Improving reporting of national greenhouse gas emissions from forest fires for emission reduction benefits: an example from Australia

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Abstract

Forest fires are a significant contributor to global greenhouse gas (GHG) emissions. Accurate reporting of GHG emissions from forest fires requires development of detailed methodologies and country specific data for estimating emissions. In recent years, Australia has updated its national methodology for reporting GHG emissions from fires on temperate forested lands, using a Tier 2 approach of the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories. This involved refinement of the equation for estimating GHG emissions from fires provided in the Guidance, and the revision of country specific data which was derived from a comprehensive literature review. The refinements were key to transparent reporting and evaluation of the climatic impacts of mitigation actions such as forest fire management. In this paper we describe the steps required to develop a Tier 2 method in reporting fire emissions using this Australian example, the lessons learnt, and the steps required to reduce uncertainties in estimates. This paper may assist other countries seeking to estimate and report GHG emissions from forest fires by moving from the default Tier 1 method to Tier 2 using country-specific information.

23 *Keywords:* forest policy, REDD+, result based payments; forest management, forest fuels, CO2
24 recovery

25

26 **1. Introduction**

27 At the 2015 international climate summit in Paris, Parties to the United Nations Framework
28 Convention on Climate Change (UNFCCC) agreed to the goals of limiting global warming below
29 2°C, and to pursue efforts to further limit temperature increase to 1.5 degrees Celsius. Parties
30 agreed to design the rules and procedures to achieve those goals, to put the world on track to avoid
31 dangerous climate change (UNFCCC, 2015). Under the new agreement, all countries, with
32 flexibility for less developed countries, are expected to contribute to global climate mitigation by
33 achieving nationally determined contributions (NDC). This includes the requirement that all Parties
34 report regularly on their national emissions and implementation efforts for emissions reduction,
35 following the IPCC guidelines.

36 Over the last twenty years an average of 2.2 Pg C y⁻¹, or about 25% of global GHG emissions, has
37 been emitted to the atmosphere from biomass burning from the agricultural, forest and other land
38 use sector [AFOLU] (UNFCCC, 2017; van der Werf et al., 2017). Biomass burning releases into the
39 atmosphere large amounts of carbon dioxide, black carbon and trace gases, including important
40 GHGs such as nitrogen oxides and methane (Andreae and Merlet, 2001). Fires are the largest global
41 source of primary carbonaceous aerosol emission, and along with other emissions affect radiation
42 forcing, air quality and climate on regional and global scales (Li et al., 2018; Ward et al., 2012).

43 To estimate both CO₂ and non-CO₂ emissions from biomass burning, including from forest fires, the
44 IPCC provides a three-Tier approach encompassing simple to more complex methodologies. The
45 Tier 1 approach applies an emission estimation equation (described below) that draws on default
46 data provided in the IPCC Guidance. Under Tier 1, emission from dead organic matter (DOM) is
47 assumed to be zero in forests that are burnt, but not killed by fire; in forests killed by fire, carbon
48 (C) contained in the killed biomass is assumed to be immediately released to the atmosphere,
49 potentially leading to overestimation of actual emission. This is in contrast to the Tier 2 approach
50 that includes a more refined application of the emission equation based on country-specific data and
51 a more complex accounting for the dynamics of DOM. Typically a Tier 3 approach considers all
52 fuel dynamics and thus relies on sophisticated modelling that draws on reasonably detailed country-
53 specific datasets (IPCC 2006).

54 A wide range of approaches for estimating GHG emissions from forest fires have been developed
55 by national and state jurisdictions around the world. Where forest fires are nearly absent or a minor
56 contributor to a country's total emissions, a Tier 1 approach is usually applied. If forest fires
57 become a significant source of GHG emissions or a 'key category' (IPCC, 2006a), the development
58 of a more refined approach (Tier 2 or 3) is recommended. Forest fires from tropical regions of
59 South America, Africa and Asia are global hotspots for fire emissions (Roman-Cuesta et al., 2016).
60 However, the financial and technical constraints relating to collection of country-specific data for
61 GHG inventories in these regions means that, commonly, reporting is conducted using a Tier 1
62 approach, severely limiting the ability to demonstrate mitigation actions to reduce emissions from
63 forest fires. For example, in the eucalypt-dominated woodland savanna of northern Australia, it was
64 possible to reduce emissions by promoting patchy and less intense fires early in the dry season to
65 reduce overall fire frequency and fire severity of late dry season fires (Cook and Meyer, 2009;
66 Russell-Smith et al., 2009a; Russell-Smith et al., 2009b). This reduction in fire frequency and fire
67 severity decreased overall burnt area, and amount of fuels burnt in fires - key factors influencing
68 fire emissions estimates. A regionally stratified country-specific accounting methodology applicable
69 to northern Australia has been developed allowing to demonstration of emission mitigation benefits
70 of altered fire management (Russell-Smith et al., 2009b).

71 Assessing and reporting the effect of mitigation actions may be of specific interest for countries
72 who seek to, or already participate in REDD+ (Reducing Emission from Deforestation and forest
73 Degradation, the sustainable management of forests, the enhancement of forest carbon stocks and
74 the role of conservation in developing countries). Currently, sixty or so countries are participating in
75 REDD+ (<http://www.un-redd.org/partner-countries>, accessed April 2018). REDD+ has been
76 negotiated under UNFCCC to encourage developing countries to contribute to climate change
77 mitigation by voluntarily undertaking REDD+ activities which may be rewarded with results-based
78 payments [RBP] (UNFCCC, 2005). To access RBP, participating countries must submit a Forest
79 Reference (Emission) Level (FREL/FRL) to UNFCCC, and report measured results assessed
80 against this FREL/FRL included in a technical annex to the Biennial Update Report (FAO, 2015;
81 UNFCCC, 2013). Because forest fire is a significant contributor to national GHG emissions in
82 many countries participating in REDD+ (e.g. Zambia and Indonesia), these countries have been
83 advised to include emissions estimates from forest fires in future FREL/FRLs (UNFCCC, 2016;
84 Zambia, 2016). Due to the complexity of IPCC terminology and methodologies for reporting
85 emissions, many countries have been reluctant to move from a Tier 1 approach to adopt more
86 sophisticated and potentially beneficial approaches (Tiers 2 and 3), because of a common
87 perception that complex models are required to do so.

88 Here we share our experiences and explain the emission calculations involved in refining country-
89 specific data for Australia, an example of a Tier 2 approach. This study aims to provide a roadmap
90 following IPCC Guidelines to establish a Tier 2 approach for estimating GHG emissions from
91 forest fires. A further objective is to highlight and discuss insights, gained during the process of
92 refining a Tier 2 approach, that may be of assistance for countries aspiring to include fire
93 management practices as a part of their mitigation actions.

94 As a part of its annual national GHG inventory submission to UNFCCC, estimates of fire emissions
95 were updated in Australia's 2016 GHG inventory based on the work described here. Although
96 Australia intends to move to a Tier 3 approach for emissions reporting through a refinement of the
97 forest fire module of its Full Carbon Accounting Model [FullCAM] (Richards and Brack, 2004;
98 Richards, 2001), the data and methods presented and discussed in this study are currently used in its
99 National Inventory System (NIS) for national and international reporting. Australia's NIS estimates
100 emissions from forest fires (wildfires and prescribed burning) on managed lands by jurisdictional
101 State based on changes in fuel loads. The methodology refinement presented here also adopts more
102 complex dynamics for estimating DOM, replacing a simple linear recovery applied previously.

103 **1.1. Estimating non-CO₂ emissions from forest fires**

104 The IPCC provides a generic methodology to estimate CO₂ and non-CO₂ emissions for any type of
105 fire in the form of Equation 2.27 in the 2006 IPCC guidelines for GHG inventories (IPCC 2006):

$$106 \quad E_i = A \cdot M \cdot CF \cdot EF_i \cdot 10^{-3} \quad \text{Eq. (1)}$$

107 Where: E_i is emission for the i^{th} GHG (Gg); A is the area burnt by the fire (ha); M is mass of fuel
108 available for combustion (tonnes ha⁻¹); CF is the combustion factor; EF_i is the emission factor for
109 the i^{th} GHG (g kg⁻¹ dry matter burnt); and 10^{-3} is a unit conversion factor. The GHGs, i , are CO₂,
110 CO, CH₄, N₂O, NO_x and VOC (volatile organic compounds).

111 To calculate CO₂ equivalent emissions (CO₂-e), the emission of each individual GHG is multiplied
112 by its global warming potential (GWP), (Table 1, UNFCCC 2014).

113 **Area burnt (A) and fire patchiness** - A is the land area affected by fire as defined by the outer
114 boundary of the fire scar. Commonly, but not invariably, this is measured by satellite remote
115 sensing such as LANDSAT or MODIS. However, fire is spatially heterogeneous. Fire seasonality,
116 vegetation type, topography, fuel moisture and age, all influence intensity and propagation of fires
117 leaving patches of unburnt land (Slocum et al., 2003) within the fire boundary. The fire patchiness
118 parameter (P) is the proportion of area burnt within the boundary of a fire scar. Patchiness is not
119 considered in Tier 1 approaches, yet it can significantly contribute to the final emissions estimates.

120 P varies with fire type, intensity and other parameters and can be derived from ground based
 121 observations (Russell-Smith et al., 2009a), analysis of high-resolution digital aerial photography
 122 (McCarthy et al., 2017), estimated from remotely sensed data (Cruz et al., 2012) or by modelling
 123 combined with digital imagery analysis (Gill et al., 2003).

124 **Mass of fuel available for combustion (M)** - this parameter refers to standing live biomass and
 125 DOM such as litter and dead wood. M varies according to vegetation class, fuel type and fuel age.

126 **Combustion Factor (CF)** - is defined as the fuel mass combusted during a fire, divided by the pre-
 127 burn fuel mass, and is reported on a dry matter basis. The calculation of CF requires estimates of
 128 fuel load before (M_{BF}) and after fire (M_{AF}). CF also varies with vegetation type, seasonality and
 129 fuel type.

130 **Emission Factor (EF)** - is the mass of a particular GHG emitted per unit of dry matter combusted.
 131 EF depends on combustion completeness and is therefore fuel-type dependent. Fine fuels such as
 132 litter and grass are usually burnt in flaming combustion which produces a range of simple highly
 133 oxidised molecules including CO_2 , H_2O , NO , NO_2 and SO_2 . Coarser fuel elements such as coarse
 134 woody debris (CWD) are usually burnt by smouldering combustion, releasing a greater proportion
 135 of partially oxidised carbon such as CO , CH_4 and other organic compounds (VOCs and
 136 particulates), than is the case for fine fuel (Andreae and Merlet, 2001). Smoke samples, required to
 137 derive EF s, can be collected using a variety of methods: from the ground near the source of the
 138 emissions (Meyer et al., 2012), from a light aircraft flying in close proximity above the fires (Hurst
 139 et al., 1994), or using various types of portable infrared spectrometers (Gurette et al., 2018;
 140 Stockwell et al., 2016).

141

142 Some typical examples of vegetation, fire and fuel types for a wide range of forest types around the
 143 world are given in Table 1.

144 *Table 1. Symbols used in algorithms for estimating emissions from forest fires*

Vegetation type (v)	Fire type (k)	Fuel type (m)	GHG (i)
Forest, Woodland, Grassland, Shrubland	Wildfire, Planned fire	Fine (i.e. litter, grasses, pine needles); Coarse (6 mm-50 mm); Heavy (>50 mm); Elevated (live herbs and shrubs).	CO_2 , CH_4 , N_2O

Equation 1 (Tier 1) can be extended by the inclusion of the patchiness parameter (P) and stratified by vegetation type (v), fire class (k) and fuel size class (m) to produce a Tier 2 approach:

$$E_i = \sum_{v,k,m} (A_{v,k} \cdot P_{v,k} \cdot M_{v,m} \cdot CF_{v,k,m} \cdot EF_{i,m}) \cdot 10^{-3} \quad \text{Eq. (2)}$$

A non-IPCC variant of equation 2 is often applied when emission factors are measured in molar units (i.e. moles of GHG i emitted per mole of fuel carbon burnt). In this form, E'_i (where $i = \text{CO}_2$, CO, CH₄ and the volatile organic compounds VOC) is in units Gg of carbon not Gg of GHG i . The advantage of this form of the equation is that EF in molar units is equal to the emission ratio which can be calculated directly from field observations (see Meyer et al., 2012).

$$E'_i = \sum_{v,k,m} (A_{v,k} \cdot P_{v,k} \cdot M_{v,m} \cdot CF_{v,k,m} \cdot CC_m \cdot EF'_{i,m}) \cdot 10^{-3} \quad \text{Eq. (3)}$$

Where CC is the carbon content of a fuel. For many fuel types, CC can be approximated to 0.5 with reasonable accuracy (Yokelson et al., 1999).

For the nitrogen gases, the nitrogen to carbon mass fraction, NC, is also required

$$E'_i = \sum_{v,k,m} (A_{v,k} \cdot P_{v,k} \cdot M_{v,m} \cdot CF_{v,k,m} \cdot CC_m \cdot NC_{v,k,m} \cdot EF'_{i,m}) \cdot 10^{-3} \quad \text{Eq. (4)}$$

Molar emissions are converted to mass emissions by the molecular to elemental mass ratio.

For CO₂,

$$E_{CO_2} = \left(\frac{44}{12}\right) \cdot E'_{CO_2} \quad \text{Eq. (5)}$$

for CH₄,

$$E_{CH_4} = \left(\frac{16}{12}\right) \cdot E'_{CH_4} \quad \text{Eq. (6)}$$

and for N₂O

$$E_{N_2O} = \left(\frac{44}{28}\right) \cdot E'_{N_2O} \quad \text{Eq. (7)}$$

1.2. Estimating CO₂ emissions - accounting for the dynamics of dead organic matter (DOM)

Apart from losses of live biomass due to fire, a Tier 1 approach assumes that the ecosystem is in equilibrium so that CO₂ emitted by combustion is ultimately re-assimilated into new biomass with no net loss of CO₂ from the biosphere to the atmosphere. Because Tier 2 methods allow for refinements to this assumption, to progress from Tier 1 to Tier 2 and explicitly account for the annual net CO₂ emission resulting from fire emissions with subsequent re-assimilation, they account

176 for the dynamics of DOM. CO₂ emission can be calculated either using the emission method
177 described above (Eq. 5), also called “flux method”, or by a mass balance method. The mass balance
178 approach was implemented for savanna fire emissions in Australia’s NIR for 2015 (NIR, 2015)
179 using the equation 2.18 of the IPCC guidance (IPCC, 2006b).

180 The annual mass balance method can be simplified to a linear recovery of CO₂ over a certain
181 number of years (red dash line, Fig. 1) or estimated as a more realistic recovery which is often
182 approximated by an ‘Olson’ curve (Olson, 1963), a traditional exponential decay model widely used
183 in ecological studies (solid black line, Fig 1).

184 The ‘Olson’ curve is defined as:

$$185 \quad X_t = X_{SS} \cdot (1 - e^{-kt}) \quad \text{Eq. (8)}$$

186 Where: X_t is the fuel load at time t (tonnes ha⁻¹); X_{SS} is steady state of fuel loads in the absence of
187 fire = $\frac{L}{k}$ (tonnes ha⁻¹); L is the rate of litterfall (tonnes ha⁻¹ year⁻¹); k is the decomposition constant,
188 assuming exponential decay; t is time since fire (years).

189 Modification to the fuel recovery function can be made to allow for fuels not consumed during fire
190 (Birk and Simpson, 1980; Fox et al., 1979), so that fuel recovery does not usually commence from a
191 post-fire fuel load of zero (solid dash line, Fig. 1):

$$192 \quad X_t = X_{SS} \cdot (1 - e^{-kt}) + X_i e^{-kt} \quad \text{Eq. (9)}$$

193 Where: X_i is the initial post-fire fuel load remaining, assuming the combustion factor was not
194 100%.

195 Dynamics of the DOM can be also estimated using either a gain-loss approach developed for
196 northern Australian savannas (Cook et al., 2016) or by other models with varying degrees of
197 complexity (Cornwell and Weedon, 2014).

198

199 *Figure 1. Estimating recovery of dead organic matter (DOM) using the mass balance method.*

200 **2. Australian case study**

201 **2.1. Area burnt (A) and fire patchiness**

202 Currently, Australia's NIR sources the fire area for savanna, arid rangelands and temperate forest
 203 from NOAA-AVHRR satellite imagery. This data product is prepared by Landgate, WA (Landgate,
 204 n.d.) with 1 km² resolution and continental extent across Australia (Fisher and Edwards, 2015).
 205 NOAA-AVHRR cannot detect fires that do not damage the canopy such as low intensity prescribed
 206 burns, unless canopy cover is less than 30%. The area of these fires is sourced from fire agency
 207 databases. Due to lack of more recent research on patchiness for Australian temperate forests, *P* was
 208 not updated for this revision and the previous values of 0.65 for prescribed burning and 0.8 for
 209 wildfires were retained (Tolhurst, 1994).

210 **2.2. Mass of fuel available for combustion (M)**

211 Prior to 2015 Australia's NIR included litter fuels, derived from a combination of field
 212 measurements and literature review, and did not include dead wood fuels or coarse woody debris
 213 (CWD). The pre-2015 FMRL method assumed that prescribed burning only affected litter (fine
 214 litter, fruits and twigs < 6 mm including the well decomposed duff layer). To estimate wildfire
 215 emissions, these litter loads were doubled as a way to account for consumption of CWD. These

assumptions were based on the fact that litter carries the spread of fire and because there was a paucity of CWD data (Tolhurst, 1994).

This current revision includes both litter and CWD fuels based on comprehensive field sampling across the States (see Appendix 1 for the data sources). To maintain consistency with previously established fuel classes, we retained the definition of litter fuels, while twigs with diameter 6 – 25 mm were added to the CWD pool, the latter now comprises all woody fuels with diameter ≥ 6 mm.

To better reflect fuel loads specific for a vegetation class, another improvement was introduced in the methodology which involved the separation of fuel loads into two vegetation classes: 1) woodlands (forests with a canopy tree cover ranging from 20% to less than 50%), and 2) forests (canopy tree cover greater than 50%) (Table A.1). Although it would be advantageous to retain the forests and woodlands separation throughout all calculations, there was insufficient data to support separate forest and woodland estimates for other components of the calculation, specifically the emission factors (EF) and combustion factors (CF). To address this data gap the spatial distribution of forests and woodlands was used to derive total fuel loads for each State (Table 2); details of the data and estimates are given in Appendix 1.

233 **Table 2:** Recommended fuel loads ($t\ ha^{-1}$) and (standard deviation) for each State and vegetation
234 class

State	Vegetation class				Combined	
	Forest		Woodland			
	Litter < 6 mm	CWD ≥ 6 mm	Litter < 6 mm	CWD ≥ 6 mm	Litter < 6 mm	CWD ≥ 6 mm
	(M_Litter _{Forest})	(M_CWD _{Forest})	(M_Litter _{Woodland})	(M_CWD _{Woodland})	(M_Litter)	(M_CWD)
ACT	9.1 (8.5)	27.6 (42.4)	5.1 (4.9)	13.9 (21.2)	8.0 (6.3)	23.7 (31.0)
NSW	13.8 (8.0)	56.4 (42.6)	12.6 (6.2)	16.0 (20.2)	13.4 (5.6)	41.9 (28.3)
QLD	15.7 (4.4)	25.6 (16.7)	13.0 (5.7)	35.2 (36.5)	14.5 (3.6)	30.1 (19.3)
SA	9.6 (7.6)	10.4 (8.7)	7.4 (5.8)	11.5 (12.4)	7.4 (5.6)	11.4 (12.0)
TAS	8.6 (3.1)	13.7 (12.0)	8.8 (3.2)	15.5 (14.0)	8.8 (2.3)	14.9 (9.9)
VIC	13.0 (8.5)	37.8 (42.2)	9.6 (5.8)	15.3 (27.3)	12.2 (6.7)	32.5 (33.0)
WA	20.2	72.7	7.1	20.5	11.8	39.3

236 **2.3. Combustion Factor (CF)**

237 Despite decades-long research into bushfire fuels, there are few empirical CF data reported for
238 Australian temperate forests. The dataset (Appendix 2, Table A.5) was dominated by combustion
239 factors for prescribed burning (n=93) rather than wildfire (n=8). The dataset was also dominated by
240 studies of litter combustion (n=62) rather than CWD combustion (n=39), with more data available
241 for some States (e.g. Victoria) than the others (e.g. Tasmania, SA, Table A.5), preventing separation
242 by jurisdiction or vegetation class. The revised CF are presented in Table 3, with details of the
243 analysis presented in Appendix 2 (Table A.5).

244 *Table 3. Combustion factors for litter and CWD fuels from prescribed burning and wildfires in*
 245 *Australia.*

Fuel type	Prescribed burning	Wildfire
Litter	0.6	0.9
CWD	0.3	0.5

246

247 **2.4. Emission factor (EF)**

248 The emission factors relevant for Australian national fire emissions calculations are methane (CH₄)
 249 and nitrous oxide (N₂O). These have been extensively investigated for Australia’s savanna region
 250 and reviewed in depth in Meyer and Cook (2015) for high and low rainfall regions of the savanna
 251 woodlands. While there has been some activity in southern Australian forests, the data set is less
 252 extensive (Table A.6). Details of the calculations, analysis and available data are presented in
 253 Appendix 3, with final EFs for litter and CWD fuels presented in Table 4.

254 *Table 4: Recommended Emission Factors for litter and CWD fuels*

Parameter	Litter <6mm	CWD ≥ 6mm
CH ₄ emission factor g kg ⁻¹ d.m (EF_CH ₄ Litter, EF_CH ₄ CWD)	0.90	10.9
N ₂ O emission factor g kg ⁻¹ d.m (EF_N ₂ O Litter, EF_N ₂ O CWD)	0.072	0.038

255

256 **2.5. Dynamic of DOM - recovery of CO₂**

257 Prior to this revision, a linear recovery of CO₂ over a 5-year period was applied in the national
 258 methodology (Fig. 1, red dash line). A comprehensive literature review was conducted to derive
 259 parameters for Olson curves (decomposition constant *k* and litterfall, *L*) across a wide range of fuels
 260 and locations (Appendix 4).
 261 From the calculation of the time to recover to 95% of steady state values (*T*_{0.95}), the data suggests
 262 recovery periods in the order of 4-16 years (average 9 years) for prescribed burning, and 5-21 years
 263 (average 11 years) for wildfire in Australian forests, a relatively rapid recovery that reflects inherent
 264 fire-adaptation of eucalypt forests relative to the global forests. The parameters adopted for fuel
 265 recovery functions are given in Table A.8 (Appendix 4).

266 3. Lessons learnt and the way forward

267 In refining the key parameters used in Australia's emissions estimates several difficulties arose that
268 are likely relevant for any country seeking to move to a higher Tier, as well as for Australia in
269 planning future emission reporting refinements. These are described below.

270 3.1 Sample size and uncertainties

271 For the parameters reviewed here the underlying data was limited to available published and grey
272 literature sources, and in some cases the number of observations was small (e.g. emission factors,
273 burning efficiency, no comprehensive data on patchiness). These small sample sizes lead to greater
274 uncertainty, as the collected data may not accurately represent the spatial variability of forests
275 across all jurisdictions (States). For fuel loads this was partially mitigated by calculating forest and
276 woodland estimates separately, allowing appropriately spatially-weighted State-wide averages to be
277 calculated, although the representativeness of the data within the forest and woodland categories
278 remains uncertain. A better approach would be to develop a national-scale fuel sampling program
279 that is statistically designed *a priori* to ensure adequate replication and representation is achieved at
280 the State or bio-region level. A key issue when developing a sampling design is that it must be large
281 enough to produce sufficiently precise estimates of the area of the activity given the policy
282 requirement and the costs involved. Options for optimizing sampling designs for emissions
283 estimates are not discussed here and readers are encouraged to refer to IPCC (2000) and Chapter 5
284 of GFOI (2016).

285 3.2 Consistency in fuel definition among sources

286 A major difficulty when compiling the data for this study was inconsistency in fuel class definitions
287 for the collected data. For example, often it was unclear if reported values for litter included the
288 duff layer and twigs with diameter < 6 mm, or whether near-surface fuels were incorporated in the
289 litter load. Different size-definitions of the CWD fuel category were used (e.g. diameter ≥ 6 mm; $\geq$
290 25 mm or ≥ 100 mm) and in many cases it was not clear what size categories researchers had
291 adopted. This is likely a very common problem when data is compiled from multiple sources. It was
292 addressed here by developing simple ratios calculated from a sub-set of the data where all class
293 sizes were available and measured simultaneously (Volkova et al., 2018a). While this approach is
294 not ideal, because such ratios are inherently variable among vegetation classes, this method allows
295 stepwise improvement in the data.

296 Another issue was the difference in the methodologies used to estimate litter loads between the
297 States, e.g. in the State of Queensland, litter loads were estimated using indirect measurements from

298 visual assessment of fuel hazards, while the other States used destructive sampling which is a direct
299 measurement. With only a few data points available based on direct measurements for the State of
300 Queensland, we had to apply recommended in the guidelines conversion factors to provide
301 estimates for the State. We appreciate the uncertainty of this approach (Volkova et al., 2016) and
302 have recommended to improve estimates based on direct measurements as one of the research
303 priorities.

304 Difficulties were also encountered when assessing the combustion factor database, where several
305 researchers had defined an upper size limit to the 'CWD' category. In some cases, this upper limit
306 was relatively small (25 mm), so that calculating a combustion factor based on this data would tend
307 to overestimate the combustion relative to data where larger CWD size classes were included. Care
308 also had to be taken when interpreting the fire behaviour across different studies, with a small
309 number of 'prescribed burns' having observed fire-line intensities above 2000 kW m⁻¹; these studies
310 were re-classified as 'wildfire' to better reflect the likely combustion outcomes.

311 *3.3. Limitations in the availability of coarse woody debris (CWD) data*

312 Whilst there is good information available for litter fuels in southern Australian forests, principally
313 because litter has been a primary focus of fire behaviour research for some time (Sullivan et al.,
314 2012), there is limited information on CWD: loads, combustion properties and recovery following
315 fire. Firstly, there are practical limitations to estimating CWD loads in forests due to typically high
316 spatial variability (Herrero et al., 2013) or anthropogenic interventions such as fuelwood collection
317 by local communities. In developing sampling protocols for CWD it is important to account for
318 vegetation class (Woldendorp et al., 2004).

319 Recovery of CWD fuels has been measured at only 10 locations in southern Australia (Appendix 4).
320 A small sampling size and variability in decomposition rates and steady state fuel loads, prevented
321 us from developing reliable recovery parameters for CWD fuels. As such, we had to recommend
322 that recovery rates for CWD for this NIS revision be based on those observed for litter fuels,
323 highlighting that improving the knowledge base of the CWD and their dynamics is a clear research
324 priority.

325 *3.4 Fuel and vegetation class limitations*

326 The current Australian methodology only considers litter and CWD fuels for estimating GHG
327 emissions from forest fires. As mentioned above, litter fuel has been extensively studied in
328 Australia since the 1960's due to its perceived importance in fire behaviour. More recent studies
329 have also highlighted the importance of other fuels such as shrubs, grasses and bark in contributing
330 to both fire behaviour (Gould et al., 2007) and GHG emissions (Haugaasen et al., 2003; Johnson et

331 al., 2007; Volkova et al., 2014). For Australia at least, inclusion of these fuels in the national
332 methodology will be an important step forward in improving emissions estimates.
333 Only two vegetation classes were considered in the current methodology: forests and woodlands.
334 Because Australia has a national vegetation information system that is digitally mapped, there are
335 good prospects for developing fuel layers for the major vegetation groupings as a step towards more
336 accurate reporting of national GHG emissions.

337 3.5 Pyrogenic carbon

338 A growing body of literature has shown that production of pyrogenic carbon during fires can
339 significantly affect emissions estimates (Krishnaraj et al., 2016; Preston and Schmidt, 2006; Santin
340 et al., 2016; Sawyer et al., 2018), so that rates of pyrogenic carbon formation under contrasting fire
341 regimes, and subsequent turnover rates, is another priority area for research.

343 4. The roadmap for improving GHG emissions estimates

344 The steps summarized here provide a simple “roadmap with hints” to assist a country to establish
345 and incrementally improve GHG emissions reporting by moving from a Tier 1 to a Tier 2.

- 346 1. Define major vegetation types affected by fire;
- 347 2. *To replace default $M \times CF$ from Table 2.4 of IPCC Guidance with a country specific M :*
 - 348 a. Define major fuels contributing to emissions (e.g. litter, deadwood, peat, grasses,
349 shrubs);
 - 350 b. Collect data in the field or extract data from the literature using examples for similar
351 fuel types;
 - 352 i. Tip for REDD+ countries: measuring loads for major fuel categories can be
353 included during the design stage of a National Forest Monitoring System
354 (NFMS) and implemented during data collection stage;
- 355 3. *To replace default $M \times CF$ from Table 2.4 of IPCC Guidance with a country specific CF :*
 - 356 a. Determine major fire types: wildfires, planned fires, early/late dry season fires, peat
357 fires;
 - 358 b. If possible, collect pre- and post-fire fuel load data in the field, or extract CF data
359 from the literature for the selected fire type;
- 360 4. *To replace default EF from Table 2.5 of IPCC Guidance with a country specific EF :*

- a. Use literature: there are vast datasets of EF available in the literature for major forest types which can be directly used in the calculations without investing resources into equipment and training;
- 5. To account for the dynamics of the DOM, either:
 - a. Collect the data in the field as described in section 1.2;
 - b. Review the literature on what is known for similar forest types;
- 6. At each of the above steps, record knowledge gaps for priority research areas when resources become available, recognising that existing data is usually imperfect. Only stepwise improvements are possible if the goal of moving to a higher Tier is to be achieved.

5. Conclusion

This paper presents a roadmap for moving to a higher Tier approach in reporting GHG emissions from biomass burning. Development of a Tier 2 methodology allows countries to establish a realistic baseline of emissions and to identify the main drivers of emissions for abatement actions. This is especially relevant for countries seeking to achieve results-based payments for emissions reduction under the REDD+ scheme.

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588 APPENDIX 1- FUEL LOADS

589 Within the Australian National Inventory System ‘Forest land’ includes all lands with a tree height
590 of at least 2 m, a crown canopy of 20 % or more, and a minimum area of 0.2 ha. The primary focus
591 of this review is temperate forests that meet the above definition but that are not included in the NIS
592 greenhouse gas calculations for Savannas (Fig. A.1).

593 To maintain consistency with previous NIS methodology, the primary classification of the fuel
594 parameters is by State. Within each State, and where data are available, fuel parameters are further
595 categorised into litter fuels (< 6mm) and coarse fuels (≥ 6mm).

596 The majority of the fuel load data included in this review were geo-referenced. The forest
597 management classification, and the broad vegetation class (woodland and forest), were obtained by
598 comparing each observation with the published spatial datasets of broad vegetation class (‘forest’ vs
599 ‘woodland’(Table A.1) (ABARES, 2014). All spatial analyses were conducted in ArcGIS 10.2.2
600 (Esri Inc. Redlands, CA, USA).

601 *Table A.1. Definitions of vegetation classes (Forest vs Woodland) based on ABARES (2014) GIS*
602 *data layers.*

Woodland	Forest
Acacia	Callitris
Casuarina	Rainforest
Eucalypt Low Woodland	Eucalypt Low Closed
Eucalypt Mallee Open	Eucalypt Low Open
Eucalypt Mallee	Eucalypt Medium Closed
Eucalypt Medium	Eucalypt Medium Open
Eucalypt Tall Woodland	Eucalypt Tall Open

603

604 **1) Fuel load datasets**

605 A wide range of data sources were accessed to provide a national coverage of both litter and CWD
606 fuel loads. These were obtained from:

- 607 • Victoria: Field measurements by Volkova and Weston (2015); fuels classes included litter
608 (diameter ≤ 25mm) and CWD (diameter > 25 mm). Litter fuels were separated into two

classes (< 6 mm and twigs of 6-25 mm). The Victoria's Forest Monitoring Program (VFMP) dataset (ca 450 plots). Data includes litter (diameter < 6 mm) and CWD (>100 mm).

- South Australia: field data by Volkova and Weston (2015), augmented with data provided by the Department of Environment, Water and Natural Resources (ca. 500 plots) measured from 1985 to 2002. Includes litter (diameter < 6 mm), fine branches (diameter 6-25 mm) and CWD (diameter >25 mm).
- Tasmania: field data by Volkova and Weston (2015) and data extracted from Marsden-Smedley and Anderson (2011); only litter (diameter < 6mm).
- ACT: field data by Volkova and Weston (2015) and field data measured by the ACT Parks and Conservation Services (ca 150 plots) collected in the period 2003-2006. Data included litter (diameter < 6 mm and 6-10 mm) and CWD (a count by class increment: 10-50 mm, 50-100 mm, up to >1000 mm, for the latter category actual diameter was provided). Van Wagner (1968) equation was used to estimate loads of CWD (tonnes ha⁻¹) assuming an average diameter for each class category.
- NSW: Rural Fire Services (RFS) provided field data (litter) for the Hunter Valley project (ca 65 plots). Additional data sourced from CSIRO databases and the literature.
- WA: litter fuel and CWD estimates for four broad vegetation classes (tall open forests, open forests, woodland, semi-arid woodland). A detailed analysis of the data has not been published, however, a review of data using land agency's reports and publications was undertaken by Dr L. McCaw and Dr C.P. Meyer for the Bushfire CRC (Meyer and McCaw, 2012) and made available for this study. Area-weighted averages of these four main vegetation types were used to provide indicative fuel load estimates for the State. These estimates were augmented with values from the literature.
- Queensland: field data by Volkova and Weston (2015) and Roxburgh et al. (2006) augmented with visual assessment data provided by Qld Parks and Wildlife Service National Parks, Sport and Racing (ca. 135 plots) and Queensland Fire and Emergency Services (ca. 75 plots). Visual assessment data included fuel hazard rating for litter fuels (< 6 mm). Hazard ratings were converted to corresponding loads using indicative fuel loads provided in Table 9.2 of the 'Overall Fuel Hazard Assessment Guide' (Hines et al., 2010). Specifically, hazard ratings were converted to loads as following: 'Low'=3 Mg ha⁻¹, 'Moderate' = 7 Mg ha⁻¹, 'High'=11 Mg ha⁻¹, 'Very High'=16 Mg ha⁻¹ and 'Extreme'=18 Mg ha⁻¹. The use of visual assessment data for this state was necessary due to a lack of field-

based measurements. We note that the accuracy of this conversion can be variable and is dependent on the assessors' training and experience (Volkova et al., 2016).

- Additional data sources includes a literature review as a part of a the University of Melbourne / CSIRO joint project on estimating forest NPP (Volkova et al., 2018b), and a previous literature review of FullCAM fire event parameters conducted by CSIRO (Surawski et al., 2012), (ca 85 data points in total).

All data were assessed for fire history. Because the fuel loads need to be representative of approximately steady-state conditions, any measurements collected within 5 years post-fire were excluded from the analysis. A conversion factor of 0.893 was applied to total litter to derive fine litter loads and 0.107 to derive loads of twigs with 6-25 mm based on data described in Volkova et al. (2018a). Twigs of diameter 6-25 mm were added to CWD pool. If data included only CWD loads, a conversion factor of 0.116 was used to adjust CWD to account for 6-25 mm twigs.

2) Fuel loads by States and vegetation classes

Spatially-referenced observations of litter and CWD fuels were compiled for the analysis (Fig. A1, Table A.1). The majority of the Western Australia and New South Wales estimates were provided as state-wide values, derived from previous compilations.

658

659 **Figure A1.** (a) Map of Australian Forest land extent including native forests (light grey colour),
 660 plantations (darker grey colour) and ‘non-Savanna’ forests (green) included in this study (Forest
 661 land extracted from ABARES 2014 a). Red markers indicate field observations of fuel load. Yellow
 662 markers show the locations of fuel recovery function studies. Blue markers show the locations of
 663 combustion factor studies. Two observations for tropical far-north Queensland are not shown.

664 Number of observations of litter and CWD fuel load available for the analysis are given in Table
 665 A.2.

666 Table A.2. Number of observations of fuel load data by jurisdiction, fuel type and vegetation class.

State	Vegetation class	Fuel type	
		Litter < 6 mm	CWD ≥ 6 mm
ACT	Forest	46	98
	Woodland	22	46
NSW	Forest	113	24

	Woodland	7	--
QLD	Forest	120	8
	Woodland	113	11
SA	Forest	91	58
	Woodland	159	104
TAS	Forest	28	3
	Woodland	78	5
VIC	Forest	229	276
	Woodland	83	113
WA	Forest	9	4
	Woodland	--	--

667

668 A three-way factorial ANOVA was used to test for difference in fuel loads between States,
669 vegetation class (forest and woodland) and fuel type (litter and CWD, Table A.3). NSW was
670 excluded from this analysis, due to the paucity of data for woodlands, and WA was also excluded,
671 given the fuel load estimates comprised aggregate State values, with only a small number of geo-
672 referenced site measurements.

673 *Table A.3. Analysis of Variance (ANOVA) testing for differences in fuel load between states,*
674 *vegetation classes and fuel types*

Parameter	SS	DF	F	P
State (S)	249.20	4	17.28	<0.0001
Vegetation Class (Veg)	20.21	1	5.61	0.017
Fuel Type (FT)	89.96	1	24.95	<0.0001
S x Veg	107.99	4	7.49	<0.0001
S x FT	40.91	4	2.84	0.023
Veg x FT	0.54	1	0.15	0.699
S x Veg x FT	88.22	4	6.12	<0.0001

675 Statistical analysis was conducted using Teddybear (Wilson, 1991)

676

677 There was a significant difference between vegetation classes, states and fuel types (Table A.3),
678 supporting the need for State-specific fuel load parameters, and indicating that fuel loads not only
679 differ between States, but also with vegetation classes and fuel type as a three-way interaction. On a
680 State-by-State basis the differences in fuel loads between forests and woodlands justifies the

681 stratification of the analysis into broad structural vegetation classes, however, care is required when
682 interpreting these results for three reasons. First, even with a square-root transformation the
683 normality (skew and kurtosis) and homogeneity of variance assumptions were violated. Secondly,
684 some of the sample sizes were small, particularly for CWD, and hence the estimates of the average
685 fuel load will be subject to high uncertainty. For example, the relatively high CWD estimate for
686 woodlands in Queensland was based on just 11 samples, and the relatively low CWD estimates for
687 forests and woodlands in Tasmania was based on five and three observations, respectively. Finally,
688 and most importantly, it is possible the underlying data violate the assumption of independence, at
689 least for some states. This is because the individual plot data that comprise the database do not
690 represent a random sample of all possible forests and woodlands; rather, plots are often
691 concentrated within certain vegetation classes or regions. For example, of the 114 plot-based litter
692 fuel estimates for NSW, 17 were collected within the south coast region of NSW, and 65 within the
693 Hunter region. This has two consequences: first, it could reduce the representativeness of the
694 sample when compared to vegetation classes across the rest of the State. Second, in the statistical
695 analysis it can lead to spatial ‘pseudoreplication’, with undue weight given to multiple separate
696 samples collected within the same area, leading to an increased chance of concluding a significant
697 difference in the analysis. Despite these potential limitations, the analysis is useful for identifying
698 underlying patterns and trends in the data.

699

700 **3) Recommended fuel load parameters**

701 Although the results are reported by vegetation class, there are consistent differences in CWD fuel
702 loads between woodlands and forests; and therefore obtaining a representative state-wide figure for
703 each parameter required calculating the average of the observations, weighted by the area of each of
704 these broad vegetation classes. Default combined forest + woodland fuel loads for each State are
705 calculated using the historical forest and woodland fractional burn areas as a guide to future fire
706 activity, with the assumption that, over time, the proportion of woodlands and forests that will be
707 subject to wildfire will be similar to historical fire activity. These historical burn fractions were
708 calculated through analysis of the historical 1988-2013 spatial fire scar data, as described in
709 Roxburgh *et al.* (2014). The area of each State was first masked to the non-savanna area (Fig. A1),
710 the total area that was burnt at least once over the observation period 1988-2013 was then
711 calculated, and the forest and woodland fractions of this burn area determined (Table A4).

712 *Table A.4. Fraction of fire-affected forest and woodland areas within the non-Savanna subset,*
713 *within each State.*

State	Total non-Savanna area (ha)	Total fire-affected woodland + forest area within the non-Savanna zone (1988-2013) (ha)	Fire-affected forest area fraction (%)	Fire-affected woodland area fraction (%)
ACT	235,980	102,486	71.7	28.3
NSW	44,152,904	2,073,901	64.1	35.9
QLD	10,976,891	1,132,018	53.0	47.0
SA	15,408,409	276,067	3.1	96.9
TAS	6,649,087	148,490	36.9	63.1
VIC	22,662,604	2,408,636	76.6	23.4
WA	31,726,012	2,232,626	36.1	63.9

714

715 The historically-determined burn fractions in Table [A.4](#) were then multiplied by the forest and
716 woodland fuel loads in the final column of Table [1](#) to yield composite weighted average (woodland
717 + forest) litter and CWD fuel loads (Table [1](#)).

718 APPENDIX 2 – COMBUSTION FACTOR

719 Across Australian forests, there are 105 unique records quantifying a combustion factor for litter or
720 CWD for prescribed burning or wildfires. The dataset (Table A.5) was dominated by combustion
721 factors for prescribed burning ($n=93$) rather than wildfire ($n=8$) and by studies of litter combustion
722 ($n=62$) rather than CWD combustion ($n=39$). There was a lack of data for wildfire for several
723 jurisdictions. Given the sparse nature of the dataset, combustion factors were pooled for a given fuel
724 component/fire type combination to obtain reasonable sample sizes.

725 Table A.5. Combustion factors for litter and CWD fuels from prescribed burning and wildfires in
726 Australia on a jurisdictional basis. Values are mean and (standard deviations).

Fuel type	State						
	ACT	NSW	QLD	SA	TAS	VIC	WA
	<i>Prescribed burns</i>						
Litter	0.57 (0.24) n = 6	0.53 (0.32) n =18	0.51 (0.01) n =2	0.65 n =1	0.57 n =1	0.59 (0.19) n =20	0.78 (0.16) n =10
CWD	0.62 (0.27) n =5	0.83 (0.16) n =10	0.30 n =1	0.19 n =1	1.00 n =1	0.29 (0.27) n =12	0.59 (0.15) n =5
	<i>Wildfires</i>						
Litter	--	0.90 (0.09) n =2	--	--	--	1.00 (0.00) n =2	--
CWD	--	--	--	--	--	0.44 (0.44) n =3	0.39 n =1

727

728

729 APPENDIX 3 - EMISSION FACTORS

730 The relevant published studies are the pioneering work of Hurst et al. (1996), supplemented recently
731 by the work of Paton-Walsh et al. (2014), Volkova et al. (2014), and Surawski et al. (2015). Hurst et
732 al. (1996) sampled smoke plumes from a series of fires in the Sydney region, three of which were
733 wildfires and one a fuel reduction fire. Paton-Walsh et al. (2014) measured surface plumes from
734 fuel reduction fires in the Sydney region of NSW using open-path spectroscopy. Volkova et al.
735 (2014) applied the technique developed by Meyer et al. (2012) for the savanna studies to fuel
736 reduction burns in Eastern Victoria, and Surawski et al. (2015) used laboratory scale experiments of
737 litter fuel combustion in the CSIRO Pyrotron facilities. These data are supplemented by current
738 laboratory and field studies of fuel reduction burns (Meyer, unpublished, Table A.6).

739 The emission factors for methane (EF-CH₄) vary with the Modified Combustion Efficiency (MCE)
740 – an index that is used to characterise the relative amount of flaming and smouldering combustion.
741 Meyer and Cook (2015) observed that the relationship between EF-CH₄ and MCE could be
742 approximated by an exponential function (the ‘Stirling curve’); however, the form of the function
743 appeared to depend on combustion conditions. Most published observations from the northern
744 hemisphere are approximated by a Stirling curve with a larger gradient than observations from the
745 Australian savanna woodlands, where combustion occurred in thin fuel beds. Indeed, pile burns of
746 savanna woodland fuels were similar to the northern hemisphere observations. The observations of
747 EF-CH₄ and MCE from temperate forests in Victoria and NSW are intermediate between the two;
748 i.e. lower than the northern hemisphere forest observations, but larger than the Australian savanna
749 woodlands (Figure A2, Table A.6).

750

751

752 *Figure A2: Relationship between methane emission factor and MCE. (A): full MCE range, (B):*
 753 *detail showing the higher (flaming) MCE range.*

754 The lines are Stirling functions fitted to the savanna data (solid line) and the pile burns conducted
 755 by Meyer and Cook (2015), which approximate field observations from Northern Hemisphere
 756 studies. The field observations from Temperate Australian forests are superimposed;
 757

758 Litter fuel is mostly consumed by flaming combustion and consequently has higher MCE and lower
 759 EF-CH₄ than the mixed plumes, while coarse fuels (CWD) tends to smoulder with low MCE, ca.
 760 0.83, and substantially higher EF-CH₄, 1.3% emitted.

761 Nitrous oxide emission factors are approximately 1% of fuel N emitted as N₂O, which is consistent
 762 with the values observed for the savanna woodlands. The number of observations is quite small
 763 because N₂O is difficult to measure accurately in combustion gas mixture using spectroscopic
 764 techniques. Nevertheless the two observations reported by Paton-Walsh et al. (2014), 1.2 and 2.7%
 765 emitted N and are within the range reported for northern Australian savanna (0.5 – 2.5% emitted N,
 766 Meyer and Cook, 2015). Meyer and Cook (2015) concluded that both combustion chemistry and
 767 fuel type were major determinants of EF-N₂O, and this is supported by Surawski *et al.* (2015) who

768 recorded significantly different EF-N₂O from heading, flanking and backing burns for identical fuel
 769 types, based on experiments conducted in the CSRIO Pyrotron. The most comprehensive set of data
 770 comes from three prescribed burns in central and eastern Victorian forest; they average 1.1% of fuel
 771 N emitted as N₂O from litter fuel combustion and 0.7% emitted N for smouldering CWD (Table
 772 A.6, Figure A3). These are close to the EF N₂O of 0.77% fuel N currently applied in the inventory
 773 methodology (Table 3).
 774 Because of the difference in emission factors between litter and coarse fuels, a stratified inventory
 775 approach is recommended, and complements the stratification of fuels by size class presented in
 776 Figure A3.

777
 778 **Figure A3.** Relationship between EF-N₂O and MCE in an Australian temperate forest (prescribed
 779 burn).

780

781

782 Table A.6. Summary of observations of CO₂, CO, CH₄ and N₂O emission factors measured in
 783 Southern Australian temperate forest.

Reference	Location	Comment	MCE	EF-CO ₂	EF-CO	EF-CH ₄	EF-N ₂ O	EF-CO ₂	EF-CO	EF-CH ₄	EF N ₂ O
						g/kg	g/kg	molar	molar	%C	%N
Paton_Walsh et al, 2014	Lane Cove		0.888	1580	136	4.8		0.862	0.109	0.720	
Paton_Walsh et al, 2014	Tuttamurra		0.913	1640	106	2.9		0.895	0.085	0.435	
Paton_Walsh et al, 2014	Abaroo Ck		0.917	1650	102	2.7		0.900	0.082	0.405	
Paton_Walsh et al, 2014	Gulgar Nature		0.909	1640	112	2.7	0.210	0.895	0.090	0.405	2.67
Paton_Walsh et al, 2014	Alfords Point		0.891	1590	133	4.5	0.090	0.867	0.106	0.675	1.15
Hurst et al, 1996	Helensburgh		0.909	1577	107	1.3		0.860	0.086	0.440	
Hurst et al, 1996	Worragee		0.887	1540	134	3.3		0.840	0.107	0.700	
Hurst et al, 1996	Sydney		0.905	1558	111	2.2		0.850	0.089	0.570	
Hurst et al, 1996	Batemans Bay		0.912	1577	104	1.3		0.860	0.083	0.440	
Surawski et al.,2015	Heading		0.863	1594	172	4.2	0.089	0.869	0.138	0.610	1.55
Surawski et al.,2015	Flanking		0.922	1709	98	4.3	0.117	0.932	0.078	0.625	2.04
Surawski et al.,2015	Pyrotron	Backing fire	0.925	1716	95	3.3	0.064	0.936	0.076	0.480	1.11
Surawski et al.,2015	Pyrotron	Heading-smouldering	0.824	1515	221	5		0.826	0.177	0.727	
Surawski et al.,2015	Pyrotron	Backing-smouldering	0.842	1546	198	7		0.843	0.158	1.017	
Volkova et al 2014	Heyfield	Litter	0.962	1730	47	1.24	0.087	0.961	0.039	0.190	1.09
Volkova et al 2014	Heyfield	CWD	0.825	1505	218	9.97	0.048	0.821	0.174	1.490	0.76
Meyer et al., (unpubl.)	Central Vic	Litter	0.947	1731	66	0.6	0.056	0.944	0.053	0.310	1.12
Meyer et al., (unpubl.)	Central Vic	CWD	0.826	1488	213	21.5	0.029	0.812	0.170	1.797	0.58

	Mean (stdev)	Plume	0.903	1614	118	3.1	0.114	0.881	0.094	0.542	1.70
			(0.018)	(57)	(22)	(1.2)	(0.057)	(0.031)	(0.018)	(0.121)	(0.66)
		Litter	0.954	1731	57	0.9	0.072	0.953	0.046	0.250	1.11
			(0.011)	(1)	(13)	(0.5)	(0.022)	(0.012)	(0.010)	(0.085)	(0.02)
		CWD	0.829	1514	213	10.9	0.039	0.826	0.170	1.258	0.67
			(0.009)	(24)	(10)	(7.4)	(0.013)	(0.013)	(0.008)	(0.478)	(0.13)

784 APPENDIX 4- FUEL RECOVERY

785 Overall, 99 litter accumulation parameters (the decomposition constant, k , and litterfall, L) were
786 identified in the review, sourced primarily from the reviews of Hutson and Veitch (1985), Watson
787 (2012) and Thomas et al. (2014), augmented with data from a range of other published studies.
788 There was insufficient data to warrant testing for differences between woodlands and forests for
789 some States, thus fuel recovery was assessed on a State-by State basis, with woodlands and forests
790 combined. To allow visualisation of the differences between fuel accumulation curves they are
791 displayed in Fig. A4 assuming 100% fuel combustion, i.e. $X_i=0$. However, to account for more
792 realistic combustion of fuels, X_i can be estimated as the steady state fuel load (X_{ss}) multiplied by
793 $1 - (P \times CF)$ (Fig A5).

794

795

796

797 *Figure A4. Olson litter recovery curves for each State (A-G) and CWD for all States combined (H).*
798 *Note for the purpose of display that fuel recovery curves assume zero initial fuel loads ($X_i=0$, 100%*
799 *combustion).*

800

801

802

803 *Figure A5. Example Olson fuel recovery curves for Victoria following wildfire, using parameters in*
 804 *Tables S3 and S4. X_i is calculated as the steady state fuel load (X_{ss}) multiplied by $1 - (P \times CF)$. (A)*
 805 *Litter; (B) CWD.*

806

807 The national inventory methodology of fuel recovery can be calculated using the Olson curves
 808 developed in this study. Olson models for each State, for both litter and CWD fuels, and for
 809 prescribed burning and wildfire, can be obtained by using the values of $T_{0.95}$ in Table A.7 as the

810 estimate of recovery time, and then solving Equation 3 for the required model parameters. These
811 parameters are given in Table A.8; an illustration of a representative model (for wildfires in
812 Victoria) is given in Figure A5.

813

Table A.8. Olson fuel recovery curve parameters for prescribed burning and wildfire (k , X_{SS} , L and X_i for litter and CWD) for each of the State-specific fuel loads in Table 1. For each State the common value of k for both litter and CWD, with CWD recovery rates set to those for litter fuel.

State	Prescribed burning							Wildfire						
	K	Litter			CWD			k	Litter			CWD		
		X_{SS_Litter}	L_Litter	X_i_Litter	X_{SS_CWD}	L_CWD	X_i_CWD		X_{SS_Litter}	L_Litter	X_i_Litter	X_{SS_CWD}	L_CWD	X_i_CWD
ACT	0.300	7.97	2.391	4.8617	23.72	7.116	19.0946	0.230	7.97	1.833	2.2316	23.72	5.466	14.232
NSW	0.422	13.37	5.642	8.1557	41.89	17.678	33.7215	0.326	13.37	4.359	3.7436	41.89	13.656	25.134
QLD	0.768	14.47	11.113	8.8267	30.10	23.117	24.2305	0.587	14.46	8.488	4.0488	30.10	17.669	18.060
SA	0.297	7.42	2.204	4.5262	11.43	3.395	9.2012	0.229	7.42	1.699	2.0776	11.43	2.617	6.858
TAS	0.267	8.76	2.339	5.3436	14.86	3.968	11.9623	0.207	8.76	1.813	2.4528	14.86	3.076	8.916
VIC	0.416	12.19	5.071	7.4356	32.53	13.532	26.1867	0.319	12.19	3.889	3.4132	32.53	10.377	19.518
WA	0.186	11.83	2.200	7.2163	39.34	7.317	31.6687	0.143	11.83	1.692	3.3124	39.35	5.627	23.610