

Framework for assessing live fine fuel loads and biomass consumption during fire



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ABSTRACT

Accurate quantification of fine fuel loads (e.g. foliage and twigs) in forests is required for many fire behaviour models, and for assessing post-fire changes in carbon stocks and modelling smoke emissions. Fine fuels burn readily and are thus often targeted for fuel load assessments. Estimates of fine live fuel loads often rely on visual assessments or utilise allometric equations that relate stem diameter of plants to total above-ground biomass. Here, we develop allometric equations for shrubs that relate stem diameter to the portion of above-ground biomass comprised of fine fuel. Our study area is within the temperate eucalypt forests of south-eastern Australia. We present equations for (i) foliage; (ii) all biomass < 3 mm diameter; (iii) all biomass < 6 mm diameter; and (iv) all above-ground biomass. Simple power-law models were developed for five shrub species and saplings of two tree species. Models combining all species ($RMSE = 0.03\text{--}0.06$) worked similarly well to species-specific models ($RMSE = 0.01\text{--}0.08$). We then applied these all-species combined models to field observations of shrub stem diameters, measured before and after planned burns. In unburnt forest, the proportion of shrub biomass comprised of fine fuel varied considerably (from 6 to 58%). Fine fuel loads were positively related to total above-ground biomass ($R^2 = 0.75$) and basal area of shrubs ($R^2 = 0.79$). There was considerable variation in consumption of fine fuel. The median reduction in fine fuel load was 22.4%, whereas the median reduction in total above-ground biomass was only 2.3%. Our models of shrub fine fuels can be readily applied to field-based assessments or combined with existing models or remotely sensed estimates of above-ground biomass to model fine fuel loads over large heterogeneous study areas.

1. Introduction

The incidence of forest fires is increasing in many parts of the world, consistent with climate change (Whitman et al., 2019; Boer et al., 2020; Nolan et al., 2020; Abram et al., 2021). One of the key preconditions required for forest fires is spatially contiguous fuel (Bradstock, 2010). Forest fuel loads are reduced by fire, then gradually re-accumulate through time (Penman and York, 2010). Thus, the potential for large forest fires varies through time, but is lowered immediately following fire. Given the relationship between fuel loads and fire behaviour (Fujioka et al., 2009), planned burns are often implemented in many jurisdictions to reduce fuel loads, and thereby reduce the risk of catastrophic fires impacting on people and assets (Price et al., 2015). At the

same time as fuel loads are being managed in forests to reduce the risk of catastrophic fires, many forested areas globally are also being managed for their capacity to offset anthropogenic carbon emissions (Bradstock et al., 2012; Hurteau et al., 2013; Nolan et al., 2018). Given that fires consume biomass, reductions in fuel loads also equate to reduction in carbon stocks. Thus, accurate quantification of biomass consumption rates during fire are important for the dual purposes of quantifying dynamics in fuel loads and carbon stocks. Accurate quantification of fine fuel is also critical for accurate prediction of fire behaviour for the purpose of operational fire response and planning of fuel management (Gould et al., 2007).

While all fuel is biomass, only a fraction of the stand biomass is consumed in a forest fire, and therefore not all biomass constitutes 'fuel'.

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For example, in wet eucalypt forests in south-eastern Australia, biomass consumed during wildfire has been estimated at 6–14% of total biomass, depending on fire severity (Keith et al., 2014). In western US forests, carbon emissions during wildfire have been estimated at 4 Tg C yr⁻¹, but the estimated amount of biomass transferred from live to dead and decomposing carbon pools was much larger, at 10.5 Tg C yr⁻¹ (Ghimire et al., 2012). The distinction between biomass and fuel is important since assumptions that all, or large proportions, of biomass are consumed in wildfires can lead to significant over-estimations of carbon emissions from wildfire (Stenzel et al., 2019). Estimates of fuel consumption rates during fire are also important for modelling smoke patterns, and subsequent risks to human health (Williamson et al., 2016). Estimates of global fire emissions do currently take into account fuel consumption rates (van der Werf et al., 2017). However, there is large variability in reported fuel consumption rates, both between and within biomes (van Leeuwen et al., 2014), which leads to large uncertainty in emissions estimates.

Fuels are generally categorised into live or dead fuels, and into different size classes, e.g. fine fuels, such as foliage and twigs, and coarse fuels, such as logs (Gould et al., 2011). Because fine fuels have a large surface area-to-volume ratio, they burn readily and are important for driving fire spread rates (Rothermel, 1972; Fujioka et al., 2009). The importance of fine fuels for fire behaviour means that they are a particular focus for fuel load assessments (e.g. Hines et al., 2010; McColl-Gausden et al., 2020). For shrubs and trees, significant advancements have been made in modelling total biomass. Woody biomass is typically estimated through the use of allometric equations, which model biomass as a function of stem diameter (e.g. Paul et al., 2016). These same types of equations have been applied to model post-fire changes in carbon stocks of shrubs (e.g. Volkova and Weston, 2013; Possell et al., 2015; Jenkins et al., 2016); as well as post-fire changes in fuel loads of shrubs (e.g. Volkova et al., 2019). However, allometric equations for biomass are not well-suited for directly estimating biomass consumption or changes in fuel loads following fire since they cannot account for changes in biomass when only the fine fuel component (e.g. foliage and twigs) is consumed. Instead, allometric equations can be applied to modelling fuel consumption rates if information is available on the proportion of biomass that constitutes fine fuel (Keith et al., 2014).

Universal biological scaling laws predict that the effective exchange area of an organism (e.g. leaf area) should scale with the volume (and therefore total mass) of that organism (with a 3/4 power scaling relationship; West et al., 1999). Consistent with this theory, Duursma and Falster (2016) demonstrated that the ratio of leaf mass to stem mass in woody plants scales with stem size, drawing on a global dataset of 656 species. Duursma and Falster (2016) examined stem height; however, similar scaling relationships with stem diameter are likely to be observed given the interdependence of stem height and diameter. This global analysis found differences in the relationships between leaf mass and stem mass among plant functional types, with these differences attributed to variation in leaf mass per area. Previous species-level studies have similarly observed co-ordination between different components of biomass, e.g. crown biomass and total biomass (Clough et al., 2018; Menéndez-Migueléz et al., 2021), and shrub fuels and crown area (Huff et al., 2017; De Caceres et al., 2019). We hypothesise that the proportion of fine fuel mass contained in woody plants should scale with total biomass, similarly to the observed relationships between leaf mass and stem mass (Duursma and Falster, 2016). We further hypothesise that fire will substantially reduce fine fuel loads in shrubs, but this will not necessarily translate to large reductions in shrub biomass, since foliage and twigs only represent a small fraction of total plant biomass.

Here, our objectives are to (i) quantify the proportion of biomass that constitutes ‘fine fuel’ in living shrubs in temperate eucalypt forests of south-eastern Australia; and (ii) quantify changes in shrub fine fuel loads and shrub total biomass before and after planned fire. We do this by developing allometric relationships between stem diameter and fine fuel

loads for common shrub species in our study area. Specifically, we develop allometric equations relating shrub stem diameter and (i) total above-ground biomass; (ii) all above-ground biomass < 6 mm diameter; (iii) all above-ground biomass < 3 mm diameter; and (iv) foliage. We fit these allometric models to five different shrub species and two different tree sapling species to encompass the variation in shrub forms in the common species across our study area. We used twig diameter classes of 3 mm and 6 mm since live ‘fine fuel’ is defined operationally in our study area as any biomass < 3 mm diameter (Hines et al., 2010). However, live fuel larger than 3 mm diameter is also consumed in fires, as demonstrated by the range of remaining shrub twig tip diameters after fire, particularly high severity fire, which can range from 0.8 to 6.7 mm (Whight and Bradstock, 1999; Hammill and Bradstock, 2006). Further, fine fuel is often delineated as biomass < 6 mm diameter in other regions (De Caceres et al., 2019). We then apply these allometric relationships to quantify fuel loads before and after planned burns.

2. Methods

2.1. Study area

Our study area was located in the Sydney Basin Bioregion in south-east Australia (Fig. 1). Climate in this region is temperate, with minimum monthly temperatures in winter between approximately 3–9 °C and maximum monthly summer temperatures between approximately 22–30 °C (Australian Government, 2018). Rainfall occurs predominately in summer, but there is no marked dry season. Mean annual rainfall across the bioregion is 951 mm year⁻¹, with considerable inter-annual variability (Australian Government, 2018). There is also variability in rainfall across the study area, with rainfall decreasing with distance from the coast, and increasing with elevation (Australian Government, 2018). Vegetation at our study sites is dry sclerophyll forest with a shrubby understory (Keith, 2004). Overstorey species are part of the Eucalypt complex of species (*Eucalyptus*, *Angophora*, *Corymbia*). The understory of this vegetation type supports a rich diversity and abundance of sclerophyllous shrub species, dominated by genera within the Proteaceae, Myrtaceae, Fabaceae and Ericaceae families (Fig. 2; Keith, 2004).

2.2. Study design

Within our study area, we established plots at locations scheduled

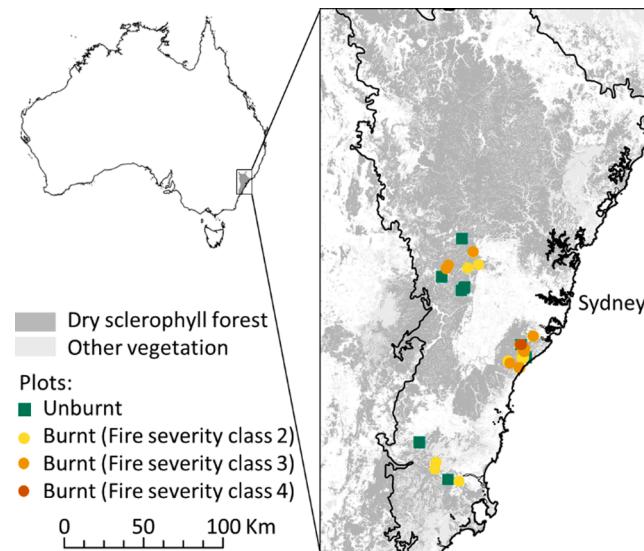


Fig. 1. Location of study sites, outline is of the Sydney Basin bioregion, in south-east Australia. All sites were measured prior to planned fire, however, not all sites were subsequently burnt (those labelled “Unburnt”).



Fig. 2. Pre- and post-fire images from three of the study sites, illustrating the diversity of shrubby understoreys at our study sites.

Table 1

Plot-level shrub above-ground biomass, fine fuel load, density and basal area before and after planned fire. Values presented are means for all plots, with ranges in parentheses. Median losses were calculated on plot-level differences in shrub metrics before and after fire.

Plot-level shrub metrics	Unburnt plots	Post-fire plots	Median losses (%)
Number of plots	54	43	NA
Total biomass ($t \text{ ha}^{-1}$)	5.02 (0.2–24.4)	4.34 (0.06–20.61)	2.3
Fine fuel load ($t \text{ ha}^{-1}$)	1.09 (0.06–4.68)	0.74 (0.01–4.32)	22.4
Shrub density (stems ha^{-1})	18,733 (679–169,946)	14,637 (170–150,142)	23.1
Shrub basal area ($\text{m}^2 \text{ ha}^{-1}$)	19.0 (0.8–82.7)	16.7 (0.3–74.4)	2.8

either for hazard reduction burns (with fuel load reduction as the primary aim) or cultural burns. For each planned burn, we established 2–3 circular plots of 45 m diameter within the planned burn area. There was a total of 54 plots measured across 19 planned burns. Of these burns, two were cultural burns conducted by the Mudjingalbaraga Firesticks Program and Koori Country Firesticks Aboriginal Corporation. The remaining burns were conducted by the New South Wales Department of Planning, Industry and Environment. Planned burns ranged in size from 0.2 to 3,000 ha. Here, we treat individual plots as independent sampling units, since plots within a given planned burn area often differed in fire severity, understorey species composition, shrub density and fine fuel load.

Each plot was circular and 45 m in diameter, with three circular sub-plots established to measure shrub biomass and fine fuel loads. The sub-plots varied in size and were either 3 m or 5 m in diameter depending on shrub density. While the centre of the 45 m diameter plots were marked with a stake, the location of the sub-plots was determined by laying out two orthogonal transects oriented N-S and E-W. The sub-plots were located at approximately 12.5 m and 32.5 m along the N-S transect, and 7.5 m along the E transect. Note, slight unintended changes of alignment in these transects between pre and post-fire surveys meant that the placement of the 3 subplots for measuring shrubs was not always in the exact same location. Within each subplot every shrub was identified to genus where possible, and stem diameter measured at 10 cm above the ground (D_{10}). We defined shrubs as any plant < 4 m in height, which included saplings of tree species. Shrub density ranged from 679 stems ha^{-1} to c. 170,000 stems ha^{-1} (Table 1). Shrub basal area ranged from 0.8 to 87.7 $\text{m}^2 \text{ ha}^{-1}$ (Table 1).

For each shrub, we estimated total biomass and total fine fuel mass, using allometric equations described below.

2.3. Shrub allometry measurements

We developed allometric equations for seven species commonly observed within the Sydney Basin. Species included five shrub species and saplings of two tree species (Table 2). These species were selected since they included the most common species in our study sites and represented the range of observed plant architectures, e.g. leaf size, shape and arrangement and branching patterns. For each species 10–15 plants were harvested. For each plant, stem diameter at 10 cm above the ground (D_{10}) was measured. For each plant we divided biomass into: (i) foliage, which included all leaves / phyllodes. For *Banksia ericifolia* which has small needle-like leaves (0.9–20 mm long, 1 mm wide) crowded onto stems, we also included green terminal shoots in foliage measurements; (ii) Twigs < 3 mm diameter; (iii) twigs 3–6 mm diameter; and (iv) all remaining above-ground biomass. Fresh biomass was

Table 2

Summary of species used for development of allometric relationships.

Species	Description	Post-fire ecological response ¹
Shrubs		
<i>Banksia ericifolia</i>	Shrub or small tree to 6 m	Fire-killed (serotinous)
<i>Dillwynia retorta</i>	Shrub to 3 m	Fire-killed (soil-stored seedbank)
<i>Lambertia formosa</i>	Shrub to 2 m	Basal resprouting
<i>Leptospermum trinervium</i>	Shrub or small tree, to 5 m	Epicormic resprouting
<i>Petrophile pedunculata</i>	Shrub to 2.5 m	Basal resprouting
Tree saplings		
<i>Allocasuarina littoralis</i>	Tree 5–15 m	Epicormic resprouting
<i>Eucalyptus piperita</i>	Tree to 20 m	Epicormic resprouting

¹ Note, this is the fire response for mature individuals, obtained from Clarke et al. (2015), the response for juveniles is uncertain.

then oven-dried at 105 °C for a minimum of 48 h, until dry weight no longer declined, and then weighed.

2.4. Development of shrub allometric equations

We developed allometric equations for total biomass and for fine fuel mass. Fine fuels are biomass less than a defined diameter, typically either 3 mm or 6 mm (Hines et al., 2010; Huff et al., 2017). Allometric equations were developed between D_{10} and (i) total above-ground biomass (AGB_{total}); (ii) all above-ground biomass < 6 mm diameter (i.e. including foliage and twigs, AGB_{D6}); (iii) all above-ground biomass < 3 mm diameter (i.e. including foliage and twigs, AGB_{D3}); and (iv) foliage only (AGB_{foliage}). Our data exhibited heteroscedasticity (Fig. 3), which is common in allometric datasets (Parresol, 1999). We tested two common approaches to correct for heteroscedasticity. In the first approach we applied a non-linear weighted regression following Huff et al. (2017; eqn. (1)).

$$AGB = a.D_{10}^b + \epsilon' \quad (1)$$

where a and b are model coefficients and ϵ' is the residual error. Weighted regression uses different weights for each observation based on their variance. If an observation has large error variance, it will have less impact (due to low weight) on the estimation of the regression coefficients (Parresol, 1999). Two forms of weighting were tested, namely $1/D_{10}$ and $1/D_{10}^2$.

For the second approach, linear models were fit by logarithmic transformations of AGB and D_{10} (eqn. (2)). Applying a linear model enables the model coefficients (a and b) to be estimated from ordinary least squares regression. Residual errors are represented by ϵ , or ϵ' in the power model.

$$\ln(AGB) = \ln(a) + b.\ln(D_{10}) + \epsilon \quad (2)$$

where a and b are model coefficients and ϵ is the residual error. When the linear model is back-transformed from a logarithmic to a natural

scale, a biased estimate of biomass is produced, and a correction factor must be applied to remove bias. We used the commonly applied Baskerville correction factor (CF; Baskerville, 1972).

For both the weighted nonlinear regression and log-linear regression we checked for heteroscedasticity through visual observation, i.e. plotting residuals against fitted values. We assessed model performance through the root mean square error (RMSE), normalized RMSE (NRMSE) and percentage bias (Bias %). Note, for the log-linear model, model fit statistics were calculated on back-transformed data to enable direct comparisons between model types.

2.5. Application of allometric equations to estimate pre- and post-fire shrub fine fuel loads and carbon stocks

We applied the allometric equations we developed to model biomass and fine fuel loads of shrubs prior to and following planned burns. Of the 54 plots established, 30 were subsequently burnt and re-measured. We determined fire severity in the field using the mean values of fire impact scores on individual shrubs and tree crowns (separately) and interpreted according to the scheme of Hammill and Bradstock (2006). Fourteen of the plots burnt at fire severity class "2" (complete understory scorch), 15 of the plots burnt at fire severity class "3" (partial overstorey canopy scorch) and one of the plots burnt at fire severity class "4" (complete overstorey canopy scorch).

In our plots, each shrub was scored according to whether foliage was retained, and an assessment of the diameter of remaining branch tips, see Table 3 for details. Note, very small individual shrubs (with a $D_{10} < 0.03$ cm) were not included in the development of the allometric equations. These very small plants are unlikely to conform to biomass scaling laws, due to relatively little secondary thickening (Enquist et al., 2007; Paul et al., 2016). Thus, although we applied the allometric equations to these small plants, corresponding estimates of plant biomass are likely to be unreliable. Plants of this size class accounted for <5% of the total shrubs measured in this study. Plant-level measurements of biomass and fine fuel mass were scaled to obtain plot-level

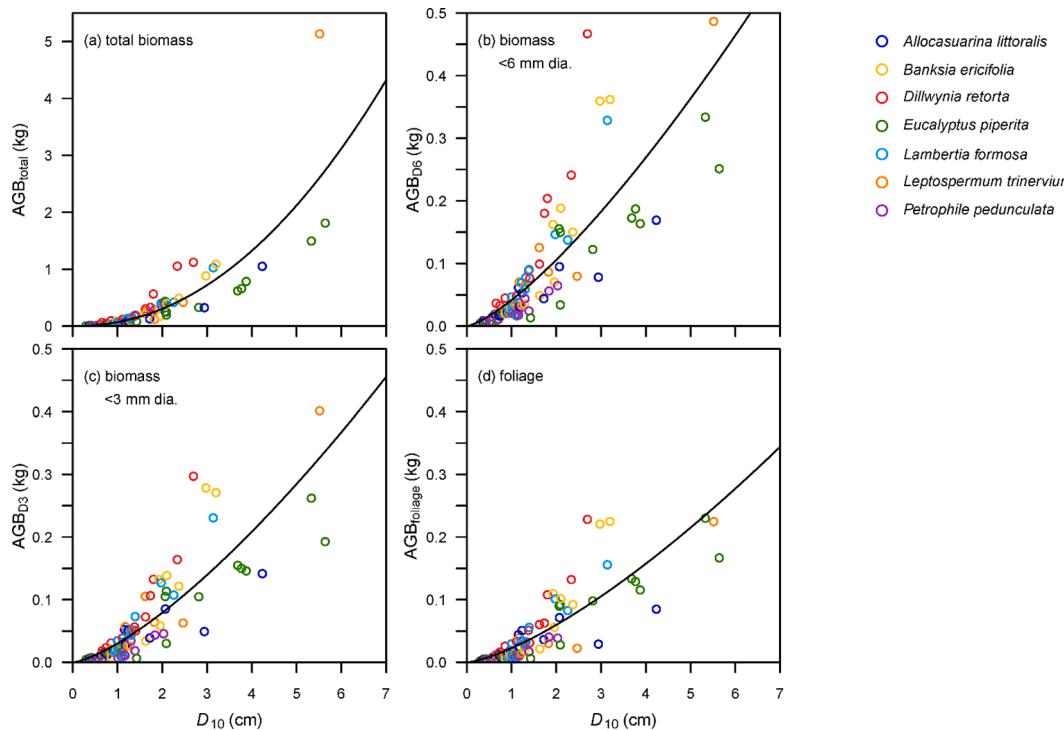


Fig. 3. Scatterplot of (a) total above-ground biomass (AGB_{total}); (b) above-ground biomass < 6 mm diameter (AGB_{D6}); (c) above-ground biomass < 3 mm diameter (AGB_{D3}); and (d) foliage (AGB_{foliage}) as a function of diameter at 10 cm height (D_{10}). Fitted lines are the weighted non-linear regressions for all species combined.

Table 3

Application of allometric equations to calculate total fine fuel mass and total above-ground biomass per plant.

Post-fire shrub canopy scores			Allometric equations	
Score	Canopy class	Description	For fine fuel mass ¹	For total biomass ¹
Foliage present				
1	Unburnt	Unchanged canopy fine fuel load.	AGB _{D6}	AGB _{total}
2	Canopy scorch < 50%	More than half the canopy is green. Scorched leaves retained on plant.	AGB _{D6}	AGB _{total}
3	Canopy scorch > 50%	Less than half the canopy is green (estimated ¼ of foliage has been consumed).	AGB _{D6} - $\frac{1}{4} \cdot AGB_{foliage}$	AGB _{total} - $\frac{1}{4} \cdot AGB_{foliage}$
4	Most of canopy consumed	>50% of canopy has been consumed (estimated ¾ of foliage has been consumed).	AGB _{D6} - $\frac{3}{4} \cdot AGB_{foliage}$	AGB _{total} - $\frac{3}{4} \cdot AGB_{foliage}$
No foliage present				
5	Twigs < 3 mm	Smallest branches remaining are < 3 mm in diameter.	AGB _{D6} - AGB _{foliage}	AGB _{total} - AGB _{foliage}
6	Twigs 3–6 mm	Smallest branches remaining are 3–6 mm in diameter.	AGB _{D6} - AGB _{D3}	AGB _{total} - AGB _{D3}
7	Twigs > 6 mm	Smallest branches remaining are > 6 mm in diameter.	NA, no fine fuel remaining	AGB _{total} - AGB _{D6}

¹ AGB_{total}: all above-ground biomass; AGB_{D6}: all above-ground biomass < 6 mm diameter (i.e. including foliage and twigs); AGB_{D3}: all above-ground biomass < 3 mm diameter (i.e. including foliage and twigs); AGB_{foliage}: mass of foliage only.

measurements of biomass (in kg) and fine fuel load (in t ha⁻¹). Stem count was also expressed as shrub density (stems ha⁻¹).

2.6. Statistical analyses

We examined whether allometric models developed using all species combined had similar accuracy to species-specific models. This was assessed by calculating the predicted biomass for each species using both the species-combined and species-specific models. For example, the difference in the root mean square error (Δ RMSE) for total above-ground biomass (AGB_{total}) for *Allocasuarina littoralis* was calculated as the RMSE for the species-combined model, subtracting the RMSE for the *A. littoralis* model.

To examine whether fine fuel mass is proportional to total biomass in shrubs, we fit a linear regression model of plot-scale fine fuel load (i.e. AGB_{D6} in t ha⁻¹) versus total above-ground biomass (i.e. AGB_{total}). We also fit a linear regression model of plot-scale fine fuel load versus total shrub basal area; and regressed the ratio of fine fuel load against total shrub biomass. This relationship was non-linear, and log-log transformations did not produce a linear relationship, similar to Duursma and Falster (2016). For this relationship we fit a generalized additive model (GAM) with a cubic regression spline (following Duursma and Falster, 2016). GAMs are a semiparametric modelling approach that make no assumptions about the shape of relationships.

Finally, we examined the relationship between post-fire shrub metrics and pre-fire shrub metrics, specifically total biomass (AGB_{total}), total fine fuel load (AGB_{D6}), stem density and stem basal area. We fitted linear regressions to these data.

All analyses were undertaken in R (Development Core Team, 2018).

3. Results

3.1. Shrub allometry

As expected, fine fuel mass and total biomass increased non-linearly with stem diameter for all species (Fig. 3). The non-linear weighted regression out-performed the log-linear regression (Table S1), with the best performing weighting being $1/D_{10}$ (rather than $1/D_{10}^2$; Table S1).

For all allometric models developed between D_{10} and (i) AGB_{total}, (ii) AGB_{D6}, (iii) AGB_{D3} and (iv) AGB_{foliage}, RMSE ranged from 0.01 to 0.08 (Table 4). Comparison of the species-specific models with the species-combined models indicated that the species-specific models performed similarly well, or better than the combined models (Table 4). Across species, the difference in RMSE between the species-specific models and the species-combined model ranged from -0.04 to 0.05. Where Δ RMSE is positive this indicates that the model fit of the species-combined is better than the species specific model. Thus, the species combined models performed similarly well or better than the species-specific

models.

3.2. What proportion of biomass constitutes fine fuel?

At the plot-scale, there was a significant, positive relationship between fine fuel load versus total shrub biomass (Fig. 4a) and fine fuel load versus total shrub basal area (Fig. 4b). At the plot-scale, the percentage of fine fuel to total shrub biomass ranged from 6 to 58%, and generally decreased with increasing shrub biomass (Fig. 4c).

3.3. Post-fire changes in shrub fine fuel loads and biomass

Post-fire estimates of shrub biomass changes following planned burns were highly variable (Fig. 5). As expected, the percentage loss of above-ground biomass (median of 2.3%) was generally much lower than the percentage loss of fine fuel mass (median of 22.4%, Table 1, Fig. 5a-b). Post-fire fine fuel loads and biomass largely reflected pre-fire values (Fig. 5a-b). Similarly, post-fire shrub density and basal area reflected pre-fire values (Fig. 5c-d). In most plots, we observed declines in shrub metrics (i.e. fine fuel load, biomass, stem density and basal area) following fire. However, some plots exhibited gains in shrub biomass, which typically occurred in the plots with few shrubs present (Fig. 5). These gains are most likely due to sampling error associated with re-measurement, rather than genuine increases in shrub biomass.

4. Discussion

Using destructively harvested shrubs, we demonstrated that fine fuel mass can be modelled as a function of stem diameter, similar to more commonly developed models of above-ground biomass. We found that the proportion of shrub biomass that was comprised of fine fuel mass at the plot scale varied considerably (from 6 to 58%, Fig. 4c). Post-fire reductions in plot-level biomass and fine fuel loads similarly exhibited wide variation (Table 1). Here, we discuss the development and application of these allometric models for modelling changes to fuel loads and carbon emissions due to fire.

4.1. Shrub allometry

Consistent with our hypothesis, we observed that fine fuel mass scaled with both stem diameter and total plant biomass (Figs. 3–5). These findings are consistent with universal scaling laws which predict that foliage mass or total biomass scales with plant height and stem diameter (West et al., 1999; Duursma and Falster, 2016; Paul et al., 2016). The results are also similar to those of Huff et al. (2017) and De Caceres et al. (2019) who developed models of fuel loads for shrubs in California and Spain, with crown area and shrub height as predictors.

We note that our allometric dataset contained very few shrubs with a

Table 4

Summary of above-ground biomass and fine fuel mass nonlinear weighted regressions, with model coefficients from Eq. (1), with standard errors in parenthesis. Δ RMSE represents the differences in RMSE between species-specific models and the species-combined model. Positive Δ RMSE values indicate that the model fit of the species-combined is better than the species specific model. All fitted coefficients were significant at $p < 0.05$.

Species and biomass model type ¹	<i>a</i>	<i>b</i>	RMSE (kg)	Δ RMSE
Total biomass (AGB _{total})				
Species combined	0.07 (0.01)	2.11 (0.13)	0.04	NA
<i>Allocasuarina littoralis</i>	0.04 (0.01)	2.16 (0.12)	0.04	0.00
<i>Banksia ericifolia</i>	0.05 (0.01)	2.63 (0.18)	0.04	0.00
<i>Dillwynia retorta</i>	0.10 (0.02)	2.50 (0.23)	0.08	-0.04
<i>Eucalyptus piperita</i>	0.05 (0.01)	2.09 (0.14)	0.07	-0.03
<i>Lambertia formosa</i>	0.07 (0.01)	2.35 (0.08)	0.03	0.01
<i>Leptospermum trinervium</i>	0.04 (0.01)	2.89 (0.12)	0.05	-0.01
<i>Petrophile pedunculata</i>	0.06 (0.00)	2.69 (0.12)	0.01	0.03
Biomass < 6 mm diameter (AGB _{D6})				
Species combined	0.04 (0.00)	1.34 (0.09)	0.06	NA
<i>Allocasuarina littoralis</i>	0.03 (0.00)	1.17 (0.11)	0.01	0.05
<i>Banksia ericifolia</i>	0.02 (0.01)	2.41 (0.32)	0.03	0.03
<i>Dillwynia retorta</i>	0.04 (0.01)	2.29 (0.23)	0.03	0.03
<i>Eucalyptus piperita</i>	0.03 (0.01)	1.33 (0.20)	0.04	0.02
<i>Lambertia formosa</i>	0.03 (0.00)	1.95 (0.12)	0.02	0.04
<i>Leptospermum trinervium</i>	0.04 (0.01)	1.51 (0.12)	0.03	0.04
<i>Petrophile pedunculata</i>	0.02 (0.00)	1.38 (0.17)	0.01	0.05
Biomass < 3 mm diameter (AGB _{D3})				
Species combined	0.03 (0.00)	1.40 (0.09)	0.04	NA
<i>Allocasuarina littoralis</i>	0.03 (0.00)	1.15 (0.14)	0.01	0.02
<i>Banksia ericifolia</i>	0.02 (0.00)	2.40 (0.32)	0.03	0.01
<i>Dillwynia retorta</i>	0.03 (0.00)	2.24 (0.18)	0.02	0.02
<i>Eucalyptus piperita</i>	0.02 (0.01)	1.34 (0.18)	0.03	0.01
<i>Lambertia formosa</i>	0.03 (0.00)	1.93 (0.14)	0.01	0.02
<i>Leptospermum trinervium</i>	0.03 (0.00)	1.55 (0.13)	0.02	0.02
<i>Petrophile pedunculata</i>	0.01 (0.00)	1.79 (0.28)	0.01	0.03
Foliage (AGB _{Foliage})				
Species combined	0.02 (0.00)	1.40 (0.09)	0.03	NA
<i>Allocasuarina littoralis</i>	0.02 (0.00)	1.01 (0.18)	0.01	0.02
<i>Banksia ericifolia</i>	0.01 (0.00)	2.50 (0.32)	0.02	0.01
<i>Dillwynia retorta</i>	0.02 (0.00)	2.28 (0.21)	0.01	0.02
<i>Eucalyptus piperita</i>	0.02 (0.01)	1.37 (0.18)	0.02	0.01
<i>Lambertia formosa</i>	0.02 (0.00)	1.95 (0.19)	0.01	0.02
<i>Leptospermum trinervium</i>	0.02 (0.00)	1.54 (0.17)	0.02	0.02
<i>Petrophile pedunculata</i>	0.01 (0.00)	1.85 (0.31)	0.01	0.03

stem diameter > 4 cm, and so caution should be applied if using our allometric models for shrubs that are larger than this. This issue is unlikely to affect our estimates of plot-level fuel loads and biomass produced by applying the equations to our plot-level shrub data, because < 5% of the 3732 measured shrubs were larger than 4 cm (Fig. S1).

The species-combined models generally performed similarly, or outperformed the species specific models (Table 4). These results indicate that the species-combined models can be used with confidence across different species within our study area. This is important since in many circumstances it is not feasible to develop species-specific models, due to the resources required for destructively harvesting plants across a range of stem sizes (Paul et al., 2016). Destructive harvesting is also not permissible in many protected areas, such as national parks. In addition to these practical constraints in developing species-specific models, there are also limitations to applying species-specific models when species identification is uncertain. Accurate species identification is a particular concern for assessments of post-fire biomass, where species identification can be challenging, if not impossible, due to loss of foliage and charring of stems. Thus, development and application of generalised biomass and fuel mass models are preferable to species-specific models under many circumstances.

While our allometric equations were developed for our local study region, allometric scaling relationships are often invariant across large climatic gradients (Duursma and Falster, 2016; Paul et al., 2016), which suggests our equations may be applicable outside of the area they were developed in. For example, both Paul et al. (2016) and Duursma and Falster (2016) observed that including climatic factors, such as mean annual temperature, mean annual precipitation or aridity, did not improve scaling relationships. Both studies concluded that, although climate may affect plant architecture and overall plant size, effects on allometric relationships are negligible. Duursma and Falster (2016) did, however, observe that scaling relationships varied across plant functional types, specifically evergreen angiosperms, evergreen gymnosperms and deciduous angiosperms. Further, in a study in North America, Duncanson et al. (2015) observed that allometric scaling relationships were spatially invariant, except in non-steady-state conditions. Thus, although our allometric models were developed within the Sydney Basin bioregion, they are likely to be robust in predicting fuel mass for shrubs in eucalypt forests and woodlands in different climatic zones, but not in vegetation with different plant functional types (e.g. gymnosperms). Further, these equations may not be as reliable in disturbed ecosystems. As discussed above, a key limitation on the application of our equations is the size range over which the equations were calibrated. Specifically, our equations may not be applicable to shrubs larger than 4 cm diameter.

4.2. Post-fire changes in shrub fuel loads and biomass

The observed losses in total shrub biomass following prescribed fire were generally small, given many models assume complete combustion during fire (Stenzel et al., 2019), with median losses of 2.3% (Table 1). These losses were much lower than those previously estimated following low intensity planned fires in eucalypt forests and woodlands, which have been estimated at 38% (Jenkins et al., 2016) and 24% (Volkova and Weston, 2013). However, there was wide variation in biomass losses across our study sites, including some sites with apparently gained biomass. These apparent gains in plot-level shrub biomass can be explained by the spatial variation in shrub size and density across our study sites, rather than any real increase in biomass through time. This spatial variation, when combined with minor changes in the placement of plots post-fire compared to pre-fire (e.g. <50 cm difference in plot centre) would account for these apparent increases in shrub density and basal area. These apparent gains in shrub biomass are most apparent in plots with low shrub biomass, indicating that future studies should either increase sampling effort or permanently mark plot boundaries. In our study, we marked the centre of the larger plot, but not the specific

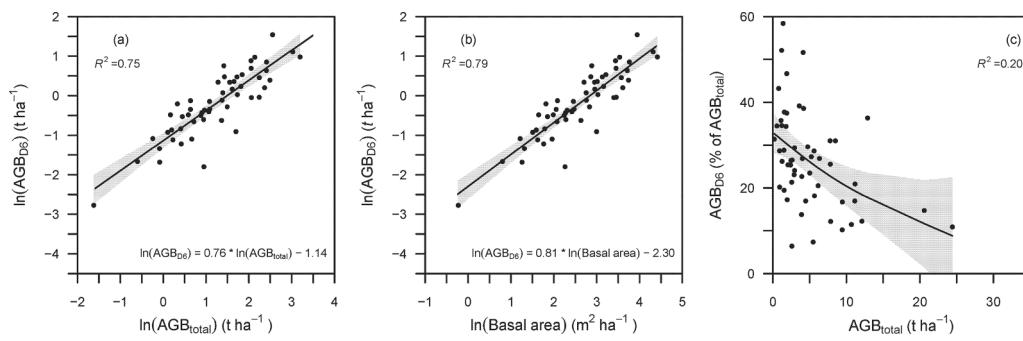


Fig. 4. Relationships between (a) fine fuel load (above-ground biomass < 6 mm diameter, AGB_{D6}) and total biomass (all above-ground biomass, $\text{AGB}_{\text{total}}$); (b) fine fuel load and plot-level basal area; and (c) the percent of fine fuel load as a function of total biomass. Data includes pre-fire observations only. Linear regressions with 95% confidence intervals are presented for (a) and (b), a GAM with 95% confidence interval is presented for (c).

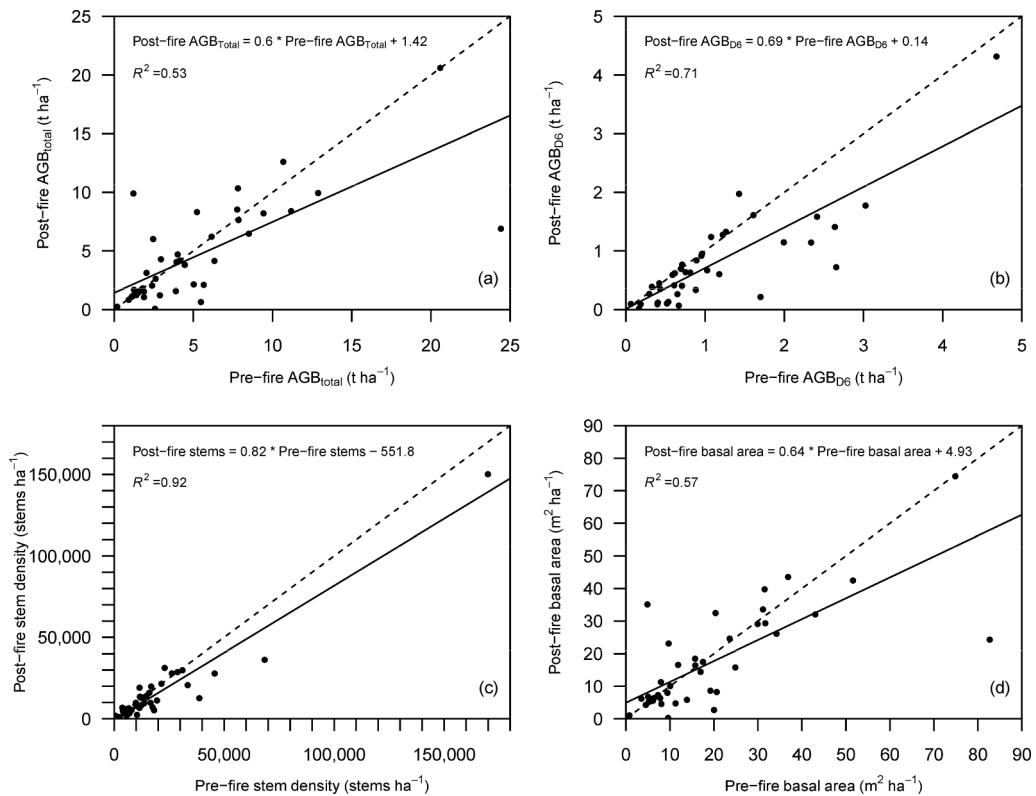


Fig. 5. Post-fire shrub metrics as a function of pre-fire shrub metrics, illustrating (a) biomass, (b) fine fuel loads, (c) stem density and (d) basal area. Solid lines represent fitted linear regressions, dashed lines represent the 1:1 line.

locations of the smaller sub-plots used to estimate shrub metrics. The observed wide variation in shrub biomass consumption is consistent with a previous study in eucalypt forests by Volkova and Weston (2013), who estimated that understorey carbon stock losses varied by 0.4–51% following low intensity planned burns. The large variation in shrub biomass losses is likely a function of pre-fire shrub size-class distributions. We observed that the median loss of shrub basal area (2.8%) was lower than the median loss of shrub density (23.1%; Table 1, Fig. 5c-d). These results indicate that many small shrubs, which contribute relatively little to total basal area, were likely completely consumed during fire. Thus, the plot-level magnitude of reductions in shrub biomass following fire is highly dependent on pre-fire shrub size and fire intensity.

Median shrub biomass loss was estimated at $< 1 \text{ t ha}^{-1}$. Given that total above-ground biomass in eucalypt forests has been estimated at 206–450 t ha^{-1} (Volkova et al., 2015; Jenkins et al., 2016), these

observed losses of shrub biomass following planned fires likely account for $< 0.5\%$ of total above-ground biomass. Carbon emissions from shrub consumption during planned fires is therefore relatively minor compared to total forest carbon stocks. However, several studies have demonstrated that much larger amounts of carbon are transferred from live carbon pools to dead and decomposing carbon pools following fire than is consumed during fire, resulting in carbon emissions over the years and decades following fire (Ghimire et al., 2012; Stenzel et al., 2019). For shrubs that resprout, such as those in our study area (Table 2), these long-term carbon emissions following fire are likely to be much lower compared to forests where species are fire-killed (Nolan et al., 2018). Taking into account the very low loss of shrub biomass due to fire, combined with the high survival rates during fire of resprouting shrubs, the impacts of planned burns on net carbon emissions is likely to be minor in our study sites.

Although observed changes in biomass following planned fires were

generally small, there were larger differences in fine fuel consumption (Fig. 5). While these results demonstrate that planned fires can reduce fuel loads substantially, fine fuel loads were never completely reduced to zero following fire (Fig. 5b). This is an important finding, since fuel accumulation curves which are developed to model fuel loads in eucalypt forests, often assume that fire reduces fine fuel loads to zero (e.g. Gould et al., 2011). Post-fire accumulation of shrub fuels may be more rapid than existing models suggest, if initial post-fire fuel loads are currently under-estimated. We note that we have not examined the long-term implications of planned burns on vegetation dynamics, with several studies indicating that fuel load recovery following planned fire can be rapid (Jenkins et al., 2016). Further, fire can stimulate vigorous shrub regeneration (Gordon et al., 2017).

4.3. Conclusions

Our study demonstrates that allometric relationships can be applied to model live fine fuel mass, similar to more commonly developed aboveground biomass models. These fine fuel models can be readily applied to: (i) field-based assessments of fuel loads, and (ii) existing models of above-ground biomass, including from LiDAR data (either from ground-based, aerial, or satellite LiDAR). Although the planned burns in our study resulted in large reductions in fine fuels, there were only small overall changes in above-ground biomass. This indicates that planned burns are compatible with the dual management goals of protecting forests for their carbon reserves, whilst reducing the risk of catastrophic fires within those forests.

CRediT authorship contribution statement

Rachael H. Nolan: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Owen F. Price:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Stephanie A. Samson:** Data curation, Methodology, Investigation, Writing – review & editing. **Meaghan Jenkins:** Conceptualization, Methodology, Writing – review & editing. **Simin Rahmani:** Investigation, Writing – review & editing. **Matthias M. Boer:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foreco.2021.119830>.

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