RESEARCH REPORT

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Coarse woody debris can reduce mammalian browsing damage of woody plant saplings in box-gum grassy woodlands

By Joseph P. Stapleton, Karen Ikin and David Freudenberger

Summary The critically endangered box-gum grassy woodlands of south-east Australia face numerous threats including the failure of woody plant regeneration caused by over-browsing. In the Australian Capital Territory, over-browsing of tree and shrub saplings is likely caused by dense populations of Eastern Grey Kangaroo (*Macropus giganteus*) found in many nature reserves free of livestock. One possible way to protect these saplings is using coarse woody debris (CWD) as a browsing deterrent. We tested this idea by planting palatable Red Stemmed Wattle (*Acacia rubida*) saplings among manually applied CWD, among naturally fallen CWD, and in the open, in five woodland reserves. We recorded the proportion of saplings browsed, the number of weeks to first browsing and the browsing severity (sapling height lost). Applied CWD protected saplings from being browsed only at relatively low-to-moderate kangaroo browsing pressure (as measured by faecal pellet counts). At relatively high browsing pressure, the probability of a sapling being browsed among applied CWD was 100%, similar to the probability in the open treatment (no CWD). Natural CWD, in contrast, provided some protection even at high browsing pressures. Time to browsing was most affected by browsing pressure, although CWD cover also had an influence. Browsing severity was similar between the three treatments and was only affected by browsing pressure. These results indicate that without protection, palatable woody plant saplings have a high chance of being browsed by kangaroos in woodland reserves, and therefore, some protection is needed for successful regeneration. The CWD being applied to reserves has a limited capacity to protect regenerating saplings. If more protection is wanted a CWD structure more resembling natural fallen timber should be used. This could be done by artificially placing branches around plantings. However, the most important action to facilitate regeneration is to manage kangaroo populations to reduce overall browsing pressure.

Key words: *box-gum grassy woodlands, browsing, coarse woody debris, kangaroo management, woody plant restoration.*

Joseph P. Stapleton *was a Masters Student with the Fenner School of Environment and Society, Australian National University (Acton, ACT 26-01, Australia (Tel: 0421 130 132; Email: joseph.staple@gmail.com).* ***Karen Ikin*** *is a Research Fellow with the Fenner School of Environment and Society, Australian National University, Frank Fenner Building 141, Linnaeus Way, Acton ACT 2601, Australia (Email: karen.ikin@anu.edu.au).* ***David Freudenberger*** *is a Senior Lecturer with the Fenner School of Environment and Society, Australian National University, Frank Fenner Building 141, Linnaeus Way, Acton ACT 2601, Australia (Email: david.freudenberger@anu.edu.au). This project was undertaken as part of a wider investigation into the restoration of box-gum grassy woodlands.*

Introduction

White Box (*Eucalyptus albens*)–Yellow Box (*E. melliodora*)–Blakely's Red Gum (*E. blakelyi*) grassy woodland (here after termed 'grassy woodland') is an ecological community consisting of a grassy understorey and a widely spaced canopy dominated by eucalypt species (Beeton 2006). This community once ranged over much of south-eastern Australia, but since European settlement much of it has been cleared and it is now listed as critically endangered under the Environment Protection and Biodiversity Conservation Act 1999 (Department of Environment 2016). Patches that remain of this type of woodland are often in a poor condition due to numerous threatening processes, including the repression of woody plant regeneration through over-browsing by domestic and wild herbivores (Liangzhong & Whelan 1993; Fischer *et al.* 2009). In the Australian Capital Territory (ACT), an area with the largest remaining grassy woodlands in good condition (Beeton 2006), dense populations of Eastern Grey Kangaroo (*Macropus giganteus*) are found in many patches of grassy woodland (ACT Parks Conservation and Lands 2010). These populations have been shown to have negative effects on other fauna (Howland *et al.* 2014) and flora (Neuve & Tanton 1989; McIntyre *et al.* 2010), and may potentially repress regeneration of palatable woody plants (Meers & Adams 2003). Therefore, management is needed to reduce the negative impacts of dense kangaroo populations. Two of the most common practices are culling or creating fenced-off areas. Both have been shown to be effective, but both also have drawbacks. Culling is controversial, and fencing is expensive to construct and maintain (Dickman 2012). Another possible strategy is to find methods for reducing the probability of kangaroos browsing saplings. Coarse woody debris could potentially perform this service.

Coarse woody debris (CWD) is large, fallen and dead woody material found throughout forest systems. It provides a number of important ecosystem services including nutrient cycling (Harmon *et al.* 1986), habitat for fauna (Mac Nally *et al.* 2001; Lindenmayer *et al.* 2002) and acting as nursery sites for woody plant saplings (Harmon & Franklin 1989; McKenny & Kirkpatrick 1999). It may also act as a browsing deterrent by obstructing herbivore access and thus increasing woody plant sapling survival (Ludwig & Tongway 1996; de Chantal & Granström 2007). However, due to human activities, CWD stocks have been depleted in many forests (Grove & Meggs 2003), including in critically endangered Australian grassy woodlands (Killey *et al.* 2010). One way to enhance the levels of CWD in these ecosystems is by manually applying it. For example, in the ACT, CWD has been manually applied to the grassy woodlands of Mulligans Flat and Goorooyaroo Nature Reserve as part of a long-term experiment (Manning *et al.* 2011). This CWD has been shown to return many ecosystem services including the improvement of nearby soils (Goldin & Hutchinson 2013, 2014) and providing refuge for fauna even under high herbivory pressure (Barton *et al.* 2011; Manning *et al.* 2013). Applied CWD may also decrease herbivory in the immediate vicinity (Goldin & Brookhouse 2015), thus improving plant regeneration. However, the possible value of applied CWD in protecting woody plant regeneration has yet to be tested in grassy woodlands. In addition, applied CWD may have different effects compared to CWD naturally present in reserves. For instance, recently fallen timber often has much of its small branches still present in dense formations (Ludwig & Tongway 1996). This natural CWD may provide greater protection from browsing than applied CWD, which is often in the form of large tree trunks (Fig. 1a).

This study aimed to investigate the effect of manually applied CWD on reducing sapling browsing by kangaroos. In many ACT reserves, CWD has been manually applied as part of the Woodlands Restoration Project (ACT Government 2015).

We took advantage of this project to experimentally address these main questions:

1 Does CWD reduce kangaroo browsing damage in the grassy woodlands of the ACT and is naturally present CWD more effective than applied CWD?

2 Does higher kangaroo browsing pressure cause greater browsing damage?

3 Do other factors, such as CWD projected cover and vegetation structure, influence browsing damage and do these factors interact with CWD?

We hypothesised that CWD would protect saplings from browsing, with natural CWD providing more protection than applied CWD. We also hypothesised that increases in browsing pressure will increase the browsing damage, increasing CWD cover will decrease browsing damage, and vegetation structure will influence browsing when interacting with CWD.

Methods

Study location

We conducted our study in the grassy woodlands of the Australian Capital Territory (ACT). Study locations were in five reserves that are part of Canberra Nature Parks. Before these woodlands were established as reserves, much of the land was used for livestock grazing and partially cleared for timber to make way for pasture (Ryan 2011). In 1913, when Canberra was declared as Australia's capital, natural reforestation was allowed to occur on many of the inner hills and ridges of the ACT. In 1993, Canberra Nature Parks were created with the aim of conserving these woodlands (Environment ACT 1999). However, many of these reserves are still affected by weed invasion and erosion due to past agricultural use. All reserves used in the study contained grassy woodland remnants, although the condition of these woodlands differed among reserves. Kangaroo densities also varied among the reserves ranging from 0.68 to 4.23 animals/ha (Table 1 (ACT Government 2017)). The Canberra region has a dry, continental climate with cool winters and hot summers.

Study design

Our experiment had three treatment types: applied CWD, natural CWD and open. Applied CWD (Fig. 1a) consisted of large, branchless tree boles manually placed in scattered clumps in 2012–2014 as part of the Woodlands Restoration Project (Table 1, (ACT Government 2015)). Natural CWD (Fig. 1b) came from *in situ* CWD already present on reserves from branch and tree falls. Fine woody material on small branches was often still attached in a dense arrangement. The open treatment (Fig. 1c) did not contain any CWD.

We established 30 sites of each treatment across five woodland reserves (90 sites in total, Table 1). A site consisted of a 1 m radius area containing a single treatment type. We randomly selected applied CWD piles based on information provided by the ACT Parks and Conservation Service. We then selected a natural CWD pile

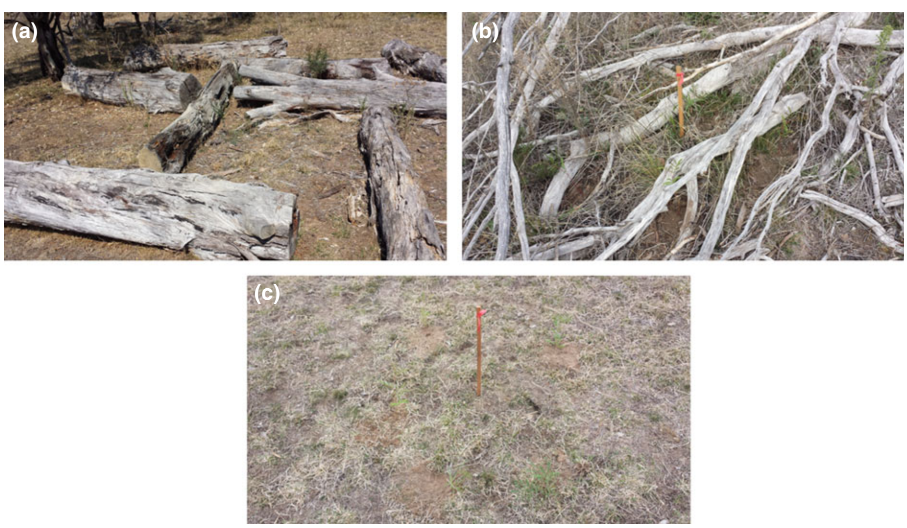

Figure 1. Typical examples of experimental treatment types (a) applied CWD, (b) natural CWD, (c) open. [Colour figure can be viewed at wileyonlinelibrary.com]

closest to an applied CWD site. The open sites were chosen 50 m away in a random direction from the applied CWD sites. Within each site, we planted five Red Stemmed Wattle (*Acacia rubida*) saplings in a 50 cm radius around a fixed stake (Fig. 2a; 450 saplings in total). We used Red Stemmed Wattle as it was found to be particularly browse-sensitive in a pilot study (unpublished data). All saplings were commercially grown and hardened off outside in cold conditions. We commenced planting in late May 2016 and finished in June 2016 during abundant cool season rainfall.

Field sampling

In the winter of 2016, one week after each site was planted, we assessed saplings for browse damage (response variable) by recording whether saplings had been browsed or not as a browse score (0 = unbrowsed, 1 = browsed). We also recorded the change in height of each sapling since the time of planting as an indicator of damage caused by browsing, following methods described by Jensen *et al.* (2012) and Vandenberghe *et al.* (2007). Due to the study taking place in winter, insect damage on the saplings was minimal. Other than kangaroos, European Rabbit (*Oryctolagus cuniculus*) was present in these reserves. The damage between the two could not be distinguished, but as the kangaroo faecal pellet density was high around heavily browsed sites, it was assumed kangaroos were responsible for most of the browsing. Swamp Wallaby (*Wallabia bicolor*), Red Necked Wallaby (*Macropus rufogriseus*) and Common Wombat (*Vombatus ursinus*) were also present in reserves, but at comparatively lower population densities, so it was assumed their impact was minimal. We continued weekly monitoring for 8 weeks postplanting. The study was conducted over winter due to the high soil moisture and this being a time of food shortages for kangaroos (Fletcher 2007), which would likely maximise browsing pressure on the *Acacia* saplings.

We measured the following explanatory environmental variables at each site to determine what other factors might affect browsing. To give an indication of kangaroo browsing pressure at each site, we used faecal pellet counts, a method modified from the permanent plot method used by Howland (2009). This involved counting all faecal pellets within a 1 m radius of the central stake at each site. Two counts were performed, one at the beginning of field sampling during which all pellets were cleared and counted from the plot, and again 8 weeks later; these two counts were then averaged. We also measured CWD projected cover using a point intersection method in which a 0.75 m × 0.75 m quadrat with 25 string intersections was placed over a sapling. We counted each string intersection over a section of CWD as a hit out of 25. We also determined herbaceous vegetation cover within sites using a 0.5 m × 0.5 m quadrat to visually estimate the per cent ground cover of grass, weeds, bareground, litter and other (unidentified forbs, moss, shrubs). We classified weeds based on their physical characteristics as either being leafy, spiky or bare stemmed. We also recorded the height of the tallest weed and tallest grass plume or leaf within the 0.5 m × 0.5 m quadrat and visually estimated canopy cover above the 0.5 m × 0.5 m quadrat.

Statistical analysis

We considered three response variables: (i) *Probability of browsing*, calculated using the browse score, which was the probability that a sapling was browsed, including browsing that reduced sapling height and browsing of lateral leaves; (ii) *Time to browsing*, which was the number of weeks it took for a browsed sapling to be first browsed; and (iii) *Browsing severity*, which was the decline in height of a sapling once it had been browsed. We also considered the measured explanatory variables (see above). Before constructing statistical models, we explored these explanatory variables for correlations and large zero values, and used ANOVA to assess significant differences between treatment types, to determine which should be used for analysis. We selected treatment type, faecal pellet count, CWD projected cover, weed condition, weed height and grass height for further analysis. We scaled all variables prior to analysis (mean = 0, standard deviation = 1) so that model estimates could be compared. We used R version 3.2.5 (The R Foundation for Statistical Computing 2016) software for all statistical analyses.

We used regression analysis to determine the effect of the chosen explanatory variables on browsing. In order to do this, we constructed a series of generalised linear mixed models using the chosen explanatory variables, including both univariate and interaction models (Appendix S3). All interaction models included treatment type combined with another variable, as treatment type was the focus of the study. We modelled probability of browsing using a binomial distribution, and time to browsing and

Table 1. Number of replicates, reserves size, applied CWD amounts (supplied by ACT Parks and Conservation Service) and kangaroo density estimates for each reserve (kangaroo density estimates obtained from ACT Government (2017))

Reserve	Reserve size (ha)	Amount of applied CWD per reserve (tonnes)	Kangaroo densities (animals/ha)	Locations	Blocks	Applied CWD sites	Natural CWD sites	Open sites
Wanniassa Hills	25	333	4.23	3	9	11	11	11
Callum Brae	50	450	2.00	1	5	5	5	5
Kambah Agistment	15	99	Unknown	1	3	4	3	4
Red Hill	25	288	1.24	1	5	5	5	5
Kama	32	270	0.68	1	5	5	6	5

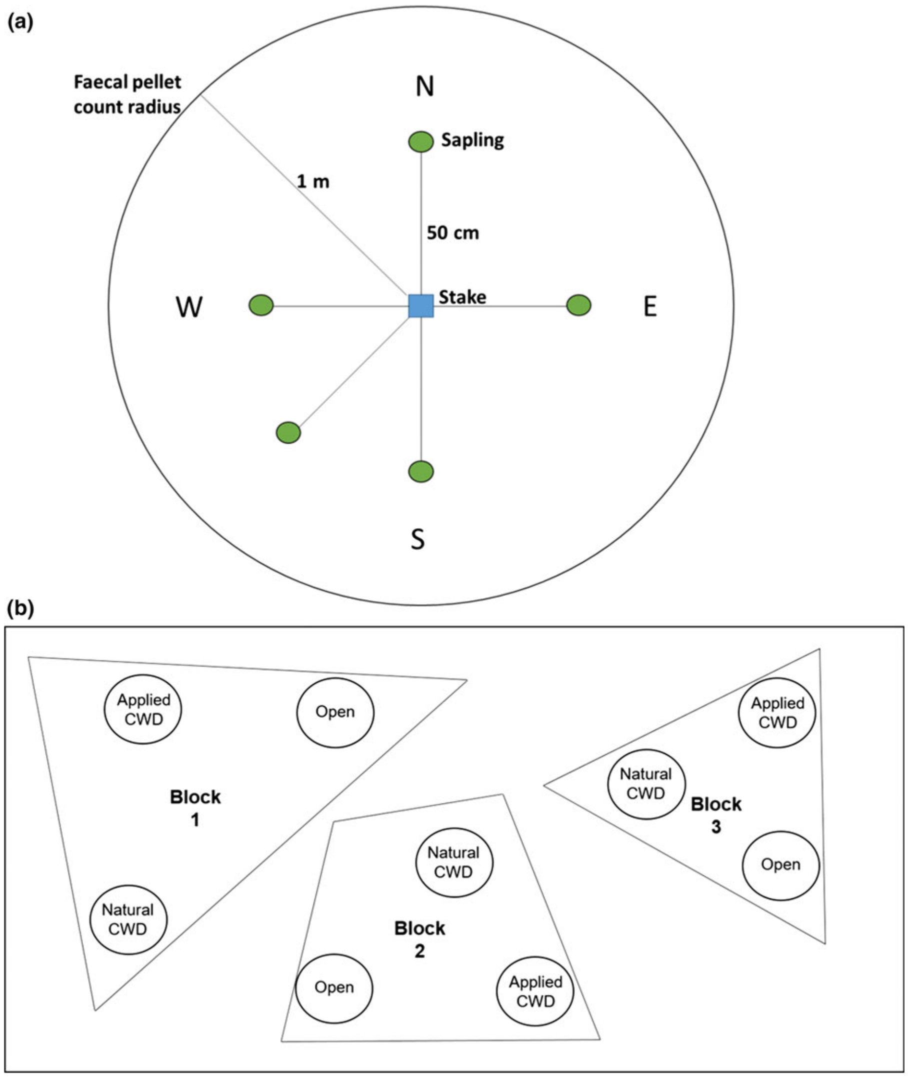

Figure 2. (a) Layout of each experimental site (shaded circle = *Acacia* sapling, square = central stake), (b) Ideal layout of a 'location': 3 treatment types surrounded by a line = a 'block', a circle with a treatment type inside = a 'site'. [Colour figure can be viewed at wileyonlinelibrary.com]

browsing severity using a Gaussian distribution. We included nested random effects to account for the three levels of spatial structure in our study design. Site was the smallest structure containing a single treatment type, and block was the next level up and contained a set of sites within close proximity, ideally one of each treatment type. The largest scale was location which contained two to five blocks (Fig. 2b).

We calculated the Akaike's Information Criterion (AIC) for each alternative model to determine which best explained the data. AIC_c, which is a modified version of AIC used to approximate AIC at smaller sample sizes, was used for this study. We considered models with Delta AIC_c of 0–2 to have substantial support (Burnham & Anderson 2002). We also used model Akaike weights (AIC_cWt) to help determine model suitability, with high scores indicating better model fit.

Results

The three treatment types were shown to differ significantly ($P < 0.05$) in the four continuous explanatory variables used in the analysis (Fig. 3, Appendices S1 and S2). Compared to CWD, open sites had significantly higher browsing pressure as estimated by kangaroo faecal pellets (Fig. 3a), lower weed heights (Fig. 3c) and lower grass heights (Fig. 3d). When comparing CWD treatment types, applied CWD sites had higher browsing pressure, lower CWD cover (Fig. 3b), and higher weed heights compared to natural CWD, although grass height was not significantly different.

The predicted probability of a sapling being browsed was influenced by the interaction of treatment type and faecal pellet density (kangaroo browsing pressure). This model was the only one with a Delta AIC_c value below 2 (AIC_cWt of 0.99; Appendix S4) indicating that these two variates had a strong influence on browsing probability. The predicted probability of browsing significantly increased with kangaroo browsing pressure across all three treatments (Fig. 4a; Table 2). Among the treatment types, saplings had a significantly greater chance of being browsed in open sites compared to both CWD treatments. Predicted browsing probability tended to be less among natural CWD compared to applied CWD (Fig. 4a), but due to high variability, this effect was not significant. The probability of being browsed approached 100% in both the applied CWD and open treatments at high browsing pressures of around 150–250 pellets. The maximum predicted probability of browsing in natural CWD, on the other hand, only reached 80% at maximum browsing pressure. This was a 20% reduction compared to open and applied CWD treatments.

Predicted time to first browsing was most influenced by browsing pressure and by CWD cover as both these models had a Delta AIC_c value under 2 (Appendix S5). However, browsing pressure explained more data as it had a higher AIC_cWt of 0.56 compared to 0.21 for CWD cover. The predicted time to browsing decreased as browsing pressure increased (Fig. 4b; Table 2). At browsing pressures close to zero, on average it took around 5 weeks for an unbrowsed plant to be found and browsed. At the maximum browsing pressure, it took on average 2 weeks. The predicted time to browsing tended to increase as the CWD cover increased (Fig. 4c; Table 2); however, this trend is not as large as in the other models. Predicted time to browsing

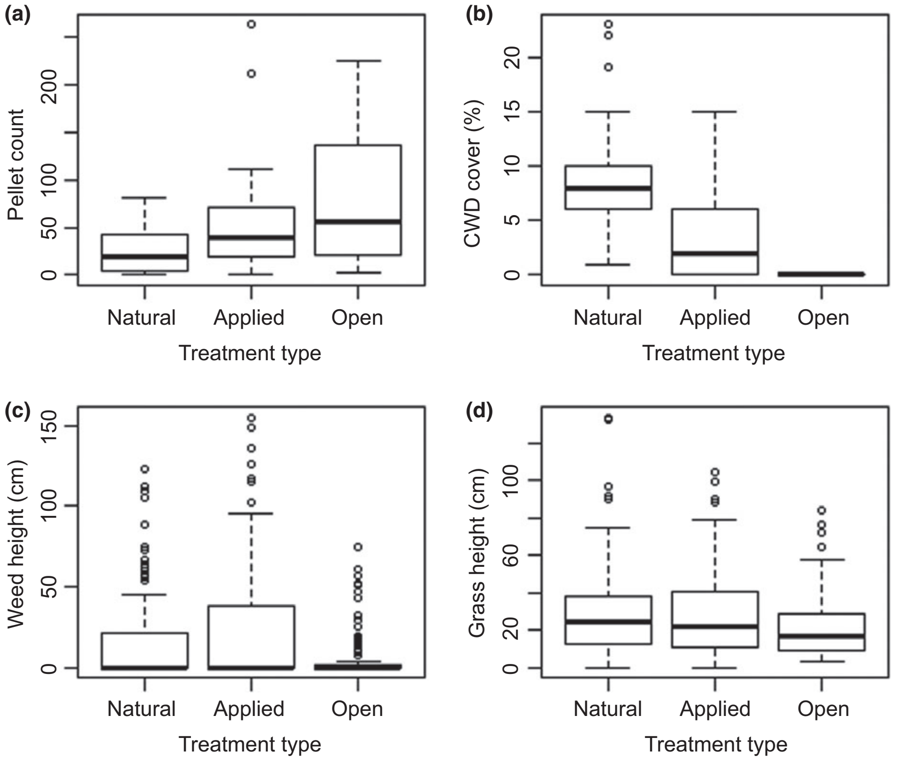

Figure 3. Comparison between treatment type and (a) pellet count (browsing pressure), (b) CWD cover, (c) weed height, (d) grass height (dark line = median, box = interquartile range, whiskers = upper and lower limits, white circles = outliers).

was on average 2 weeks at low CWD cover (~5%); at high CWD cover (~65%), time to browsing was on average 3.5 weeks. The CWD cover was significantly higher in natural CWD compared to applied CWD (Fig. 3b).

Predicted browsing severity (change in sapling height) was best explained by browsing pressure alone (Fig. 4d). This model had a high AIC_cWt of 0.99 and was the only model with a Delta AIC_c value under 2 (Appendix S6). Predicted browsing severity increased as browsing pressure increased (Table 2). A sharp rise in severity occurred at low browsing pressure before the increase in severity became more consistent at a browsing pressure of around 50 pellets (Fig. 4d). Unlike the other models, the trend did not begin to plateau indicating that predicted browsing severity would continue to rise with increasing browsing pressure. At the maximum browsing pressure for this study, mean predicted sapling height loss was 19 cm. This was a 60% decline in height from the mean starting height of 31 cm. Among the treatment types, the mean height loss was 12.8 cm in the open, 4.0 cm in natural CWD and 7.7 cm in applied CWD.

Discussion

What influences browsing inside woodland reserves?

This research is the first of its kind in grassy woodlands to show that CWD can protect woody plant saplings from browsing by mammalian herbivores. However, kangaroo browsing pressure, as indicated by faecal pellet counts, also has a strong influence on the predicted probability that a highly palatable sapling will be browsed. At low browsing pressure, both applied and natural CWD provided a reduction in browsing probability compared to the control (no CWD). However, at high browsing pressure almost no protection was provided by applied CWD.

Natural CWD, in comparison, did provide some reduction in sapling browsing probability even at high browsing pressure, indicating that this type of CWD was more effective as a deterrent to browsing. This may be due to differences in structure between the CWD types. Applied CWD had a much more open structure made up of large and branchless tree boles (Fig. 1a). The lack of small branches may have made it easier for kangaroos to access the saplings. Naturally fallen CWD, on the other hand, had a denser structure (Fig. 3b), which usually still included large and small branches (Fig. 1b). The denser structure of the natural CWD may make it more difficult for herbivores to access the saplings by hiding them or obstructing access. This denser structure of fine woody components has been shown to be a deterrent to herbivores in other studies by acting as an exclosure for regenerating plants (Ludwig & Tongway 1996; de Chantal & Granström 2007). Studies also in the ACT by Barton *et al.* (2011) and Manning *et al.* (2013) showed that applied CWD increased beetle and reptile abundance under high grazing pressure when applied in a clumped arrangement. However, this benefit was often reduced when placed in a dispersed arrangement similar to the arrangement of the applied CWD used in the project. In our study, both CWD treatments decreased browsing pressure around them, particularly natural CWD. This indicates that CWD may decrease the density of herbivores in the immediate vicinity which will likely also help reduce browsing on saplings.

In contrast to the probability of browsing, the presence of CWD had no effect on predicted browsing severity (loss of height); only browsing pressure had a strong influence. This shows that CWD can reduce the probability of a sapling being found and subsequently browsed, but once found, CWD has little influence on the severity of browsing as measured by height reduction.

Implications for conservation

Our results indicate that in open, CWD depleted areas, natural regeneration, at least of highly palatable *Acacia* saplings, will most likely be suppressed by kangaroo browsing. Even though the saplings were manually planted in the study, it is

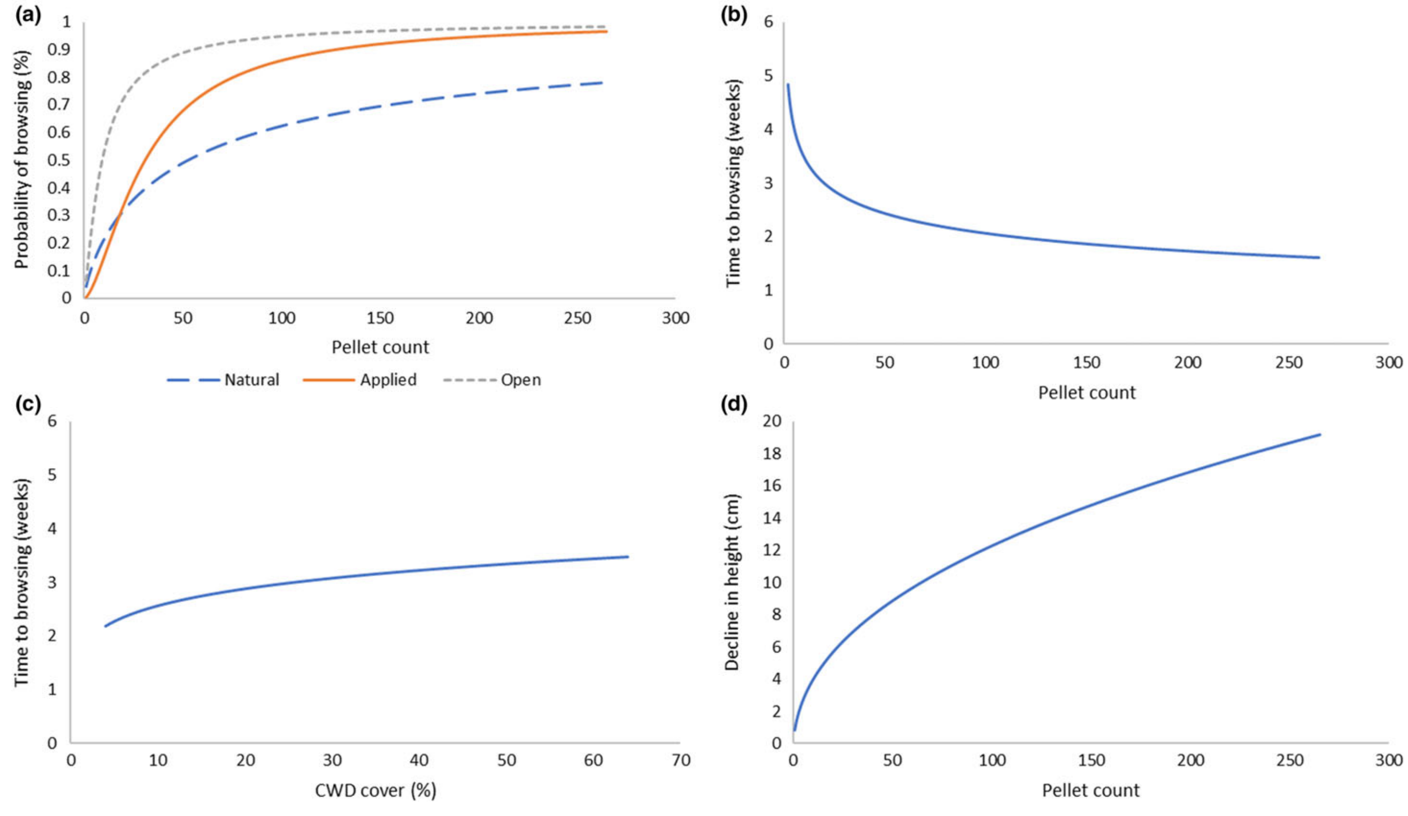

Figure 4. (a) Predicted probability of an *Acacia rubida* sapling being browsed over an 8-week period across treatment types with increasing kangaroo browsing pressure as estimated by pellet counts. (b) Predicted time to first browsing in weeks with increasing kangaroo browsing pressure. (c) Predicted time to browsing in weeks with increasing cover of CWD. (d) Predicted decline in height (cm) over an 8-week period with increasing kangaroo browsing pressure (Source: Table 2). [Colour figure can be viewed at wileyonlinelibrary.com]

Table 2. Fixed effects for the most supported models

		Estimate	Std. Error	Pr(>|z|)
Predicted probability of browsing	Model 3			
	(Intercept)	−0.11	0.39	0.779
	Kangaroo pellet count	2.12	0.61	0.001
	Treatment Natural CWD	−0.37	0.46	0.421
	Treatment Open	1.52	0.46	0.001
	Pellet count x Treatment Natural CWD	−1.05	0.66	0.116
	Pellet count x Treatment Open	−0.45	0.65	0.493
Predicted time to browsing	Model 2			Pr(>|t|)
	(Intercept)	0.05	0.13	0.717
	Kangaroo pellet count	0.32	0.09	<0.001
	Model 4			
	(Intercept)	0.13	0.16	0.428
	CWD cover	0.24	0.07	0.001
Predicted decline in height	Model 2			
	(Intercept)	0.54	0.14	0.012
	Kangaroo pellet count	0.41	0.07	<0.001

likely that any palatable woody plant saplings naturally regenerating in the study areas would experience similar browsing probabilities and severity. This may be because as browsing pressure rises, pastures may become over-grazed resulting in food shortages. When this happens, kangaroos may consume more items they would not usually eat such as woody plant saplings (Taylor 1983). This may also explain why browsing pressure decreases time to browsing as hungrier animals may be more intensively searching for food and, therefore, may find and choose to browse saplings sooner.

The amount of height loss during this study would likely be more severe for naturally regenerating saplings which would not have the advantage of being relatively tall at the time of planting. Substantial height reduction can result in death or the suppression of growth in woody plant saplings and repress natural regeneration (Zamora *et al.* 2001). This adds to the other potential negative impacts of high kangaroo densities within grassy woodland reserves, such as reducing habitat for fauna (Howland *et al.* 2014). The findings are consistent with research by Meers and Adams (2003), who also found that kangaroo over-browsing can repress the regeneration of some woody plants. In order for natural regeneration to occur under high browsing pressure, plant saplings would likely need to be grown within a protected area (fenced or tree guards). CWD could provide protection for natural regeneration, and the results of the study show that both applied and natural CWD reduce browsing probability, but only at low and moderate browsing pressures.

However, for natural regeneration to occur, saplings must first establish themselves among CWD. This may be difficult as we found that CWD, particularly applied CWD, had significantly higher densities of exotic weeds (Fig. 3c); which may prevent the establishment of woody plants through increased competition (Goldin & Brookhouse 2015). Fire can help germination around CWD by creating favourable soils (Bailey *et al.* 2015) and by clearing competition. However, due to many ACT woodland reserves being close to urban settlement the intense fires needed for this to happen would unlikely be allowed to occur. Therefore, there will likely be little to no natural regeneration of woody plants around CWD. One way to overcome this would be to manually plant nursery grown seedlings in and around applied and natural CWD, which then might receive sufficient protection benefits from CWD.

Management recommendations

Based on our results, a series of actions are recommended for restoration in degraded grassy woodland patches:

1. Where browsing pressure is low to moderate, saplings can be planted around large, branchless pieces of CWD, such as the applied CWD used in this experiment, as it will provide some extra protection from browsing. However, when browsing pressure is high there is unlikely to be any extra protection provided by this type of CWD.

2. At all levels of browsing pressure, a natural CWD-like structure is recommended to reduce kangaroo browsing. This approach would involve sourcing wood which still has fine woody components attached, such as branch cuttings. Such branches should then be placed around restoration plantings to add extra protection. Unlike the applied CWD from the study, this should protect the saplings from browsing even under high browsing pressure. The denser structure will likely also increase the time to browsing. This method is already used by some volunteer groups who work in some of the ACT woodland reserves (pers. obs.) and should also be more widely used in restoration plantings. However, care should be taken when placing this type of CWD to avoid the accidental introduction of seeds which may come with some of the fine woody components sourced from nonindigenous species (Manning *et al.* 2011). Fine woody debris will likely also increase fire risk by providing more fine fuel (McArthur 1967); therefore, its placement must also be carefully planned to avoid fire risks especially in reserves adjacent to residential areas.

3. Although CWD can be useful for protecting planted saplings, the most important action for facilitating regeneration is kangaroo population management. Reduction in over-abundant kangaroo populations will likely reduce the probability and severity of browsing, as well as increase the time taken for saplings to be found and browsed. A reduction to low-to-moderate browsing pressure will also allow applied CWD to provide protection services.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Summary of continuous variables.

Appendix S2. Summary of factors.

Appendix S3. Models used for analysis.

Appendix S4. AIC ranking for the Probability of browsing models.

Appendix S5. AIC ranking for the Time to browsing models.

Appendix S6. AIC ranking for the Browsing severity (decline in height) models.

