Collapse rates of hollow-bearing trees following low intensity prescription burns in the Pilliga forests, New South Wales

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Hollows in trees are recognized as a critical and threatened resource for a wide range of fauna in Australian forests and woodlands, yet little data are available on the impact of fire on hollow-bearing trees. We report an opportunistic, post-fire assessment of the proportion of burnt, hollow-bearing trees that collapsed in stands near roads following low intensity prescription burns in three areas of mixed eucalypt forest in the Pilliga forests. Mean collapse rates on 29 plots (40 by 50m), separated by burn Area, ranged from 14–26% for a total of 329 burnt hollow-bearing trees. Collapse rates on individual plots ranged from 0–50%. Collapsed, hollow-bearing trees were predominantly older, with 40% of senescent trees and 44% of live stags collapsing. The best predictor in models of tree collapse was the presence of a basal fire entry point. We cannot determine the extent to which collapse rates on our plots are representative of burnt areas away from containment roads due to sampling limitations, but they appear to be higher than those reported from wildfire and more intense prescription burns in southern Australia. Our results point to an urgent need for comprehensively designed studies to address the impacts of prescribed burns on hollow-bearing trees.

Key words: hollow-using fauna; fire; prescription burn; forest management; tree hollows, Australia.

INTRODUCTION

HOLLOW-bearing trees are a critical resource for fauna but they are now scarce in many landscapes dominated by agriculture (Gibbons *et al.* 2008b), as well as in some forests and woodlands, such as the box-ironbark forests (Soderquist 1999; Adkins 2006) and box woodlands (Bennett *et al.* 1994) of northern Victoria. Their numbers continue to be depleted by clearing, logging, fire, removal of firewood, wind throw, drought, disease and senescence, but the formation of hollows suitable for use by fauna, particularly the larger hollows, requires centuries (Mackowski 1984; Wormington *et al.* 2003). Tree age cohorts in many landscapes are now dominated by young and old trees (e.g. Gibbons *et al.* 2008b), and a critical shortage of hollows is predicted in the near future (Lindenmayer *et al.* 1997; Vesk and Mac Nally 2006). Recognition of these threats is reflected in decisions in several States: the Victorian *Flora and Fauna Guarantee Act 1988* listed *Loss of hollow-bearing trees from Victorian native forests* and *High frequency fire resulting in disruption of life cycle processes in plants and animals and loss of vegetation structure and composition* as Potentially Threatening Processes; the NSW Scientific Committee listed *Loss of hollow-bearing trees* and *Ecological consequences of high frequency fires* as Key Threatening Processes under the NSW *Threatened Species Conservation Act 1995*.

The need for research on the impacts of fire on tree hollows has been identified (Meredith 1987; Lamb *et al.* 1998; Gill 2002). In general, wildfire results in a marked reduction in hollow availability in eucalypt forests and woodlands (Woinarski *et al.* 1997). Eyre *et al.* (2010) found that time since wildfire was second only to logging intensity in influencing the number of live hollow-bearing trees at sites in dry eucalypt forest of inland southern Queensland. However, low intensity fires have generally been viewed as having minimal long-term impacts on fauna (e.g. Woinarski *et al.* 1997; Tolsma *et al.* 2007). The impact of fire on the availability and number of hollows has remained unclear. While fire can destroy hollows or entire hollow-bearing trees, fire can also assist hollow creation by killing limbs in which hollows could then form, breaching bark to enable entry by termites and fungi that facilitate hollow formation, burning out the centres of limbs and boles and by enlarging existing hollows (Woinarski and Recher 1997). Gill (2002) identified that this confusion had arisen because fire can have a range of quite different outcomes regarding hollow formation. Maximum hollow formation will occur at intermediate fire intensities, where the fire is intense enough to kill some of the large crown branches and penetrate bark on the trunk, while higher fire intensity will kill the stem, and fire of lower intensity will not lead to hollow formation (Gill and Catling 2002). Several studies identified branch shedding as a more significant factor than fire scars for initiating hollow formation, but were unable to establish the importance of fire among the other factors that lead to branch shedding (Whitford 2002; Koch *et al.* 2008).

We found only one published study (Inions *et al.* 1989) that specifically measured destruction rates of live hollow-bearing trees following a single fire in Australian forests or woodlands. Inions *et al.* (1989) found that 13% of healthy

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den trees used by brushtail *Trichosurus vulpecula* and ringtail *Pseudocheirus occidentalis* possums were destroyed, i.e., burnt to the ground, following a prescription burn in Western Australia. Several studies have examined collapse rates of trees, but have not assessed collapse specifically due to fire, e.g. Lindenmayer *et al.* (1997) for dead trees and Gibbons *et al.* (2008a) for live trees. The effect of fire on mature trees has been examined, but the studies either did not distinguish hollow-bearing trees (Lonsdale and Braithwaite 1991; Williams 1995; Williams *et al.* 1999; Gibbons *et al.* 2000a), or distinguish live from dead standing trees (e.g. Braithwaite *et al.* 1984), or assessed only a subset of mature trees (e.g. Abbott and Loneragan 1983). Other studies have reported fire-induced, tree mortality or collapse rates, but these were measured over periods ranging up to several decades (e.g., Whitford and Williams 2001).

Fuel reduction from prescribed burning aims to decrease the incidence, severity and spread of unplanned fires by reducing ground fuel loads (McArthur 1962). It remains a significant forest management tool throughout Australian and, in some States, large areas are burnt each year (e.g., Ellis *et al.* 2004). The frequency of prescribed burning varies with management objectives, but have typically been 3 to 10 years in southern Australian forests and woodlands in the past (e.g., Moore and Shields 1996). Burn cycles aimed at asset protection are typically less than five years, because fuel levels in many forest types accumulate to pre-burn levels during that period (McCarthy and Tolhurst 2001; Price and Bradstock 2010). Prescription burning programmes evolved primarily to protect timber resources from destructive wildfires, initially without regard for their impact on biodiversity (Morrison *et al.* 1996). The subject remains controversial (e.g., Abbott and Burrows 2003; Oliveras and Bell 2008; Clarke 2008), as does the effectiveness of prescribed burns in reducing the incidence and spread of unplanned fire (e.g., Fernandes and Botelho 2003; Price and Bradstock 2010).

We report an opportunistic, post-fire assessment of collapse rates of hollow-bearing trees near fire boundary roads in the central and eastern Pilliga forests of inland, northern New South Wales. The Pilliga is the largest remaining forest remnant in inland NSW and is an important refuge for hollow-dependent fauna. Low intensity prescription fires were undertaken during April and May 2006 by the Department of Environment, Climate Change and Water (DECCW) in fire management zones in accordance with the Pilliga Fire Management Plan (Pilliga Special Joint Committee 2000). Despite the constraints arising from an opportunistic design, in view of the dearth of studies on the impacts of fire on hollow-trees, we consider that our data allow us to constructively address the question of whether destruction rates of hollow-bearing trees by low intensity prescription burns warrant closer attention by forest managers.

METHODS

We conducted an opportunistic, post-fire assessment of the number of hollow-bearing trees that collapsed in 29 plots, of 50 x 40 m, in three areas of the Pilliga forest. All plots were located in stands of hollow-bearing trees and the majority of plots were next to dirt roads that formed the containment boundary of prescription burns. Plots were assessed from 5–14th June 2006, ranging from several days to 6 weeks following prescriptions burns. All plots were re-visited during February 2007 to determine collapse rates of hollow trees subsequent to our initial assessment.

Prescription burn areas

The location of the study region and the 29 plots in the three burn Areas are shown in Fig. 1. The study plots were located in forest types dominated principally by ironbarks (*Eucalyptus fibrosa*, *E. crebra*, *E. beyeriana* and *E. sideroxylon*) or red gum species (*E. blakelyi*, *E. chloroclada* and *E. dealbata*). The burn areas were:

Area 1 — ignition commenced 15th May, bounded on the north by Allens Rd, Pattons Rd on the south, Macrozamia Rd to the east and Nobby Rd to the west. The northern side of Pattons Rd was also burnt from Nobby Rd, to the junction with Black Pine Road, 4 km to the south-west;

Area 2 — ignition commenced 17–26th May. Area (a) was bounded on the north by No.1 Break Rd, Top Crossing Rd to the east, and Dandry Creek to the south. Area (b) is a narrow burnt strip extending approximately 250 m along the northern bank of Dandry Ck, west from Top Crossing Rd;

Area 3 — ignition commenced 28th April, bounded on the north by Crawl Rd, Delwood Rd on the south, Beedel Trail to the east and Craighs Rd to the west.

Sampling in Area 3 was abandoned because the extent of damage to trees from the greater intensity of this prescribed burn made it difficult to identify the presence of external hollows. Consequently, data from Area 3 were excluded from the models, but were included in other analyses.

Prescription burns were ignited along perimeter roads and aerial ignition was

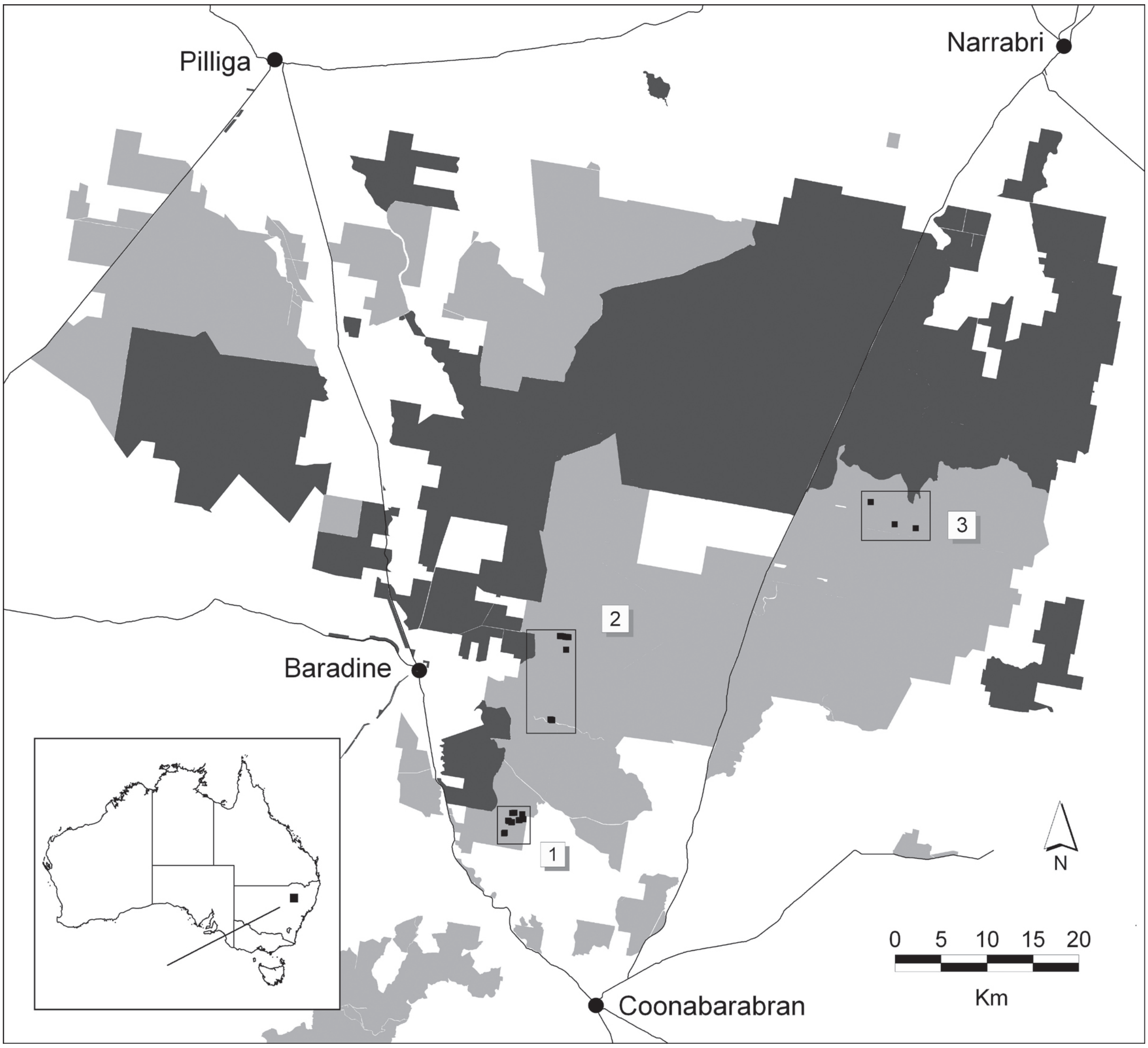

Fig. 1. Map of Pilliga forests indicating locations of the three prescription burn Areas, labelled 1 to 3, in relation to land managed by Department of Environment Climate Change and Water (DECCW) (pale shade) and Forests NSW (dark shade).

undertaken along lines several hundred metres apart, across the burn area. (J. Whittall, DECCW, pers. comm.). Quantitative estimates of fire intensity were not made, but all prescription burns were considered to be light, i.e., relative to previous prescribed burns undertaken in the Pilliga (John Whittall, pers. comm.).

Fire history

Two broad fire regimes have been recognized in the Pilliga forest, which correspond to landform, forest type, and management priorities (Brookhouse and Nicholson 1999; Date *et al.* 2002; see Fig. 6 of Milledge 2004). Burn Area 1 is in a regime of less frequent fire, which corresponds roughly with the Pilliga Outwash. Burn Area 3 falls within a regime of more frequent, intense fires in the eastern and central Pilliga. Burn Area 2 is adjacent to the boundary between both fire regimes, but is located in the lower frequency fire regime. Area 1 was last burnt by wildfire in 1950, when detailed fire records commenced (FCNSW 1987; DECCW data). Prior to the prescription burns of this study, the western end of Area 2a was last burnt by wildfire in 1951, while the eastern part was also burnt by wildfire in 1997. Burn Area 2a was also burnt in a severe wildfire of November 2006, after our initial plot assessments. Area 2b, along Dandry Creek, appears to have last experienced wildfire in 1951, based on old charcoal observed around large hollow entrances of several trees. Burn Area 3 has experienced four wildfires since 1950, those of 1951, 1957, 1974 and 1982. A plot in the western end of Area 3 was also burnt in the 1994 wildfire. Areas 1 and 2 do not appear to have been burned by prescription burns since records commenced in the 1970s.

Sampling protocol

Sampling focused on stands of hollow-bearing trees within 40 m of a road or creek line that formed the burn perimeter, to maximize the total number of burnt hollow-bearing trees assessed. Plots were located in stands that met two criteria: a minimum of 4 live, standing or collapsed hollow-bearing trees for which fire had reached the base of the tree; and a minimum of 75% ground burnt within the plot. Time constraints dictated that we could not determine the total number of stands of hollow-bearing trees that met the criteria of plot selection, nor the total number of individual hollow-bearing trees, whether burnt or not, within 40 m of the perimeter road edge of each burn area.

Trees were initially assessed from a vehicle moving slowly along roads that formed the fire boundary. Stands of trees were then assessed in every 100 m section from a starting point at road junctions. A plot was located at every section meeting the criteria for plot selection. A dirt road formed one boundary of 19 plots, with the long axis of the plot parallel to the road; 7 plots were along creek lines and 3 were located away from the road edge but within 100 m of the road.

Most sections of the boundary roads of burn Areas 1 and 2 did not meet the criteria for plot establishment, either because fire did not extend far enough from the road (i.e. less than 30 m), or because densities of hollow-bearing trees were too low due to previous logging operations, fires and removal of hazardous trees adjacent to roads.

Plot variables

Eight variables, selected because they are relevant to fire behaviour and intensity (Tolhurst and Cheney 1999; Catchpole 2002), were scored for each plot: dominant tree species; proportion of hollow-bearing trees that collapsed; topographic position; aspect; percent ground burnt; percent total canopy leaf scorch; number of years since last wildfire; and number of wildfires since 1950 (see Table 1).

Table 1. The 8 plot variables and 6 variables measured for each hollow-bearing tree.

Plot variables	
Proportion of collapsed hollow-bearing trees	Main stem collapse of live trees for which fire reached the butt. Coppice stems from a common root stock, and multi-stemmed trees which forked < 0.5 m above ground, were treated as separate trees.
Aspect	8 cardinal points.
Topographic position	Creek line, mid-slope, ridge.
% Canopy scorch	% of total canopy leaf scorch, in incremental categories of 25%.
% Ground burnt	% of ground burnt in the plot.
Dominant tree species	Dominant canopy tree species on plot in 5 categories (Lindsay (1967) forest types in brackets): ironbark (COP); ironbark mixed species (COP, NTPp); scribbly gum (BAP); red gum (BAP); red gum mixed species (BA, BAP, PAB, PBA, TBCP). Composition of some plots differed from mapped Lindsay types.
Years since last wildfire	Number of years since last wildfire, records from 1950: >56 years; 56 years; 23 years, 11 years.
Number of wildfires	Number of wildfires since 1950: 0, 1, 4, 5.
Tree variables	
Tree standing or collapsed	Multi-stemmed trees scored as collapsed if one or more main stems had collapsed.
Tree species group	Each tree was assigned to the following species or species group: Angophora (*A. floribunda*, *A. costata*), Bloodwood (*Corymbia trachyphloia*), ironbark (*E. crebra*, *E. fibrosa*, *E. beyeriana*), red gum (*E. chloroclada*, *E. blakelyi*, *E. dealbata*), Scribbly Gum (*E. rossii*), Fuzzy Box (*E. conica*).
DBH	Diameter at breast height (1.3 m above ground) over bark (cm).
Hollow size class	Size class of largest hollow entrance visible from the ground, estimate of largest dimension of largest hollow in one of four categories: 2–5 cm, 6–10cm, 11–20 cm and >20 cm.
Tree growth form	Growth form of hollow-bearing trees scored in 6 categories: **coppice** with visible hollows; **mature** — healthy crown, hollows visible; **senescent** - reduced crown vigour, medium/large hollows present; **live stag** — bole, main crown branches collapsed, final stages of life; **suppressed** — subdominant tree, hollows visible, mature crown branches; **Undetermined** — most of bole and main branches combusted.
Fire entry point at base	presence/absence of a fissure or hollow at the stem base, or bole, that would allow fire entry into the main stem.

Tree variables

In each plot, all live, burnt and unburnt hollow-bearing trees were scored. Burnt trees were defined as those for which fire had reached the base of the bole. Trees were scored for the following six criteria (see Table 1): 1), whether the tree had collapsed following the fire. Live trees which had collapsed before or after fires could readily be distinguished by the fresh state of foliage and wood scars; 2), tree species group, which can influence flammability and vulnerability to fire, e.g., from differing bark type (Gill 1995) and hollow characteristics (Wormington *et al.* 2003); 3), diameter at breast height (DBH), an approximation to tree age class (Mackowski 1984; Gibbons *et al.* 2000b), which also influences fire-induced mortality (Williams *et al.* 1999) and the number, type and size of hollows (Todarello and Chalmers 2007; Rayner 2008); 4), size of the largest entrance hollow visible from the ground, an indication of degree of hollow development; 5), tree growth form, an indication of the presence of hollows (Gibbons *et al.* 2000b); and 6), the presence of fire scars, basal hollows, or fissures that could act as fire entry points to the bole, thereby increasing the likelihood of collapse (Whitford and Williams 2001; Gibbons *et al.* 2008a). The entry point had to be linked to an internal cavity, and fire scars or hollowing of the butt of otherwise sound trunks, was not scored.

Modelling burnt hollow-tree collapse

Logistic regression, using binary response models, was used to examine the relationship between hollow-tree collapse and the tree- and plot-based variables, and was generated using the LOGISTIC procedure of SAS/STAT software (version 9.1.3 SP4) of SAS for Windows (SAS 2003). Step-wise regression was used to find explanatory variables useful in explaining tree collapse.

Two separate sets of models were constructed to predict the collapse of hollow-bearing trees as a result of the prescription burns:

a) *Plot models:* The proportion of burnt hollow-bearing trees that collapsed on each plot, was modelled against the seven other plot-based variables (see Table 1).

b) *Tree models:* the status of individual trees (collapsed vs. standing) was modelled against a combination of the five other variables measured for each hollow-bearing tree, and the seven plot-based variables (see Table 1).

Separate models were run for each of Areas 1, 2a, 2b, and for the latter three areas combined, for both plot-based and tree-based models. The burn Areas were modelled separately because they differed in topographic position and tree species composition, both of which could have influenced fire behaviour.

For each type of model, a binary dependent variable was coded as (0) if the bole collapsed, and (1) if the main stem remained standing. Multi-stemmed trees were scored as collapsed if one or more main stems had collapsed. The plot models were based on an extension of the binomial modelling procedure using the grouped input option for binary response data in PROC LOGISTIC.

In contrast to linear models, the units of our model coefficients do not have a readily interpretable meaning because we used the log link function. We estimated odds ratios to enable a clearer and more intuitive interpretation of the models (Quinn and Keough 2002; Rita and Komonen 2008). The odds ratio expresses the increase in odds of a tree collapse for a unit change in the associated dependent variable (Quinn and Keough 2002). Rita and Komonen (2008) provide a more detailed explanation of the use of odds ratios in this context.

The odds ratio associated with the only continuous variable, "% ground burnt per plot", was expressed in intervals of 20%, i.e., the change in odds that is estimated to occur for a 20% change in percentage ground area burnt. The odds ratios for the dichotomous variables represent the change in odds when the associated variable changes from *not present* to *present*.

RESULTS

Overall collapse rates

A total of 381 hollow-bearing stems was measured, 329 of which were burnt and 57 of these burnt stems had collapsed. The mean collapse rate on plots were: Area 1: 14% of 179 stems for plots dominated by red gum; Area 2a, 25.8 % of 62 stems for the ironbark dominated mixed species plots on No. 1 Break Road; Area 2b, 18.5% of 54 stems for the red gum dominated plots along Dandry Creek; and Area 3, 17.6% of 34 stems for plots dominated by Scribbly Gum and mixed species. The total number of live, hollow-bearing stems in each plot, estimated to be standing before the prescription burns, ranged from 4 to 22. The proportion of collapsed, live hollow-bearing stems per plot ranged from 0–50% (Fig. 2) and collapse rates exceeded 20% on 13 of the 29 plots. Collapse of live stems did not occur on 6 of the 29 plots (Fig. 2), where the majority of hollow-bearing trees reached by fire had sound bases, with no entry points for fire. Of the six plots, three were mixed red gum stands, one a mature stand of Scribbly Gum *Eucalyptus rossii* and two plots were dominated by mature ironbarks.

Collapse rates per tree species group

Measured collapse rates of burnt, hollow-bearing trees for tree species group, pooled across plots separated by burn Area, are shown in Fig. 3. Excluding the smallest sample sizes (n<5), collapse rates for *Angophora* ranged from 8.3 to 33.3% of burnt stems; red gums, 13.5 to 30.7%; ironbarks, 23% for Area 2a; and bloodwoods 27.3% for Area 2a. No Scribbly Gums collapsed on the plots in Area 3, which was inadequately sampled, although a substantial number of collapsed mature Scribbly Gums were observed in the vicinity of the plots.

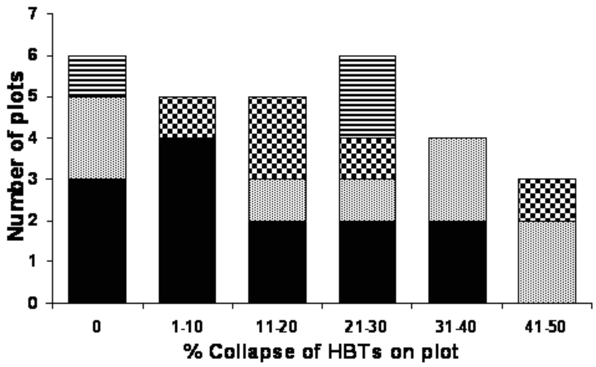

Fig. 2. Percentage collapse rates of hollow-bearing trees per plot for each of the 29 plots in June 2006, plots grouped by burn Area: Area 1 (solid), Area 2a (speckled), Area 2b (checkered) and Area 3 (stripes). HBT = hollow-bearing tree.

Collapse rates for tree growth forms

Percentage collapse rates of hollow-bearing trees in different tree growth forms, aggregated across tree species on all plots, show that the highest collapse rates occurred in the oldest growth forms, i.e., live stags (trees in the final stages of senescence, 44.4% of 27 stems) and senescent trees (40.0% of 45 stems), and was lowest in suppressed trees (7.1% of 14 stems) and mature hollow-bearing trees (8.8% of 209 stems). Hollow-bearing coppice stems had a collapse rate of 17.6% of 34 stems. These broad trends are also evident when plots are separated by burn Area (Fig. 4).

The percentage collapse of burnt, hollow-bearing trees, pooled across all plots, increased with the size class of the largest, visible, hollow entrance per tree. Collapse rates were: 7.7% of 103 stems in the 2–5 cm entrance class; 9.5% of 95 stems for the 6–10 cm class; 26.9% of 78 trees in the 11–20 cm class, and 30.6% of 49 trees with maximum hollow entrances greater than 20 cm. The majority (36 trees, 68%) of the 53 burnt, collapsed, live trees contained at least one hollow in the larger (>11 cm) entrance-diameter size classes (hollow size could not be determined in a further 4 collapsed trees). This trend is also evident when plots are separated

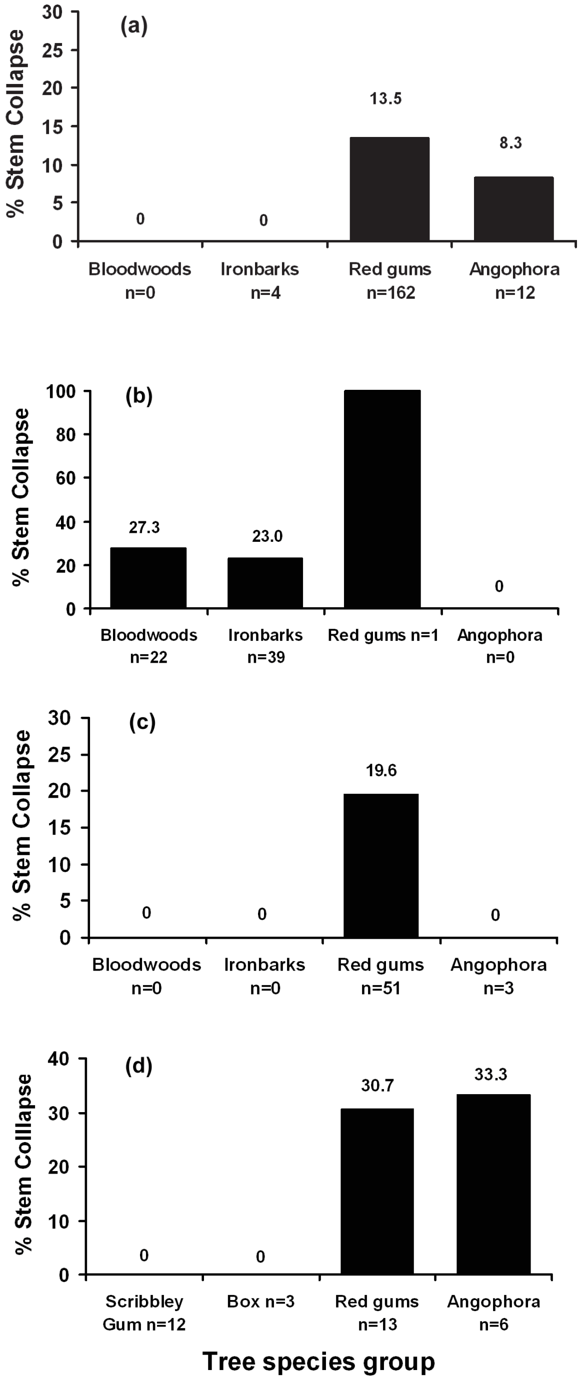

Fig. 3. The percentage of live hollow-bearing stems that collapsed in June 2006, for each tree species group, pooled across plots for each burn Area: (a), Area 1, (b), Area 2a; (c), Area 2b, and (d), Area 3. n = total number of standing and collapsed, burnt hollow-bearing trees.

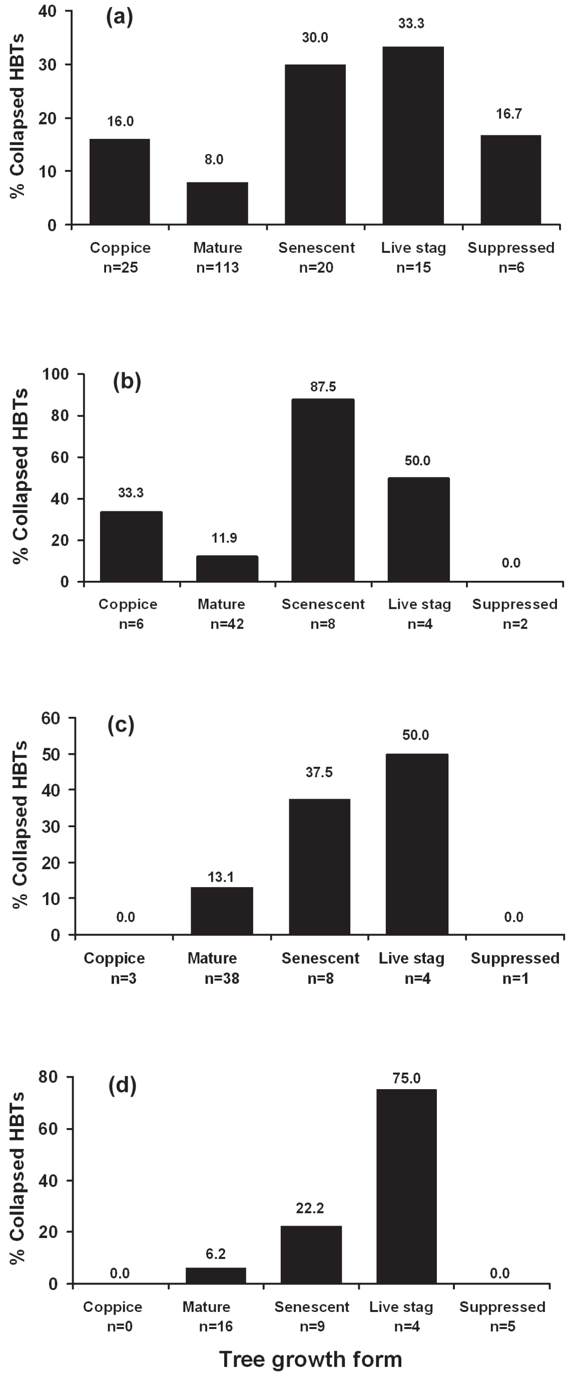

Fig. 4. Percentage collapse of hollow-bearing trees in June 2006, by tree growth form, pooled across tree species for combined plots in each burn Area: (a), Area 1, (b), Area 2a; (c), Area 2b, and (d), Area 3. n = total number of standing and collapsed, burnt hollow-bearing trees.

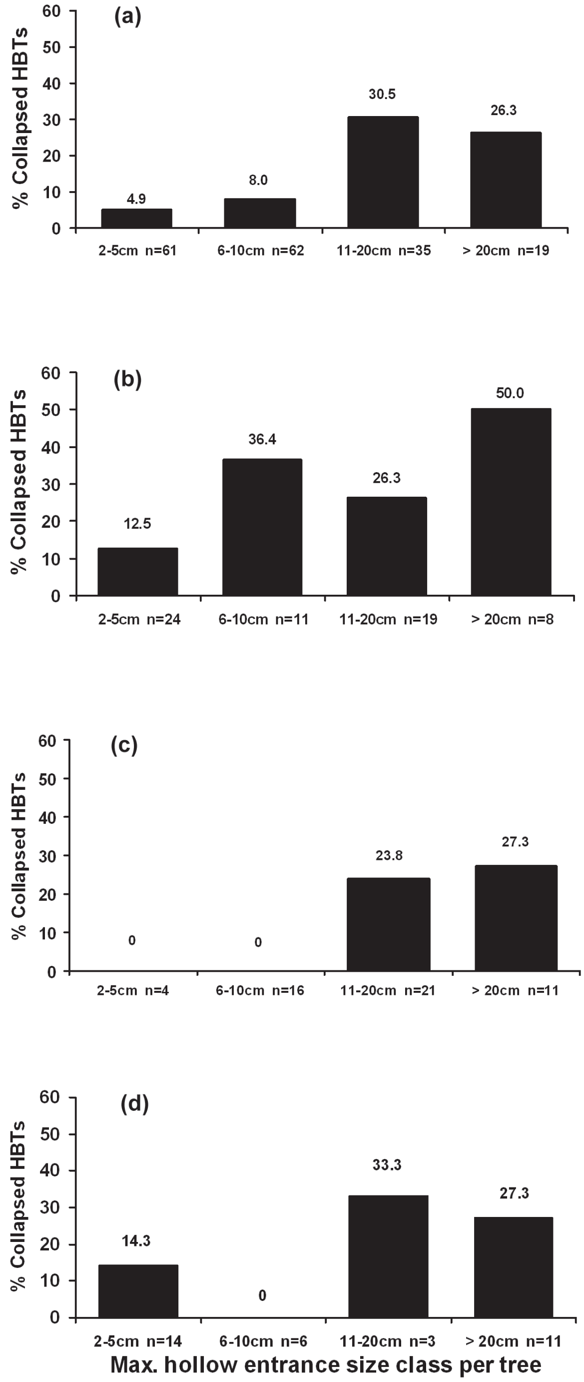

Fig. 5. The proportion of collapsed, live hollow-bearing trees in June 2006, per maximum hollow entrance size class, pooled for tree species for combined plots in each burn Area: (a), Area 1, (b), Area 2a; (c), Area 2b, and (d), Area 3. n = total number of standing and collapsed, burnt hollow-bearing trees.

by burn Area (Fig. 5). A comparison of Figs 4 and 5 shows a trend of collapsed stems being either in the mid to late senescent stage, with larger entrance hollows, or were suppressed, hollow-bearing stems or hollow-bearing coppice. Hollow-bearing trees in the mature category had low collapse rates, and collapsed stems were typically either of poor growth form, poor health, or had the base weakened by previous fire scars.

Tree collapse 9–10 months after prescription burns

Collapse, or stem death, of all burnt and unburnt hollow-bearing trees in all plots was re-assessed in February 2007, 8 months after the initial assessment and 9–10 months following the prescription burns. There was no further collapse or death of hollow-bearing trees, with the exception of one plot on Top Crossing Rd.

This plot was on a rocky ridge and had been burnt by wildfire in November 2006. Three hollow-bearing trees had collapsed following the prescription burn: one ironbark, a multi-stem bloodwood, and a live senescent hollowed-out bole.

Modelling the collapse of hollow-bearing trees

In the models of the proportion of collapsed, hollow trees per plot, none of the plot-based variables usefully predicted hollow-tree collapse, i.e., no significant relationship was found between the seven plot variables and tree collapse.

The models of collapse of individual, hollow-bearing trees, using plot-based and individual tree variables, were run separately for Areas 1, 2a, 2b as well as the three areas combined. Variables with missing values were excluded to maximize the number of trees included in the analyses, leaving three variables in the final analyses: the presence of a fire entry point at the base of the tree; the dominant tree species of the associated plot; and the percentage of ground burnt per plot. In the four models, all three explanatory variables showed a useful relationship with the chance of tree collapse (Table 2).

The models of the four Areas strongly identified the presence of a base hole as greatly increasing the likelihood of tree collapse, and the estimated odds of tree collapse increased by an order of magnitude. The 95% confidence interval for the odds ratio indicates that this is unlikely to fall below a factor of 2.

We could not estimate the contribution of dominant tree species to the likelihood of tree collapse in separate model runs for Areas 1, 2a and 2b, due to too few trees in the five categories. Consequently, the five groups were amalgamated into two, red gum dominated and ironbark dominated (Scribbly Gum was restricted to Area 3, which was excluded from this model). In the model of combined burn Areas, variability in the estimates for dominant tree species was too high to be able to conclude that it was a contributing factor in explaining tree collapse. This is also reflected in the odds ratio, where the best estimate of the effect of a change in dominant tree species (red gum versus ironbark, while other factors remain the same) is to reduce the odds of tree collapse by approximately half. However, the estimated 95% confidence interval on these odds (0.22 to 1.28) rules out the assertion that the odds ratio differed from 1:1, i.e., it is non-significant (see Table 2).

The third variable, the percentage ground burnt per plot, was also non-significant (Table 2). While it is possible that a 20% increase in ground area burnt will lead to an increase of approximately 1.5–2 in the odds of trees collapsing, the associated confidence intervals for these odds in all four models include unity. Hence, we cannot assert that the odds of collapse will definitely increase with increase in percentage ground burnt.

DISCUSSION

The low-intensity prescription burns studied resulted in mean collapse rates of 14% to 26% on our plots in different burn Areas. The collapse of burnt, hollow-bearing trees on individual plots ranged from 0 to 50%, and exceeded 20% on 13, of the 29 plots. Although we consider these fire-induced collapse rates of hollow-bearing trees severe, the opportunistic nature of our post-fire sampling and associated biases (see below) means that we cannot determine how representative collapse rates on our plots are of other areas burnt by prescription fires. Consequently, we have not extrapolated collapse rates on our plots either to other areas, such as stands deeper within the burn area, or to other areas of the Pilliga forest.

Table 2. Variables that significantly contributed to explaining hollow tree collapse for different Areas burnt in May–June 2006, in four models based on combined plot-based variables and individual tree variables. (* = significant, Ns = not significant).

Model	Variable	Coefficient (ß)	Odds ratio with [95% confidence interval]	Significance at 95%
Area 1	Base Hole	2.29	9.90 [3.78–25.91]	*
N=179	% Ground Burnt	3.74	2.11 [0.91–4.88]	Ns
Area 2a	Base Hole	3.41	30.2 [3.06–297.8]	*
N=62	% Ground Burnt	1.87	1.45 [0.49–4.34]	Ns
Area 2b	Base Hole	2.17	8.81 [1.83–42.48]	*
N=54	% Ground Burnt	1.95	1.48 [0.63–3.44]	Ns
Combined areas	Base Hole	2.45	11.55 [5.45–24.46]	*
1 and 2	% Ground Burnt	2.2	1.56 [0.97–2.48]	Ns
N=295	Dominant tree species: red gums versus ironbarks.	-0.63	0.53 [0.22–1.28]	Ns

Further, we cannot quantify what proportion of all hollow-bearing trees had collapsed as a result of each prescription burn. Prescription fires typically have a variegated burn pattern (Catchpole 2002; Penman *et al.* 2007) and the proportion of all unburnt, hollow trees within the burn perimeter needs to be determined to evaluate the impacts of a single fire.

Collapse rates on our plots could be overestimated due to potential bias arising from the plot selection criteria, i.e., the presence of 4 or more hollow-bearing trees and a minimum of 75% ground burnt. This restricted sampling to higher density stands, which could have had higher ground fuel loads, thereby potentially biasing sampling toward areas of higher fire intensity. In contrast, several sources of bias could have resulted in underestimating collapse rates. Most plots were located close to the edge of roads used as fire containment boundaries and ignition lines, where hollow-tree mortality could have been higher than areas distant from roads due to edge effects, more intense logging, a higher likelihood of removal of dangerous trees and a greater chance of being ignited in past fires. Burn Area 3 has experienced a fire regime of more frequent and intense fires than Burn Areas 1 and 2. Collapse rates on plots in Area 3 could be underestimates of hollow-bearing trees burnt by that fire. The higher intensity of this burn had incinerated many trees, making it difficult to detect hollow entrances. Consequently, plots could only be located in the limited areas of lower fire intensity and sampling was abandoned.

Ground-based observations of entrance hollows, such as those undertaken in this study, are recognized as providing biased estimates of hollow numbers (Lindenmayer *et al.* 2000; Koch 2008). Large hollows that are not visible from the ground will result in underestimates, and errors could arise from distinguishing small hollows from occluded branch stubs. These issues did not apply to collapsed trees in this study, which were inspected for hollow size.

We do not consider that the limitations of the assessment of hollow tree collapse rates in our study, and any associated sampling bias of our plots, detract from our primary conclusion that collapse rates measured on our plots are of concern and warrants closer attention from wildlife managers.

Although we are unable to extrapolate collapse rates from our plots to remaining areas burnt by these fires, they appear to be high compared to the limited published data. In particular, we suspect that fire-induced collapse rates of hollow-bearing trees reported from southern Australia have resulted from prescription burns of higher intensity than those of our study, or from wildfire. For example, the collapse rate of live, hollow-bearing trees of 13% reported by Inions *et al.* (1989) resulted from a prescription burn with fire intensities up to 1500 kW per m, compared to maximum intensities of 350 kW per m considered typical for that region. This is likely to have been higher than fire intensities of Areas 1 and 2 of our study. Braithwaite *et al.* (1984) found that 21% of the 47 trees greater than 60 cm DBH had collapsed following a severe wildfire. Although the presence of hollows was not reported, half of these trees were dead before the fire and were presumably more flammable than live trees, thereby increasing the collapse rate. Whitford and Williams (2001) documented collapse rates of 19% for hollow-bearing Marri *Corymbia calophylla* and Jarrah *Eucalyptus marginata* trees which they attributed solely to fire, but these rates had accumulated over several decades and could have included the impacts of wildfire. Gibbons *et al.* (2000a) examined tree mortality (as opposed to tree collapse) from 2–5 years following logging and post logging burns in East Gippsland and southern NSW. Their southern NSW sites were subject to low to medium, post-logging prescription burns, which were more likely to be comparable to the low fire intensity of our study. Although mortality rates of hollow-bearing trees were not given separately from all trees, they were below 10% for all trees greater than 120 cm DBH, i.e. those with a higher probability of being hollow-bearing (Gibbons *et al.* 2000b). Murphy and Legge (2007) assessed individual hollows used for breeding by the Palm Cockatoo *Probosciger aterrimus* in tropical savannah in north Queensland. Although estimates of tree collapse rates due to fire were not given, fire destroyed per year an average of 5.2% of the hollows used for breeding.

Trees are more susceptible to fire damage when a hollow or fissure, present near ground level, enables flames to enter a hollow bole, leading to a chimney effect and, in some cases, complete destruction of the tree (Gill 2002). Such hollows are more likely to be present in older trees, so it is not surprising that old trees and live stags made up 84% of the collapsed trees on our plots, and that presence of a basal fire entry point was a significant predictor of tree collapse in our models, increasing the likelihood of tree collapse by at least a factor to 2. Gibbons *et al.* (2008a) also found that trees with fire damage to the butt were twice as likely to collapse in models of live tree collapse following logging and fire in eastern Victorian mixed eucalypt forest. Hollowing of the butt by fire was also a significant predictor of hollow-tree collapse for marri and jarrah trees retained after logging in Western Australia (Whitford and Williams 2001).

We suggest one reason the impact of fire on hollow-bearing trees has remained obscure is because most fire-prone hollow trees would have been removed by broad scale prescription burning that has been applied across southern Australian States since the 1960s. Thus sites with a low fire frequency, or from which fire has been absent for decades, are likely to be scarce. This would be compounded by the scarcity of hollow-bearing trees in many forest areas, e.g. Adkins (2006) found only three hollow-bearing trees in his study area in Victoria.

We conclude that low intensity prescription burns may cause levels of destruction of hollow-bearing trees that are substantial enough to warrant immediate attention from managers. The destruction rates of hollow-bearing trees documented in this study, and elevated fire frequency and severity predicted in the immediate future due to climate change (e.g. CSIRO 2007; Pitman *et al.* 2007), highlight the urgency for gathering detailed data on the impacts of fire on hollow-bearing trees for managing hollow-using fauna. Preliminary data on the impact of a low intensity prescription burn on habitat trees at Mt Alexander, Victoria is consistent with this view (Goonan 2009). More extensive, well-designed studies of the impacts of single prescribed burns are warranted. Given that prescription burning is widely applied in all Australian States and, in our view, are of equivalent or greater intensity to those of our study, it would be appropriate to conduct such studies in other regions of Australia. The sampling strategy would include replicated, pre- and post-fire assessments of hollow-tree collapse across the mosaic of burnt and unburnt forest and account for stand fire history. In the interim, a precautionary interpretation of our results is that low intensity prescribed burns are progressively depleting the hollow-bearing tree resource that is already formally recognized as threatened.

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