Measuring forest carbon and fire emission from southern *Eucalyptus* forests: key findings and some lessons learnt

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Abstract

Managing the frequency and intensity of planned burning in forests to reduce the risk of uncontrolled wildfire as well as maximize long-term carbon storage in biomass and soil is wholly dependent on a good understanding of the impacts of burning, across a range of intensities, on forest carbon density and carbon emissions to the atmosphere. Australia's current approach for estimating State and National fire-related emissions of greenhouse gases from forests is constrained by a limited knowledge of the mass of fuels consumed and emissions from major fuel type. To assist in addressing these gaps in knowledge we describe a methodology for measuring fire impact on each of the main categories of forest carbon and discuss key findings from application of the method across a wide range of eucalypt forests in south- eastern Australia. This forest fuels and emissions dataset clearly shows that coarse woody fuels, currently not included in fuel inventories, contribute significantly to emissions. We also suggest a range of sampling intensities to improve carbon emission estimates for each major fuel category and discuss the advantages of moving towards accounting for all fuels strata in fire and emissions management at a landscape scale.

Introduction

Planned burning, or deliberate application of fire under favourable conditions, is crucial for reducing the risk of large-scale and uncontrollable bushfires that can threaten people, towns and important assets such as water catchments and commercial plantations (McCaw 2013). There are good incentives for improving knowledge of fire impacts on fuels and forest carbon as a number of studies from around the globe, including from Northern Australia, have indicated considerable potential for emission mitigation using planned fires (e.g. Hurteau and North 2009; Vilén and Fernandes 2011). Emission reductions can be considered as arising from burning only under identified optimum conditions and through a reduction in the area of forest burnt in high intensity wildfires in the future. Because estimates of emissions from biomass burning in southeastern Australia vary widely, opinion is divided on the opportunity that planned fire presents for mitigating wildfire emissions in the longer term (e.g. Adams 2013) to against any likely carbon benefits of planned fire giving high rate of planned fires and relatively low reoccurrence of wildfires (Bradstock et al. 2012). These uncertainties point to the need for land managers to strengthen the mandate for planned burning in Australia's southern eucalypt forests.

Improving the scientific basis for fuel reduction burning requires better knowledge of fuels consumed and emissions from these fuels. Fire management agencies have developed estimates of fine (litter) and elevated (shrubs) fuels in forests as a basis for planned fire scheduling and for fire behavior modeling (e.g. Phoenix), yet knowledge of all fuel categories, including fallen trees and large branches, is currently lacking for southern eucalypt forests. To assess the effectiveness of prescribed burning and emissions from planned burning, the distribution of fuels among the entire fuel strata is required. We describe here a method applicable to both measuring the components of forest biomass that become fuels during planned burning, and for calculating emissions to the atmosphere from these fuels. The aim of this report is to relate our experience gained in applying this method, to identify data gaps in knowledge of fuels, and to suggest improvements to the current AGO (2008) method for estimating emissions from forest burning.

The current approach for estimating fire emission from forest fires

Currently Australia's national approach for estimating emissions is based on a generalized equation provided by AGO (2008):

$$E_{ij=}A * EF_{ij} * F * BE * \ M_{i} \qquad \text{(Eq. 1)}$$

Where E_{ij}- an emission for gas *ij*; *A*-area burnt, ha; EF_{ij}-emission factor for gas *ij* from vegetation (range from 0.0054 to 0.15 greenhouse gas dependent); *F*- fuel load, Mg C $^{-1}$; BE – burning efficiency (0.42 for planned fires and 0.72 for wildfires), M_{ij}-a conversion factor from elemental mass of species *ij* to molecular mass.

Each of the above parameters, except area burnt, is provided in the AGO methodology. Due to a lack of all fuels data, it is assumed that only fine fuels comprising dead organic material including sticks of a diameter less than 6 mm are burnt in planned fire (Tolhurst 1994a). An average fine fuel load for all forests in each State or Territory has been adopted, as shown in Figure 1 (adapted from Table 3 of AGO 2008). The AGO methodology assumes that coarse or heavy fuels only contribute to emission in wildfires, with allowance for this consumption in wildfire generally estimated as twice the fine fuel load (Tolhurst 1994a). These AGO-provided fuel loads cannot be verified in the published literature as they are based on information from State Agencies that likely reflects the experience and judgment of land managers and their operational research staff. For Australia to meet greenhouse gas emissions reporting against international treaties it is crucial that these fuel load estimates are updated with published and verifiable fuel consumption estimates. More accurate emission estimates require fuel load and emission factors that are refined for a range of forest types and burn intensities.

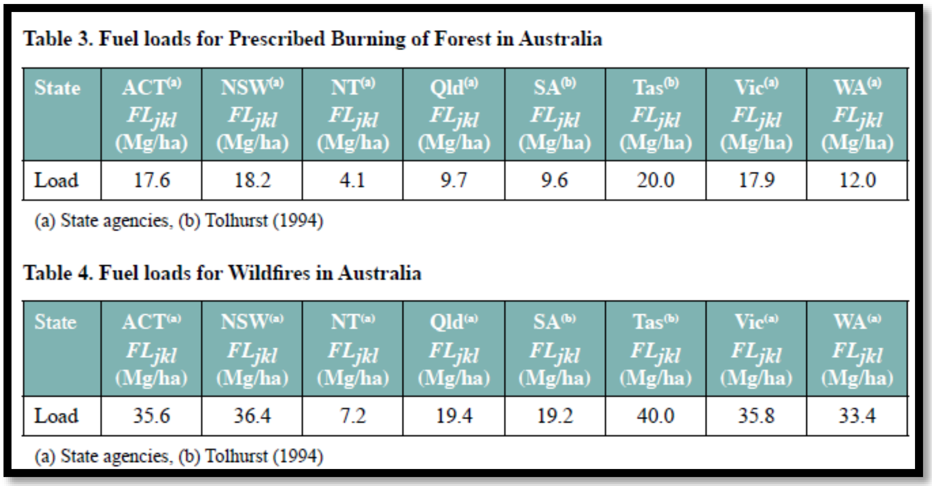

Table 3. Fuel loads for Prescribed Burning of Forest in Australia

State	ACT[a] FL_{jkl} (Mg/ha)	NSW[a] FL_{jkl} (Mg/ha)	NT[a] FL_{jkl} (Mg/ha)	Qld[a] FL_{jkl} (Mg/ha)	SA[b] FL_{jkl} (Mg/ha)	Tas[b] FL_{jkl} (Mg/ha)	Vic[a] FL_{jkl} (Mg/ha)	WA[a] FL_{jkl} (Mg/ha)
Load	17.6	18.2	4.1	9.7	9.6	20.0	17.9	12.0

(a) State agencies, (b) Tolhurst (1994)

Table 4. Fuel loads for Wildfires in Australia

State	ACT[a] FL_{jkl} (Mg/ha)	NSW[a] FL_{jkl} (Mg/ha)	NT[a] FL_{jkl} (Mg/ha)	Qld[a] FL_{jkl} (Mg/ha)	SA[b] FL_{jkl} (Mg/ha)	Tas[b] FL_{jkl} (Mg/ha)	Vic[a] FL_{jkl} (Mg/ha)	WA[a] FL_{jkl} (Mg/ha)
Load	35.6	36.4	7.2	19.4	19.2	40.0	35.8	33.4

(a) State agencies, (b) Tolhurst (1994)

Figure 1. A snap shot from the Australian methodology for estimating greenhouse gas emission and sinks 2006 providing fuel loads for each State and fire regime (from AGO 2008).

To demonstrate the opportunity to improve fuel load estimates we present three separate estimates for six forest sites in Figure 2, with a great variance amongst assessments of fuel loads: visual assessment (average 18 t/ha), a detailed field sampling (average 14t/ha) and the default value from the AGO (9.7 t/ha, Fig 2).

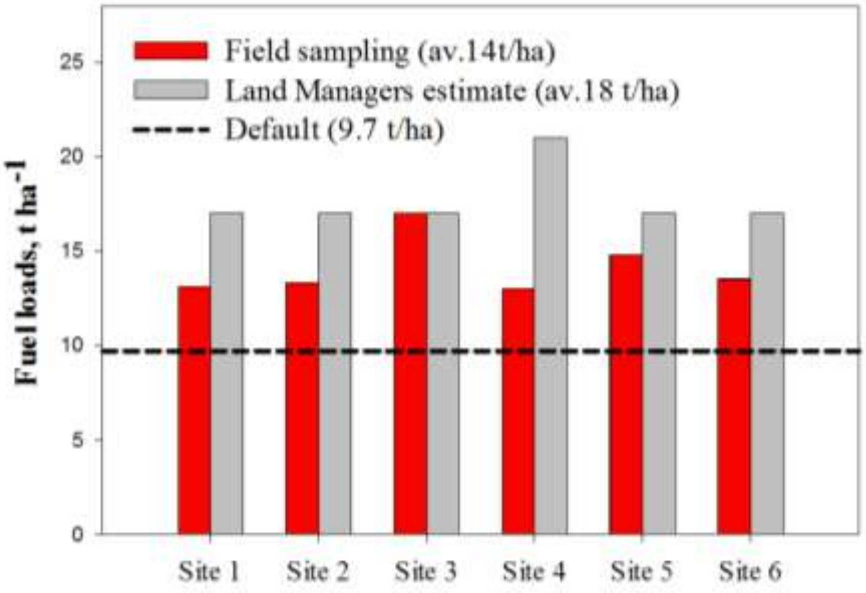

Figure 2. Fine fuel loads derived from field sampling (red bar), visual assessment by land management officer (grey bar) and default value for the State (dashed line from AGO 2008).

This example also highlights the opportunity for refining fuel loads by categorizing forest and vegetation types rather than relying on a single value for all forests across a State or Territory.

However, our main concern is that default fuel loads, which significantly influence State and National emission estimates, are not accessible or traceable in the literature. Evidence of climate change and the recognition that fuel loads are sensitive to rainfall and temperature (Matthews et al. 2012) is a further reason for improving fuel load estimates and for maintaining a rolling inventory of them to ensure accurate information for a range of purposes from fire emergency response to emissions estimates. We believe that up-to-date information on all forest fuels, derived from repeatable and transparent methodologies, is required for a range of forest types for realistically estimating fire emission and impacts on forest carbon.

We also question why only fine fuels were considered for planned fire emission estimates. Since the 1980s the literature has shown that other fuels including elevated bark, ground cover, understorey, snags and coarse woody debris are also affected by fire (e.g. Bennett et al. 2013; North and Hurteau 2011; Raison et al. 1985; Tolhurst 1994b) so that excluding those from fuel loads leads to potential significant underestimation of fire emission (Volkova and Weston 2013). Our research has found as fire intensity increases, loss from other, non-fine fuels, also increases, thus greater underestimation of emission can be from wildfires than planned fires (Volkova et al, in submission). To understand the impact of fire on forest fuels and released emission requires a field studies in a diverse range of forests where planned burning is practiced. However, the focus of recent fire-carbon research in southern Australia has been in wet sclerophyll forests where routine planned burning is not practiced (e.g. Benyon and Lane 2013; Simkin and Baker 2008). While these estimates of fire impact on forest carbon help to set the upper limit for emissions from eucalypt forests, they are of limited use for land managers responsible for planned fire operations.

Methodology and pitfalls in measuring forest carbon

We have developed, tested and improved a sampling protocol designed to accurately estimate fire impact on forest fuels in routinely burnt, open forest of *Eucalyptus* in southeastern Australia. We devised the sampling protocol based on the best advice available in technical reports developed by the Australian Greenhouse Office (e.g. Snowdon et al. 2002) in combination with our experience in forest carbon and biomass studies (Bennett et al. 1997; O’Brien at al. 2002; Bauhus et al. 2002). Given that fire impacts on all forest biomass components include duff and soil had not been measured before in Australia, we chose among a diverse range of approaches before settling on the survey protocol described here. Since developing the protocol we have been approached by a number of researchers and land management agencies seeking to implement the protocol to measure fire impacts on carbon stocks. Therefore we believe that describing our methodology along with lessons learnt will benefit agencies interested in measuring fire impacts on forest fuels. Although we have published an outline of the sampling protocol in reporting fire impacts on carbon density and emissions (Volkova and Weston 2013), our intention here is to provide greater details on the development of the protocol and commentary on its application in a wide range of forests.

After considering all published methodologies on assessing forest fuels and carbon at the time, e.g. fuel hazard assessment guide (Hines et al. 2010) and technical reports by Greenhouse

Office (2010, http://www.greenhouse.gov.au/ncas), we adapted a definition of forest carbon categories from the Intergovernmental Panel on Climate Change (IPCC 2004), and from now on will refer to forest fuels as forest carbon pools.
According to the IPCC (2004), forest biomass is divided into five carbon pools:

1) Aboveground alive
2) Deadwood
3) Litter
4) Soil organic carbon
5) Belowground biomass (live roots, not included when fire effect on forest carbon is estimated)

We measured forest carbon as four aboveground pools within circular sampling plots of 22.5 m radius (Fig.2). We prefer circular plots as they are quick and simple to set up and once center point is marked with a metal peg and its coordinates recorded, plot boundaries can be reconstructed years after if required. To estimate carbon loss, it is necessary to re-measure the same carbon pools afterwards and based on the difference, estimate fire emission from equation 1 accounting for carbon re-distribution.

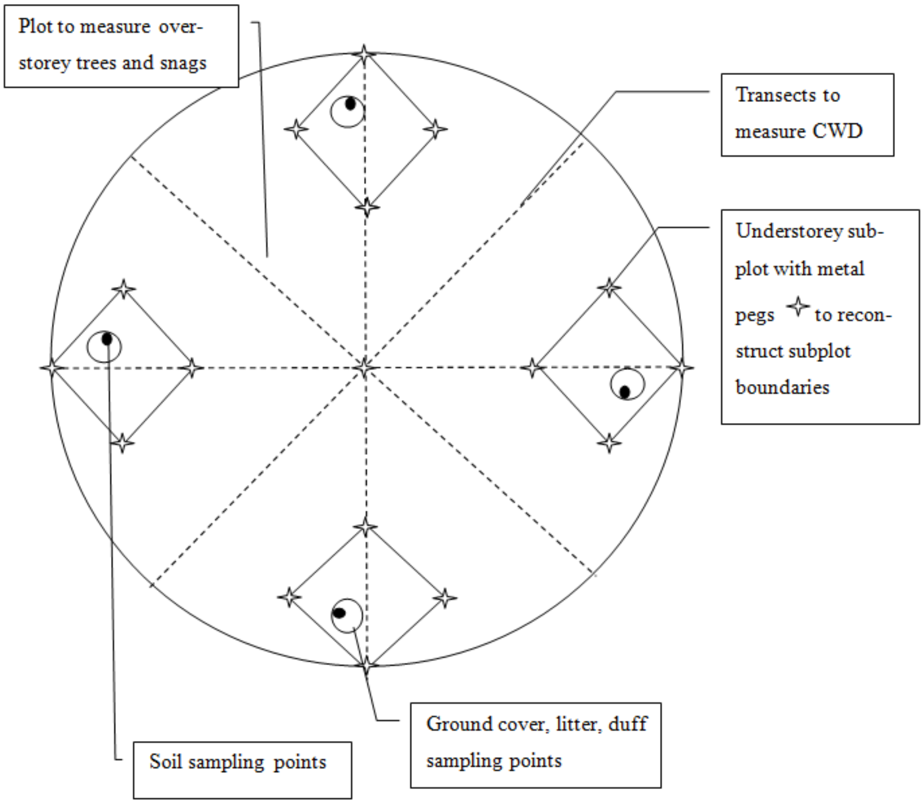

Figure 2. Circular sampling plot of 22.5 m radius to measure forest carbon pools Where ✧ indicates permanent metal pegs to reconstruct boundaries of a plot and subplots

Aboveground alive, i.e. all living biomass above the soil consist of (1) overstorey, (2) understorey and (3) ground cover. Overstorey trees can account for the half of total forest carbon to 30 cm soil depth in the southeastern *Eucalyptus* forest (based on our field data across

60 sites). Each overstorey tree should be measured at least for diameter at breast height (1.3 m) and if possible for height. Tree biomass can be estimated either from species-specific allometric equations or from a geometric equation by estimating tree volume multiplied by wood density and a conversion factor to convert stemwood biomass to aboveground biomass. Allometric equations have been developed for particular species using destructive sampling, and logically those estimates should be comparable regardless of the equation used. We caution that biomass estimates vary considerably depending on the allometric equation selected. For example, we estimated biomass for *E. obliqua* based on diameter and height measurements for >300 trees and biomass numbers varied from 145 t ha^{-1} to double this number to 357 t ha^{-1} (Table 1) depending on the equation adopted. Therefore, one should be careful when estimating biomass or comparing results with published data. For our estimates we use Bi et al. (2004), where authors reviewed 27 equations for *E. obliqua* and came up with an additive allometric equation that eliminates the inconsistency between the sum of predicted values for components such as stem, bark, branch and leaf and the prediction for the total tree (see Bi et al. 2004).

Table 1. Biomass of overstorey tree species *E.obliqua* calculated by a number of published equations.

Method to calculate biomass	Input values	AGB, t/ha	Reference
Geometric equations (stemwood volume * wood density * *e*)	DBHOB, Height	357	Snowdon et al. (2002)
Generic equation, 1/3 BA * 1.12	DBHOB, Height	366	Whiteman (1988)
Allometric equation for *E. obliqua*	DBHOB	241	Adams and Attiwill (1988)
Allometric equation for *E. obliqua*	DBHOB, Height	254	Attiwill (1966)
Allometric equation for *E. obliqua*	DBHOB, Height	145	Feller (1980)
Additive allometric equation for *E. obliqua*	DBHOB	251	Bi et al. (2004)

Where: *e*, conversion factor; DBHOB, Diameter at Breath Height Over Bark; BA, Basal Area

Bark of live overstorey trees is the most affected carbon pool of live trees during fire (Tolhurst 1994b). Loss in bark should be estimated as difference between tree biomass before fire and after fire, the latter is estimated as following:

$$M(kg) = \left(\exp(-1.870)\, {d_1}_i^{2.218}\right) + \left(\exp(-1.360)\, {d_2}_i^{1.598}\right) + (\exp(-9.399)\, {d_1}_i^{3.629}) + (\exp(-5.760)\, {d_1}_i^{2.326}) \qquad \text{(Eq.2)}$$

Where ${d_1}_i$ is a diameter of a tree *i* before fire and ${d_2}_i$ diameter of the same tree after fire. Equation 2 is modified from Bi et al., (2004)

Understorey biomass (i.e. small trees and shrubs) can account for 6% of total forest biomass (based on average values from our dataset, in submission). Our research showed that understorey can be significantly affected by fire and should not be disregarded during emission estimates (as in the case of AGO 2008). Due to the potential for sampling high numbers of understorey plants in a 22.5 m circular plot, they need to be measured in smaller subplots. Their biomass can be estimated by applying the same allometric equations as overstorey, providing that trees (>5cm in diameter) are measured for diameter, while shrubs need to be destructively sampled. In our research we adopted small, 5 m radius circular, subplots established at the north, east, west and south end points of 22.5 m plot, resulting in 0.006 ha of measuring area. The difficulty was to clearly identify the boundaries of the subplot and determine understorey within the boundaries as the change in understory from pre- to post-burning can significantly affect carbon loss estimate in this pool. To avoid this, we suggest that each understorey subplot is marked with permanent metal pegs in its center and at the end points; stretching ropes between end points will make subplot boundaries visual (Fig. 2).

Ground cover of the surface vegetative layer (grasses and shrubs <0.5 m height) can account for 1% of total forest carbon and our laboratory analysis showed that its high in nitrogen, so it plays an important role when estimating N_2O emission. Ground cover can be easily estimated from destructive sampling using 0.5-1 m^2 frames.

Deadwood biomass includes dead standing trees (snags) and coarse woody debris (CWD) on the forest floor. Based on our field data, this carbon pool on average accounts for 9% of total forest carbon in south-eastern *Eucalyptus* forest and can be significantly affected by fire, its loss increases in wildfires (our data in submission; North and Hurteau 2011). Because deadwood biomass mainly burnt in smoldering combustion dominated by CO and CH_4 (Andreae and Merlet 2001), emission from this pool can be several times higher than emission from litter and ground cover that is mainly burnt in flaming combustion. The biomass of snags can be calculated using the same allometric equation, and we suggest that snag properties such as branch number and % rotten wood be noted to enable more accurate estimation of its biomass (e.g. by excluding foliage or branch components from the allometric equation).

The mass of coarse woody debris (CWD) with diameter ≥2.5 cm is commonly estimated by a line intersect method (van Wagner 1968) well-described elsewhere (e.g. Gould and Cruz 2012). Due to great variability in CWD numbers and branches fallen down during fires, the number of transects should be relatively large to assess effect of fire on this carbon pool (Table 2). In our field measurements we used diagonal transects of the plot as line transects, resulting in 8 x 22.5 m total transect length (Fig. 2), though trees that fall during the fire can make it difficult to measure CWD obscured beneath them.

Table 2. Number of plots required to detect 50%, 25% or 10% change in deadwood biomass with a probability ≥ 90% (modified from Volkova and Weston 2013).

Deadwood carbon pool	Minimal number of plots required		
	50% change	25% change	10% change
Snags	3	3	6
Coarse woody debris	8	23	131

Litter biomass can account for up to 4% of forest carbon (based on our field data, in submission) and includes dead plant material such as fruits, leaves, bark, and small branches (<2.5 cm) on the forest floor. Often the terms litter and fine fuels are used interchangeably, though fine fuels exclude sticks >0.6 cm diameter (Tolhurst 1994a). Our field sampling of litter in foothill forests of Victoria showed that those sticks can account for about 30% of litter loads and they are best separated from finer litter at the point of collection.

Soil organic carbon includes soil surface organic materials intimately mixed with soil mineral components, referred to as duff, and organic matter in soil to 30 cm depth. Our field data from 60 sites across 5 States of south-eastern Australia showed that duff ranges from being absent through to accounting for up to 10% of forest carbon. Prior to burning, duff can be difficult to separate from litter and from mineral soil. After fire fragmented and charred forest components, including litter and aboveground biomass, are deposited on the duff layer or soil surface. We chose to sample these materials as duff after fire to allow for describing changes in the nature and decomposability of surface organic materials (Volkova and Weston 2013). We recommend characterizing surface soil carbon using durable metal frames of known area as shown in Fig 3, so the fate of charred organic material can be properly accounted after burning.

To estimate loss of litter and duff after fire, the forest plot must be assessed for patchiness of the burn so loads of unburnt litter and duff can be calculated. In burnt patches, the surface of the forest floor needs to scraped and later sieved to soil, charcoal and unburnt organic matter. Depending on fire intensity, production of charcoal can account for 3 to 20% of aboveground carbon (based on field data, Volkova at el, in submission) that is important to account in emission estimates. Charcoal is often viewed as an important carbon sink because it can remain in the soil for decades, centuries and millennia due to its resistance to decomposition (Preston and Schmidt 2006).

Soil to 30cm depth is generally the second biggest carbon pool in the forest (up to 40+% of forest carbon, e.g. Grierson et al., 1991) and stores carbon semi-permanently (millennia), in contrast to trees where carbon is released back to the atmosphere during decay over decades and centuries (Adams and Attiwill 2011). To properly assess soil carbon the soil bulk density must also be accurately measured using well-engineered soil volumetric sampling equipment because forest soils can be hard, stony or even rocky; this equipment is usually expensive (up to AU$6000, Fig 3)

Figure 3. Heavy duty square sampling frame, soil bulk density corer and extraction handle developed for accurate sampling of forest floor carbon before and after fire.

Concluding remarks

Given the variability in forest fuels and burn conditions, further empirical measurements will significantly improve model estimates of forest carbon and emissions. The provision of more robust and accurate fuel estimates will also improve fire behaviour prediction and fire-risk reduction decisions. There is good scope to establish a systematic forest fuels inventory that can service these key aspects of public safety and land management and that demonstrates that Australia is addressing this challenging aspect of climate change. With clear evidence for a rising occurrence of wildfires in southern Australia (Liu et al. 2010) and the need to manage wildfire risk with planned fire, managers need access to accurate and up-to-date fuel assessments. These fuel assessments need to be verifiable and encompass the entire fuel strata.

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