.3267 + 2.485\ x\ lnDBH\ (cm)$ (1) (Keith *et al.*, 2000)

$lnM\ (kg) = 0.0375\ x\ DBH^{-}\ (cm)\ x\ H^{-}$ (2) (Ximenes *et al.*, 2018)

$lnM(kg) = -2.642 + 2.551\ x\ lnDBH\ (cm)\ x\ 1.109$ (3) (Montagu *et al.*, 2005)

Understorey

Within each circular plot (22.5 m radius), at the ends of north-south and east-west transects, a circular subplot (5 m radius) was used to subsample understorey trees; DBH was measured and height estimated for all trees <10 cm in diameter that were within each circular subplot. The abovementioned allometric equations (1-3) were used and the average of the three values was taken as an estimate of biomass (M) per unit area for each subplot and hence, the average of four values from subplots was then taken as the estimate for each plot (22.5 m radius).

Surface litter and soil

At the north point of each circular plot (22.5 m radius) a circular quadrat (approx. 0.1 m^2) was used to subsample surface litter and soil. Surface litter samples were oven dried at 70˚C for at least 48 hours, weighed, and were subsequently analysed for their C content (only data from LR reported here). Surface litter from two of the sites (BC and LR) was sorted into fractions of twigs, leaves, other materials (bark, seeds, fruits) and fine fraction (<9 mm) and weighed.

A steel corer (5 cm in diameter × 10 cm long) was used to collect soil samples. Surface litter was cleared away to expose the mineral soil surface and the corer was driven vertically and fully into the soil with a mallet. Cores were carefully extracted into plastic zip-lock bags, sealed and stored in an esky, then transported to the laboratory. Soil samples were air dried and analysed for C and nitrogen (N) content (Elementar Vario Max CNS, Analysensysteme GmbH, Hanau, Germany); samples for the other three sites will be analysed for their C and N content, in due course.

Coarse woody debris

The volume of coarse woody debris (CWD) was determined using the line intersect method (Van Wagner, 1968). The diameter and length and point of intercept of woody debris >2.5 cm and state of decay (solid, rotten) were recorded along north-south and east-west transects that intersected at the centre point of the circular plot with 22.5 m radius. Specific gravity (Ilic *et al.*, 2000) of CWD samples was used to assign density multiplies of 0.827 and 0.742 g cm^{-3} for solid and rotten states of decay, respectively, to convert units of volume per area into tonnes dry weight biomass per hectare. For each plot, the average of the two transects was taken.

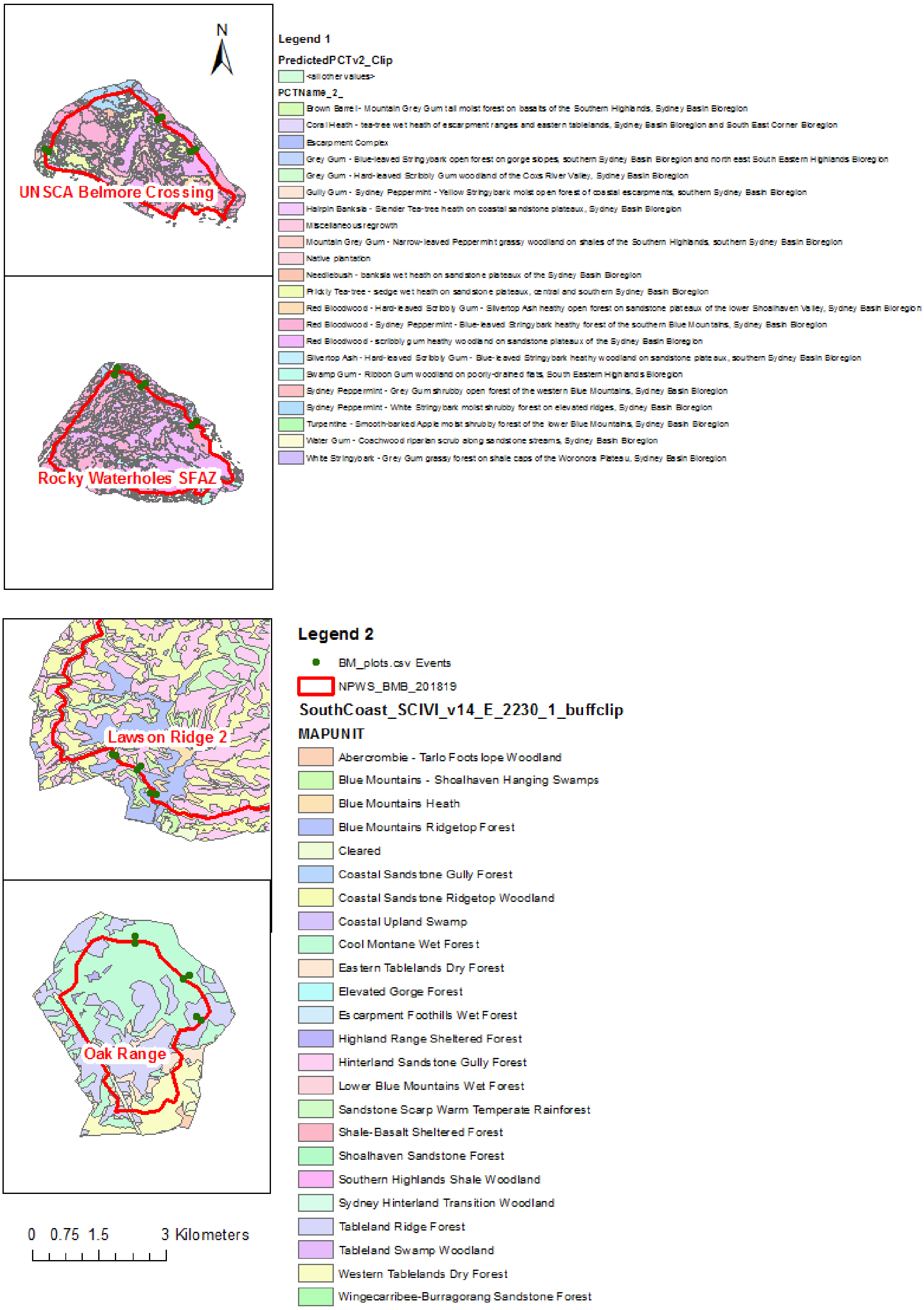

Figure 5. Clipped maps of plant community types show variation in vegetation between plots and among field sites; based on Southeast NSW Native Vegetation Classification and Mapping - SCIVI (VIS_ID 2230; State Government of NSW and Department of Planning, Industry and Environment 2010).

Leaf area index and derived leaf mass

Leaf area index estimates derived from digital photography

Procedures for taking digital photography to estimate leaf area index (LAI) followed Macfarlane *et al*. (2007) for overstorey vegetation and Macfarlane and Ogden (2012) for understorey vegetation. A digital camera (Nikon Coolpix 4500) fitted with an F2 lens, set to Automatic Exposure and to Aperture-Priority mode, was mounted onto a pole 2 m above ground level. Using a bubble level to guide, the lens was held horizontally as each photograph was taken. The camera and lens were pointed up for taking overstorey (canopy) images and down for taking ground cover images (understorey). An algorithm was used to analyse the photographic images following the method of Fuentes *et al*. (2008) to estimate LAI for overstorey and foliage cover (FC) for understorey, including estimate of crown cover (CC) from FC, and then converted to LAI, with CC = FC (1 – 0.25) and LAI = -CC × LN(0.25)/0.6, where canopy porosity was assumed to be 0.25 based on Macfarlane and Ogden (2012), and light extinction coefficient for understorey was assumed to be 0.6 based on Vertessy *et al*. (1996). Digital photographs were taken systematically within 3 × 45 m diameter circle plots (Figure 4B) within and adjacent to each of four different prescribed burn sites located in the Greater Blue Mountains region (Figure 2).

DERIVATIONS AND ESTIMATIONS

Field data and estimations using field data were used to derive variables that help to characterise each of the four sites selected in eucalypt open forest and associated biogeochemical function (i.e. are informative regarding stocks and flows of C). In some cases, these data provided a variable to compare simulated output against. An itemised list of derivations and estimations is given in Table 1 along with values for each site where possible otherwise for one (e.g. soil C) or two sites (e.g. surface litter fractions). An associated itemised list of Comments (Table 2) provides brief descriptions of derivations and assumptions for each item. Values for more than 30 FullCAM simulated variables are provided in Table 1, each beneath their corresponding comparative variable; coinciding item number, with prefix 's' for simulated, is included in the same format in the list of Comments and these can be used to lookup simulated items in Table 3 (Simulations). For example, s2 is 'C mass of tree stems (tC/ha)' which appears directly underneath and is compared with 'stem 50% AGB' (item 16 in Table 1).

Leaf mass was derived from estimates of LAI and specific leaf area (SLA) of 6 m^2 kg^{-1}. This moderately low value for SLA was used to represent an average value for forests dominated by older eucalypt trees comprising overstorey and understorey along with saplings, shrubs and some grasses comprising understorey.

FULLCAM

We used FullCAM, the current preferred model for tracking C stocks and flows from Australia associated with land use and management (DEE, 2019). FullCAM

(Figure 6) integrates C accounting sub-models to estimate net greenhouse gas emissions (CO_2 uptake via primary production and CO_2 release via autotrophic and heterotrophic respiration (R_a and R_h, respectively)), allocation and changes in biomass (above- and belowground), turnover and litterfall and decomposition (also referred to as breakdown) that drive changes in debris and soil C pools in forest ecosystems. In two decades, FullCAM has been refined over several versions (e.g. Richards, 2001; Brack *et al.*, 2006; Waterworth *et al.*, 2007; Paul *et al.*, 2016; Roxburgh *et al.*, 2019). In this study we use a public release version 6.19.07.1114 [2019].

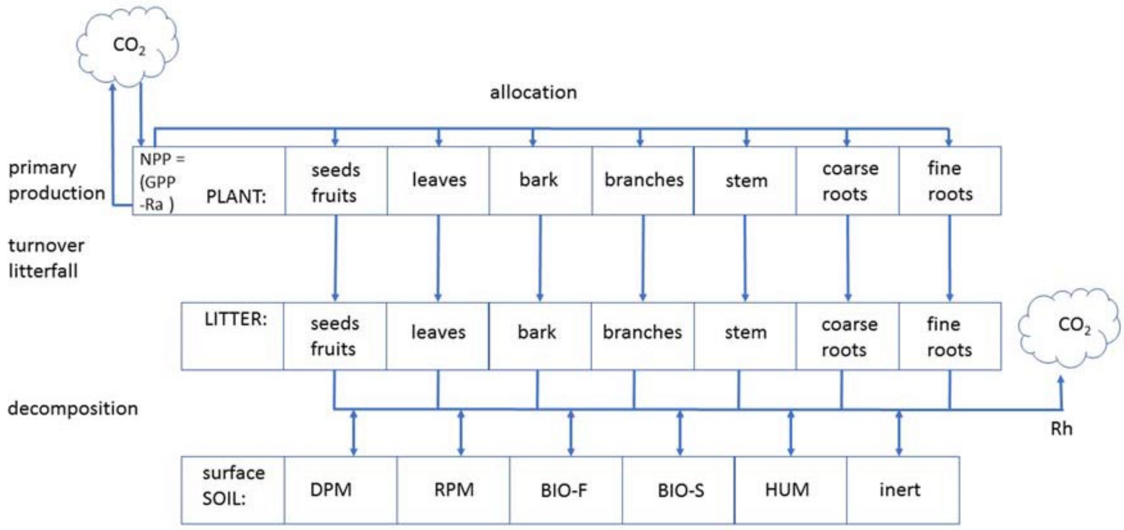

Figure 6. Carbon (C) stocks and flows incorporated in the FullCAM model applied to forest ecosystems by deploying the forest system option. Briefly, photosynthesis in plants generates gross primary production (GPP) which is partly used by the plant as a source of energy to drive metabolism (the process of autotrophic respiration, R_a that releases CO_2 into the atmosphere) and the remaining net primary production (NPP) is allocated to the different plant components which turnover on different time scales to produce litterfall inputs to litter pools (debris), which are subsequently decomposed by macro and micro fauna and fungi that release CO_2 via heterotrophic respiration (R_h). Living plant biomass turns over to generate dead litter comprising surface litter (from leaves, twigs, bark, seeds and fruits), coarse woody debris (from branches and stem) and a dead soil organic matter pool (from coarse and fine roots, plant exudates and heterotrophs, which also turnover). The forest system in FullCAM comprises forest only, an assumption is used to simulate overstorey and the understorey (1-30%) plant systems that both essentially follow the above schematic flow diagram (see FullCAM description in Methods section of this report as well as the help files associated with the FullCAM program available from Department of Industry, Science, Energy and Resources (DISER)).

Simulations

Approach

FullCAM allows different configurations to model different types of systems, including forest, grassland, mixed grass – woody systems (e.g. Russell-Smith *et al.*, 2009; Law and Garnett, 2011), agricultural or mixed forest – agricultural systems.

In previous approaches to modelling prescribed fire effects on eucalypt open forest with FullCAM, a 'mixed forest – agricultural system' has been deployed, where the agricultural fraction has been set as a 'perennial grassland' and subsequently used as a surrogate for the 'understorey' fraction of the ecosystem (Karunaratne *et al*., 2018). The mixed forest – agricultural system configuration is more suited to spatial variation in ecosystem types laterally (e.g. across landscape) rather than for vertical differences in ecosystem structure (i.e. overstorey and understorey, Figure 4A). In this study we deployed a more straightforward 'forest system' configuration but, necessarily, with key assumptions about the understorey fraction of the ecosystem (of aboveground biomass) and about the twig fraction of branches and its turnover rate – as these partitions are not yet readily configured in this version of FullCAM. We opted for this approach because it allowed for a more authentic representation of the biomass components of the forests, and sites had only minor grass cover (see Figure 3) compared to total aboveground biomass, and live woody components (particularly of understorey) could also flow to dead organic matter pools. We also opted to simulate on a monthly time step, with time series (average year of data) inputs for site variables: Water (Rainfall and Open-pan evaporation), Temperature and Productivity; tree age of maximum growth was set at 10 years.

Model calibration involved downloading the parameter set from the FullCAM server (using the Data Builder feature in FullCAM) for the latitude and longitude of the site, then adjusting key parameters (Table 4). Site 'maximum aboveground biomass' was adjusted based on estimates of aboveground biomass using DBH measurements in allometric equations. Simulations were run from zero initial pools for approximately 10,000 years with approximate allocation, turnover and debris breakdown rates to establish a steady state equilibrium and carbon pool sizes approximating estimates (Figure 7). Allocations, turnover and breakdown rates were subsequently adjusted to achieve reasonable simulated values for surface litter. Key assumptions related to surface litter fractions were an important consideration (see below). Prescribed burn settings were guided by changes (losses or gains) observed in surface litter and its fractions, understorey LAI (and estimates of leaf mass), and soil C. Essentially, simulated outputs were compared with observations (derived and estimated variables) to 'calibrate' the model to the four slightly different eucalypt open forest sites.

Key assumptions

The prescribed burn clearly affects surface litter and understorey LAI by reducing it quantitatively. For simulations we use field data to estimate these effects via parameter value settings. The prescribed burn, in practice, qualitatively affects understorey biomass and CWD, and in some cases can scorch the underside of the upper canopy (e.g. Figure 3D, in the distance showing scorched brown leaves in the canopy; Figure 3E showing new leaf litterfall shortly after prescribed fire). For simulations, we assume that the understorey biomass and CWD are affected to a similar degree to that of surface litter. Qualitative observations revealed that much of the live understorey leaf fraction was burnt by prescribed fires, which is supported by estimates of understorey LAI (Table 1, item 5); likewise, much of the understorey live twig fraction was burnt; bark on understorey live saplings and woody shrubs was blackened or charred; and some of the smaller trees were killed.

Three estimates for twigs fraction of branches: twigs as a 3-10% fraction of branches that are a 48% fraction of aboveground biomass (AGB), equivalent to twigs (t C ha^{-1}) = 0.03 branches (t C ha^{-1}); twigs proportional to LAI, equivalent to twigs (t C ha^{-1}) = 1.02 LAI ($m^2 m^{-2}$); and twigs as a variable fraction of branches, twigs (t C ha^{-1}) = frac 0.48 AGB, where 'frac' was set at 0.08 for three sites: BC, LR, and RW, and 0.04 for one site: OR.

Three estimates of the aboveground understorey fraction of total aboveground biomass (AGB): understorey related to the inverse of height, understorey (t C ha^{-1}) = 170/Ht; understorey as 1-10% of AGB, understorey (t C ha^{-1}) = 0.1 AGB; and understorey related to the inverse of LAI and height, understorey (t C ha^{-1}) = 200/(LAI total + Ht).

Estimates of litterfall (relative to leaves – leaf mass estimated from LAI and constant SLA of 6 $m^2 g^{-1}$): two estimates of leaf litterfall, leaf litterfall = 0.3 leaf mass or leaf litterfall = 0.3 (0.02 AGB); bark litterfall = 0.2 (0.024 AGB); twig litterfall = 0.08 (0.35 branches); aboveground deadwood litterfall = 0.35 branches; coarse roots litterfall = 0.1 coarse roots; and fine roots litterfall = 0.5 fine roots.

Total surface litter and its fractions (only available for BC and LR sites) were used to guide turnover and debris breakdown rates.

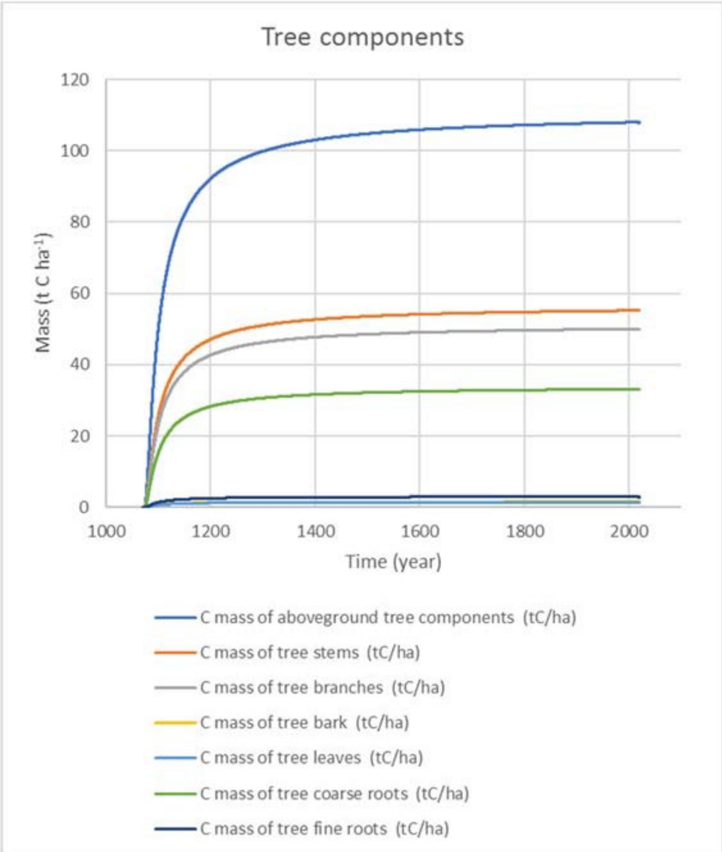

Figure 7. Spin up of FullCAM model to steady state equilibrium, approximately – a manifestation of maximum aboveground biomass and allocation settings. C = carbon.

RESULTS AND DISCUSSION

The results for Field Data, Derivations and Estimations (including comparable variables), Comments and Simulations are presented in Tables 1-3 (attached) in itemised lists to facilitate cross referencing among tables. Key parameters are shown in Table 4 (attached) for the simulated values displayed in Tables 1 and 3.

FIELD DATA

All sites were generally characterised as eucalypt open forest (dry sclerophyll), however, key similarities and differences between the four sites are evident from Table 1 (Field Data). Two sites, RW and LR, had similarly low productivity (less aboveground live biomass) than OR, which has the highest productivity, and BC has an intermediate productivity. The same pattern was seen for overstorey tree height and total leaf area index (LAI total) but not for overstorey LAI where RW and LR were higher than BC. Estimates for understorey biomass (Table 1, items 28-30) tended to be higher for RW and LR and lowest for OR with BC as intermediate, a pattern opposite to overstorey tree height. Estimates for CWD (Table 1, item 50) show a similar pattern across sites to tree height (Table 1, item 14). Surface litter was higher for RW than OR with both LR and BC as intermediate. Therefore, broadly characterising sites, OR is the most productive and tallest with the smallest understorey and surface litter, followed by BC then LR; and RW is least productive with greatest surface litter and what may be an anomalously large CWD pool. It is important to note that the standard error for surface litter and its component fractions were high relative to other field data variables, which is not unexpected due to the heterogeneous nature typical of surface litter and soil organic matter (Jackson and Caldwell, 1993).

Values for aboveground biomass derived from DBH and allometric equations (Table 1, item 1), were reasonable compared with maximum aboveground biomass values downloaded from the FullCAM server (corresponding to values depicted in Figure 1). Values for total LAI (Table 1, item 8) previously compared well with satellite values (Pepper *et al*. 2020, Milestone Report 3.2.2), after leaf mass conversions using a SLA of 6 $m^2 g^{-1}$ (Table 1, item 8.1), also compared reasonably well with values reported in the literature for old-growth forest (Mitchell *et al*., 2010).

Three estimates for twigs fraction (Table 1, items 23, 24, 25) were made given the uncertainty of this fraction of litter input and its importance as a component of forest debris and fuel. Three estimates of understorey fraction (Table 1, items 28, 29, 30) were also made given the uncertainty of this fraction and its importance as a component of forest debris and fuel. Estimates of CWD (Table 1, item 50) reflected measured CWD (Table 1, item 9) and provided an estimate for one site, RW, when the measured value seems anomalous.

The estimates for twig biomass have a large influence on twig litterfall and twig fraction of surface litter, where the latter has significant influence on the surface litter fuel level affected by prescribed burning. Likewise, estimates for understorey biomass influence the fuel level affected by prescribed burning, and thus on the amount of C emitted during prescribed burning (i.e. C loss from the ecosystem), the C flowing to standing dead mass and the C flowing to the inert soil pool (see later for further discussion). These key assumptions in the approach to modelling prescribed burning in eucalypt open forest are of major importance to simulating the effect on the stocks and flows (and hence, C emitted) from these forest systems.

SIMULATIONS

As simulations were essentially a calibration exercise, as expected, simulations for overstorey and tree components compare well with derived and estimated values (Table 1, items 16-22). However, simulated understorey depends directly on the assumption of what fraction of the ecosystem is understorey. Given the importance of this ecosystem component as one of the most affected components by prescribed fire, a more certain estimate is required, and might indeed be closely approximated by one of the three estimates made in this study – but this remains uncertain.

Simulated deadwood (most comparable to DWD + twig fraction of surface litter) tended to be too high for CWD estimates and deadwood (Table 1, items 50 and 50.1, respectively) except perhaps for deadwood (item 50.1) at one site, LR, and both (items 50 and 50.1) at another (OR).

Simulated surface litter (sum of simulated bark, leaf and twig debris) varied by plus 15% and minus 10% for BC and LR, respectively and by minus 44% and plus 120% for RW and OR, respectively. This is a poor result that needs to be improved. Any improvement here will likely have positive flow-on effects to simulation of components affected by prescribed fire.

For the two sites for which we had surface litter fractions, BC and LR, simulated fractions tended to be high for leaf litter and bark litter at both sites and for twig litter at LR only (Table 1, items 55-57). The fine fraction (Table 1, item 58) simulation was closer but the sum of simulated leaf, twig and bark reveals that the fine fraction was included in the individually simulated leaf, bark and twig fractions, which makes the simulated values more representative than they would otherwise appear.

Fire effect on overstorey

Simulated scorching of overstorey leaves contributed to a fraction of C mass moved from leaf to standing dead leaf, due to prescribed fire (Table 3, item s48). Simulated burning of 5% of fine roots (in the very top layer of soil) contributed to a flow of C from live biomass to atmosphere for which there is no direct equivalent FullCAM output variable but rather a fraction of C mass emitted due to fire, from trees (item s51).

Fire effect on understorey

Live biomass to atmosphere: The fractions of understorey leaves, twigs, bark and fine roots burnt and lost (Table 1, items 80-83) represented the mass of C emitted due to prescribed fire, from trees (Table 3, item s51), which was underestimated across all four sites by an order of magnitude.

Live biomass to standing dead: The loss fractions of components of aboveground understorey, namely stem, branch, twig, leaf and bark (Table 1, items 84-88) and inferred belowground components of understorey, namely coarse roots and fine roots (Table 1, items 89, 90), were assumed to flow to standing dead pools, estimated at 1% of each of the component fractions of understorey (i.e. the estimated understorey fraction of ecosystem). The proportion of 1% was based on qualitative observations of understorey vegetation that looked burned and had no visible signs of life. The corresponding simulated variables depend on the assumption and resultant t C ha^{-1} of understorey used. Most of the simulated values were trending in the correct direction towards estimates, except the simulated flow of twigs, a fraction of C mass moved from branch to standing dead branch, due to fire (Table 1, item s46) was overestimated; similarly, for bark (Table 1, item s47).

Fire effect on debris

Debris to atmosphere: The loss of debris components (Table 1, items 91-95) were based on loss fraction, calculated as the difference between unburnt and burnt averages of three plots, which were generally overestimated for both BC and LR, except for twig litter loss. The degree of overestimation is likely to be greatly improved when more accurate simulations of surface litter pools are achieved.

Simulated total loss of debris to the inert pool was low across all sites, which suggests that the assumption that 10% fraction of debris becomes char and therefore flows to the inert pool may be overestimated.

Fire effects in general

Good use of the field data was made to gain insights into eucalypt open forests and variations and similarities in their structure across the four sites, and to derive variables that were comparable to FullCAM simulated outputs. However, both field data collection and FullCAM outputs could be better aligned to make it easier to apply the model to eucalypt open forest sites and simulate effects of prescribed burning. The framework of the generic ecosystem model could include an option to partition understorey as an ecosystem component because it is directly affected by the scale of the prescribed burn. The framework could also include an option to partition a twig fraction as part of branch biomass, allowing twig turnover (twig litterfall) and its contribution to surface litter to be explicit. Moreover, the framework should add C mass moved from tree components to atmosphere rather than from whole tree to atmosphere or to standing dead only, because this would more truly reflect the loss of live material from prescribed burn sites as well as make the modelling more tractable.

Field data collection design could improve estimates of understorey; perhaps measurements of understorey LAI and overstorey LAI could be adapted by adjusting the position of camera aboveground between understorey and mid-storey (often above and sometimes below the 2 m aboveground level). Moreover, similar protocols as those used for LAI could be developed for estimating stem and branch biomass vertically as this might greatly aid C accounting with models such as FullCAM. Better alignment between model and data would probably allow simulations to be extended to N cycling and water cycling via, respectively, C:N ratio characteristics of biomass pools (Elser *et al.*, 2010) and water-use efficiency relationships that tend to be fairly stable within ecosystems (Monteith, 1986).

A set of fundamental field measurements would include:

- DBH of overstorey trees
- Overstorey LAI
- DBH of understorey trees and saplings
- Understorey LAI[1]
- Surface litter, both fine leaves, twigs and bark as well as CWD[2]
- Soil C in the top layer

Notes: 1. Any measurements to quantitatively characterise the understorey that are likely to be affected by a prescribed burn-scale fire would be very useful.

2. A sampling design that provides a representative quantitative estimate of CWD per unit area also would be very useful.

CONCLUSIONS

While the generic framework of FullCAM is suited to modelling carbon stocks and flows in eucalypt open forest systems, there are improvements required to better simulate the effect of prescribed burning on C stocks and flows. Such improvements are likely to make it easier to use FullCAM for simulating prescribed burns in eucalypt open forest and achieve more rigorous C accounting results. With respect to data, the somewhat standard approach to field data collection is not completely suited to a generic framework for accounting C, such as that in FullCAM as well as in other models, nor is it completely suited to measuring the full effect of the typical scale of prescribed burning. Better measurements to derive estimates of understorey biomass, the twig litter fraction of surface litter and aboveground deadwood are needed to apply the C accounting framework of FullCAM.

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ATTACHMENTS

The following four tables are included as attachments.

TABLE 1

Table 1. Main list of results for field data, derivations and estimations, comparing simulated variables where available, for the four field sites, BC = Belmore Crossing, LR = Lawson Ridge, RW = Rocky Waterholes and OR = Oak Range.

TABLE 2

Table 2. Comments associated with Table 1.

TABLE 3

Table 3. FullCAM simulation for sites, BC = Belmore Crossing, LR = Lawson Ridge, RW = Rocky Waterholes and OR = Oak Range.

TABLE 4

Table 4. Key parameters for FullCAM

TABLE 1 Main list of results for field data, derivations and estimations, comparing simulated variables where available, for the four field sites, BC = Belmore Crossing, LR = Lawson Ridge, RW = Rocky Waterholes and OR = Oak Range.

		Sites:	BC				LR				RW				OR			
		Treatment:	Burnt		Unburnt		Burnt		Unburnt		Burnt		Unburnt		Burnt		Unburnt	
			Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Item no.	item	units																
	FIELD DATA																	
1	Aboveground biomass (AGB; trees, shrubs and grasses)	$t\ C\ ha^{-1}$	47	9	109	19	49	8	65	11	25	4	44	6	266	38	186	15
2	Overstorey	$t\ C\ ha^{-1}$	46.64	9.05	109.11	18.92	47.96	7.81	64.58	10.65	24.96	3.94	43.70	6.42	265.45	38.06	186.27	15.14
3	LAI_over	m^2 leaf m^{-2}	0.950	0.016	1.013	0.005	1.443	0.027	1.097	0.002	0.941	0.022	1.171	0.012	1.367	0.011	1.463	0.011
4	Understorey ('elevated fuel')	$t\ C\ ha^{-1}$	0.09	0.01	0.16	0.01	0.75	0.35	0.38	0.16	0.31	0.13	0.37	0.07	0.20	0.02	0.17	0.10
5	LAI_under	m^2 leaf m^{-2}	0.058	0.002	0.537	0.006	0.102	0.003	0.458	0.003	0.099	0.005	0.315	0.011	0.096	0.001	0.277	0.005
6	Near surface	$t\ C\ ha^{-1}$			n/a				n/a				n/a				n/a	
7	Surface litter	$t\ C\ ha^{-1}$	6.53	3.10	9.30	3.08	5.62	1.59	9.48	4.13	7.05	3.00	11.46	3.84	5.46	3.01	6.96	4.56
7.1	leaves	$t\ C\ ha^{-1}$	1.29	0.40	3.01	1.10	0.89	0.61	4.05	1.86								
7.2	twig	$t\ C\ ha^{-1}$	2.08	2.53	4.50	3.44	1.43	1.02	4.34	2.79								
7.3	other (bark, seeds, fruit)	$t\ C\ ha^{-1}$	1.41	2.24	2.52	3.18	1.51	0.90	3.81	3.12								
7.4	fine fraction	$t\ C\ ha^{-1}$	4.54	3.65	6.43	3.02	7.21	2.55	6.99	3.72								
7.5	dry litter total	$t\ C\ ha^{-1}$	9.32	5.96	16.46	6.83	11.04	3.30	19.20	8.36								
8	LAI_total (over+under)	m^2 leaf m^{-2}	1.008	0.015	1.550	0.006	1.545	0.028	1.555	0.004	1.039	0.018	1.486	0.021	1.463	0.010	1.740	0.006
8.1	Leaf mass	$t\ C\ ha^{-1}$			1.29				1.30				1.24				1.45	
9	Coarse woody debris (CWD)	$t\ C\ ha^{-1}$	2.83	1.63	2.14	3.79	6.80	4.87	1.48	0.74	3.23	2.58	14.72	21.54	10.25	8.56	11.76	11.10
10	Soil C	$t\ C\ ha^{-1}$					53.39	11.61	28.85	3.76								
11	Soil N%	%					0.09	0.02	0.17	0.01								
12	Soil C%	%					3.56	0.77	1.92	0.25								
13	Soil H%	%					0.69	0.11	0.38	0.04								
14	Height	m			16.03				13.15				13.34				27.04	
	DERIVATIONS AND ESTIMATIONS																	
	OVERSTOREY																	
15	overstorey	$t\ C\ ha^{-1}$			96.95				51.09				31.27				181.38	
16	stem 50% AGB	$t\ C\ ha^{-1}$			54.63				32.48				22.04				93.22	
	C mass of tree stems (tC/ha)				54.93				32.20				21.78				92.51	
17	branches 48% AGB	$t\ C\ ha^{-1}$			52.45				31.18				21.16				89.49	
	C mass of tree branches (tC/ha)				49.77				30.12				20.37				86.87	
18	bark 2.4% AGB	$t\ C\ ha^{-1}$			2.62				1.56				1.06				4.47	
	C mass of tree bark (tC/ha)				2.15				1.51				1.02				4.08	
19	Leaf mass_overstorey	$t\ C\ ha^{-1}$			0.84				0.91				0.98				1.22	
20	leaves 2% AGB	$t\ C\ ha^{-1}$			2.19				1.30				0.88				3.73	
	C mass of tree leaves (tC/ha)				1.14				1.31				0.88				3.66	
21	coarse roots 30% AGB	$t\ C\ ha^{-1}$			32.78				19.49				13.22				55.93	
	C mass of tree coarse roots (tC/ha)				32.96				19.00				12.85				55.51	
22	fine roots 3% AGB	$t\ C\ ha^{-1}$			3.28				1.95				1.32				5.59	
	C mass of tree fine roots (tC/ha)				2.90				1.89				1.28				5.51	
23	twigs 3-10% of branches	$t\ C\ ha^{-1}$			1.57				0.94				0.63				2.68	
24	twigs proportional to LAI	$t\ C\ ha^{-1}$			1.58				1.59				1.52				1.77	
25	twigs (~10% of 48% of AGB)	$t\ C\ ha^{-1}$			4.20				2.49				1.69				3.58	
26	twig fraction of branches	fraction			0.08				0.08				0.08				0.04	
27	branches 48% of AGB	fraction			0.48				0.48				0.48				0.48	
	UNDERSTOREY																	
28	understorey: these estimates reflect inverse of height	$t\ C\ ha^{-1}$			10.61				12.92				12.75				6.29	5.44
29	aboveground understorey (1-10% of AGB)	$t\ C\ ha^{-1}$			10.93				6.50				4.41				18.64	
30	aboveground understorey (inverse LAI_under)	$t\ C\ ha^{-1}$			12.32				13.86				12.81				5.05	
	10% AGB, 0.1xs1				10.80				6.51				4.41				6.17	
31	understorey 7% AGB, adjusted to:	fraction			0.10				0.20				0.29				0.03	
32	AG understorey fraction of AGB	fraction			0.113				0.213				0.291				0.027	
33	stem (50% AG_understorey)	$t\ C\ ha^{-1}$			6.16				6.93				6.40				2.53	
34	branch (48% AG_understorey)	$t\ C\ ha^{-1}$			5.91				6.65				6.15				2.43	
35	twig (10% branch understorey)	$t\ C\ ha^{-1}$			0.591				0.665				0.615				0.243	
36	twigs 1.5-5% of aboveground understorey	$t\ C\ ha^{-1}$			0.554				0.624				0.576				0.227	
37	leaf understorey	$t\ C\ ha^{-1}$			0.45				0.38				0.26				0.23	
38	bark understorey (5% AG_understorey)	$t\ C\ ha^{-1}$			0.62				0.69				0.64				0.25	
39	coarse root (30% AG_understorey)	$t\ C\ ha^{-1}$			3.70				4.16				3.84				1.52	
40	fine root (3% AG_understorey)	$t\ C\ ha^{-1}$			0.37				0.42				0.38				0.15	
41	LM/AGB	fraction			0.012				0.020				0.028				0.008	
	leaf mass/aboveground tree biomass, s5/s1				0.011				0.020				0.020				0.020	
42	LAI_under / LAI_total	fraction			0.35				0.29				0.21				0.16	

(continued over…)

		Sites:	BC				LR				RW				OR			
		Treatment:	Burnt		Unburnt		Burnt		Unburnt		Burnt		Unburnt		Burnt		Unburnt	
Item no.	item	units	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
	LITTERFALL																	
43	leaf (based on LAI_over+under)	t C ha^{-1} $year^{-1}$			0.39				0.39				0.37				0.44	
44	leaf	t C ha^{-1} $year^{-1}$			0.66				0.39				0.26				1.12	
45	bark	t C ha^{-1} $year^{-1}$			0.52				0.31				0.21				0.89	
46	twig (part of deadwood not CWD)	t C ha^{-1} $year^{-1}$			1.34				0.80				0.54				2.29	
47	deadwood (aboveground only)	t C ha^{-1} $year^{-1}$			16.78				9.98				6.77				28.64	
48	coarse roots	t C ha^{-1} $year^{-1}$			3.28				1.95				1.32				5.59	
49	fine roots	t C ha^{-1} $year^{-1}$			1.64				0.97				0.66				2.80	
	DEBRIS																	
50	CWD estimate				2.47				1.38				1.43				11.58	
50.1	deadwood(twigs+CWD)	t C ha^{-1}			6.64				5.82				14.71984				11.76	
	C mass of forest resistant deadwood (tC/ha)				12.42				6.01				4.06				10.88	
51	CWD fraction of AGB	fraction			0.020				0.023				0.334				0.063	
52	CWD fraction of branches	fraction			0.041				0.047				0.696				0.131	
53	twig litter fraction of deadwood	fraction			0.38				0.37									
54	Surface litter	t C ha^{-1}			9.30	0.15			9.48	-0.09			11.46	-0.44			6.96	1.17
	sum of bark, leaf and twig debris, s13+s14+0.1xs10				10.68				8.63				6.37				15.08	
55	leaves	t C ha^{-1}			1.70				2.00									
	leaf debris, s14	t C ha^{-1}			3.51				4.01									
56	twig	t C ha^{-1}			2.54				2.15									
	twig debris, 0.4xs10	t C ha^{-1}			4.35				2.10									
57	other (bark, seeds, fruit)	t C ha^{-1}			1.43				1.88									
	bark debris, s13	t C ha^{-1}			2.83				2.52									
58	fine fraction	t C ha^{-1}			3.63				3.45									
	fine fraction, 0.5x(s14+0.35xs10+s13)	t C ha^{-1}			3.52				2.85									
	sum of leaf, twig and bark debris, sum(s14,0.35xs10,s13)	t C ha^{-1}			10.68				8.63									
59	Surface litter/AGB	fraction			0.085				0.146				0.260				0.037	
	(s13+s14+0.35*s10)/s1				0.099				0.133				0.145				0.081	
60	leaf litter/dry litter total	sub-fraction			0.18				0.21									
	s14/(s13+s14+0.35xs10)				0.33				0.46				0.46				0.50	
61	twig litter/dry litter total	sub-fraction			0.27				0.23									
	0.35xs10/(s13+s14+0.35*s10)				0.41				0.24				0.22				0.25	
62	other litter (bark, seeds)/dry litter total	sub-fraction			0.15				0.20									
	s13/(s13+s14+0.35*s10)				0.26				0.29				0.32				0.25	
63	fine fraction (<9 mm sieve)/dry litter total	sub-fraction			0.39				0.36									
	0.5x(s14+0.35xs10+s13)				0.5				0.5				0.5				0.5	
64	dry litter total/dry litter total	sub-fraction			1				1									
	LOSSES																	
65	LAI_under	m^2 leaf m^{-2}	0.48				0.36				0.22				0.18			
66	LAI_under	fraction	0.89				0.78				0.69				0.65			
67	Surface litter	t C ha^{-1}	2.77				3.86				4.41				1.50			
68	leaves	t C ha^{-1}	1.71				3.16											
69	twig	t C ha^{-1}	2.43				2.92											
70	other (bark, seeds, fruit)	t C ha^{-1}	1.12				2.30											
71	fine fraction	t C ha^{-1}	1.89				-0.22											
72	dry litter total	t C ha^{-1}	7.15				8.16											
73	LAI_total (over+under)	m^2 leaf m^{-2}	0.54				0.010				0.45				0.28			
74	Leaf mass	t C ha^{-1}	0.40				0.30				0.18				0.15			
75	Coarse woody debris (CWD)	t C ha^{-1}	-0.69				-5.32				11.49				1.52			
76	Soil C	t C ha^{-1}					-24.54											
	(continued over…)																	

		Sites:	BC				LR				RW				OR			
		Treatment:	Burnt		Unburnt		Burnt		Unburnt		Burnt		Unburnt		Burnt		Unburnt	
Item no.	item	units	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
	FIRE EFFECT																	
	on overstorey:																	
77	Leaf scorch fraction (based on obs and relative to height)	fraction			0.08				0.10				0.10				0.00	
78	Leaf_over to standing dead (SD)	t C ha^{-1}			0.07				0.09				0.10				0.00	
	frac s48		0.00				0.00				0.00				0.00			
79	fine root, 5%	t C ha^{-1}			0.16				0.09				0.06				0.28	
	frac s51		0.19				0.16				0.11				0.45			
	on AG_understorey: live to atm (losses associated with understorey)																	
80	leaves, 65-90% understorey leaves	t C ha^{-1}	0.32				0.36				0.33				0.13			
81	twigs, 70% understorey twigs	t C ha^{-1}	0.39				0.44				0.40				0.16			
82	bark, 2% understorey stems and branches + 50% of 70% twigs	t C ha^{-1}	0.44				0.50				0.46				0.18			
83	fine roots, 5%	t C ha^{-1}	0.02				0.02				0.02				0.01			
	sum items 80 to 83		1.17				1.31				1.21				0.48			
	C mass emitted due to fire, from trees (tC/ha)		0.187986				0.163327				0.110468				0.450118			
	on AG_understorey: live to SD, 1% understorey killed																	
84	stem	t C ha^{-1}			0.062				0.069				0.064				0.025	
	C mass moved from stem to standing dead stem, due to fire (tC/ha)		0.03845				0.022542				0.015247				0.064758			
85	branch	t C ha^{-1}			0.059				0.067				0.061				0.024	
	C mass moved from branch to standing dead branch, due to fire (tC/ha)		0.034842				0.021084				0.01426				0.060812			
86	twig	t C ha^{-1}			0.006				0.007				0.006				0.002	
	fracs46		0.01219				0.00738				0.00499				0.02128			
87	leaf_under	t C ha^{-1}			0.000				0.000				0.000				0.000	
	C mass moved from leaf to standing dead leaf, due to fire (tC/ha)		8E-05				9.14E-05				6.18E-05				0.000256			
88	bark	t C ha^{-1}			0.006				0.007				0.006				0.003	
	C mass moved from bark to standing dead bark, due to fire (tC/ha)		0.00045				0.00032				0.00022				0.00086			
89	coarse root	t C ha^{-1}			0.037				0.042				0.038				0.015	
	C mass moved from coarse root to standing dead coarse root, due to fire (tC/ha)		0.02307				0.0133				0.008996				0.038855			
90	fine root	t C ha^{-1}			0.004				0.004				0.004				0.002	
	C mass moved from fine root to standing dead fine root, due to fire (tC/ha)		0.00203				0.00132				0.000893				0			
	on debris: to atm																	
91	Surface litter	t C ha^{-1}			2.774				3.860				4.412				1.503	
	sum(s54, frac52,s53)		4.63				4.07				3.01				7.16			
92	leaf litter	t C ha^{-1}			0.969				1.562									
	C mass emitted due to resistant leaf litter to atmosphere, due to fire (tC/ha)		1.997952				2.284053				1.667312				4.28			
93	twig fraction of deadwood	t C ha^{-1}			1.371				1.441									
	frac s52		1.39				0.67				0.45				1.22			
94	bark litter	t C ha^{-1}			0.631				1.137									
	C mass emitted due to resistant bark litter to atmosphere, due to fire (tC/ha)		1.243716				1.110764				0.890441				1.656379			
95	CWD fraction of deadwood (aboveground)	t C ha^{-1}			0.494				0.276				0.287				2.317	
	C mass emitted due to resistant deadwood to atmosphere, due to fire (tC/ha)		3.9758				1.9220				1.3000				3.4823			
	on debris: to inert																	
96	Surface litter	t C ha^{-1}			0.930				0.948				1.146				0.696	
97	leaf litter	t C ha^{-1}			0.301				0.405				0.000				0.000	
98	twig fraction of deadwood	t C ha^{-1}			0.450				0.434				0.000				0.000	
99	bark litter	t C ha^{-1}			0.252				0.381				0.000				0.000	
100	CWD fraction of deadwood (aboveground)	t C ha^{-1}			0.247				0.138				0.143				1.158	
101	Total debris to inert	t C ha^{-1}			1.177				1.086				1.290				1.854	
	C mass moved from forest debris to inert soil due to fire (tC/ha)		0.080569				0.058626				0.042269				0.110121			

TABLE 2 Comments associated with Table 1.

Item no.	Comments
	FIELD DATA
1	Sum of overstorey and understorey
2	Allometric equations using DBH of overstorey trees; see Overstorey under Methods
3	Derived from digital photographs (Macfarlane)
4	Allometric equations using DBH of understorey trees; see Undertorey under Methods
5	Derived from digital photographs (ref)
6	
7	Subsampling surface litter in the field
7.1	Separation of surface litter in the laboratory; see Surface litter under Methods
7.2	Separation of surface litter in the laboratory; see Surface litter under Methods
7.3	Separation of surface litter in the laboratory; see Surface litter under Methods
7.4	Separation of surface litter in the laboratory; see Surface litter under Methods
7.5	Sum of surface litter in the laboratory; see Surface litter under Methods
8	Sum of LAI (items 2 and 4)
8.1	converted from LAI to LM using specific leaf area of 6 m^2 kg^{-1} (ref) and 0.5 g C g^{-1} DW
9	van V method; see CWD under Methods
10	Subsampling top 10 cm soil in the field, elemental analysis in the laboratory; see Soil C under Methods
11	Subsampling top 10 cm soil in the field, elemental analysis in the laboratory; see Soil C under Methods
12	Subsampling top 10 cm soil in the field, elemental analysis in the laboratory; see Soil C under Methods
13	Subsampling top 10 cm soil in the field, elemental analysis in the laboratory; see Soil C under Methods
14	Estimated using clinometer in the field
	DERIVATIONS AND ESTIMATIONS
	OVERSTOREY
15	AGB (item 1) minus understorey (item 30)
16	50% of AGB
	s2
17	48% of AGB
	s3
18	2.4% of AGB
	s4
19	Leaf mass (item 8.1) times LAI_over/LAI-total (item 3/item 8)
20	2% of AGB
	s5
21	30% AGB
	s6
22	3% AGB
	s7
23	Estimate of twigs as 3-10% branches (item 17)
24	Estimate of twigs as proportional to LAI
25	Estimate of twigs as a faction of AGB (similar to item 23)
26	Site based fraction
27	Site based fraction
	UNDERSTOREY
28	Estimate of undrestorey based on inverse of height (170/item 14)
29	Estimate of undrestorey based on a fraction of AGB (item 1)
30	Estimate of undrestorey based on LAI (item 8) and height (item 14); 200/(LAI_over x Ht)
	0.1 s1
31	Site based fraction
32	Site based fraction
33	50% understorey AGB
34	48% understorey AGB
35	10% understorey branch
36	1.5-5% aboveground understorey; 50% burnt and goes to atmosphere
37	Leaf mass (item 8.1) minus overstorey leaf mass (item 19)
38	5% of aboveground understorey
39	30% of aboveground understorey
40	3% of aboveground understorey
41	mass fraction of leaves; Leaf mass / AGB (item 5/item 1)
	s5/s1
42	area fraction of understorey leaves; LAI understorey / LAI total (item 5/item 8)

(continued over…)

Item no.	Comments
	LITTERFALL
43	30% turnover per annum
44	30% turnover of leaves, 2% of AGB (item 20)
45	20% turnover of bark, 2.4% of AGB (item 20)
46	8% of deadwood (item 47)
47	32% of CWD (item 9)
48	10% coarse roots (item 21)
49	50% fine roots (item 22)
	DEBRIS
50	y=0.0007*x^2.9548; increased by a power of ht; branch canopy increases like a inverted cone, with double height get 4x canopy but complicated by branching
50.1	twigs (item 7.2) + CWD (item 9)
	s10
51	10% CWD estimate (item 50)
52	CWD / branches (item 9/item 17)
53	twig debris / deadwood (item 56/item 47)
54	Subsampling surface litter in the field (item 7)
	(s13+s14+0.35*s10)
55	leaf fraction of surface litter (item 7 x item 7.1/item 7.7)
	s14
56	fraction of surface litter (item 7 x item 7.1/item 7.7)
	0.4 s10; based on twig litter fraction of deadwood (item 53)
57	fraction of surface litter (item 7 x item 7.1/item 7.7)
	s13
58	fraction of surface litter (item 7 x item 7.1/item 7.7)
	0.5 (s14+0.35 s10+s13)
	s14+0.35 s10+s13
59	Surface litter/AGB (item 7/item 1)
	(s13+s14+0.35 s10)/s1
60	Leaf litter fraction (item 7.1/item 7.5)
	s14/(s13+s14+0.35 s10)
61	twig litter fraction (item 7.2/item 7.5)
	0.35 s10/(s13+s14+0.35 s10)
62	bark litter fraction (item 7.3/item 7.5)
	s13/(s13+s14+0.35 s10)
63	fine fraction (item 7.4/item 7.5)
	0.5 (s14+0.35 s10+s13); fine fraction is about 1/3 and other 2/3 is leaf, twig and bark litter
64	Total surface litter measured in the laboratory (adjusted for inoganic matter?); (item 7.5/item 7.5)
	LOSSES
65	item 3 Uburnt treatment -Burnt treatment (UB-B)
66	understorey LAI loss as fraction of unburnt undersotey LAI (item 65/item 3 UB)
67	Surface litter loss, i.e. item 7 UB - item 7 B (denoted, item 7UB-B)
68	leaf litter loss (item 7.1 UB-B)
69	twig litter loss (item 7.2 UB-B)
70	bark litter loss (item 7.3 UB-B)
71	fine fraction loss (item 7.4 UB-B)
72	loss of total surface litter measured in the laboratory (item 7.5 UB-B)
73	LAI loss (item 8 UB-B)
74	leaf mass loss (item 8.1 UB-B)
75	CWD loss (item 9 UB-B)
76	Soil C loss (item 10 UB-B; note that negative value indicates a gain in C)

(continued over...)

Item no.	**Comments**
	FIRE EFFECT
	on overstorey:
77	Estimate fraction of overstorey canopy scorched; site-to-site variation
78	scorched overstorey leaf mass (item 77 x item 19)
	s48
79	5% fine roots excluding fine roots of understorey killed and moved to standing deadwood (SD)
	frac s51, fraction of C mass emitted due to fire, from trees (tC/ha)
	on AG_understorey: live to atm (losses associated with understorey)
80	65% of 2% of aboveground understorey that is leaf mass
81	70% of 2.4% of aboveground understorey that is twig mass
82	2% of understorey stem and branch mass + 50% of the 70% of 2.4% of aboveground understorey that is twig mass
83	5% of 3% of aboveground understorey that is fine root mass
	s51
	on AG understorey: live to SD, 1 % understorey killed
84	1% understorey seedlings killed including stem, branch, coarse roots and fine roots
	s45
85	1% understorey seedlings killed including stem, branch, coarse roots and fine roots
	s46
86	1% understorey seedlings killed including stem, branch, coarse roots and fine roots; 70% twigs go to atm
	frac s46 (frac=0.35)
87	1% understorey seedlings killed including stem, branch, coarse roots and fine roots; 70-90% leaves go to atm
	s48
88	1% understorey seedlings killed including stem, branch, coarse roots and fine roots; 2% stem bark and branch bark and 50% of twig bark go to atm (some to SD and/or inert?)
	s47
89	1% understorey seedlings killed including stem, branch, coarse roots and fine roots
	s49
90	1% understorey seedlings killed including stem, branch, coarse roots and fine roots; excluding 5% fine roots go to atmosphere (a fraction of s51)
	s50
	on debris: to atm
91	Surface litter loss; loss fraction (item 7 UB-B/)
	0.35 s52+s53+s54
92	leaf litter loss, normalised to field/lab (item 7.1 UB-B x item 7.1 UB x item 7/item 7.5); 55-80% leaf litter to atm
	s54
93	twig litter loss, normalised to field/lab (item 7.2 UB-B x item 7.2 UB x item 7/item 7.5); 55-70% twig deadwood to atm
	0.35 s52
94	bark litter loss, normalised to field/lab (item 7.3 UB-B x item 7.3 UB x item 7/item 7.5); 44-60% bark litter to atm
	s53
95	CWD loss, 20% CWD est. (item 50); 10-20% to atm, 10% to inert
	s52
	on debris: to inert
96	10% to inert?
97	10% to inert?
98	10% to inert?
99	10% to inert?
100	10% to inert?
101	10% sum of debris (item 96 + item 100)
	s58

TABLE 3 FullCAM simulation for sites, BC = Belmore Crossing, LR = Lawson Ridge, RW = Rocky Waterholes and OR = Oak Range.

Site:	BC		LR		RW		OR	
Treatment:	**Burnt**	**Unburnt**	**Burnt**	**Unburnt**	**Burnt**	**Unburnt**	**Burnt**	**Unburnt**
Item no. item								
SIMULATIONS								
prefix 's'								
1 C mass of aboveground tree components (tC/ha)	108	108	65	65	44	44	186	187
2 C mass of tree stems (tC/ha)	55	55	32	32	22	22	92	93
3 C mass of tree branches (tC/ha)	50	50	30	30	20	20	87	87
4 C mass of tree bark (tC/ha)	2.05	2.15	1.44	1.51	0.97	1.02	3.88	4.08
5 C mass of tree leaves (tC/ha)	1.03	1.14	1.18	1.31	0.79	0.88	3.25	3.66
6 C mass of tree coarse roots (tC/ha)	32.93	32.96	18.99	19.00	12.84	12.85	55.47	55.51
7 C mass of tree fine roots (tC/ha)	2.89	2.90	1.88	1.89	1.27	1.28	5.48	5.51
8 C mass of forest litter (tC/ha)	19.12	23.20	13.58	17.51	9.45	12.37	35.75	43.32
9 C mass of forest deadwood (tC/ha)	14.40	18.40	7.52	9.45	5.08	6.39	17.43	20.94
10 C mass of forest resistant deadwood (tC/ha)	8.42	12.42	4.07	6.01	2.75	4.06	7.37	10.88
11 C mass of forest resistant coarse dead roots (tC/ha)	5.97	5.97	3.44	3.44	2.33	2.33	10.06	10.06
12 C mass of forest resistant fine dead roots (tC/ha)	15.94	16.79	10.37	10.92	7.01	7.38	30.26	31.87
13 C mass of forest resistant bark litter (tC/ha)	1.58	2.83	1.41	2.52	1.13	2.02	2.09	3.76
14 C mass of forest resistant leaf litter (tC/ha)	1.54	3.51	1.76	4.01	1.28	2.93	3.33	7.51
15 C mass moved from tree leaves to leaf litter due to turnover (tC/ha)	0.031	0.033	0.035	0.038	0.025	0.027	0.102	0.103
16 C mass moved from tree branches to deadwood due to turnover (tC/ha)	0.063	0.063	0.030	0.030	0.020	0.020	0.065	0.065
17 C mass moved from tree bark to bark litter due to turnover (tC/ha)	0.022	0.023	0.020	0.020	0.015	0.016	0.043	0.043
18 C mass moved from tree fine roots to dead roots due to turnover (tC/ha)	0.164	0.163	0.107	0.106	0.072	0.072	0.310	0.309
19 C mass moved from trees to debris due to fire (tC/ha)	0.057	0	0.065	0	0.044	0	0.183	0
20 C mass of forest standing dead litter (tC/ha)	0.037	0	0.023	0	0.015	0	0.066	0
21 C mass of forest standing dead deadwood (tC/ha)	0.061	0	0.036	0	0.024	0	0.104	0
22 C mass of forest standing dead stem (tC/ha)	0.038	0	0.022	0	0.015	0	0.065	0
23 C mass of forest standing dead branch (tC/ha)	0.035	0	0.021	0	0.014	0	0.061	0
24 C mass of forest standing dead bark (tC/ha)	0.000448	0	0.000315	0	0.000214	0	0.000856	0
25 C mass of forest standing dead leaf (tC/ha)	7.9E-05	0	9.02E-05	0	6.12E-05	0	0.000256	0
26 C mass of forest standing dead coarse roots (tC/ha)	0.022789	0	0.013128	0	0.008906	0	0.038799	0
26.1 C mass of forest standing dead fine roots (tC/ha)	0.0020	0	0.001312	0	0.000888	0	0.003852	0
27 C mass moved from stem to standing dead stem, due to fire (tC/ha)	0.03845	0	0.022542	0	0.015247	0	0.064758	0
28 C mass moved from branch to standing dead branch, due to fire (tC/ha)	0.034842	0	0.021084	0	0.01426	0	0.060812	0
29 C mass moved from bark to standing dead bark, due to fire (tC/ha)	0.000452	0	0.000318	0	0.000215	0	0.000857	0
30 C mass moved from leaf to standing dead leaf, due to fire (tC/ha)	8E-05	0	9.14E-05	0	6.18E-05	0	0.000256	0
31 C mass moved from coarse root to standing dead coarse root, due to fire (tC/ha)	0.02307	0	0.0133	0	0.008996	0	0.038855	0
31.1 C mass moved from fine root to standing dead fine root, due to fire (tC/ha)	0.0020	0	0.00132	0	0.000893	0	0.003854	0
32 C mass moved from forest litter to soil due to breakdown (tC/ha)	0.017	0.023	0.012	0.017	0.009	0.012	0.039	0.040
33 C mass moved from forest dead roots to soil due to breakdown (tC/ha)	0.030	0.034	0.019	0.021	0.013	0.014	0.062	0.062
34 C mass moved from forest debris to inert soil due to fire (tC/ha)	0.081	0.000	0.059	0.000	0.042	0.000	0.110	0.000
35 C mass of forest DPM (tC/ha)	0.0072	0.0100	0.006761	0.007805	0.004026	0.004786	0.02557	0.022468
36 C mass of forest RPM (tC/ha)	3.98	4.00	2.67	2.67	1.85	1.86	7.08	7.07
37 C mass of forest BIO-F (tC/ha)	0.136	0.137	0.092	0.092	0.064	0.064	0.245	0.246
38 C mass of forest BIO-S (tC/ha)	0.017	0.017	0.012	0.012	0.008	0.008	0.031	0.031
39 C mass of forest BIO (tC/ha)	0.153	0.154	0.104	0.104	0.072	0.072	0.276	0.277
40 C mass of forest HUM (tC/ha)	3.70	3.70	2.50	2.50	1.73	1.73	6.70	6.70
41 C mass of forest inert soil (tC/ha)	27.68	27.60	27.66	27.60	27.64	27.60	27.71	27.60
42 C mass of forest soil (tC/ha)	35.52	35.46	32.95	32.89	31.30	31.27	41.79	41.66
43 C mass of forest standing dead (tC/ha)	0.098	0	0.058	0	0.039	0	0.169	0
44 C mass of forest aboveground standing dead (tC/ha)	0.073	0	0.044	0	0.030	0	0.127	0
45 C mass moved from stem to standing dead stem, due to fire (tC/ha)	0.038	0	0.023	0	0.015	0	0.065	0
46 C mass moved from branch to standing dead branch, due to fire (tC/ha)	0.035	0	0.021	0	0.014	0	0.061	0
47 C mass moved from bark to standing dead bark, due to fire (tC/ha)	0.000452	0	0.000318	0	0.000215	0	0.000857	0
48 C mass moved from leaf to standing dead leaf, due to fire (tC/ha)	8E-05	0	9.14E-05	0	6.18E-05	0	0.000256	0
49 C mass moved from coarse root to standing dead coarse root, due to fire (tC/ha)	0.023	0	0.013	0	0.009	0	0.039	0
50 C mass moved from fine root to standing dead fine root, due to fire (tC/ha)	0.0020	0	0.00132	0	0.000893	0	0.003854	0
51 C mass emitted due to fire, from trees (tC/ha)	0.188	0	0.163	0	0.110	0	0.450	0
52 C mass emitted due to resistant deadwood to atmosphere, due to fire (tC/ha)	3.98	0	1.92	0	1.30	0	3.48	0
53 C mass emitted due to resistant bark litter to atmosphere, due to fire (tC/ha)	1.24	0	1.11	0	0.89	0	1.66	0
54 C mass emitted due to resistant leaf litter to atmosphere, due to fire (tC/ha)	2.00	0	2.28	0	1.67	0	4.28	0
55 C mass emitted due to resistant coarse dead root to atmosphere, due to fire (tC/ha)	0	0	0	0	0	0	0	0
56 C mass emitted due to resistant fine dead root to atmosphere, due to fire (tC/ha)	0.839	0	0.546	0	0.369	0	1.593	0
57 C mass moved from trees to debris due to fire (tC/ha)	0.057	0	0.065	0	0.044	0	0.183	0
58 C mass moved from forest debris to inert soil due to fire (tC/ha)	0.081	0	0.059	0	0.042	0	0.110	0
59 C mass emitted from standing dead stem to atmosphere, due to fire (tC/ha)	0	0	0	0	0	0	0	0
60 C mass emitted from standing dead branch to atmosphere, due to fire (tC/ha)	0	0	0	0	0	0	0	0
61 C mass emitted from standing dead bark to atmosphere, due to fire (tC/ha)	0	0	0	0	0	0	0	0
62 C mass emitted from standing dead leaf litter to atmosphere, due to fire (tC/ha)	0	0	0	0	0	0	0	0

TABLE 4 Key parameters for FullCAM

PARAMETERS Function	Name	Code name	Units	Site: BC Value	LR Value	RW Value	OR Value
Productivity	Max. aboveground forest biomass	maxAbgMF	t DW ha^{-1}	228	137.5	93	395
Allocation	Relative allocation to stems	allocStemF	fraction relative to stem allocation	1	1	1	1
Allocation	Relative allocation to branches	allocBranF	fraction relative to stem allocation	0.964	0.995	0.995	0.999
Allocation	Relative allocation to bark	allocBarkF	fraction relative to stem allocation	0.04	0.048	0.048	0.045
Allocation	Relative allocation to leaves	allocLeafF	fraction relative to stem allocation	0.02	0.039	0.039	0.038
Allocation	Relative allocation to coarse roots	allocCortF	fraction relative to stem allocation	0.6	0.59	0.59	0.6
Allocation	Relative allocation to fine roots	allocFirtF	fraction relative to stem allocation	0.055	0.061	0.061	0.062
Turnover	Turnover percent of branches	turnFracBranF	% p.a.	1.5	1.2	1.2	0.9
Turnover	Turnover percent of bark	turnFracBarkF	% p.a.	15	15	15	12
Turnover	Turnover percent of leaves	turnFracLeafF	% p.a.	29	30	30	28
Turnover	Turnover percent of coarse roots	turnFracCortF	% p.a.	1.3	1.3	1.3	1.3
Turnover	Turnover percent of fine roots	turnFracFirtF	% p.a.	50	50	50	50
Breakdown	Breakdown percent of resistant deadwood	bkdnFracRDdwdF	% p.a.	5.9	5.9	5.9	7.0
Breakdown	Breakdown percent of resistant bark litter	bkdnFracRBlitF	% p.a.	9.3	9.3	9.3	13
Breakdown	Breakdown percent of resistant leaf litter	bkdnFracRLlitF	% p.a.	8.5	8.5	8.5	12
Breakdown	Breakdown percent of resistant coarse dead roots	bkdnFracRCodrF	% p.a.	7	7	7	7
Breakdown	Breakdown percent of resistant fine dead roots	bkdnFracRFidrF	% p.a.	7	7	7	7
Fire effect: Fraction affected	Fraction of forest affected by fire	fracAfctFirF	fraction	1	1	1	1
Fire effect: Live to atm	% of stems to atmosphere, in fire affected portion	fracStemToAtmsFirF	%	0	0	0	0
Fire effect: Live to atm	% of branches to atmosphere, in fire affected portion	fracBranToAtmsFirF	%	0.0007	0.0007	0.0007	0.0007
Fire effect: Live to atm	% of bark to atmosphere, in fire affected portion	fracBarkToAtmsFirF	%	4.9	4.9	4.9	4.9
Fire effect: Live to atm	% of leaves to atmosphere, in fire affected portion	fracLeafToAtmsFirF	%	6.3	6.3	6.3	6.3
Fire effect: Live to atm	% of fine roots to atmosphere, in fire affected portion	fracFirtToAtmsFirF	%	0.35	0.35	0.35	0.35
Fire effect: Live to debris	% of leaves to litter , in the fire-affected portion	fracLeafToLlitFirF	%	5	5	5	5
Fire effect: Live to SD	% of stems to standing dead stems , in the fire-affected portion	fracStemToSDdwdFirF	%	0.07	0.07	0.07	0.07
Fire effect: Live to SD	% of branches to standing dead branches , in the fire-affected portion	fracBranToSChwdFirF	%	0.07	0.07	0.07	0.07
Fire effect: Live to SD	% of bark to standing dead bark , in the fire-affected portion	fracBarkToSBlitFirF	%	0.021	0.021	0.021	0.021
Fire effect: Live to SD	% of leaves to standing dead leaves , in the fire-affected portion	fracLeafToSLlitFirF	%	0.007	0.007	0.007	0.007
Fire effect: Live to SD	% of coarse roots to standing dead course roots , in the fire-affected portion	fracCortToSCodrFirF	%	0.07	0.07	0.07	0.07
Fire effect: Live to SD	% of fine roots to standing dead fine roots , in the fire-affected portion	fracFirtToSFidrFirF	%	0.07	0.07	0.07	0.07
Fire effect: Debris to atm	% of resistant deadwood to atmosphere, in the fire-affected portion	fracRDdwdToAtmsFirF	%	32	32	32	32
Fire effect: Debris to atm	% of resistant bark litter to atmosphere, in the fire-affected portion	fracRBlitToAtmsFirF	%	44	44	44	44
Fire effect: Debris to atm	% of resistant leaf litter to atmosphere, in the fire-affected portion	fracRLlitToAtmsFirF	%	57	57	57	57
Fire effect: Debris to atm	% of resistant fine roots to atmosphere, in the fire-affected portion	fracRFidrToAtmsFirF	%	5	5	5	5
Fire effect: Debris to inert (char)	% of resistant deadwood to inert soil, in the fire-affected portion	fracRDdwdToInrtFirF	%	0.32	0.32	0.32	0.32
Fire effect: Debris to inert (char)	% of resistant bark litter to inert soil, in the fire-affected portion	fracRBlitToInrtFirF	%	0.44	0.44	0.44	0.44
Fire effect: Debris to inert (char)	% of resistant leaf litter to inert soil, in the fire-affected portion	fracRLlitToInrtFirF	%	0.57	0.57	0.57	0.57
Fire effect: Debris to inert (char)	% of resistant fine roots to inert soil, in the fire-affected portion	fracRFidrToInrtFirF	%	0.05	0.05	0.05	0.05
Regrowth	Years to fully regrow stems	yrsStemRegrowFirF	year	4	4	4	4
Regrowth	Years to fully regrow branches	yrsBranRegrowFirF	year	4	4	4	4
Regrowth	Years to fully regrow bark	yrsBarkRegrowFirF	year	4	4	4	4
Regrowth	Years to fully regrow leaves	yrsLeafRegrowFirF	year	0.5	0.5	0.5	0.5
Regrowth	Years to fully regrow coarse roots	yrsCortRegrowFirF	year	4	4	4	4
Regrowth	Years to fully regrow fine roots	yrsFirtRegrowFirF	year	0.5	0.5	0.5	0.5