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Long-Term Effect of Prescribed Burning Regimes and Logging on Coarse Woody Debris in South-Eastern Australia

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Abstract: Coarse woody debris (CWD) is vital within forest ecosystems for an array of fauna. Forest management practices, such as prescribed burning and logging, influence the creation or loss of CWD. We examined the effect of long-term prescribed burning and logging on (i) the abundance of hollow-bearing CWD, (ii) the volume of CWD in different decay classes, (iii) the probability of hollow presence, and (iv) the size of hollows at a long-term (28 years) experimental site. Volume of CWD in moderate and advanced stages of decomposition decreased with increasing fire frequency while moderately decomposed material was higher in logged plots. The likelihood of a hollow being present increased with diameter and decreased when CWD was extensively charred. Hollow size was smaller when material was externally charred but larger when charring affected a pre-existing hollow. Increases in moderately decayed CWD reflect a pulse input of unmerchantable timber following the one-off logging event 28 years ago, though future loss of mature trees may lead to reduced input rates of woody debris in the future. Charring effects on hollow formation, increasing hollow size but decreasing overall presence, demonstrate the complex effect of fire on this resource. Our research highlights the need to develop a fundamental understanding of CWD input and loss dynamics in response to fire and logging in order to predict changes to this resource under a broad range of management scenarios.

Keywords: hollows; cavities; logs; fire frequency; temperate eucalypt forest; logging

1. Introduction

Fallen coarse woody debris (CWD) is an important habitat resource for a large range of taxa, including small mammals, birds, reptiles, fungi, and invertebrates [1,2]. CWD includes dead woody material in all stages of decay, resting on the ground or partially buried [3–5]. Hollows in CWD are used as shelter and breeding dens by mammals, amphibians, and reptiles [6,7]. Decayed CWD are foraging sites for insectivores and fungivores [1,6], and CWD provides movement pathways for mammals and reptiles [2]. Forest management practices, such as prescribed burning and logging, may create or remove CWD, potentially altering the availability of this resource [8–10]. There is limited research on the long-term effects of management practices on CWD, such as the sustained application of prescribed burning at short intervals (see [8] for an exception). Furthermore, there has been limited research on the long-term interactive effects of multiple management strategies, which may have important additive, opposing, or synergistic effects on CWD habitat.

Fire plays an important role in the creation and destruction of CWD and hollows. Injuries to trees as a result of prescribed burning or wildfire provide access for termites and fungi to standing trees, allowing the process of hollow formation to begin [11–13]. Importantly, the lack of vertebrate excavators (e.g., woodpeckers) in Australia, unlike many other regions of the world, means the presence of fire and saproxylic organisms is essential for hollow formation [14]. Furthermore, fire can excavate and increase the size of pre-existing hollows [11]. Tree collapse, which can occur due to factors such as fire and strong wind, provides a source of both CWD and hollows [11,15]. However, fire can also reduce the amount of CWD and hollows available through direct consumption during burning [4,16,17].

Prescribed burning is used to reduce fuel loads for asset protection and, to a lesser extent, to promote vegetation regrowth or habitat development for ecological purposes [18]. In eucalypt forests, the rapid accumulation of fuel requires burning to be conducted at short intervals (4–7 years) in order to maintain low fuel hazard [19,20]. As a result, production forests often implement recommendations for a regime of frequent low intensity fires, which can significantly affect plant and animal communities through simplification of understory vegetation, and direct mortality [19,21,22]. Previous research on the effects of fire frequency and CWD has largely focused on the volume or biomass of CWD available after fire [8,23] with little research on important habitat components such as hollows [9]. Bassett et al. [23] found a decrease in CWD volume with short inter-fire intervals while Aponte et al. [8] found a decrease in CWD biomass and changes to CWD chemical attributes through a repeated low-intensity prescribed fire regime. Collins et al. [9] found a higher likelihood of CWD containing hollows in areas experiencing 'low' compared to 'high' fire frequencies, though this study examined a mixed regime of both prescribed burning and wildfire in which burning was not experimentally manipulated. These studies reveal the need for experimental research on the response of CWD habitat to long-term regimes of frequent prescribed burning.

Logging can have a mixed effect on CWD, increasing input in the short term, but potentially reducing input in the longer term. Standard logging practices can create a pulse input of CWD into a system when unmerchantable timber (i.e., hollow or decayed trees) is left on the forest floor [9,24]. Logging practices in Australia typically involve post-harvest burns that are conducted to reduce fuel loads accumulated through logging slash (i.e., felled tree crowns and unmerchantable timber) and to stimulate regeneration of *Eucalyptus* seed [25]. The introduction of fire into these logged systems, either through post-harvest burns or prescribed burning, may reduce this pulse input and could lead to decreased CWD stocks in the future. Furthermore, decreased tree biomass as a result of logging may reduce CWD input over longer time frames [24,26].

Due to difficulties in manipulating fire at large scales over long periods, research on the impact of long-term frequent prescribed burning is rare. The Eden Burning Study Area (EBSA) is an example of a long-term experiment manipulating burning at scales relevant to operational fire management (i.e., 8–56 ha treatment coupes). The EBSA was established in 1986 with the aim of understanding how frequent prescribed burning and logging interact to affect forest ecosystems. The EBSA consists of a logging treatment (unlogged and logged at the start of the experiment) and a prescribed burning treatment, covering a range of fire frequencies (0–4 fires), replicated across the landscape [27].

Our study aimed to use the EBSA to examine the effect of frequent prescribed burning and logging on (i) the abundance of hollow-bearing CWD, (ii) the total volume of CWD, (iii) the volume of CWD in different decay classes, (iv) the probability of hollow presence within CWD, and (v) the size of hollows. We hypothesised that (a) repeated prescribed burning following logging would create a synergistic effect resulting in a decline in CWD, and (b) that unmerchantable timber left by logging would contain a greater abundance of hollows which, when burnt by low intensity fire, would increase in size.

2. Materials and Methods

2.1. Study Area and Experimental Design

The EBSA covers 1080 ha within Yambulla State Forest, 29 km southwest of Eden, south-eastern Australia (37°14′ S, 149°38′ E). The EBSA was established with three replicate coupes/experimental blocks randomly distributed for each of six treatments. Treatment coupes/experimental blocks range in size from 8 to 56 ha with an average size of 32 ha [27].

Experimental treatments involved combinations of two logging treatments, which included a one-off logging event ('logged') or no logging ('unlogged') and three burning treatments, which included no burning ('unburnt'), burning at 4-year intervals ('routine') and burning at 2-year intervals ('frequent'). However, due to operational and weather delays, the proposed burning treatments of 4- and 2-year intervals is no longer reflected in the fire history of the coupes [28]. Logging involved an integrated operation that selectively removed saw-logs and pulp logs for woodchipping, with approximately 30% of pre-harvest over-storey basal area being retained, as was routine practice at the commencement of the study. Logged sites were harvested between November 1987 and April 1988 [28]. A post-logging burn was applied following harvest in 1988 to each of the logged coupes that were assigned to the routine and frequent burning treatments. Prescribed burning treatments commenced following the implementation of the logging treatments. Prescribed fires have been extremely patchy and heterogeneous during the study, with coupe burning ranging from 6% to 90% of the planned area [28]. Consequently, fire frequencies achieved in the study were lower than planned and varied across sites within the burnt coupes [28]. As a result of the patchy prescribed burns, fire frequency was derived at the plot scale rather than the broad experimental treatments. Plot scale fire frequency was obtained from the Forest Science Unit, NSW Department of Primary Industries. Following each fire, ten 4-m circular quadrats per reference plot were assessed for fire occurrence [28]. The proportion of these ten quadrats burnt by each fire was calculated and summed over the duration of the experiment for each reference plot to derive a measure of fire frequency incorporating fire patchiness.

To survey a range of vegetation and faunal characteristics, six permanently marked reference plots were established in each coupe prior to the implementation of logging and burning treatments, giving a total of 108 plots (see [27] for further details on the study site). These overstorey reference plots were 20-m radial plots originating from a marked site midpoint.

2.2. Coarse Woody Debris and Hollow Surveys

Seventy of the initial 108 reference plots were surveyed between January–May 2015 using a 25 m × 25 m quadrat centred around the site midpoint, oriented with the predominant aspect. Four sites per treatment coupe were selected to represent a full range of fire frequency across the logging treatments on ridgetops and slopes. Three sites did not use the site midpoint as the quadrat centre, due to the close proximity of the midpoint to a fire trail. In these circumstances, the midpoint was located 20–25 m from the fire trail. CWD was defined as any piece of fallen timber greater than 10 cm in diameter and 50 cm in length. Every piece of CWD with more than half its total length within a plot was measured. For all CWD meeting these criteria, the length as well as the large- and small-end diameters were measured.

CWD were assessed for decomposition using a visual and tactile assessment adapted from Williams and Faunt [29] and Bunnell and Houde [1] and modified to suit the *Eucalyptus* species present in the Eden region (Table 1). CWD were assessed for fire damage based on the overall percentage of charring on the visible area of the piece, as per Williams and Faunt [29] (Table 1). Each piece of CWD was assessed for hollows with an entrance width ≥ 2 cm and a minimum hollow depth of 10 cm, as these dimensions are representative of tree hollows suitable for fauna [30]. CWD volume (m^3) was estimated using a modified Smalian's formula [31], accounting for the internal hollow volume:

$$\text{Volume} = (\text{Length} \times (\pi \times (\text{LDIAM} \times 0.5)^2 + \pi \times (\text{SDIAM} \times 0.5)^2)/2) - (\text{Depth} \times (\pi \times (\text{Width} \times 0.5)^2 + \pi \times (0.02 \times 0.5)^2)/2) \tag{1}$$

where length is the total length (m) between each diameter, LDIAM is the large-end diameter (m), SDIAM is the small-end diameter (m), Depth is the hollow length (m), and Width is the hollow entry width (m). As the end diameter of each hollow could not be measured, hollow volume calculations have assumed a minimal diameter of 0.02 m (as per the 2 cm habitat requirement; [30]). CWD with multiple hollows or connected hollows were accounted for in the calculation.

Along with hollow entry diameter and depth, internal hollow charring was scored (1–3) based on the severity of fire damage (Table 1). We distinguished between external CWD charring and internal hollow charring due to the different effects these can have on CWD. Fire can alter the external characteristics (e.g., length, width), as evidenced by external charring. However, fire may expand hollows by consuming internal material, as evidenced by internal charring [32]. These two fire effects are of ecological importance as they can affect not only CWD availability and structural integrity, but also affect hollow suitability and availability for many hollow dependant organisms [33,34].

Table 1. Description of coarse woody debris (CWD) and site variables used in the study.

Variable	Variable Code	Description
Log variables		
Small-end Diameter	SDIAM	Small-end diameter (cm).
Large-end Diameter	LDIAM	Large-end diameter (cm).
Length	LEN	Length (to nearest 10 cm) from LDIAM to SDIAM.
Decay state *Adapted from Williams and Faunt* [29] *and Bunnell and Houde* [1]	DEC	Decay State of CWD (1–5) 1: Freshly fallen, bark intact, no cambium/sapwood can be pulled off. 2: No bark, small amounts of cambium/sapwood pulled off, full structural integrity. 3: Can pull moderate pieces of cambium or sapwood apart, will show bending when pressure is applied, fissures present. 4: Large pieces of cambium or sapwood can be pulled off, log will maintain shape but collapse under pressure. 5: No structural integrity, log has collapsed on itself.
CWD Fire Damage *Adapted from Williams and Faunt* [29]	EXCHAR	Amount of fire damage across the whole piece (none, low, high). None: ≤1% surface area fire damage; Low: >1–25%; High: >25%.
Hollow Entry Width	WIDTH	Minimum entry width of hollow (cm). Hollows tapering in to smaller entry size within 10 cm of initial entry will be measured at the smallest entry size.
Hollow Depth	DEPTH	Hollow depth (cm) measured from hollow entry to the end of hollow.
Internal charring	INCHAR	Internal charring of hollow (none, low, high) None: No sign of charring; Low: ≤2 mm of charring; High: >2 mm of charring, chunks of charcoal visible.
Site variables		
Fire Frequency	FREQ	Continuous measure of prescribed burn frequency that incorporates fire patchiness at the site scale since 1986. Calculated as the sum of the proportion of a site burnt following each prescribed burn over the course of the experiment. See Penman et al. [28] for this method. Frequency—0–4.0 fires.

Table 1. *Cont.*

Variable	Variable Code	Description
Logging Treatment	LOGT	Amount of timber removed from a site, categorised as a nominal factor. Unlogged: 0 m^2/ha; Logged: >0 m^2/ha.

2.3. Statistical Analysis

The influence of fire frequency and logging on CWD was assessed at two different scales: the site level and individual piece level. For the site level, the effect of fire frequency and logging on the abundance of hollow-bearing CWD, total volume of CWD, and volume of CWD in different decay classes was examined to establish how management practices influence the availability of CWD. The individual piece level analysis examined the effect of CWD characteristics (decay, charring etc.) and site variables on the presence and size of hollows to determine important characteristics for hollow formation and size that can be modified by prescribed burning and logging.

In all analyses, logging was treated as a categorical factor, whereas fire frequency was treated as a continuous variable in all analyses, except for the charring analysis, where it was categorised (Table 1). The decay index was reclassified into three categories: low decay (decay 1–2), moderate decay (decay 3), and highly decayed (decay 4–5).

Linear mixed effects models (LMEs) were used to analyse the effect of logging and fire frequency on the volume of CWD and the abundance of hollow-bearing CWD per site. Logging and fire frequency were treated as fixed effects. Treatment coupe was included as a random effect to account for the nested hierarchical nature of the experimental design (i.e., sites were nested in treatment coupes). All possible combinations of logging and fire frequency and their interaction terms, as well as the intercept only model (i.e., 'null model'), were assessed using Akaike's Information Criterion, corrected for small data samples (AICc). The model with the lowest AICc score was considered to provide the best fit while penalising for complexity, while models within two AICc points of the best model were considered as plausible alternatives [35]. A square root transformation was applied to the number of hollow-bearing CWD and a logarithmic transformation was applied to all CWD volume analyses in order to satisfy the assumption of normality.

The probability of hollow presence in CWD was analysed using generalised linear mixed models (GLMMs) with a binomial distribution following approaches used by Fox et al. [36] and Collins et al. [9]. Changes in hollow size were analysed using LMEs. Site and treatment coupe were specified as random effects in all models to account for the nested hierarchical nature of the experimental design (i.e., CWD were nested within sites, which are nested within treatment coupes). Models were fit in a two-step process. First, all possible combinations of CWD diameter, decay, and external charring and their interactions were assessed using AICc, as described above, to determine how these CWD characteristics influence hollow presence. Secondly, the most influential suite of CWD characteristics (i.e., those contained in the 'best' model in the first step) were then modelled with fire frequency, logging, and their interaction to understand how fire frequency and logging influence characteristics and hollow presence. Model selection followed the same procedure outlined above, however, greater emphasis was placed on the statistical significance of variables, due to limitations in the use of AICc for GLMM model selection [37]. This allows us to have confidence that the preferred model contains the variables that were the most influential in determining hollow presence. Predicted values were plotted for the preferred model. For the hollow size analysis, a subset of CWD containing hollows (n = 524) was used. Model selection followed the same two-step process as the hollow presence analysis, with the inclusion of internal charring as an added characteristic. A logarithmic transformation was applied to hollow diameter to satisfy normality assumptions.

The effect of fire frequency on the probability of charring on CWD was assessed using two GLMMs for no charring and low vs. high charring, each with a binomial distribution. No charring was modelled as the number of successes/failures for its category compared to the rest of the data set, therefore modelling at the scale of the individual log. The low vs. high charring analysis was conducted as a binomial analysis to compare the difference in response to fire frequency between the charring categories. Fire frequency was included in the model as a fixed effect; however, the "nofire" category was excluded from analyses due to a high number of zero data points for charred CWD pieces in the unburnt plots. All analysis and modelling was conducted using R [38]. GLMM analysis was undertaken using the 'lme4' package while LME analysis was undertaken using the 'nlme' package following procedures outlined in West et al. [39]. LMEs were assessed for normality using quantile plots and homogeneity of variance was assessed using visual assessment of residual plots. Post hoc Tukey's Honest Significant Difference (HSD) analysis was run between categories, within factors, to determine significant differences between categories for LMEs. Tukey's analysis was undertaken using the 'multcomp' package following procedures outlined in Bretz et al. [40].

3. Results

A total of 1663 pieces of CWD were measured during the study with 524 (31.5%) containing hollows. The number of hollow-bearing CWD per site ranged from 1–21 with an average (±SE) of 7.49 ± 0.52. The average length was 390.88 ± 8.55 cm with an average large-end diameter of 21.61 ± 0.36 cm and small-end diameter of 13.69 ± 0.26 cm. The average volume of CWD per plot was 67.79 ± 6.50 m^3 ha^{-1}. The mean volume of CWD in low decomposition states (decay index 1 and 2) was 39.94 ± 4.67 m^3 ha^{-1}, moderate decomposition states (decay index 3) was 19.64 ± 2.76 m^3 ha^{-1}, and high decomposition states (decay index 4 and 5) was 5.67 ± 1.22 m^3 ha^{-1}.

The intercept-only model had the lowest AICc for the abundance of hollow-bearing CWD, indicating that there was no effect of fire frequency or logging on abundance. There was one competing model containing logging, however, the effect of logging was not significant (Table 2). Similarly, the intercept-only model had the lowest AICc for the total volume of CWD and the volume of CWD in low states of decay. In each analysis there was one competing model containing logging or fire frequency, respectively. Neither logging or fire frequency was significant. As a result, the null model was selected and we concluded that logging and fire had no effect on these variables (Table 2).

Table 2. Summary of the competing models from the Akaike's Information Criterion (AICc) multi-model comparison. Models within 2 AICc points were considered as plausible alternatives. W is the weight each model carries, presented as a proportion. All variable codes are listed in Table 1. Selected models are underlined.

Response Variable	Model Terms	AICc	ΔAICc	W
CWD Volume	<u>NULL</u>	763.3	0.00	0.449
	LOGT	764.7	1.37	0.226
Hollow-Bearing CWD	LOGT	409.1	0.00	0.424
	<u>NULL</u>	409.8	0.76	0.290
High Decay	<u>FREQ</u>	199.6	0.00	0.618
Moderate Decay	<u>LOGT + FREQ</u>	192.0	0.00	0.640
	LOGT + FREQ + LOGT × FREQ	193.3	1.30	0.334
Low Decay	<u>NULL</u>	198.3	0.00	0.398
	FREQ	198.7	0.40	0.326
Hollow Presence	<u>EXCHAR + DEC + LDIAM + DEC × LDIAM</u>	1811.4	0.00	0.791
Hollow Size	EXCHAR + DEC + INCHAR + LDIAM	1018.5	0.00	0.478
	EXCHAR + DEC + INCHAR + LDIAM + DEC + LDIAM	1019.7	1.18	0.265
	<u>EXCHAR + INCHAR + LDIAM</u>	1020.0	1.53	0.222

The best model to explain variation in the volume of highly decayed CWD contained fire frequency as the only predictor variable (Table 2). The volume of CWD in high states of decay decreased with increasing fire frequency, with the model explaining 21.2% of the variation (Figure 1, Table 3).

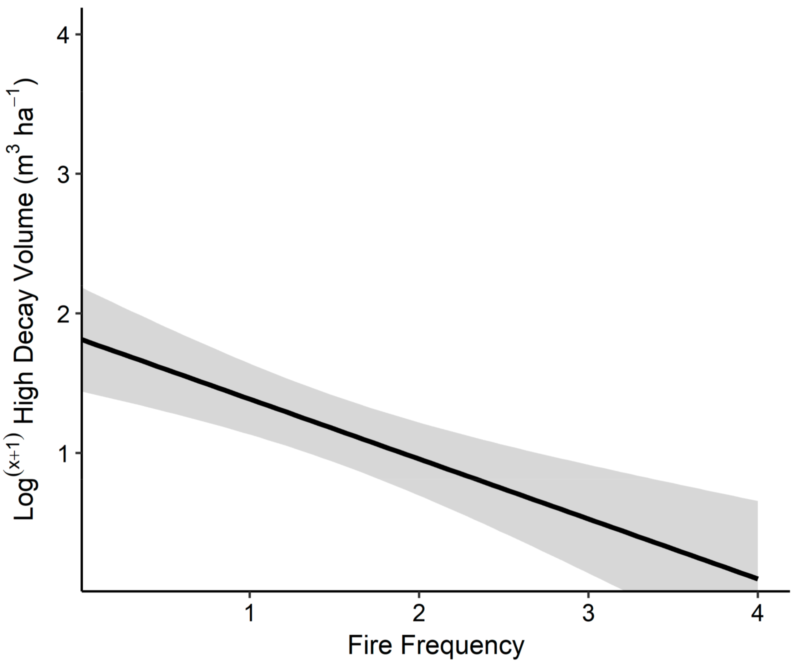

Figure 1. The effect of fire frequency on volume of CWD in high decay states (±95% confidence intervals). Volume of CWD in high states of decay was transformed using a log(x+1) transformation. R^2 = 0.212.

Table 3. Coefficients for the preferred model in each analysis. The coefficient estimate presented for each factor is the difference from the reference level (intercept). Model terms not connected by the same letter represent statistical difference ($p < 0.05$) between categories within a factor, based off Tukey's HSD.

Model Terms	Coefficient	SE	Test Statistic	*p*-Value
High Decay			***t*-value**	
Intercept	1.817	0.191	9.533	0.000
FREQ	−0.429	0.101	−4.244	>0.001
Moderate Decay				
Intercept	3.218	0.203	15.831	0.000
FREQ	−0.346	0.095	−3.632	0.0007
LOGT	−0.704	0.228	−3.082	0.0034
Hollow Presence			***z*-value**	
Intercept	−1.857	0.178	−10.421	>0.001
LDIAM	0.053	0.007	7.850	>0.001
DEC (low)				
DEC (mod)	0.920	0.265	3.69	>0.001
(high)	0.468	0.379	1.237	0.216
EXCHAR (none) [a,b]				
(low) [a]	0.231	0.144	1.602	0.109
(high) [b]	−0.379	0.171	−2.214	0.027
LDIAM:DEC (low)				
LDIAM:DEC (mod)	−0.023	0.011	−2.128	0.033
(high)	−0.027	0.013	−2.135	0.032

Table 3. *Cont.*

Model Terms	Coefficient	SE	Test Statistic	*p*-Value
Hollow Size			***t*-value**	
Intercept	−0.150	0.152	−0.988	0.324
LDIAM	0.716	0.047	15.159	>0.001
EXCHAR (none) [a]				
(low) [b]	−0.163	0.064	−2.544	0.011
(high) [b]	−0.292	0.080	−3.636	>0.001
INCHAR (none) [a]				
(low) [b]	0.166	0.070	2.356	0.020
(high) [b]	0.216	0.066	3.253	0.001
No Char			***z*-value**	
Intercept	0.320	0.252	1.267	0.205
FREQ (low) [a]				
(moderate) [b]	−1.300	0.2165	−6.006	>0.001
(high) [b]	−1.125	0.2216	−5.077	>0.001
Low vs. High Char			***z*-value**	
Intercept	0.417	0.231	1.808	0.071
FREQ (low) [a]				
(moderate) [a]	−0.153	0.2543	−0.601	0.548
(high) [a]	−0.0983	0.2548	−0.386	0.699

The best model to explain variation in the volume of moderately decayed CWD contained fire frequency and logging as additive effects (Table 2). The volume of moderately decayed CWD was lower at unlogged sites than logged sites (Figure 2, Table 3), whilst decreasing consistently with increasing fire frequency. This model explained 27.2% of the variation in the data. No significant interaction between logging and fire frequency was present for CWD in moderate states of decay.

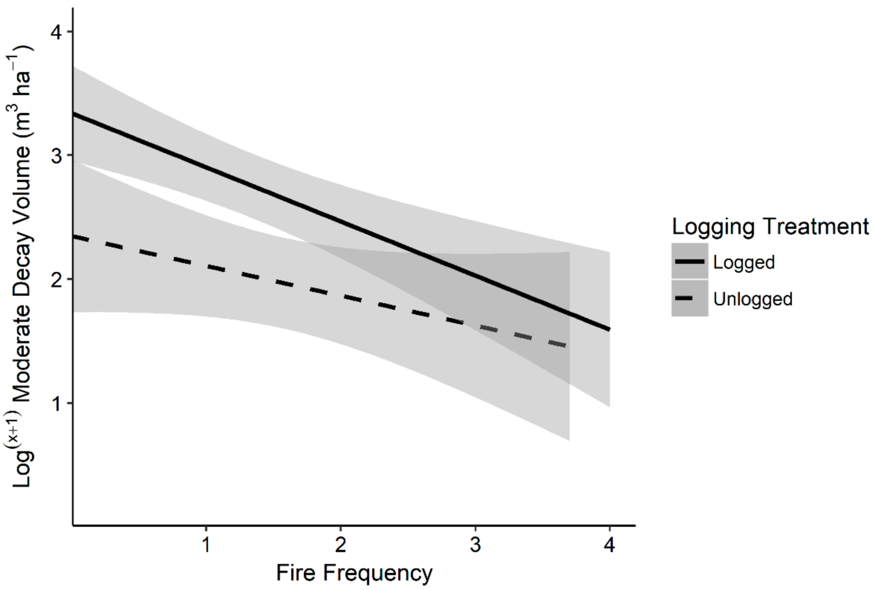

Figure 2. The effect of logging and fire frequency on the volume of CWD in moderate states of decay (±95% confidence intervals). Moderate decay volume was transformed using a log(x+1) transformation. Logging treatment and fire frequency are additive effects and not interactive. R^2 = 0.273.

Fire frequency had a significant effect on the degree of external charring on CWD (Table 3). The probability that a piece of CWD was uncharred was higher on sites experiencing low fire frequency than sites experiencing moderate or high fire frequencies (Table 3). Low and highly charred CWD saw higher probabilities of occurrence with moderate and high fire frequencies, however, both low and highly charred CWD were not statistically different in their response to fire frequency (Figure 3).

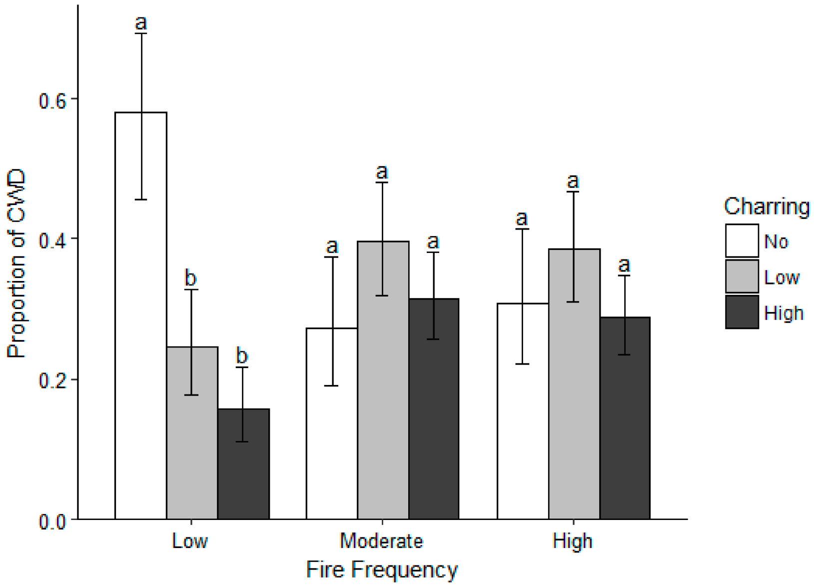

Figure 3. The effect of fire frequency on the mean proportion (±SE) of CWD with different levels of charring. The "nofire" category of fire frequency was removed from this analysis due to skewed data from the lack of charred CWD in "nofire" treatments. Bars in each graph not connected by the same letter represents statistical difference ($p < 0.05$), based off Tukey's HSD within each level of fire frequency.

The best model for the probability of hollow presence contained large diameter, decay, external charring, and the interaction term between large diameter and decay (Table 2). The inclusion of logging and fire frequency did not improve model fit. At small diameters (<30 cm) the probability of hollow presence was lower in CWD with low decay states, but at large diameters (>35 cm) the probability of hollow presence was higher in low decayed CWD (Figure 4a; Table 3). The probability of hollow presence was lower in highly charred CWD (>25% charred surface area) than in CWD with low and no charring (Figure 4b). Regardless of external charring and decay, the probability of hollow presence increases with an increase in large-end diameter.

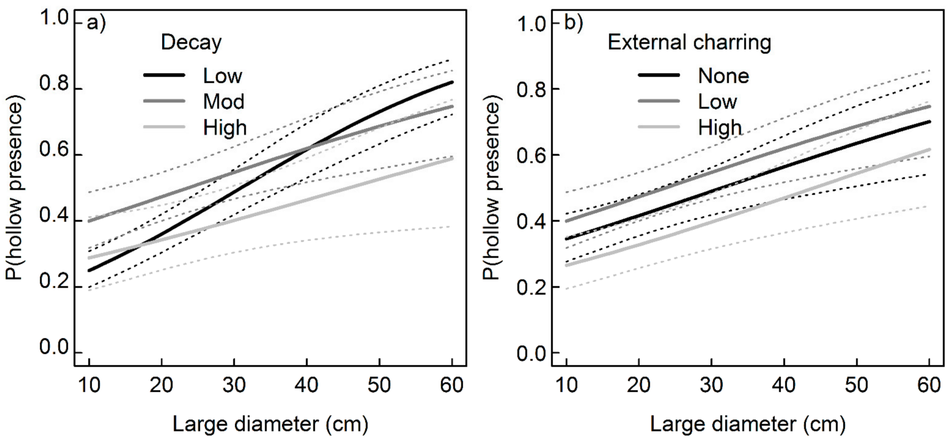

Figure 4. Model predictions showing the effect of (**a**) log decay and (**b**) log charring on the probability of a hollow being present. Predictions are based off the preferred model from AICc model selection. Broken lines represent 95% confidence intervals.

The best model to explain variation in hollow size contained external charring, internal charring, and large diameter. There were two competing models within two AICc points of this model, each containing additional variables: decay and the interaction between decay and large diameter (Table 2). As these additional variables had no significant effect, they were excluded. Hollow size was significantly larger in CWD that had no external charring (≤1% charred surface area) than in charred CWD (Figure 5a; Table 3). Differences in hollow size due to external charring were greater at higher diameters. Hollows with internal charring were significantly larger than those that were not charred internally (Figure 5b). Regardless of external charring or internal hollow charring, hollow size increased significantly with increasing large-end diameter.

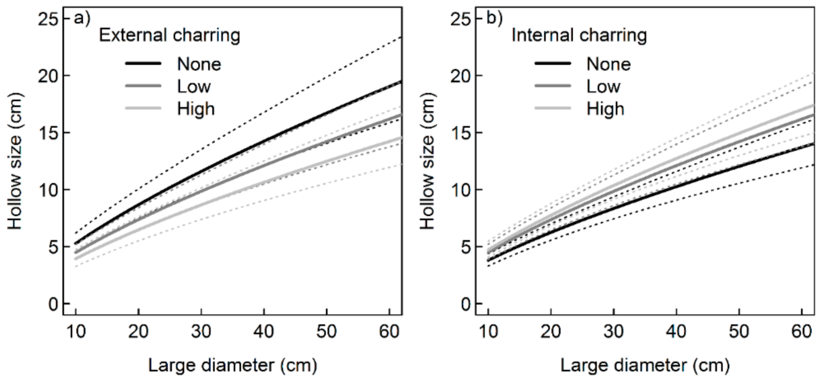

Figure 5. Model predictions of the effect of (**a**) log charring and (**b**) internal hollow charring on hollow size. Predictions are based off the preferred model from AICc model selection. Broken lines represent 95% confidence intervals.

4. Discussion

The long-term management regimes of one-off timber harvesting followed by frequent prescribed burning implemented at the Eden Burning Study Area had numerous impacts on CWD. The volume of moderately decayed CWD was the only parameter showing a clear response to both the harvesting and burning treatments, being greater in harvested plots and lower with increasing fire frequency. This result partially supports our first hypothesis, as logging and repeated prescribed burning influenced the volume of moderately decayed CWD, but additively, not synergistically. The volume of highly decayed CWD showed a clear reduction with increasing fire frequency. The size and presence of hollows in CWD were influenced by fire (i.e., the degree of external and internal hollow charring), though there was no direct correlation with fire frequency recorded at a plot. However, CWD in frequently burnt plots had a higher probability of charring than CWD in less frequently burnt plots, thus showing an indirect link between frequent prescribed burning and hollow characteristics. Our hypothesis was supported by this finding, as low intensity burns did increase hollow size (albeit indirectly), however, logging showed no effect on hollow abundance. These findings indicate that CWD habitat will be responsive to fire and logging, though effects are complex and are probably dependent on the effect of these disturbances on both CWD and standing trees (i.e., the source of CWD input).

The volume of CWD present in the Eden Burning Study Area is higher than most comparable forests, however, this is likely a product of the one-off harvesting event and the patchy heterogeneous burns. The mean CWD volume of 67.79 $m^3\ ha^{-1}$ in this study is greater than presented values of other temperate forests of Australia (0.03–31.04 $m^3\ ha^{-1}$ [9]; approximately 20 $m^3\ ha^{-1}$ [23]). However, a similar experiment presented by Aponte et al. [8] had an almost identical mean volume of 68 $m^3\ ha^{-1}$ in its experimental plots, while the long unburnt plots presented were much higher at 96 $m^3\ ha^{-1}$. Northern American boreal (42.3 $m^3\ ha^{-1}$) and subtropical (50.4 $m^3\ ha^{-1}$) floodplains are lower than our presented value, while temperate floodplains are considerably higher (116.3 $m^3\ ha^{-1}$) [41].

The reduction in CWD volume in moderate and high decay states with increasing fire frequency supports the findings of an experimental approach in a similar forest: the Wombat State Forest Experiment [8]. The Wombat State Forest Experiment aimed to investigate the long-term effects of frequent prescribed fires (unburnt, 10-year intervals, 4-year intervals) and season of burning (spring vs. autumn) in a southern Australian temperate eucalypt forest [8,42].

The greater volume of moderately decayed CWD on logged sites compared to unlogged sites is likely to represent the pulse input of logging debris, in the form of unmerchantable timber left onsite, during the harvesting treatments [9,24]. This suggests that a single logging event provides a one-time benefit in increasing CWD which has likely reached a moderate state of decay in the ~30 years since logging. However, the removal of large trees by logging may reduce inputs of CWD in the future. Future CWD loads (particularly large CWD) will be highly dependent on the dynamic between CWD loss (decomposition processes, fire consumption, etc.) and creation (tree growth, tree collapse, limb breakage, etc.), the latter of which may be hindered by the removal of existing large trees by the previous logging. Our study investigated a logging practice that removed both saw-logs and pulp for woodchips, but further intensification of CWD removal (e.g., biofuel, firewood, etc.) would need to consider the potential for depletion of CWD in the future [43].

The increased likelihood of hollow presence with CWD size reflects established relationships between tree size and tree hollow occurrence, whereby larger trees are more likely to contain hollows [36,44]. Therefore, maintaining a supply of hollow trees will be important for maintaining hollow CWD stocks, which will be potentially compounded by inappropriate logging regimes. To mitigate this, tree retention in net logging zones is required at the scale of individual trees, interspersed with buffers (informal reserves) where logging is excluded [45]. As CWD size increases, we see a lower probability of hollow presence in highly decayed CWD than in low and moderately decayed CWD due to reduced structural integrity at high decay stages. High surface area-to-volume ratios in large CWD means it is less likely to retain shape and hence collapse [5], particularly when considering decreased rigidity due to decay. CWD with high external charring had a lower likelihood of hollow presence, which is probably due to fire reducing CWD form and destroying existing hollows via consumption [29].

Charring influenced hollow size in contrasting ways, depending on the degree of charring to the external or internal (i.e., within hollows) surfaces of CWD. Smaller hollows were present in CWD with high amounts of external charring, possibly reflecting the destruction of larger hollows when CWD is burned by fire. Conversely, high levels of internal hollow charring led to greater hollow diameters, possibly due to hollow expansion by fire in standing trees [32]. The same pattern has been observed in other temperate eucalypt forests [9]. While we were unable to detect a direct effect of fire frequency on CWD hollow availability or size, the increased proportion of charred CWD in frequently burnt sites (Figure 3) suggests that there is the potential for frequent burning regimes to reduce hollow availability. Furthermore, other characteristics of fire not examined in our study, such as fire severity or post-burn weather, which will affect CWD smouldering time, may be more important than the frequency of low intensity prescribed burns in determining the destruction and creation of hollows in CWD.

Our findings suggest low intensity prescribed burning may have implications for fungivorous and insectivorous fauna, as spatial patterns of highly decayed CWD alter the availability of saproxylic fungi and invertebrates [2,46]. Materials in late stages of decay are known to have a larger community of fungi, including not only early successional fungi such as brown and white rot fungi, but also other taxa such as mycorrhizae and litter decomposing fungi [47,48]. While not completely known at this stage, it can be surmised from other research that the extent of CWD charring may also have implications on fungal community composition, providing alternative substrate conditions [49]. As a result, maintaining large volumes of CWD across different decay stages and charring conditions is likely to allow for an abundant, and possibly more diverse, community of fungi, thus supporting fungivorous invertebrates and vertebrates. Furthermore, spatial patterns of decayed logs and uncharred logs may have important implications for hollow-dependent mammals and reptiles, due to changes in the availability and quality of hollows [2,7,50,51], and many litter-dwelling invertebrates [52]. Future research should focus on determining at what levels/availability these resources are limiting for fauna and how the use of logs by fauna is affected by charring.

5. Conclusions

Low intensity, patchy burns present in the EBSA decreased decayed CWD and increased the abundance of charred CWD, whilst charring significantly decreased the probability of hollow presence, compared to CWD without charring. Williams and Faunt [29] suggest that low to moderate intensity burns (frequent prescribed burns or wildfires) can promote hollow formation (supported by our results), whilst high intensity burns may destroy CWD and hollows, suggesting mitigation of high intensity burns by prescribed burning may be advantageous for this resource. However, for more effective management of CWD it is important to address the gap in knowledge regarding fire and logging effects on the inputs and losses of CWD. Characterizing this is fundamental to understanding or predicting changes to CWD stocks in response to fire or logging regimes. With fire regimes predicted to change in response to a changing climate, increasing our fundamental knowledge of CWD dynamics will assist in the management of this important habitat resource.

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