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MODELLING EMISSIONS FROM PRESCRIBED BURNING USING FULLCAM

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ABSTRACT

The Full Carbon Accounting Model (FullCAM) is a software tool developed by the Australian Government, Department of the Environment and Energy as a standard method for carbon accounting. It is primarily used as a means to report national greenhouse gas dynamics from the land sector due to anthropogenic activities. This study assessed the accuracy and usefulness of FullCAM in determining the mass of carbon (C) emissions produced from prescribed burning.

FullCAM proved to be a simple and reasonably reliable method for estimating C emissions from prescribed burning activities and for tracking recovery of C pools related to forest ecosystems. In addition, C emissions from different prescribed burning scenarios and from wildfire can be easily compared. The FullCAM model can be used by land managers as a means to manage an important aspect of risk associated with planned burning. If land managers are required to perform C accounting activities in the future, the adoption of FullCAM will enable them to be compatible with the national standard of carbon accounting.

END-USER STATEMENT

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The capacity to accurately predict carbon (C) emissions produced during prescribed burning activities is essential for designing regional burning programs aimed at optimising trade-offs among outcomes involving risk reduction and multifaceted ecosystem services including C storage.

Investigating the potential of models such as FullCAM to predict C emissions from prescribed burning in a cost- and time-effective way can potentially simplify the planning process involved in designing such programs. It can also support and improve the decision making required of burn planners to incorporate the effects of prescribed burning on C within each burn block over the short- to medium-term. Testing the predictive capacity and limitations of FullCAM and its practicality for fire managers to use during planning can also be used to identify and address gaps in the model.

The initial investigation described here suggests that the publicly-available version of FullCAM can be used to predict emissions and simulate post-fire fuel loads with moderate accuracy. It is important to highlight that, in most cases for bark and in all cases for litter, FullCAM underpredicted post-fire biomass of these components when compared to field data. The discrepancies found between predicted and analysed data are discussed in this report and will be investigated further.

1. INTRODUCTION

Empirical evidence collated over time has shown that prescribed burning can reduce the incidence and intensity of unplanned fires in the Australian landscape (Boer *et al*. 2009). However, due to increasing interest in evaluating the environmental impacts of prescribed burning, the importance of assessing carbon (C) dynamics and estimation of emissions from planned and unplanned fire is increasing. There are several approaches that land managers can use to assess carbon emissions based on empirical models that use field-collected data and/or process-based simulation modelling.

While the use of empirical data will provide land managers with more accurate estimates, this method requires extensive collection of field data. Conversely, process-based simulation models allow field-collated datasets to be used in different scenarios to estimate various C pools in above- and belowground biomass, before and after fire, and C losses (emissions) as a result of fire and subsequent biomass recovery. The Full Carbon Accounting Model (FullCAM) is a software tool developed by the Australian Government, Department of the Environment and Energy that has been used as a means to report National greenhouse gas dynamics from the land sector due to anthropogenic activities (Department of the Environment and Energy 2016). A detailed description of the development of FullCAM has been reported by Richards (2001) and Richards and Evans (2004). This study assessed the usefulness of FullCAM in determining the mass of emissions produced from prescribed burning and use of this tool by fire and land management agencies when planning prescribed burning activities.

FullCAM uses a mass balance approach for C accounting. It is comprised of sub-models that track changes in vegetation growth and litter decomposition, two processes intrinsically related to fuel accumulation, and soil C dynamics. FullCAM can be used to estimate C fluxes during undisturbed forest growth and the transition of plant components to debris (litter or surface fuels) and soil, and to predict regrowth of trees after disturbance such as harvesting and fire.

Models that are used to estimate emissions from the land sector can be categorised into three broad tiers based on their simplicity, the use of country-specific datasets and parameters, and the use of spatially-explicit datasets (Penman et al. 2003). FullCAM is classified as a Tier 3 model as it provides more accurate and reliable estimates than Tier 1 and 2 models. This model uses spatially-explicit, fine resolution soil datasets (e.g. soil C and its fractions) and spatial-temporal climatic datasets available at 1 km spatial resolution (Department of the Environment and Energy 2016). Inputs or model drivers used in FullCAM can be readily added or adjusted. Changes in C stocks (above- and belowground) and atmospheric emissions are estimated on a continuous basis (generally at monthly intervals) using non-linear processes that consider interactions among climate, soil and plant growth characteristics and land management activities. This contrasts to linear approaches that are commonly used in Tier 1 and 2 models.

1.1 OVERVIEW OF THE FULLCAM MODELLING FRAMEWORK

FullCAM is a collection of sub-models that have been integrated to track C flows and emissions from agricultural systems (cropping and pasture) and forests (natural and managed). As this study used the FullCAM model for forests, a greater deal of attention will be directed towards the 'forest' suite of sub-models. FullCAM also has the capacity to incorporate 'land transitions' such as deforestation and reforestation. Brief descriptions of the main sub-models that make up the FullCAM model are provided in Table 1 and a depiction of the sub-models for C flow in both forest and agricultural systems are represented in Fig. 1.

TABLE 1. DESCRIPTION OF THE MAIN SUB-MODELS WITH THE FULLCAM MODEL. C = CARBON.

Sub-model name	Description	Key reference
CAMFor	C accounting model for forest systems; tracks C flows between living and non-living biomass pools (litter and soil)	Richards and Evans (2000a)
CAMAg	C accounting model for agriculture systems; allocates aboveground biomass of crops and pasture to plant components; used for plant growth and tracks movement of C from plants to debris and soil	Richards and Evans (2000b)
RothC model	C accounting model for soils; provides detailed description of movement of C flows in soil; C pools are categorised as four active pools and one inert pool (i.e. char)	Jenkinson *et al.* (1987; 1991)

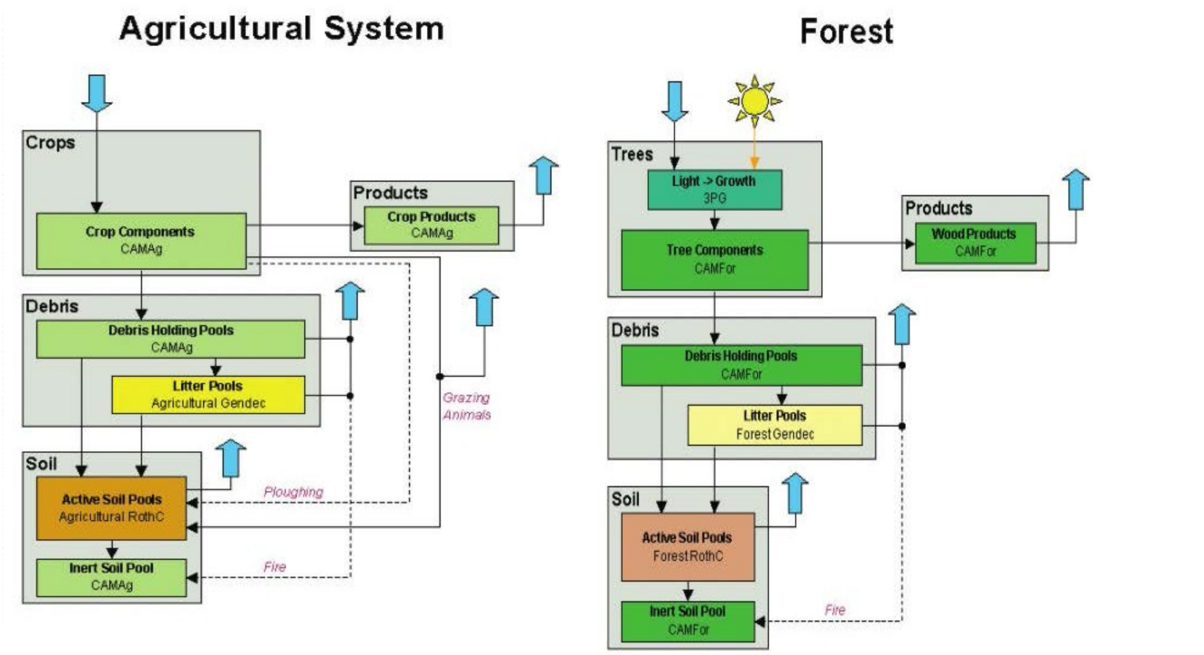

FIGURE 1. FLOW OF CARBON FOR SUB-MODELS IN FULLCAM INCLUDING THE AGRICULTURAL SYSTEM SUB-MODEL (LEFT) AND THE FOREST SYSTEM SUB-MODEL (RIGHT) (SOURCE: RICHARDS AND EVANS 2000A, B).

1.2 TREE GROWTH MODELLING USING FULLCAM

FullCAM adopts a hybrid approach for predicting the accumulation of aboveground biomass in woody vegetation at a given location. This approach requi res development of rela tionships between a long-term average process-based output called 'Forest Productivity Index' (FPI; a dimensionless index) that is derived using the 3-PG forest growth model and fi eld measurements of the maximum aboveground biomass from a forest stand that has had minimal disturbance (Landsberg and Waring 1997; Kesteven et al. 2004; Richards and Brack 2004). This empirical relationship is used to predict the parameter M (maximum aboveground biomass) for a given location using the FPI raster layer described as: The aboveground biomass of woody vegetation is predicted using a tree y ield formula (Waterworth et al. 2007) and is calculated as:

$$M = \left(6.011 \times \sqrt{FPI} - 5.291\right)^2$$ Equation 1

where k is a stand constant which reflects the age of the maximum current annual increment, G is the age of maximum growth (in years), AGB is aboveground tree mass (t DM ha-1), r and y are tree y ield multipliers, M is maximum aboveground biomass (Equation 1) and d is the forest age (years) that can be adjusted to reflect different management actions.

Once aboveground biomass is estimated it is partitioned into various defined components using speci es-specific allocation tables (i.e. stem, branches and bark (aboveground) and coarse and fine roots (belowground)).

$$k = 2G - 1.25$$ Equation 2.1

$$AGB(t) = rMy.e^{-k/d}$$ Equation 2.2

where k is a stand constant which reflects the age of the maximum current annual increment, G is the age of maximum growth (in years), AGB is aboveground tree mass (t DM ha^{-1}), r and y are tree yield multipliers, M is maximum aboveground biomass (Equation 1) and d is the forest age (years) that can be adjusted to reflect different management actions.

Once aboveground biomass is estimated it is partitioned into various defined components using speci es-specific allocation tables (i.e. stem, branches and bark (aboveground) and coarse and fine roots (belowground)).

1.3 FIRE MODELLING USING FULLCAM

Disturbances to forests, such as fire, are included in FullCAM as an 'event'. Generally, there are six types of fires in FullCAM: (i) forest fire, (ii) prescribed burning, (iii) site preparation – broadcast burn, (iv) site preparation – windrow and burn, (v) wildfire – trees killed, and (vi) wildfire – trees not killed. The event category referred to as 'forest fire' is used when it cannot be determined if trees are or will be 'killed' or not 'killed'. The event category referred to as 'prescribed burning' is used for a human-i nduced fire when no trees are killed and 'forest fire' or 'wildfire' is used for a natural event.

Using the publicly available version of FullCAM software (Version: 4.1.6 19417), the model has the ability to calculate: (a) emissions from the combustion of live and dead organic material, (b) transition of derived resistant C (char) to soils, and (c) regrowth of vegetation (Fig. 2).

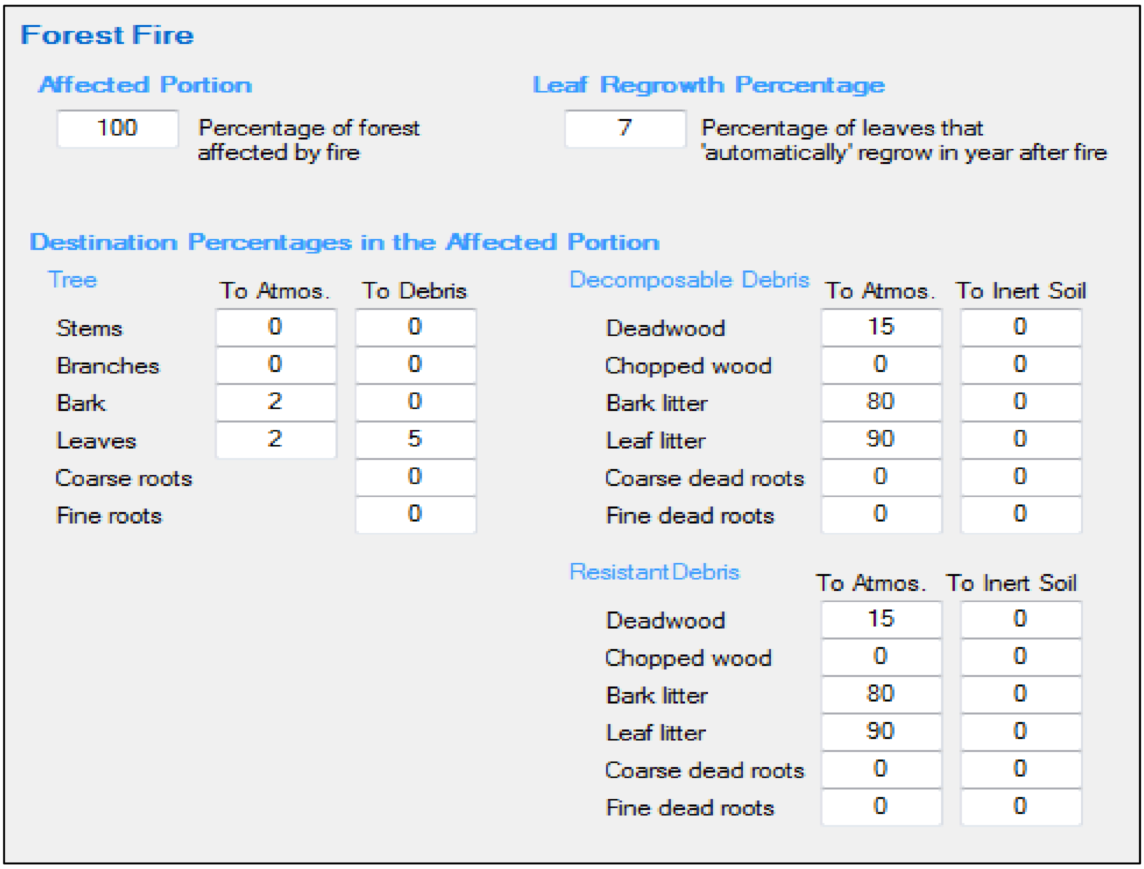

FIGURE 1. PARAMETER SETTINGS FOR FULLCAM FOR PRESCRIBED BURNING EVENTS (SOURCE: FULLCAM SOFTWARE).

In FullCAM, vegetation regrowth only happens if the fire is not a clearing event. There are 36 parameters associated with a forest fire event (Fig. 3) and brief descriptions of these parameters are described in the Appendix, Table A1.

Recent efforts to develop fire-related modelling capacity in FullCAM has been led by CSIRO Land and Water and supported by the Australian Government, Department of Environment. For this study, we were given access to the most recent research edition of FullCAM to test our simulation modelling (under a license agreement) and, as such, the fire-related parameters that have been introduced were used (Fig. 3). One of the newest additions are 'standing dead' parameters which are important for wildfires and 'year to re-growth' for post-fire recovery of vegetation. For certain parts of the study, the most recently available public version of the model was used to ensure the information provided was relevant to the level of access available to End Users.

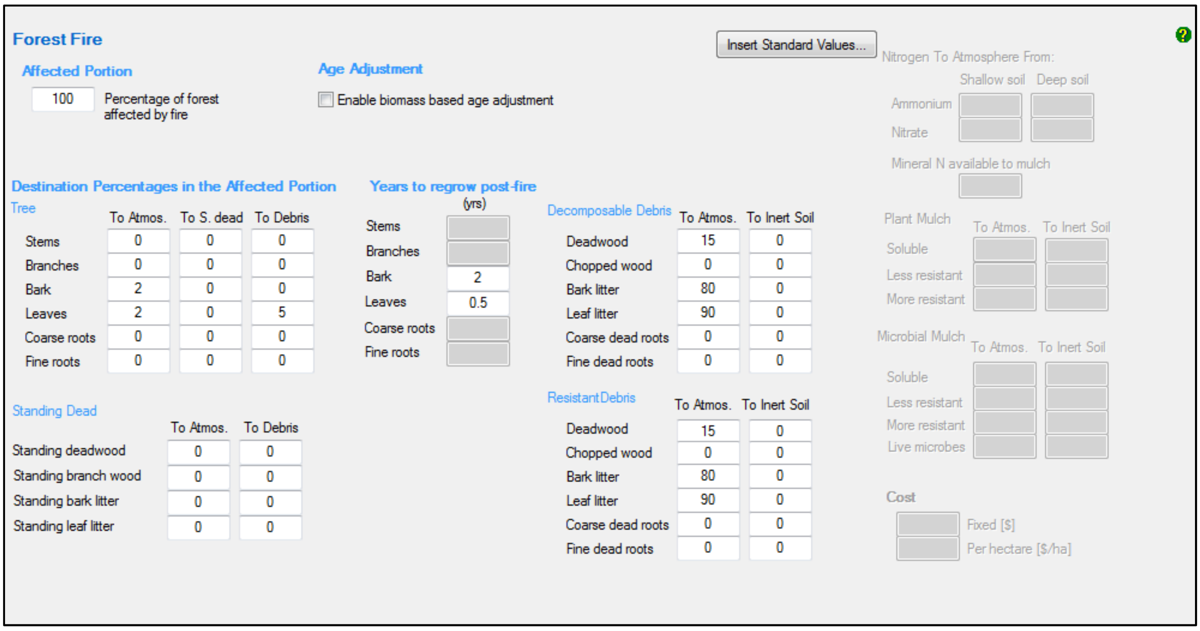

FIGURE 2. UPDATED PARAMETER SETTINGS FOR FULLCAM FOR PRESCRIBED BURNING EVENTS (SOURCE: FULLCAM SOFTWARE).

The parameters related to 'Affected Portion' are associated with the combustion ratios of the exiting masses (both living and non-living) to the atmosphere and to debris or inert soil (see Table A1 in the Appendix). The current default values for fire event-related parameters are derived from previous research on native forest fires from southern Australia and south eastern Queensland (Gould and Cheney 2008). A detailed review of these fire-related parameters can be found in Surawki *et al*. (2012).

This study will test the ability of FullCAM to estimate C emissions from different fuel components as a result of prescribed burning using field collated data to populate the simulation files.

2. METHODS

2.1. INITIALISATION OF FULLCAM USING FIELD-COLLECTED FUEL LOADS

One of the major challenges of this study was mapping the field-collated datasets in FullCAM. Data collected from sites in the Australian Capital Territory (ACT; three sites, 2015) and New South Wales (NSW; nine sites, 2015–2016) were used (see Gharun *et al.* 2015; 2017; 2018; Bell *et al.* 2018). A brief description of the sites and ignition data included in the FullCAM plot file and field sampling dates are presented in Table 2.

2.2. BUILDING FULLCAM PLOT FILES

Using the location information for the study sites, FullCAM plot files were built using the publicly available version of FullC AM and were later imported into the research edition. All input datasets (e.g. soil, climate) and default parameters were downloaded through the FullCAM database. The 'Eucalyptus Low Open Forest' forest type was used to build FullCAM plot files.

TABLE 2. GENERAL DESCRIPTION OF THE STUDY SITES IN NEW SOUTH WALES (NSW) AND THE AUSTRALIAN CAPITAL TERRITORY (ACT) TREATED WITH PRESCRIBED BURNING AND USED FOR MODELLING WITH FULLCAM.

Site name	Latitude	Longitude	Ignition date	Sampling date
NSW				
Haycock Trig (HT)	-33.45	151.09	20 August 2015	September 2015
Spring Gully (SG)	-34.09	151.15	20 August 2015	September 2015
Helicopter Spur (HES)	-33.80	150.51	20 August 2015	September 2015
Paterson (PTS)	-33.53	150.58	20 August 2015	October 2015
Lakesland (LAK)	-34.16	150.49	15 September 2015	October 2015
Left Arm (LEF)	-33.36	150.80	1 April 2016	May 2016
Joadja (JOD)	-34.37	150.21	1 April 2016	April 2016
Martins Creek (MTC)	-34.30	150.44	8 March 2016	April 2016
Kief Trig (KIF)	-33.29	150.94	15 April 2016	May 2016
ACT				
Googong (GOO)	-35.51	149.28	11 March 2015	April 2015
Tidbinbilla (TID)	-35.46	148.90	17 March 2015	April 2015
Lone Pine (LP)	-35.87	148.93	30 March 2015	May 2015
Cotter (COT)	-35.61	148.82	30 March 2015	May 2015

2.3. INITIAL TREE BIOMASS

Since FullCAM simulates the understorey vegetation as part of the total biomass rather than explicitly simulated as a separate pool, understorey and overstorey biomass data were amalgamated to determine the total aboveground biomass value for constraining in FullCAM. 'Total Biomass' (*TB*) was therefore calculated as:

$$Total\ biomass = \left(\frac{\alpha}{\beta}\right) \times 100 \qquad \text{Equation 3}$$

where α is the total aboveground biomass (*AGB*) and β is the FullCAM allocation sum for aboveground biomass which includes fractions for stems, branches, bark and leaves.

Once the total biomass was calculated, masses for tree parts were allocated (Fig. 4). FullCAM required biomass inputs as dry matter (t DM ha^{-1}). The total biomass calculated for tree components for sites sampled in NSW and the ACT is provided in Table A2 in the Appendix. In the absence of field measured data, biomass in different tree components can be derived by using a separate plot file where *M* (Equation 1) is a set value equal to the total *AGB*, then determining the output of mass of the components at equilibrium, with the assumption that a mature forest is present. In such a case, the model will run for a long time (500 years) using long-term climate datasets and allow the model to come to an equilibrium state.

2.4. INITIAL TREE DEBRIS/LITTER

Under the 'Tree Debris' tab in FullCAM, information regarding coarse woody debris (CWD) and debris can be found. In this study, 'debris' represents litter or surface fuel and is quantified in t C ha^{-1}. It is important to note that CWD is referred to as deadwood in FullCAM.

The measured biomass of CWD was converted to mass of C by assuming the C content was 50% (the default FullCAM C content value for CWD). The calculated mass of C in CWD is segregated in FullCAM into two fractions; decomposable and resistant. Based on the latest calibration work by CSIRO Land and Water, CWD was assigned in the model as 0% decomposable and 100% resistant plant material (Fig. 5) (Paul, 2018, pers. comm.). After these calculations, data were inserted in to the 'Deadwood' allocation under debris parameter (Fig. 5). The values used are provided in Table A2 in the Appendix.

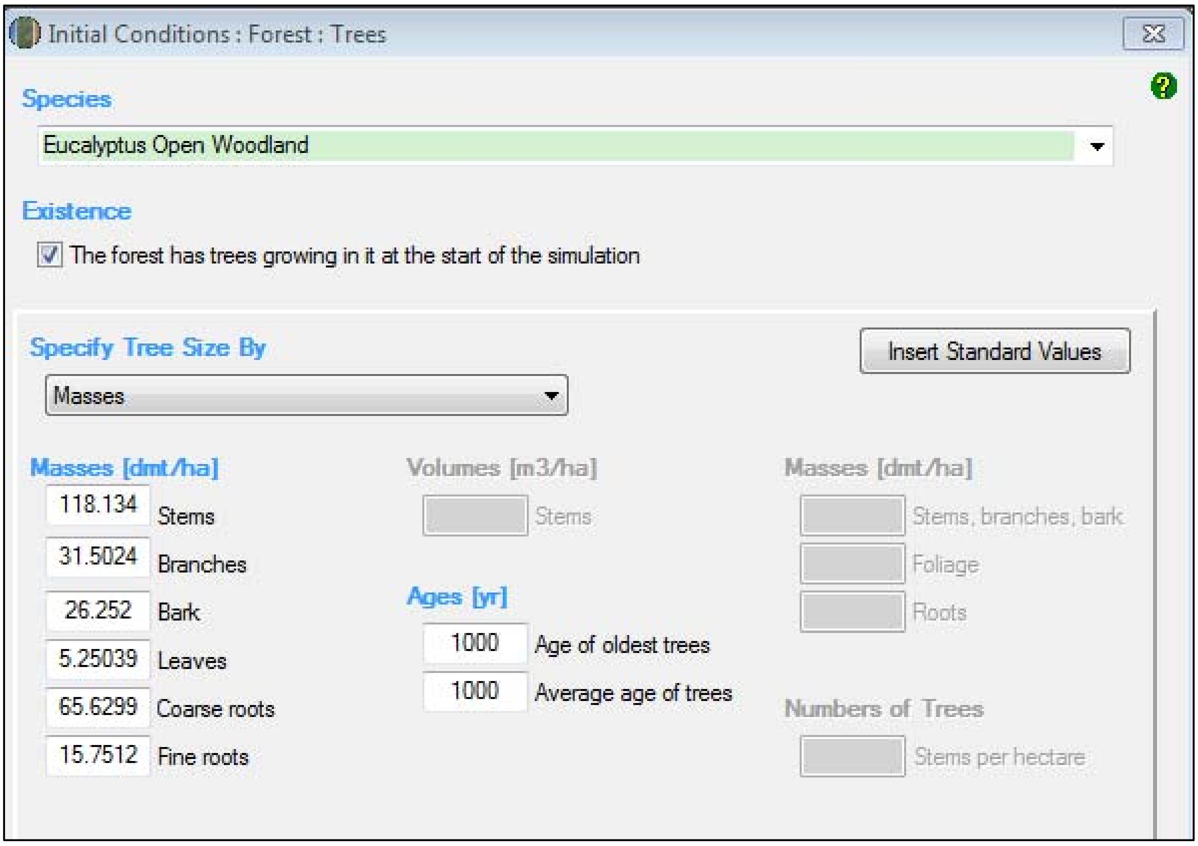

FIGURE 4. ALLOCATION OF TOTAL BIOMASS TO COMPONENTS AS DRY MATTER (T DM HA^{-1}) (SOURCE: FULLCAM SOFTWARE).

The litter biomass measured at the study sites only accounted for the aboveground litter. For ‘Belowground litter’ (an input required by FullCAM is the ‘litter’ generated by roots), initial values were kept as default. Measured ‘leaf’ and ‘decomposable leaf’ fractions were considered as litter mass. Litter biomass (t DM ha^{-1}) measured in the field was converted to C mass with the assumption that the C content is 52% (the default FullCAM C content value for leaves). A second assumption made was that the field litter biomass data was composed of leaves. Field data for ‘Other’ and ‘Twigs’ (t DM ha^{-1}) were amalgamated and considered as ‘Bark’ to be compatible with the fuel load set up for litter in FullCAM. The mass of C in bark was calculated using 49% (the default FullCAM C content value for bark). Finally, decomposable plant material and resistant plant material segregations were done assuming that 0% bark litter and 77% of leaf litter went to the ‘decomposable’ fraction whilst 100% and 23%, respectively, went to the ‘resistant’ fraction for ‘bark’ and ‘leaf’ litter allocations (Paul, 2018, pers. comm.; Fig. 5). The calculations are displayed in Table A3 in the Appendix.

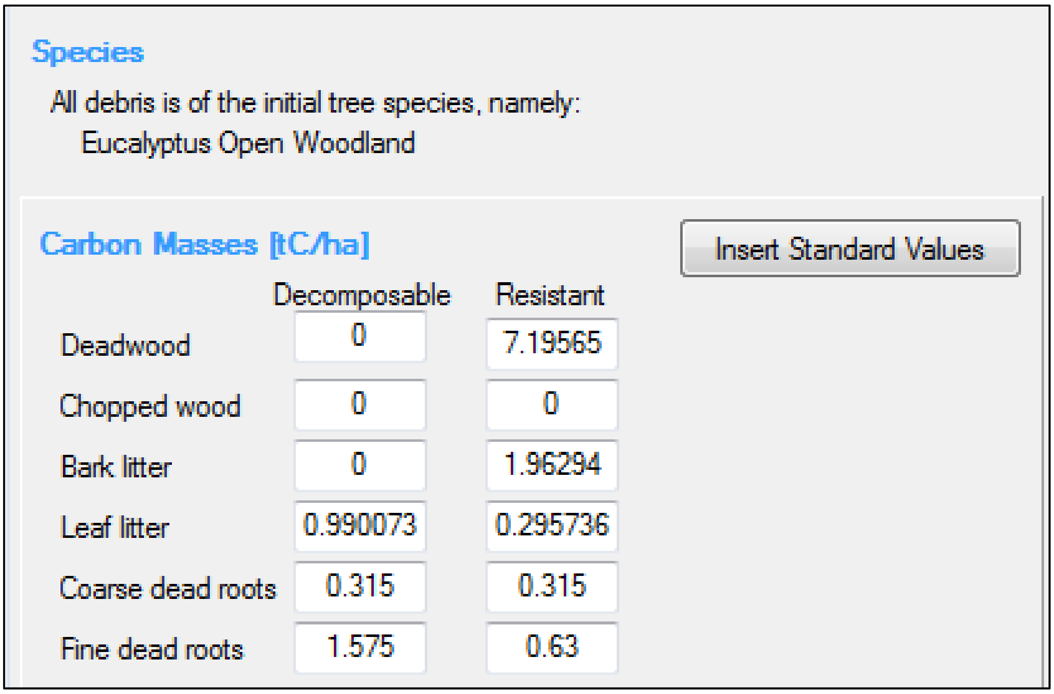

FIGURE 5. UPDATED LITTER POOLS IN FULLCAM USING FIELD DATA (SOURCE: FULLCAM SOFTWARE).

2.5 NEAR SURFACE LIVE PLANT BIOMASS

As might expected, field data for the near surface plant material (t DM ha^{-1}) was small in contrast to the FullCAM downloaded data, given the near surface live plants growing under a forest receives less light than near surface live plants in a grassland context. For the simulation, an assumption was made that the most common native grass type in the area were grown under these forests. Measured biomass for grasses were assumed at equilibrium and inserted to FullCAM under the growth tab, under the native grass species selection. Some values reported were too low to use (<0.01) as the system requires at least one decimal value. Therefore, measured values for near surface biomass were rounded to one decimal point and used in the FullCAM model (Table A2 in the Appendix).

2.6 DEVELOPING EVENTS IN FULLCAM

The prescribed fire events created and simulated in FullCAM were based on the reported ignition dates for the sites studied (Table 2). When a range of ignition dates were given for site, the mid-date was considered. Two types of fire-related events were introduced; a ‘prescribed fire’ event that controls the impact of fire on tree components and tree litter and a ‘grass fire’ event that controls the impact of fire on near surface fuels and litter generated from grasses. In FullCAM, these C pools are tracked as separate entities in forest and agriculture systems.

2.7 SENSITIVITY ANALYSIS

Key parameters associated with a prescribed burning event in FullCAM are CWD, bark and leaf litter. Each of these fuel components are further subdivided into decomposable and resistant C fractions. Because these components are the major parameters that govern emissions from prescribed burning activities it is important to determine the effect that small changes in each of the fractions might have on overall C emissions. To do this, a simple approach was developed to test the sensitivity of key model parameters associated with the amount of C emitted during prescribed fire.

Three representative sites were selected for the sensitivity analysis, two sites sampled in NSW, Haycock Trig (HT) and Joadja (JOD), and one sampled in the ACT, Long Pine (LP). A total of 90 simulations were run for each site considering ± 10% of the default parameter values (Table 3). Amounts of total C emitted were reported when one parameter was changed within this range keeping all other parameters constant. In this way, the impact of individual parameters on total C emitted could be assessed.

TABLE 3. KEY PARAMETERS RELATED TO PRESCRIBED BURNING IN FULLCAM. DPM = DECOMPOSABLE PLANT MATTER; RPM = RESISTANT PLANT MATTER.

Parameter name	Parameter value – proportion to atmosphere (%)
Deadwood (DPM/RPM components)	15
Bark (DPM/RPM components)	80
Leaf (DPM/RPM components)	90

2.8 TESTING DIFFERENT BURN SCENARIOS USING FULLCAM AND THE IMPACT ON CARBON EMISSIONS

Five different burn scenarios were tested for each of the sites listed in the Table 2. The scenarios involved reduction of surface fuel (bark and litter fuels) by 25, 50, 75 and 100%. In addition, the default wildfire parameter settings available in the FullCAM were simulated for each site (Fig. 6). Descriptive statistics are reported, and a linear mixed model was fitted using total C emitted as the response variable and the different scenarios as fixed effect terms (treatments). In the linear mixed model, the three plots for each site was treated as random effect terms. Once the model was fitted, mean separation was done using a Tukey's pair-wise mean separation test to assess whether there was a significant impact on C emissions based on the different scenarios tested. Fitting of the linear mixed model was done using nlme package in R statistical programming language (Pinheiro *et al*. 2018).

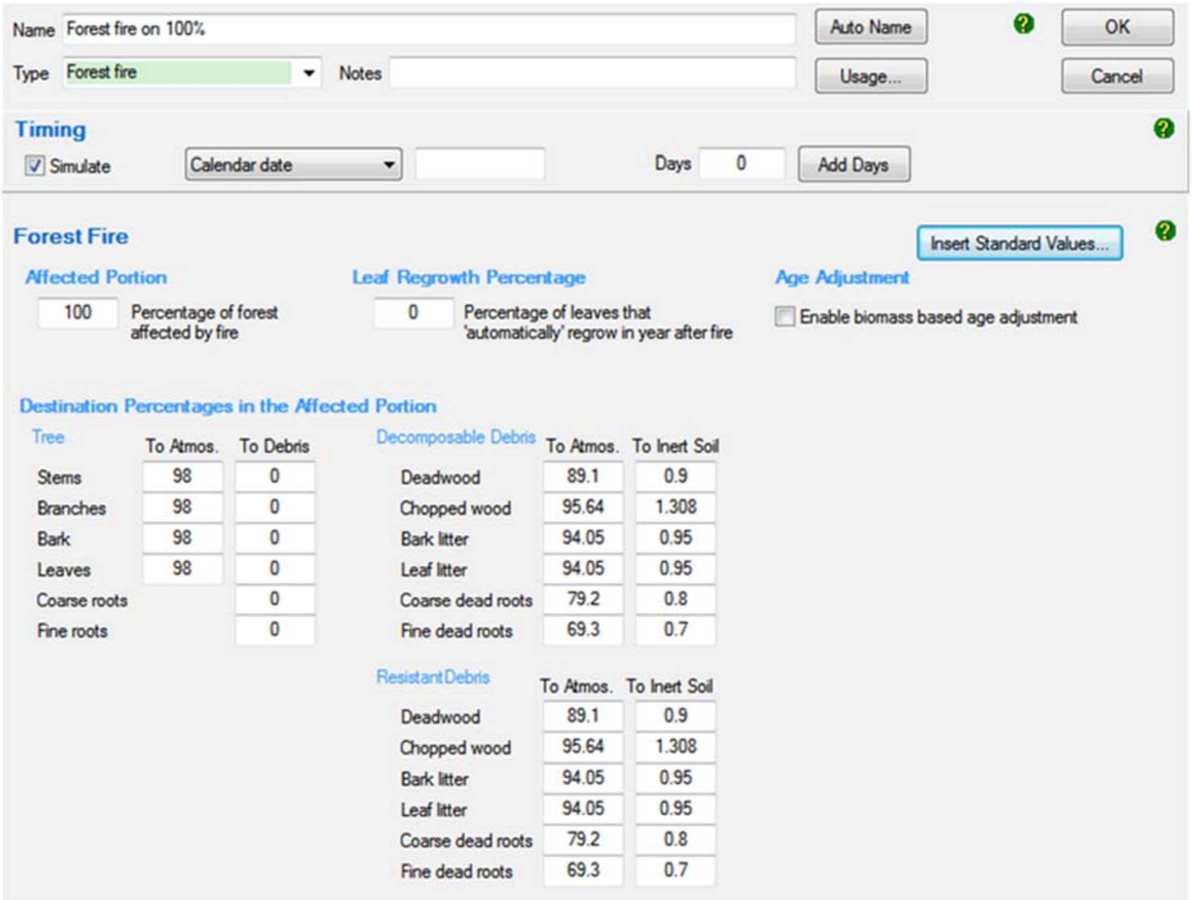

FIGURE 6. DEFAULT SETTINGS FOR WILDFIRE IN FULLCAM (SOURCE: FULLCAM SOFTWARE).

3. RESULTS AND DISCUSSION

3.1 REPRESENTATION OF MEASURED FUEL LOADS IN FULLCAM

As mentioned previously, FullCAM only includes one vegetation layer for woody trees. Therefore, the amalgamation of elevated and overstorey fuel loads represented the total aboveground biomass for compatibility with FullCAM specifications. Since prescribed burning does not generally target live woody fuel loads, this assumption is considered reasonable (Jenkins *et al*. 2015). Measured dry matter for the near surface live fuel was included in the model and, although not an accurate reflection, was represented as a native perennial grass species. In case of CWD and litter, these are represented in FullCAM under 'forest debris'. Within this section, bark fuel load is amalgamated with 'twig' and 'other' fuel load as FullCAM currently does not have the capacity to consider twigs as a separate entity.

3.2 EFFECT OF PRESCRIBED BURNING ON FINE FUEL LOAD MODELLED USING FULLCAM

The simulation modelled using FullCAM showed that for sites in both NSW and the ACT, the highest emissions were associated with the litter layer (Fig. 7). This fuel layer was comprised of CWD, bark, twigs, leaf litter and contributions of litter from the grass species present. Individual plots (1, 2 or 3) from each sampling site emitted varying amounts of C. For example, plots in the site referred to as Cotter in the ACT showed the greatest variation in C loss from the litter layer after a prescribed burning (Fig. 7b). Despite emission from Plots 1 and 2 at this site being relatively similar (2.5–3.0 t C ha^{-1}), Plot 3 emitted approximately 8 t C ha^{-1}, almost four times more than emitted from Plots 1 and 2 (Fig. 7b). Other sites in the ACT (Googong, Lone Pine, Tidbinbilla) remained relatively consistent for each plot (Fig. 7b).

Emissions from the litter fuel layer for sites in NSW were relatively consistent among plots (Fig. 7a). The exception was Martins Creek (MTC), where emissions from Plot 3 were lower (2 t C ha^{-1}) compared to Plots 1 and 2 (5–6 t C ha^{-1}). Influences such as initial biomass, fire intensity, fuel moisture content and position within the landscape would all have had an effect on how much fuel was actually burnt and, consequently, how much C was emitted.

The total C emitted was also simulated through FullCAM to visually depict the overall C loss across all plots at each site (Fig. 8). At two sites in NSW, Joadja (JOD) and Martins Creek (MTC), the greatest emissions were produced in one plot only at each site (Fig. 8a). For sites in the ACT, Plot 3 at Cotter produced the greatest amount of C lost to the atmosphere (Fig. 8b).

For sites in NSW, the mean emitted total C varied from 2.0–6.8 t C ha^{-1} (Table 4). These values are similar to emission estimates calculated for C emitted after prescribed burning in a previous study (Volkova and Weston 2013). Variation in emissions was low at most sites, except for at Joadja (JOD) and Martins creek (MTC) as previously noted. Mean emitted C values estimated for sites in the ACT did not show much variation in contrast to sites in NSW, however, the standard deviation for plots in Cotter (COT) was much larger than for the o ther sites (Table 4). Once again, this shows the large variation of emissions at the plot level. Overall, mean values for emitted C for the four sites sampled in the ACT were higher compared to the nine sites sampled in NSW (4.20 M 0.80 SD and 3.67 M 1.64 SD t C ha^{-1}, respectively).

(a)

(b)

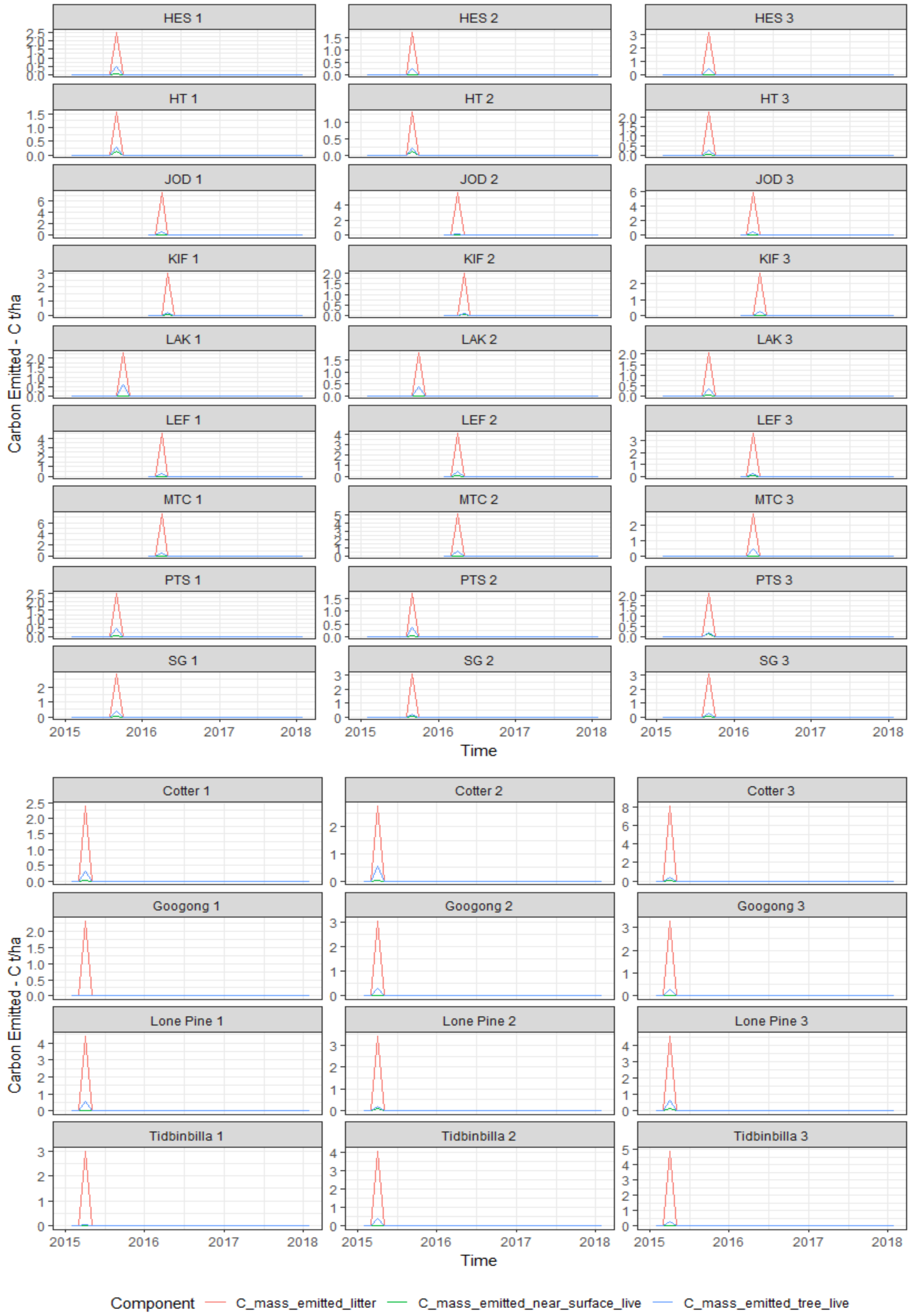

FIGURE 7. CARBON (C) EMISSION ESTIMATES (T C HA^{-1}) FOR DIFFERENT FUEL COMPONENTS (LITTER, NEAR SURFACE, TREE) EMITTED DURING PRESCRIBED BURNING FOR STUDY SITES IN (A) NEW SOUTH WALES (NSW) AND (B) THE AUSTRALIAN CAPITAL TERRITORY. REFER TO TABLE 2 FOR NAMES OF SITES FROM NSW.

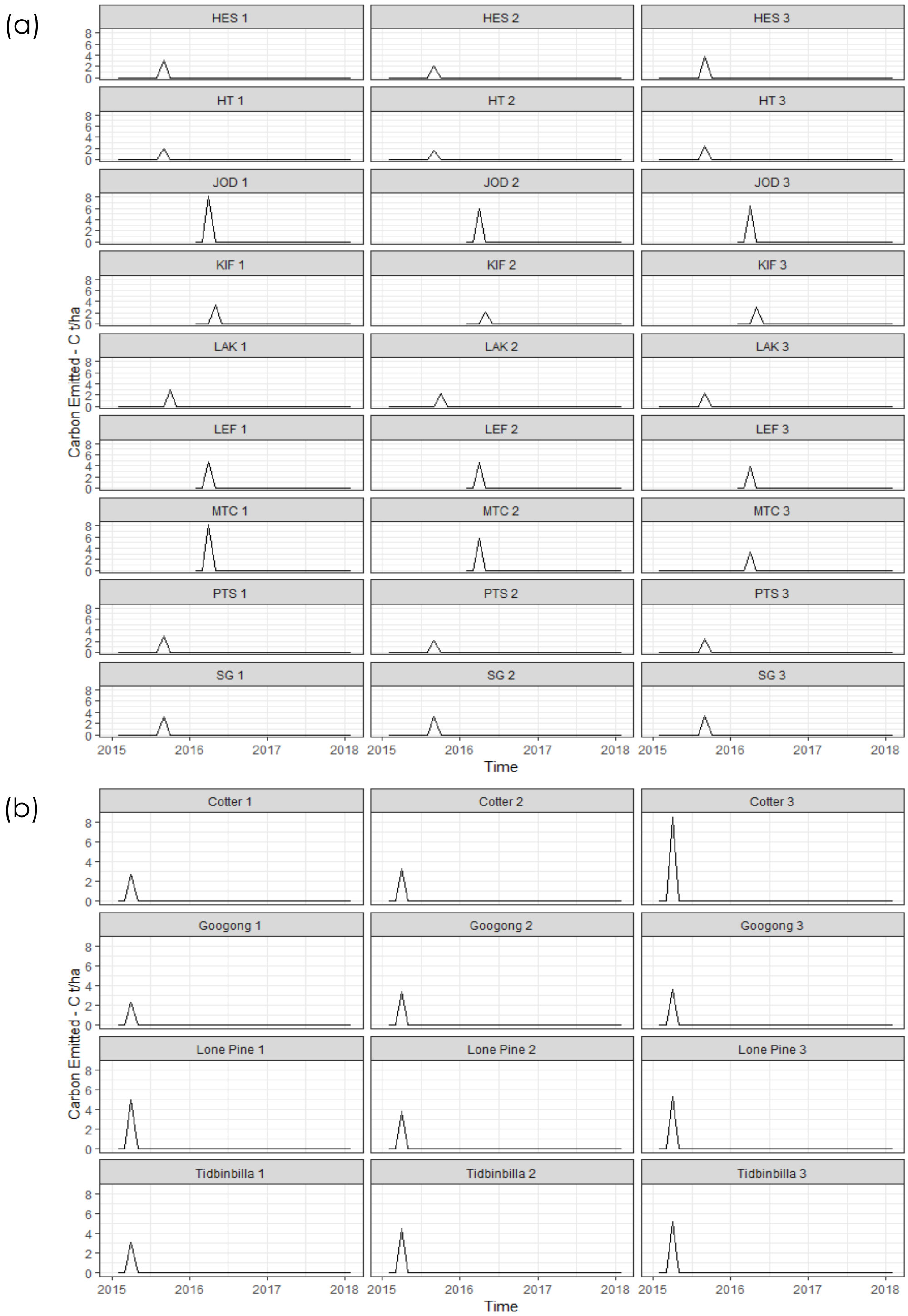

FIGURE 8. TOTAL CARBON (C) EMITTED (T C HA^{-1}) DUE TO PRESCRIBED BURNING FOR STUDY SITES IN (A) NEW SOUTH WALES (NSW) AND (B) THE AUSTRALIAN CAPITAL TERRITORY. REFER TO TABLE 2 FOR NAMES OF SITES FROM NSW.

TABLE 4. ESTIMATED AMOUNT OF CARBON (C) EMITTED (MEAN ± STANDARD DEVIATION) FOR SITES IN NEW SOUTH WALES (NSW) AND THE AUSTRALIAN CAPITAL TERRITORY (ACT).

Site name	Carbon emitted ($t\ C\ ha^{-1}$)	Site name	Carbon emitted ($t\ C\ ha^{-1}$)
NSW		***ACT***	
Haycock Trig (HT)	2.05 ± 0.47	Googong (GOO)	3.08 ± 0.66
Spring Gully (SG)	3.31 ± 0.08	Tidbinbilla (TID)	4.24 ± 1.09
Helicopter Spring (HES)	2.93 ± 0.89	Lone Pine (LP)	4.66 ± 0.82
Paterson (PTS)	2.48 ± 0.43	Cotter (COT)	4.88 ± 3.20
Lakesland (LAK)	2.50 ± 0.33		
Left Arm (LEF)	4.41 ± 0.43		
Kief Trig (KIF)	2.82 ± 0.58		
Joadja (JOD)	6.81 ± 1.20		
Martins Creek (MTC)	5.74 ± 2.51		

3.3 ESTIMATION OF CARBON EMITTED ACROSS THE LANDSCAPE

Using the calculated mean C emission values and t he corresponding standard deviation values for respective sites, a simple approach was ado pted to calculate landscape-scale C emitted due to prescr ibed burning for the sites in NSW (Table 5). The upper and low er confidence intervals around the mean emitted C (95% confidence interval) were estimated using the burnt areas for the respective sites in NSW. These estimates provided a range over which we can be 95% certa in contains the true mean. The calculated confidence intervals for all sites reported high variation due to limited number of sam ples for a giv en site. Nevertheless, reporting such uncertainties are essenti al for effective decision making, planning an d policy directions related to prescribed burning activities in fire and land management agencies.

TABLE 5. UPPER AND LOWER CONFIDENCE INTERVALS OF ESTIMATED AMOUNT OF TOTAL CARBON (C) EMITTED FROM STUDY SITES BURNT WITH PRESCRIBED FIRE IN NEW SOUTH WALES.

Site	Area burnt (ha)	Mean emitted C from prescribed burning (t)	Lower confidence interval (t)	Upper confidence interval (t)
Haycock Trig (HT)	611.90	1251.36	688.95	1813.77
Spring Gully (SG)	166.18	550.79	525.43	576.14
Helicopter Spring (HES)	634.17	1857.23	746.27	2968.18
Paterson (PTS)	319.27	793.28	522.97	1063.60
Lakesland (LAK)	807.86	2019.73	1498.71	2540.75
Left Arm (LEF)	2669.26	11761.45	9517.34	14005.55
Kief Trig (KIF)	46.04	313.72	205.01	422.43
Joadja (JOD)	916.00	5255.85	753.63	9758.06
Martins Creek (MTC)	591.16	1669.67	998.39	2340.95

3.4 RECOVERY OF BIOMASS LOSS FROM TREES DUE TO PRESCRIBED BURNING

According to FullCAM, biomass lost from the woody trees was recovered within 2–3 years after the prescribed burning. Since prescribed burns do not target live woody compartments, the recovery rates simulated by FullCAM model are acceptable. Recovery of the live woody compartments in terms of aboveground biomass (t DM ha^{-1}) for the selected sites are shown in Fig. 9.

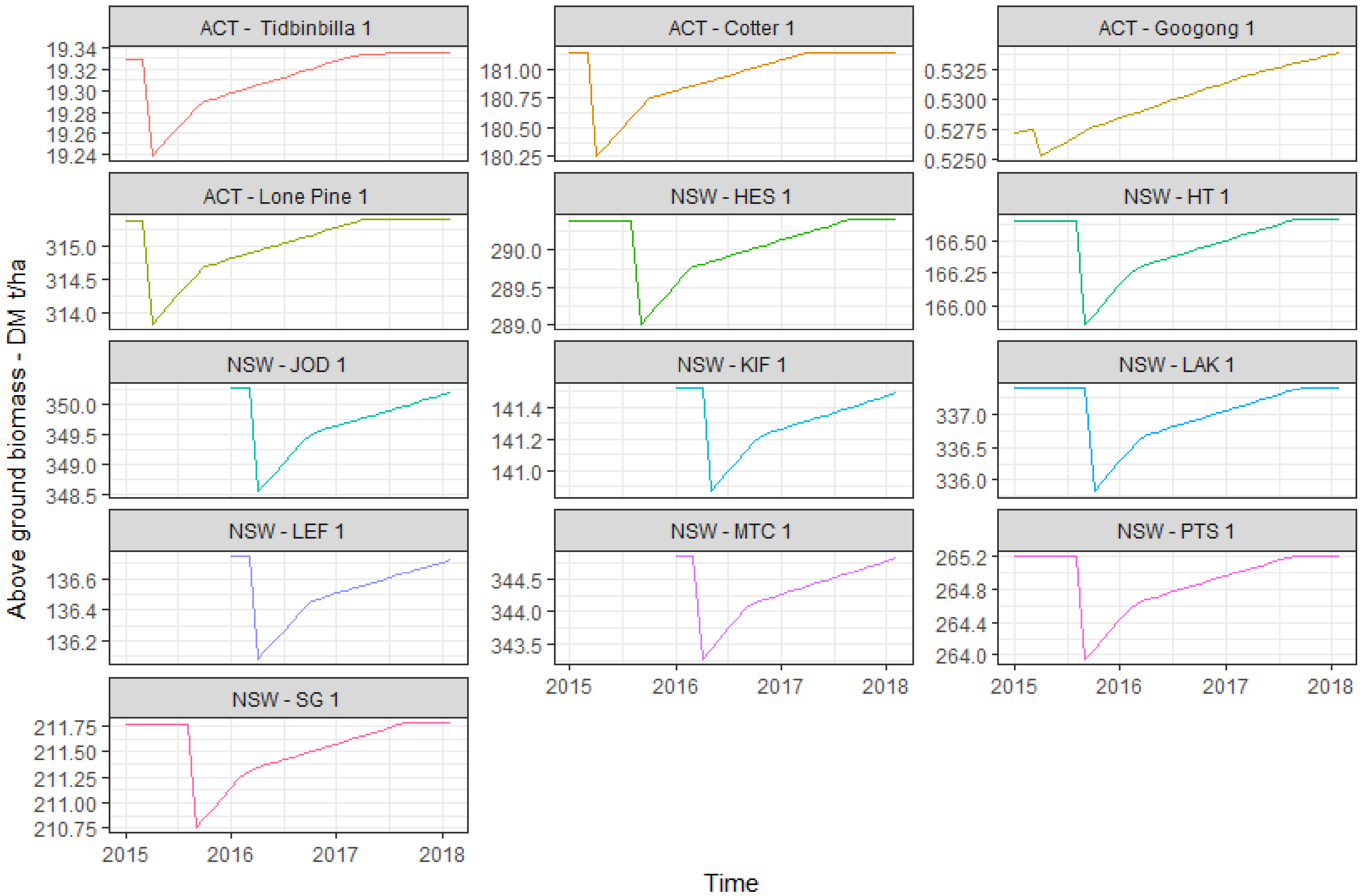

FIGURE 9. RECOVERY OF WOODY VEGETATION AFTER FUEL REDUCTION BURNING AT SITES IN NEW SOUTH WALES (NSW) AND THE AUSTRALIAN CAPILTAL TERRITORY (ACT) AS MODELLED BY FULLCAM. REFER TO TABLE 2 FOR NAMES OF SITES FROM NSW.

3.5 SENSITIVITY ANALYSIS

Changing the default parameter values associated with prescribed burning, had negligible effect generally on the average amounts of C emitted from each site and fuel component considered (Table 6). The standard deviation reported for HT was the same for all fuel components. For the other two sites, JOD and LP, values varied only slightly for each of the fuel components tested.

Changing the default parameters by 10% had little effect on total C emitted (Fig. 10). As expected from the small changes in individual fuel components (Table 6), the distribution (mean ± standard deviation) of values was the same for HT and very similar for JOD and LP. Litter, CWD and bark biomass for HT was two to five times smaller compared to the other two sites (Table 7), suggesting that the sensitivity of the three parameters considered was mainly due to variation in fuel loads.

It should be noted that this sensitivity analysis was done by considering one parameter at a time. Use of advanced sampling schemes, such as conditional latin hypercube, using a much higher number of iterations (n = 1000) and running all parameters simultaneously are recommended for a more detailed sensitivity analysis. For example, Paul *et al*. (2013) assessed the sensitivity of the FullCAM model parameters using a similar framework.

TABLE 6. AMOUNTS OF CARBON (C) EMITTED AFTER VARYING (± 10%) KEY DEFAULT PARAMETERS IN FULLCAM RELATED TO PRESCRIBED BURNING. CWD = COARSE WOODY DEBRIS.

Site	Fuel component	Mean C emitted (t C ha^{-1})	Standard deviation (t C ha^{-1})	Minimum C emitted (t C ha^{-1})	Maximum C emitted (t C ha^{-1})
Haycock Trig (HT)	Bark	1.99	0.04	1.94	2.04
	CWD	1.99	0.04	1.94	2.04
	Litter	1.99	0.04	1.94	2.04
Joadja (JOD)	Bark	8.17	0.10	8.02	8.31
	CWD	8.17	0.16	7.94	8.40
	Litter	8.17	0.27	7.79	8.55
Lone Pine (LP)	Bark	4.96	0.15	4.75	5.17
	CWD	4.96	0.08	4.85	5.07
	Litter	4.96	0.09	4.84	5.08

TABLE 7. DERIVED DATA FOR COARSE WOODY DEBRIS (CWD), LITTER AND BARK FUEL FOR THE TWO TEST SITES SAMPLED IN NEW SOUTH WALES (HAYCOCK TRIG AND JOADJA) AND ONE TEST SITE SAMPLED IN THE AUSTRALIAN CAPITAL TERRITORY (LONE PINE). DM = DRY MATTER.

Site	Plot number	Bark ($t\ DM\ ha^{-1}$)	CWD ($t\ DM\ ha^{-1}$)	Litter ($t\ DM\ ha^{-1}$)
Haycock Trig (HT)	1	2.30	10.14	2.86
	2	2.73	2.36	3.27
	3	4.82	3.84	5.95
Joadja (JOD)	1	5.88	44.36	14.86
	2	6.15	21.50	12.03
	3	12.33	14.47	9.35
Lone Pine (LP)	1	8.42	21.30	4.68
	2	3.63	35.21	2.73
	3	8.63	36.87	1.84

The emissions reported for the 90 simulations used in this analysis are available in Table A4 in the Appendix.

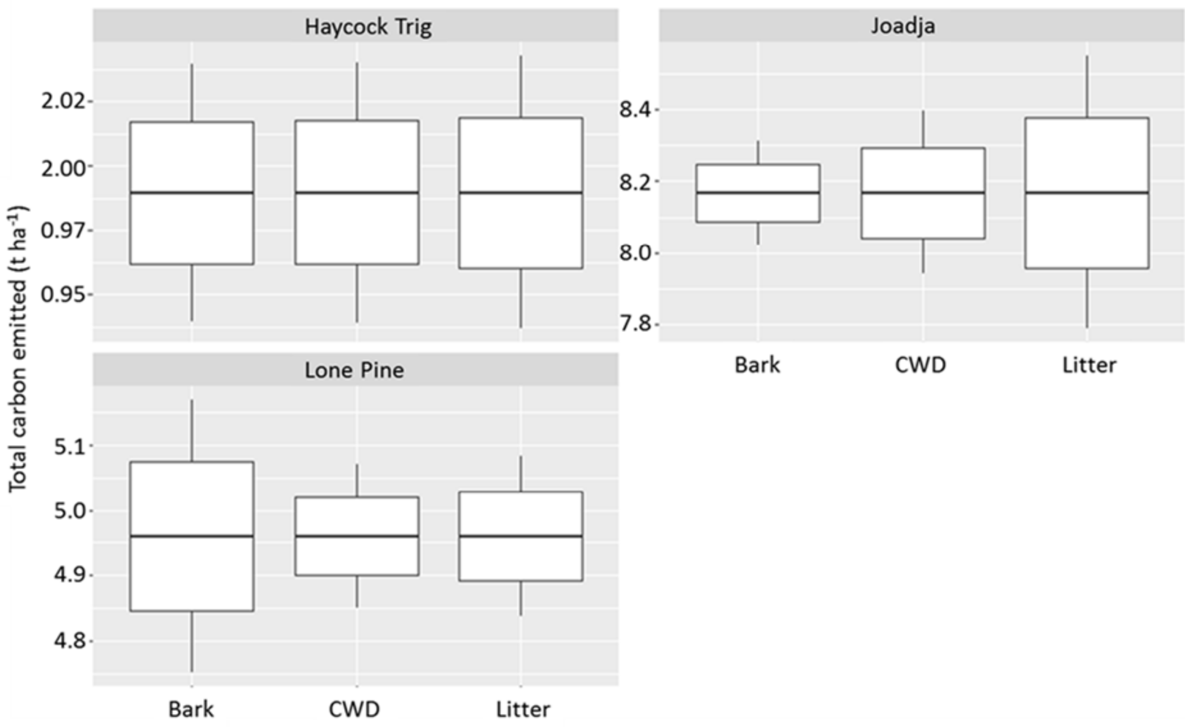

FIGURE 10. DISTRIBUTION (MEAN ± STANDARD DEVIATION) OF TOTAL CARBON EMISSIONS FOR THREE SITES WITH RESPECT TO CHANGING DEFAULT PARAMETERS BY ± 10% FOR BARK, COARSE WOODY DEBRIS (CWD) AND LITTER.

3.6 CARBON EMISSIONS FROM DIFFERENT BURNING SCENARIOS AND WILDFIRE

As expected, when the 'burn percentage' parameters of surface fuel (bark and litter) were increased from 25 to 100%, FullCAM simulated C emissions also increased (Fig. 11). For example, the mean total C emissions from Cotter in the ACT was approximately 3 t C ha^{-1} for the scenario with 25% of the vegetation burnt and 5.4 t C ha^{-1} for the scenario with 100% of the vegetation burnt (Fig. 11). This pattern was common for the all the sites considered in the study. A wildfire scenario was also simulated for all sites (Fig. 12). Carbon emissions from simulated wildfire were up to 40 times greater compared to the prescribed burning scenarios. Variability in the standard error values associated with total C emitted from simulated wildfire at each site reflects site-specific variation in fuel loads (Fig. 12).

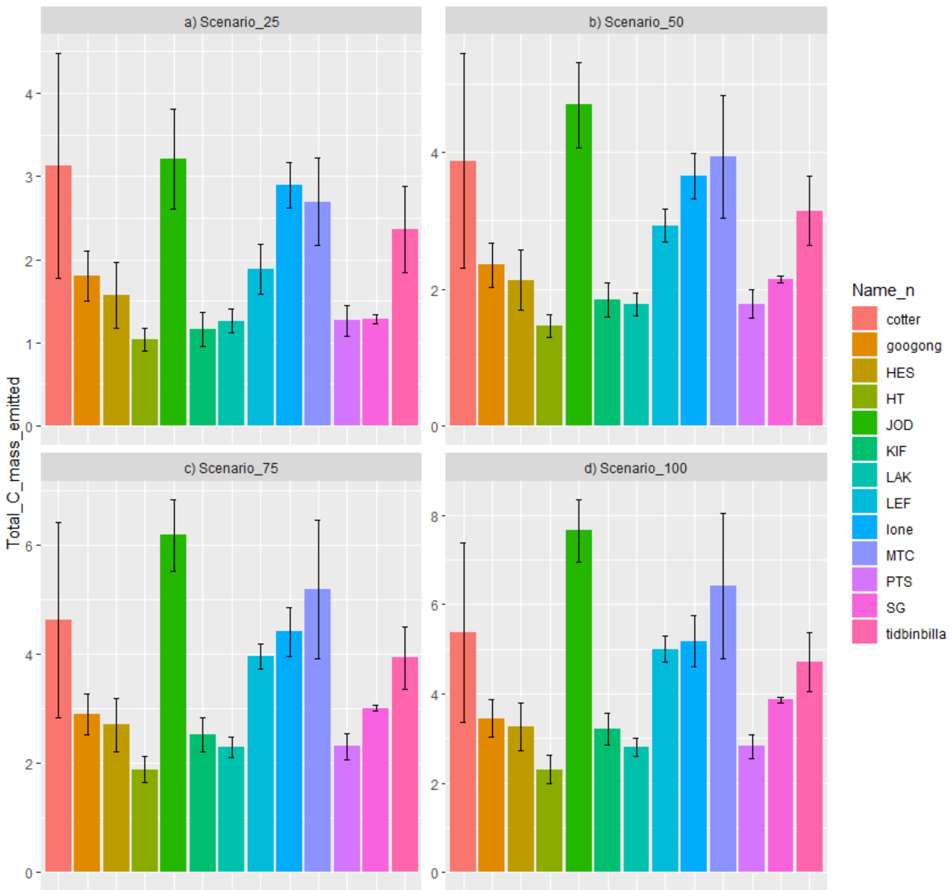

FIGURE 11. CARBON (C) EMISSIONS (MEAN ± STANDARD ERROR OF MEAN; T C HA^{-1}) FOR FOUR BURN SCENARIOS VARYING SURFACE FUEL (BARK AND LITTER) AND KEEPING ALL OTHER MODEL PARAMETERS CONSTANT: (A) SCENARIO_25 = 25% OF BARK AND LEAF LITTER REMOVED; (B) SCENARIO_50 = 50% OF BARK AND LEAF LITTER REMOVED; (C) SCENARIO_75 = 75% OF BARK AND LEAF LITTER REMOVED; (D) SCENARIO_100 = 100% OF BARK AND LEAF LITTER REMOVED. REFER TO TABLE 2 FOR NAMES OF SITES FROM NEW SOUTH WALES.

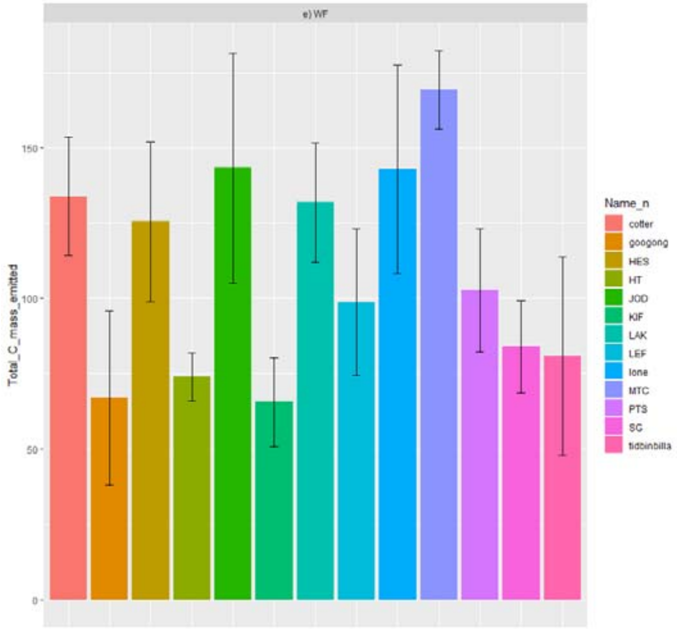

FIGURE 12. CARBON (C) EMISSIONS (MEAN ± STANDARD ERROR OF MEAN; T C HA^{-1}) FOR WILDFIRE SIMULATED USING THE DEFAULT VALUES (FIG. 6) IN FULLCAM. REFER TO TABLE 2 FOR NAMES OF SITES FROM NEW SOUTH WALES.

The simulation analysis showed that for each of the prescribed burning scenarios tested, the amounts of C emitted to the atmosphere was highly variable and site specific (Table 8). To assess whether the different burn scenarios had a statistically significant effect on the total amount of C emitted, linear mixed modelling and Tukey's paired-wise mean separation tests were used. A summary of the estimated fixed effect terms derived from the linear mixed models are presented in Appendix A5 (Summary of the linear mixed model analysis). Each paired-wise comparison was statistically significant at 0.05 probability level (Table 9).

TABLE 8. TOTAL CARBON (C) EMISSIONS ESTIMATED FOR EACH SITE FOR THE SCENARIOS TESTED. SCENARIO_25 = 25% OF BARK AND LEAF LITTER REMOVED; SCENARIO_50 = 50% OF BARK AND LEAF LITTER REMOVED; SCENARIO_75 = 75% OF BARK AND LEAF LITTER REMOVED; SCENARIO_100 = 100% OF BARK AND LEAF LITTER REMOVED; SCENARIO_WF = SIMULATED WILDFIRE USING DEFAULT VALUES. REFER TO TABLE 2 FOR NAMES OF SITES FROM NEW SOUTH WALES.

Fire scenario	Site	Area burnt (ha)	C emitted from prescribed burning (t C)	Lower confidence interval (t C)	Upper confidence interval (t C)
Scenario_25	HES	634.17	994.88	148.35	1841.41
Scenario_25	HT	611.90	638.00	350.62	925.38
Scenario_25	JOD	46.04	147.91	53.95	241.87
Scenario_25	KIF	591.16	685.23	273.93	1096.53
Scenario_25	LAK	807.86	1018.20	632.76	1403.64
Scenario_25	LEF	2669.26	5031.25	2297.74	7764.76
Scenario_25	MTC	916.00	2470.00	832.81	4107.20
Scenario_25	PTS	319.27	404.11	205.15	603.07
Scenario_25	SG	166.18	213.42	181.31	245.54
Scenario_50	HES	634.17	1352.88	403.95	2301.81
Scenario_50	HT	611.90	894.06	535.31	1252.81
Scenario_50	JOD	46.04	216.10	118.78	313.43
Scenario_50	KIF	591.16	1089.10	577.50	1600.70
Scenario_50	LAK	807.86	1432.24	986.62	1877.86
Scenario_50	LEF	2669.26	7801.79	5628.12	9975.46
Scenario_50	MTC	916.00	3606.70	822.63	6390.76
Scenario_50	PTS	319.27	569.63	345.39	793.88
Scenario_50	SG	166.18	356.28	328.70	383.85
Scenario_75	HES	634.17	1710.88	655.61	2766.15
Scenario_75	HT	611.90	1150.12	651.42	1648.81
Scenario_75	JOD	46.04	284.30	181.94	386.67
Scenario_75	KIF	591.16	1492.97	871.62	2114.31
Scenario_75	LAK	807.86	1846.28	1340.31	2352.24
Scenario_75	LEF	2669.26	10572.32	8446.74	12697.91
Scenario_75	MTC	916.00	4743.39	806.65	8680.13
Scenario_75	PTS	319.27	735.15	479.33	990.98
Scenario_75	SG	166.18	499.13	471.01	527.25
Scenario_100	HES	634.17	2068.88	904.40	3233.35
Scenario_100	HT	611.90	1406.18	740.92	2071.43
Scenario_100	JOD	46.04	352.50	243.65	461.35
Scenario_100	KIF	591.16	1896.83	1160.51	2633.16
Scenario_100	LAK	807.86	2260.31	1693.89	2826.74
Scenario_100	LEF	2669.26	13342.86	10725.25	15960.47
Scenario_100	MTC	916.00	5880.09	788.81	10971.37
Scenario_100	PTS	319.27	900.68	609.01	1192.34
Scenario_100	SG	166.18	641.98	608.48	675.49
Scenario_WF	HES	634.17	79618.63	22477.20	136760.07
Scenario_WF	HT	611.90	45279.75	28730.20	61829.31
Scenario_WF	JOD	46.04	6599.72	617.27	12582.18
Scenario_WF	KIF	591.16	38815.87	8971.80	68659.93
Scenario_WF	LAK	807.86	106636.95	52362.69	160911.21
Scenario_WF	LEF	2669.26	263867.74	43575.44	484160.04
Scenario_WF	MTC	916.00	155091.54	114467.18	195715.89
Scenario_WF	PTS	319.27	32837.37	10599.92	55074.83
Scenario_WF	SG	166.18	13966.03	5390.37	22541.68

TABLE 9. TUKEY'S PAIRED-WISE MEAN SEPARATION FOR TOTAL CARBON EMITTED UNDER DIFFERENT PRESCRIBED BURNING SCENARIOS. * = SIGNIFICANT AT 0.95% CONFIDENCE INTERVAL (0.05 PROBABILITY LEVEL); SCENARIO_25 = 25% OF BARK AND LEAF LITTER REMOVED; SCENARIO_50 = 50% OF BARK AND LEAF LITTER REMOVED; SCENARIO_75 = 75% OF B ARK AND LEAF LITTER REMOVED; SCENARIO_100 = 100% OF BARK AND LEAF LITTER REMOVED.

Comparison	*P* value
Scenario_100 – Scenario_25	<0.0001*
Scenario_100 – Scenario_50	<0.0001*
Scenario_100 – Scenario_75	<0.0001*
Scenario_25 – Scenario_50	<0.0001*
Scenario_25 – Scenario_75	<0.0001*
Scenario_50 – Scenario_75	<0.0001*

3.7 COMPARISON OF SIMULATED POST-FIRE BIOMASS FOLLOWING PRESCRIBED BURNING

To assess the quality of prediction estimates simulated with the FullCAM model, post-fire fuel loads ('simulated'; total biomass, CWD, bark and litter) were compared with field observations ('measured') (Figs. 13–16). Overall, FullCAM was able to s imulate post-fire fuel loads wit h moderate accuracy. Me an values for si mulated and measured total aboveground biomass were similar for Googong, Haycock Trig (HT), Left Arm (LEF) and Lone Pine (Fig. 12) but were noticeably different for the other sites with examples of both under- and overprediction from FullCAM. For C WD, close matches between mean measured and simulated biomass values were found for HT, LEF, Joadja (JOD) and Martins Creek (MTC) (Fig. 14) and, again, for the remaining sites with evidence of both under- and overpredictions. For bark and litter, there were very poor relationships between model predictions and field data for all sites (Figs. 14 and 15). In most cases for bark and in all cases for litter, FullCAM underpredicted biomass of these two components when compared to field data.

The discrepancy between measured and simulated fuel loads may, in part, be due to the decision made i n the initial stage of modelling to aggregate both o ver- and understorey biomass instead of treating both fractions as separate biomass pools. The requirement to use partiti oning, decomposition and growt h parameters relating to grasses as a substitute for woody sclerophyllous shrubs as understorey fuel is far more likely to be the reason for poor compari sons between measured and si mulated fuel loads. This is a shortcoming of the FullCA M model that could be addressed in future reiterations of the model.

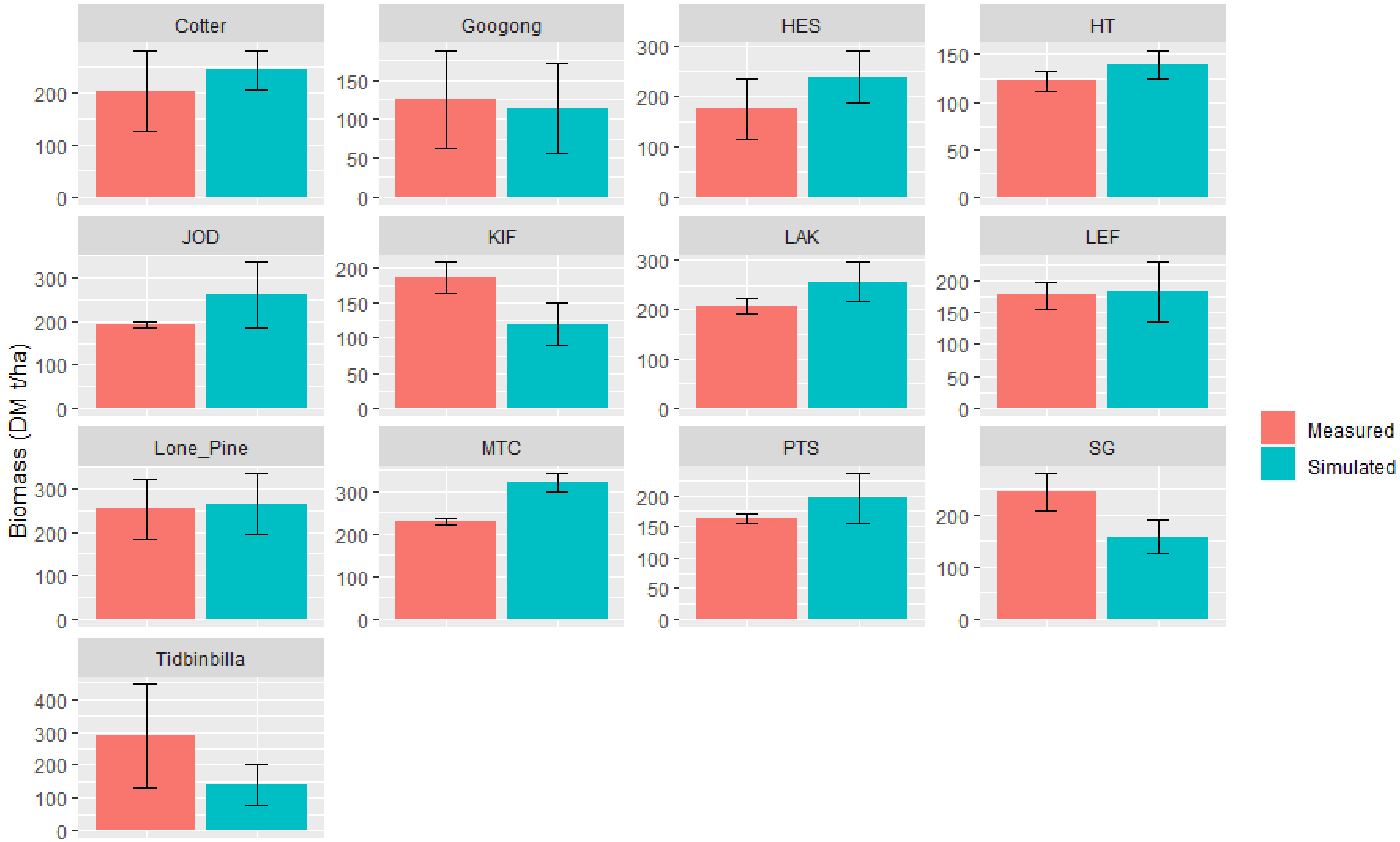

FIGURE 13. COMPARISONS BETWEEN SIMULATED AND MEASURED TOTAL ABOVEGROUND BIOMASS (T DM HA^{-1}) AFTER PRESCRIBED BURNING AT EACH OF THE STUDY SITES. STUDY SITES IN NEW SOUTH WALES INCLUDE: HES = HELICOPTER SPUR; HT = HAYCOCK TRIG; JOD = JOADJA; KIF = KIEF TRIG; LAK = LAKESLAND; LEF = LEFT ARM; MTC = MARTINS CREEK; PTS = PATERSON; SG = SPRING GULLY; AND IN THE AUSTRALIAN CAPITAL TERRITORY INCLUDE: COTTER; GOOGONG; LONE PINE; TIDBINBILLA.

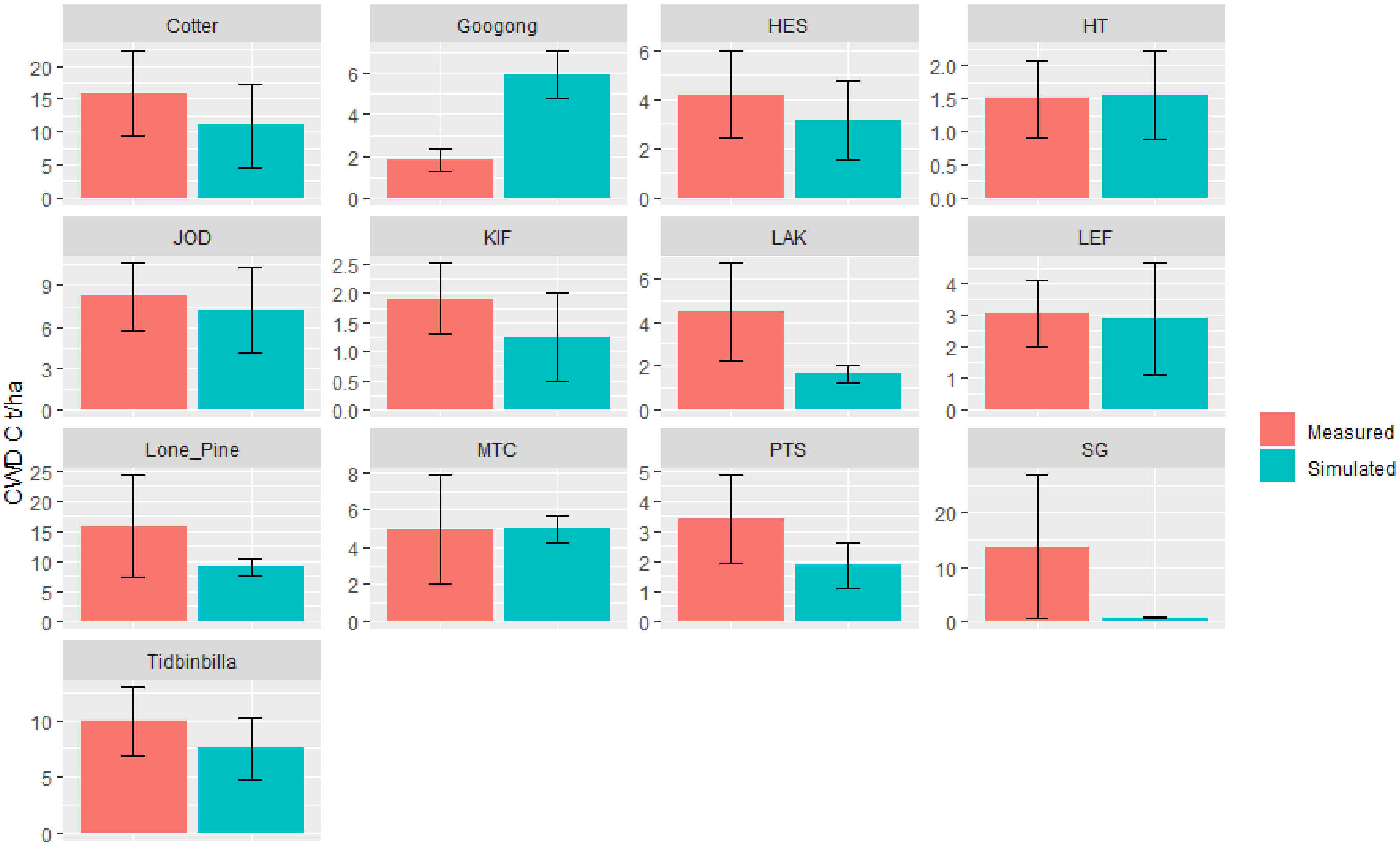

FIGURE 14. COMPARISONS BETWEEN SIMULATED AND MEASURED COARSE WOODY DEBRIS BIOMASS (CWD; T DM HA^{-1}) AFTER PRESCRIBED BURNING AT EACH OF THE STUDY SITES. STUDY SITES IN NEW SOUTH WALES INCLUDE: HES = HELICOPTER SPUR; HT = HAYCOCK TRIG; JOD = JOADJA; KIF = KIEF TRIG; LAK = LAKESLAND; LEF = LEFT ARM; MTC = MARTINS CREEK; PTS = PATERSON; SG = SPRING GULLY; AND IN THE AUSTRALIAN CAPITAL TERRITORY INCLUDE: COTTER; GOOGONG; LONE PINE; TIDBINBILLA.

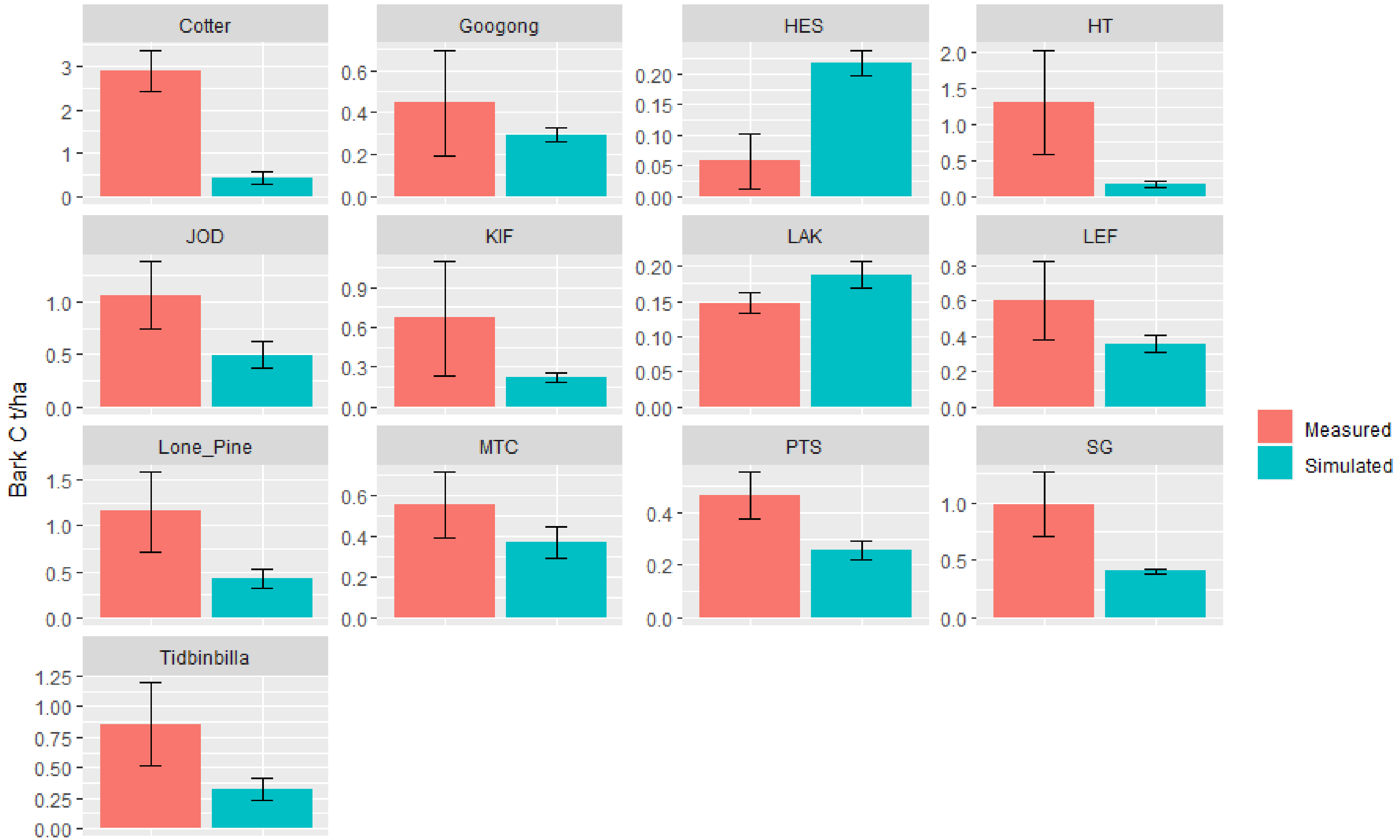

FIGURE 15. COMPARISONS BETWEEN SIMULATED AND MEASURED BARK BIOMASS (T DM HA^{-1}) AFTER PRESCRIBED BURNING AT EACH OF THE STUDY SITES. STUDY SITES IN NEW SOUTH WALES INCLUDE: HES = HELICOPTER SPUR; HT = HAYCOCK TRIG; JOD = JOADJA; KIF = KIEF TRIG; LAK = LAKESLAND; LEF = LEFT ARM; MTC = MARTINS CREEK; PTS = PATERSON; SG = SPRING GULLY; AND IN THE AUSTRALIAN CAPITAL TERRITOY INCLUDE: COTTER; GOOGONG; LONE PINE; TIDBINBILLA.

FIGURE 16. COMPARISONS BETWEEN SIMULATED AND MEASURED LITTER BIOMASS (T DM HA^{-1}) AFTER PRESCRIBED BURNING AT EACH OF THE STUDY SITES. STUDY SITES IN NEW SOUTH WALES INCLUDE: HES = HELICOPTER SPUR; HT = HAYCOCK TRIG; JOD = JOADJA; KIF = KIEF TRIG; LAK = LAKESLAND; LEF = LEFT ARM; MTC = MARTINS CREEK; PTS = PATERSON; SG = SPRING GULLY; AND IN THE AUSTRALIAN CAPITAL TERRITORY INCLUDE: COTTER; GOOGONG; LONE PINE; TIDBINBILLA.

4. CONCLUSIONS

We have demonstrated a cost- and time-effective, simple approach to deriving estimates of C emissions from prescribed burning. This simple approach will assist land managers to estimate C emissions associated with prescribed burning that can be used for multiple planning activities, such as to manage bushfire risk and carbon dynamics. While we acknowledge that FullCAM has limitations in modelling C emission estimations, it has the capacity to track carbon pools related to forest ecosystems. As FullCAM is used in Australia for the national standard of carbon accounting, it is subject to continuous ongoing development, with improved model versions released through the Department of Environment and Energy. The use of FullCAM by fire and land management agencies will enable them to be compatible with the national standard of carbon accounting and agencies will be prepared for any carbon accounting activities that are required in their practice.

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6. APPENDIX

TABLE A1. GENERAL DESCRIPTION OF FIRE EVENT-RELATED PARAMETERS WITHIN FULLCAM (FULLCAM HELP).

Parameter name	Description
General parameters	
Affected portion	Percentage of forest affected by fire
Leaf re-growth percentage	The percentage of leaves that automatically regrow after 1 year following fire event
Age adjustment	Allows biomass-based age adjustment
Parameters related to affected portions – tree components	
Stem – to atmosphere and to debris	Sum of the fraction that goes to atmosphere and debris should not exceed maximum value of 100
Branches – to atmosphere and to debris	Sum of the fraction that goes to atmosphere and debris should not exceed maximum value of 100
Bark – to atmosphere and to debris	Sum of the fraction that goes to atmosphere and debris should not exceed maximum value of 100
Leaves – to atmosphere and to debris	Sum of the fraction that goes to atmosphere and debris should not exceed maximum value of 100
Coarse roots – to atmosphere and to debris	Only affects belowground debris. Does not affect belowground live material
Fine roots – to atmosphere and to debris	Only affects belowground debris. Does not affect belowground live material
Parameters related to affected portions – debris (decomposable)	
Dead wood	Sum of the fraction that goes to atmosphere and to insert soils should not exceed maximum value of 100
Chopped wood	Sum of the fraction that goes to atmosphere and to insert soils should not exceed maximum value of 100
Bark litter	Sum of the fraction that goes to atmosphere and to insert soils should not exceed maximum value of 100
Leaf litter	Sum of the fraction that goes to atmosphere and to insert soils should not exceed maximum value of 100
Coarse dead roots	Sum of the fraction that goes to atmosphere and to insert soils should not exceed maximum value of 100

Parameters related to affected portions – debris (resistant)	
Dead wood	Sum of the fraction that goes to atmosphere and to insert soils should not exceed maximum value of 100
Chopped wood	Sum of the fraction that goes to atmosphere and to insert soils should not exceed maximum value of 100
Bark litter	Sum of the fraction that goes to atmosphere and to insert soils should not exceed maximum value of 100
Leaf litter	Sum of the fraction that goes to atmosphere and to insert soils should not exceed maximum value of 100
Coarse dead roots	Sum of the fraction that goes to atmosphere and to insert soils should not exceed maximum value of 100
Fine dead roots	Sum of the fraction that goes to atmosphere and to insert soils should not exceed maximum value of 100

TABLE A2. DERIVED DATA FOR TREE COMPONENTS AND COARSE WOODY DEBRIS FOR SITES IN NEW SOUTH WALES (NSW) AND THE AUSTALIAN CAPITAL TERRITORY (ACT) AS REQUIRED BY FULLCAM. THE UNIT FOR ALL BIOMASS SAMPLES IS T DM HA^{-1}. CWD = COARSE WOODY DEBRIS; DM = DRY MATTER; LAT. = LATITUDE; LONG. = LONGITUDE; AGB = ABOVEGROUND BIOMASS; BGB = BELOWGROUND BIOMASS; C = CARBON; RPM = RESISTANT PLANT MATTER. STUDY SITES IN NSW INCLUDE: HT = HAYCOCK TRIG; SG = SPRING GULLY; HES = HELICOPTER SPUR; PTS = PATERSON; LAK = LAKESLAND; LEF = LEFT ARM; JOD = JOADJA; MTC = MARTINS CREEK; KIF = KIEF TRIG; AND IN THE ACT INCLUDE: GOO = GOOGONG; TID = TIDBINBILLA; LP = LONE PINE; COT = COTTER.

Site	Plot	CWD DM	Ground (live) DM	Under-storey DM	Over-storey DM	Lat.	Long.	Total AGB	Total biomass (AGB + BGB)	Stem DM	Branch DM	Bark DM	Leaves DM	Coarse roots DM	Fine roots DM	CWD C RPM
HT	1	10.14	1.65	28.84	137.81	-33.46	151.10	166.65	241.52	108.68	28.98	24.15	4.83	60.38	14.49	5.07
HT	2	2.36	1.27	20.28	94.19	-33.46	151.09	114.47	165.90	74.66	19.91	16.59	3.32	41.48	9.95	1.18
HT	3	3.84	0.74	21.90	115.29	-33.44	151.10	137.19	198.82	89.47	23.86	19.88	3.98	49.71	11.93	1.92
SG	1	1.60	0.34	40.88	170.89	-34.09	151.15	211.76	306.90	138.11	36.83	30.69	6.14	76.73	18.41	0.80
SG	2	1.31	0.36	34.37	68.90	-34.09	151.16	103.27	149.66	67.35	17.96	14.97	2.99	37.42	8.98	0.66
SG	3	3.46	0.64	12.61	148.80	-34.09	151.14	161.40	233.92	105.26	28.07	23.39	4.68	58.48	14.04	1.73
HES	1	6.89	0.73	34.84	255.55	-33.80	150.51	290.39	420.85	189.38	50.50	42.09	8.42	105.21	25.25	3.44
HES	2	3.84	0.19	47.48	90.00	-33.81	150.52	137.48	199.25	89.66	23.91	19.93	3.99	49.81	11.96	1.92
HES	3	22.47	0.20	33.69	261.56	-33.81	150.52	295.26	427.91	192.56	51.35	42.79	8.56	106.98	25.67	11.24
PTS	1	11.90	0.29	54.74	210.46	-33.54	150.58	265.20	384.35	172.96	46.12	38.43	7.69	96.09	23.06	5.95
PTS	2	4.61	0.28	55.48	147.43	-33.54	150.58	202.91	294.08	132.33	35.29	29.41	5.88	73.52	17.64	2.30
PTS	3	3.19	1.89	40.17	83.81	-33.55	150.58	123.99	179.69	80.86	21.56	17.97	3.59	44.92	10.78	1.60
LAK	1	7.20	0.13	36.55	300.85	-34.17	150.49	337.40	488.98	220.04	58.68	48.90	9.78	122.25	29.34	3.60
LAK	2	2.74	0.10	25.88	202.98	-34.20	150.50	228.86	331.68	149.26	39.80	33.17	6.63	82.92	19.90	1.37
LAK	3	6.90	0.34	25.28	182.52	-34.20	150.51	207.81	301.17	135.53	36.14	30.12	6.02	75.29	18.07	3.45
LEF	1	2.66	0.09	13.71	123.04	-33.37	150.81	136.75	198.19	89.18	23.78	19.82	3.96	49.55	11.89	1.33
LEF	2	22.04	0.37	32.67	244.17	-33.37	150.81	276.85	401.23	180.55	48.15	40.12	8.02	100.31	24.07	11.02
LEF	3	5.09	0.74	14.12	120.61	-33.36	150.82	134.73	195.26	87.87	23.43	19.53	3.91	48.82	11.72	2.54
JOD	1	44.36	0.38	24.79	325.47	-34.38	150.21	350.26	507.63	228.43	60.92	50.76	10.15	126.91	30.46	22.18
JOD	2	21.50	0.07	15.44	94.15	-34.36	150.22	109.59	158.83	71.47	19.06	15.88	3.18	39.71	9.53	10.75
JOD	3	14.47	0.06	15.15	170.30	-34.35	150.23	185.45	268.77	120.95	32.25	26.88	5.38	67.19	16.13	7.23
MTC	1	8.24	0.67	53.43	272.19	-34.30	150.44	325.62	471.91	212.36	56.63	47.19	9.44	117.98	28.31	4.12
MTC	2	19.57	0.27	55.79	289.05	-34.29	150.44	344.85	499.78	224.90	59.97	49.98	10.00	124.95	29.99	9.78
MTC	3	12.93	0.35	50.48	225.74	-34.26	150.42	276.23	400.33	180.15	48.04	40.03	8.01	100.08	24.02	6.47

KIF	1	9.50	1.18	6.68	134.85	-33.29	150.95	141.52	205.11	92.30	24.61	20.51	4.10	51.28	12.31	4.75
KIF	2	1.76	1.00	20.41	41.83	-33.30	150.94	62.24	90.20	40.59	10.82	9.02	1.80	22.55	5.41	0.88
KIF	3	1.59	0.43	9.11	149.02	-33.29	150.93	158.13	229.18	103.13	27.50	22.92	4.58	57.30	13.75	0.80
GOO	1	14.44	0.04	0.53		-35.52	149.29	0.53	0.76	0.34	0.09	0.08	0.02	0.19	0.05	7.22
GOO	2	27.69	0.12	4.50	178.39	-35.53	149.30	182.88	265.05	119.27	31.81	26.50	5.30	66.26	15.90	13.85
GOO	3	19.13	0.00	0.44	159.10	-35.53	149.30	159.55	231.23	104.05	27.75	23.12	4.62	57.81	13.87	9.57
TID	1	13.04	0.17	19.33		-35.46	148.91	19.33	28.01	12.61	3.36	2.80	0.56	7.00	1.68	6.52
TID	2	43.87	0.05	47.01	190.71	-35.47	148.90	237.71	344.51	155.03	41.34	34.45	6.89	86.13	20.67	21.94
TID	3	20.34	0.03	25.80	138.66	-35.47	148.89	164.46	238.35	107.26	28.60	23.83	4.77	59.59	14.30	10.17
LP	1	21.30	0.17	4.60	310.78	-35.88	148.94	315.38	457.07	205.68	54.85	45.71	9.14	114.27	27.42	10.65
LP	2	35.21	1.89	13.34	112.73	-35.88	148.94	126.07	182.71	82.22	21.93	18.27	3.65	45.68	10.96	17.60
LP	3	36.87	2.22	7.54	350.29	-35.88	148.95	357.82	518.58	233.36	62.23	51.86	10.37	129.65	31.11	18.44
COT	1	14.39	0.10	48.22	132.91	-35.62	148.83	181.14	262.52	118.13	31.50	26.25	5.25	65.63	15.75	7.20
COT	2	16.79	0.85	62.06	246.40	-35.64	148.82	308.46	447.04	201.17	53.64	44.70	8.94	111.76	26.82	8.39
COT	3	81.34	0.96	66.08	176.93	-35.62	148.80	243.01	352.19	158.49	42.26	35.22	7.04	88.05	21.13	40.67

Data measured in field/site location

Calculated values for the FullCAM model

TABLE A3. DERIVED DATA FOR LITTER FOR SITES IN NEW SOUTH WALES (NSW) AND THE AUSTRALIAN CAPITAL TERRITORY (ACT) AS REQUIRED BY THE FULLCAM MODEL. DM = DRY MATTER; C = CARBON; DPM = DECOMPOSABLE PLANT MATTER; RPM = RESISTANT PLANT MATTER. STUDY SITES IN NSW INCLUDE: HT = HAYCOCK TRIG; SG = SPRING GULLY; HES = HELICOPTER SPUR; PTS = PATERSON; LAK = LAKESLAND; LEF = LEFT ARM; JOD = JOADJA; MTC = MARTINS CREEK; KIF = KIEF TRIG; AND IN THE ACT INCLUDE: GOO = GOOGONG; TID = TIDBINBILLA; LP = LONE PINE; COT = COTTER.

Site	Plot	Mean litter stock (t DM ha^{-1})	Mean bark stock (t DM ha^{-1})	Mean litter (t C ha^{-1})	Mean bark RPM (t C ha^{-1})	Mean litter DPM (t C ha^{-1})	Mean litter RPM (t C ha^{-1})
HT	1	2.86	2.30	1.49	1.13	1.14	0.34
HT	2	3.27	2.73	1.70	1.34	1.31	0.39
HT	3	5.95	4.82	3.10	2.36	2.38	0.71
SG	1	7.17	7.24	3.73	3.55	2.87	0.86
SG	2	7.83	8.21	4.07	4.02	3.14	0.94
SG	3	6.31	8.71	3.28	4.27	2.52	0.75
HES	1	7.96	3.26	4.14	1.60	3.19	0.95
HES	2	3.69	4.14	1.92	2.03	1.48	0.44
HES	3	5.90	4.72	3.07	2.31	2.36	0.71
PTS	1	4.66	4.61	2.43	2.26	1.87	0.56
PTS	2	3.53	3.77	1.84	1.84	1.42	0.42
PTS	3	3.14	6.48	1.63	3.17	1.26	0.38
LAK	1	6.16	3.82	3.20	1.87	2.47	0.74
LAK	2	6.32	2.76	3.29	1.35	2.53	0.76
LAK	3	4.88	3.77	2.54	1.85	1.95	0.58
LEF	1	10.04	7.39	5.22	3.62	4.02	1.20
LEF	2	6.80	4.69	3.54	2.30	2.72	0.81
LEF	3	8.24	5.27	4.29	2.58	3.30	0.99
JOD	1	14.86	5.88	7.73	2.88	5.95	1.78
JOD	2	12.03	6.15	6.26	3.02	4.82	1.44
JOD	3	9.35	12.33	4.86	6.04	3.74	1.12
MTC	1	16.70	8.02	8.68	3.93	6.69	2.00
MTC	2	9.61	5.91	5.00	2.89	3.85	1.15
MTC	3	11.43	5.23	5.94	2.56	4.58	1.37
KIF	1	6.88	3.35	3.58	1.64	2.76	0.82
KIF	2	5.08	2.83	2.64	1.39	2.04	0.61

KIF	3	5.78	4.86	3.01	2.38	2.31	0.69
GOO	1	2.07	4.06	1.08	1.99	0.83	0.25
GOO	2	1.87	4.32	0.97	2.12	0.75	0.22
GOO	3	2.96	5.85	1.54	2.86	1.19	0.35
TID	1	2.68	6.54	1.40	3.20	1.07	0.32
TID	2	4.45	2.32	2.31	1.14	1.78	0.53
TID	3	8.10	6.79	4.21	3.33	3.24	0.97
LP	1	4.68	8.42	2.43	4.13	1.87	0.56
LP	2	2.73	3.63	1.42	1.78	1.09	0.33
LP	3	1.84	8.63	0.96	4.23	0.74	0.22
COT	1	2.47	4.01	1.29	1.96	0.99	0.30
COT	2	2.01	5.35	1.04	2.62	0.80	0.24
COT	3	3.48	12.12	1.81	5.94	1.39	0.42

Mean values were calculated using pseudo replicates for a given site/plot using measured datasets

Calculated values to insert into the FullCAM model

TABLE A4. SUMMARY OF CARBON EMITTED FOR 90 SIMULATIONS USING DATA FROM PRESCRIBED FIRES IN THREE SITES IN NEW SOUTH WALES AND THE AUSTRALIAN CAPITAL TERRITORY. CWD = COARSE WOODY DEBRIS.

Site name	Fuel component	± 10% variation	Carbon emitted (t C ha^{-1})
Haycock Trig	Bark	Lower	1.94
			1.95
			1.96
			1.97
			1.98
Haycock Trig	Bark	Upper	2.00
			2.01
			2.02
			2.03
			2.04
Haycock Trig	Litter	Lower	1.94
			1.95
			1.96
			1.97
			1.98
Haycock Trig	Litter	Upper	2.00
			2.01
			2.02
			2.03
			2.04
Haycock Trig	CWD	Lower	1.94
			1.95
			1.96
			1.97
			1.98
Haycock Trig	CWD	Upper	2.00
			2.01
			2.02
			2.03
			2.04
Joadja	Bark	Lower	8.02
			8.05
			8.08
			8.11
			8.14
Joadja	Bark	Upper	8.20
			8.23
			8.26
			8.28
			8.31
Joadja	Litter	Lower	7.79
			7.86
			7.94
			8.02
			8.09
Joadja	Litter	Upper	8.24
			8.32
			8.40

			8.47
			8.55
Joadja	CWD	Lower	7.94
			7.99
			8.03
			8.08
			8.12
Joadja	CWD	Upper	8.21
			8.26
			8.30
			8.35
			8.40
Lone Pine	Bark	Lower	4.75
			4.79
			4.84
			4.88
			4.92
Lone Pine	Bark	Upper	5.00
			5.04
			5.08
			5.13
			5.17
Lone Pine	Litter	Lower	4.84
			4.86
			4.89
			4.91
			4.94
Lone Pine	Litter	Upper	4.98
			5.01
			5.03
			5.06
			5.08
Lone Pine	CWD	Lower	4.85
			4.87
			4.89
			4.92
			4.94
Lone Pine	CWD	Upper	4.98
			5.00
			5.03
			5.05
			5.07

A5. SUMMARY OF THE LINEAR MIXED MODEL ANALYSIS

```
Linear mixed-effects model fit by REML
 Data: stacked_all
       AIC      BIC    logLik
  371.0246 389.1679 -179.5123

Random effects:
 Formula: ~1 | Source
        (Intercept)  Residual
StdDev:    1.441097 0.4776447

Fixed effects: Total_C_mass_emitted ~ Fire
                    Value Std.Error  DF    t-value p-value
(Intercept)      4.309696 0.2431052 114  17.727701       0
FireScenario_25 -2.343778 0.1081652 114 -21.668499       0
FireScenario_50 -1.562519 0.1081652 114 -14.445666       0
FireScenario_75 -0.781259 0.1081652 114  -7.222833       0
 Correlation:
                (Intr) FrS_25 FrS_50
FireScenario_25 -0.222
FireScenario_50 -0.222  0.500
FireScenario_75 -0.222  0.500  0.500

Standardized Within-Group Residuals:
         Min           Q1          Med           Q3          Max
-3.340618482 -0.402741244 -0.001257532  0.369200929  3.704903609

Number of Observations: 156
Number of Groups: 39
```