Limited long-term effectiveness of roller-chopping for managing woody encroachment

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Running header: Roller-chopping for shrub removal

Abstract

The encroachment of woody plants into grasslands, woodland and savanna has increased markedly over the past century, prompting the use of different physical methods to remove woody plants and restore grasses. Roller-chopping is used extensively in the Americas, but little is known about its long-term effectiveness for restoration, and whether its effectiveness varies with the intensity of encroachment. We compared the effects of roller-chopping, under three treatment intensities (control, single treatment, double treatment), on woody plant density, ground cover and groundstorey plants at sites of low, moderate and high woody plant density in a semi-arid eastern Australian woodland over 10 years. Both single and double treatment significantly altered the size distribution of *Dodonaea viscosa*, which comprised more than 85% of woody plants at all sites. Thus, roller-chopping changed the size distribution of the community from an even-size distribution to one dominated by shorter plants, irrespective of initial encroachment level. The effectiveness of roller-

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chopping was strongly site-specific, with significant reductions in density at low- and high-density sites, but no clear trend in relation to the intensity of treatment (i.e., single *cf.* double treatment). The effectiveness of roller-chopping was unsustained over the long term, with the suppressive effect on woody density diminishing over time. Grass cover increased with increasing intensity of woody removal, but only at the low-density site and with some ill-defined, variable and short-term effects on plant composition. Managers should consider that the short-term effects may not adequately reflect the long-term results of woody plant removal using the roller-chopper.

Key words: shrubland, woody plants, mechanical treatment, thickening, physical removal

Implications for Practice

- The effects of roller-chopping on plant density, cover and composition varied with woody plant density and was highly variable over time.
- Programs that aim to restore encroached woodlands and grasslands should consider whether the target plants are resprouters.
- Although long-term control is unlikely, short-term reductions may be useful in some situations such as reducing vegetation cover along roads and tracks

Introduction

Woody plant encroachment, characterized by an increase in woody cover and density, is a global phenomenon that has affected extensive areas of grasslands, open woodlands and savanna over the past century (Eldridge et al. 2011; Archer & Predick 2014; Stevens et al. 2016). Encroachment is thought to result from a number of causal mechanisms including overgrazing by livestock, increases in atmospheric carbon dioxide levels, reductions in the frequency and intensity of fire that remove woody seedlings, and more recently, extirpation of top predators that indirectly suppress woody seed harvesting (Bond & Midgley 2012; Eldridge et al. 2013; Gordon et al. 2017; Wilcox et al. 2018).

The literature is replete with many examples of the negative effects of woody plants on ecosystems, particularly those where pastoralism is the primary land use (e.g. Schlesinger et al. 1990; Archer et al. 2011). Because encroachment is generally associated with reductions in grass and herbaceous cover, it has the potential to threaten the social and ecological viability of pastoral enterprises. An increasing body of literature, however, suggests that encroachment is a response to alterations to ecosystem disturbance and therefore represents a recovery process that is critical for restoring ecosystem functions and services (Maestre et al. 2009, 2016). Aggregations of woody plants often form 'fertile islands' (Bolling & Walker 2002) beneath their canopies, which support greater nutrient concentrations (Ward et al. 2018), more diverse fungal and bacterial populations (Ochoa-Hueso et al. 2018), and potentially, greater richness of groundstorey protégé species (species that benefit from growing beneath larger plants; Soliveres & Eldridge 2020). However, despite the many putative ecosystem benefits of woody plants, even under encroached conditions (Eldridge & Soliveres 2015), woody encroachment is still regarded as a symptom of poor ecological health, particularly in systems that rely heavily on forage production to support livestock grazing (Eldridge & Soliveres 2015). Considerable capital has been invested worldwide in an effort to remove woody plants and reverse the loss of herbaceous plants on which pastoralism depends, generally with limited long-term success (Ding & Eldridge 2019).

Physical (mechanical) and chemical (herbicide) methods, burning and browsing have been used to manage woody (shrub, brush) encroachment worldwide, predominantly in arid and semiarid environments (Archer et al. 2011). Some of this work, which is supported by government initiatives, such as the Restore New Mexico program in the United States of America (USA; www.blm.gov/press-release/blm-grassland-restoration-treatments-begin-southern-new-mexico), and similar programs in Mexico (Schindler et al. 2004) and Australia (CWCMA 2010) aim to support land managers to maintain productive pastoral enterprises in the belief that removal of woody plants will result in increasing forage (grass) production. Physical removal is a particularly favoured way to remove woody plants, with variable methods depending on the situation. All physical methods involve the removal of aboveground woody biomass in different ways and have different effect on soils. For example, methods involving pushing (bulldozing), chaining (chain dragged between two bulldozers; Stephens et al. 2016), cutting and mowing (Liu et al. 2019) result in minimal soil disturbance. Root ploughing (Robson 1995; Weiderman & Kelly 2001) maintains soil structure and above-ground material *in situ* but severs the roots below the surface, and roller-chopping (rolling and chopping) severs and cuts above-ground material.

Roller-chopping has been used widely to manage woody plants in rangelands, particularly in dry regions (e.g. Argentina and USA). Unlike mowing and root ploughing, roller-chopping severs vegetative material into small segments and creates indentations on the soil surface that are designed to trap seeds and organic matter and prevent soil loss (Bozzo et al. 1992; Schindler et al. 2004). Roller-chopping has been used to reduce shrub cover to promote herbaceous biomass and cover (Adema et al. 2004; Sabattini et al. 2018), to improve water capture and storage (Adema et al. 2004), soil condition (Ledesma et al. 2018) and microbial activity (Anriquez et al. 2005). It is regarded as a relatively cheap method of managing dense stands of fire-resistant woody species (Huffman & Werner 2000) such as saw palmetto (*Serenoa repens*; Tanner et al. 1988) without reducing soil quality (Kunst et al. 2016). It has also been shown to have few effects on tree species diversity (Rejžek et al. 2017) and generally no negative effects on birds (Fitzgerald & Tanner 1992; Willcox & Giuliano 2011), though it can alter plant functional diversity (Steinaker et al. 2016). Its effectiveness can be enhanced by seeding with grass species (Blanco et al. 2005). In Australia, there have been few attempts to test the effectiveness of roller-chopping as a woody control method despite its relatively lower cost than other physical methods. Roller-chopping could have a role in suppressing woody plants due to its ability to treat a relatively wide area. It could also potentially stimulate herbaceous response to competitive release after woody removal and could help to maintain surface stability by retaining woody debris on the soil surface.

Here we report on a study based on long-term field experiment to test the effectiveness of roller-chopping as a restoration tool to reduce woody plant density and increase groundstorey plant cover where encroachment is recognised as a major environmental issue by pastoralists. In our study we tested three hypotheses about the long-term control of woody plants using a roller-chopper. Global syntheses of woody plant removal indicate that its effectiveness is generally short-lived, with increases in herbaceous biomass and diversity lasting less than five years and generally diminishing over time due to subsequent recruitment (Archer et al. 2011; Ding & Eldridge 2019). We expected therefore that any potential effects of roller-chopping on either woody plants or groundstorey communities would dissipate within a decade (Hypothesis 1). Effective long-term control is more difficult as woody density or cover increases (Bestelmeyer et al. 2018). Therefore, we expected that the effectiveness of control would be greater at sites of lower initial woody density (Hypothesis 2). Finally, we expected that a more intensive treatment (double rolling) would be more effective than single rolling because plants are effectively treated twice with a second roller placed behind the first, thereby increasing the degree of cutting (Hypothesis 3). Our study is the first to examine the long-term effectiveness of roller-chopping as a woody control method under different encroachment stages in eastern Australia. The results provide a scientific basis for deciding whether roller-chopping is a viable restoration tool for managing woody cover and density over areas of eastern Australia that are dominated by woody plants, particularly *Dodonaea viscosa*.

Methods

Study area

Shrub removal experiments were established at three sites characterized by different levels of woody density in western New South Wales, Australia in 1984; 1) low density (3125 ± 717 shrubs ha^{-1}; mean ± SE), Koralta, 20 km north of Little Topar (-31.63, 142.23), 2) moderate density (6417 ± 1255 shrubs ha^{-1}), Langawirra, 80 km north-east of Broken Hill (-31.38, 142.12), and 3) high density (10375 ± 1736 shrubs ha^{-1}), Annalara north-west of

Wilcannia (-31.25, 143.93). Most sites in the area were developed by European pastoralists in the mid-19th century as large pastoral stations. The three properties would have been established sometime in the mid-20th century when larger holdings were subdivided. Differences in woody plant density at the three sites could be due to variable levels of historic overgrazing, given the known links between grazing intensity and woody density (Eldridge et al. 2013). The low-density site was located in the middle of a large paddock whereas the moderate and high-density sites were located within holding paddocks that periodically supported large numbers of sheep during routine shearing operations, and would therefore have been subjected to high grazing intensities. All three sites occur on extensive plains and sandplains of deep Quaternary alluvium, with slopes to 1%, and isolated low sandy rises and occasional depressions (Walker 1991). The soils vary slightly among the three study sites. Soils at low and moderate-density sites are typically coarser (less clay) and dominated by red sandy earths or calcareous red earths (Calcarosols, Isbell 2016; low-density site) or calcareous loamy sands (Calcarosol; moderate-density site) with predominantly sandy and loamy sand surface textures. Soils at the high-density site are predominantly calcareous earths (Gc2.13) and red duplex soils (Dermosol) with sandy loam to clay loam surface textures. Average temperatures across the three sites range from 35.6ºC for the three summer months to 18.3ºC during the three winter months. Average rainfall varies from 223 mm (low-density) to 290 mm (high-density), with about 23% more rainfall in the six warmer months (September-February; Supplementary Material Fig. S1). The vegetation community across the three sites is mapped as Sandplain Mulga Shrubland (Keith 2004), but with slight differences in species composition among sites. Low- and moderate-density sites supported a community dominated by a mixture of mulga (*Acacia aneura*), nelia (*Acacia loderi*), rosewood (*Alectryon oleifolius*), punty bushes (*Senna* spp.), narrow-leaved hopbush (*Dodonaea viscosa*) and black bluebush (*Maireana pyramidata*). The tree and shrub layer at the high-density site comprised a mixture of belah (*Casuarina cristata*), leopardwood (*Flindersia maculosa*), black bluebush, narrow-leaved hopbush, turpentine (*Eremophila sturtii*) and budda (*Eremophila duttonii*). All of these shrubs are reseeders, but *Eremophila* spp. and *Dodonaea viscosa* are also known to reshoot from epicormic and belowground buds (Wiedemann & Kelly 2001, Vesk et al. 2004). The groundstorey at all sites was dominated by semi-perennial grasses such as *Austrostipa* and *Aristida* spp., and forbs such as *Sclerolaena* spp., *Goodenia* spp., and *Atriplex* spp., depending on seasonal conditions. This study was carried out under slightly above-average rainfall conditions at the low (Koralta; 25% above average) and moderate (Langawirra, 33% above average) density sites, but conditions at the high-density site (Annalara) were 65% above average values. Rainfall values at the end of the study were average at all three sites (Fig. S1).

Site establishment and treatment

At each site we established an area of about 500 m by 500 m within a relatively uniform community dominated by dense shrubs and small trees. Within that site we established 12 plots arranged in a 6 x 2 configuration. Each plot was 60 m long by 40 m wide, with a 10 m buffer around all edges. The 12 plots were randomly assigned to three treatments: i) control (no roller-chopping), ii) single treatment (tandem), where two rollers were placed side-by-side, and iii) double (offset) treatment, where one roller was placed behind the first roller but slightly offset. The plots were rolled and chopped with a Marden ® Roller-Chopper (Model L7) pulled by a Caterpillar D-4 tractor. All sites were treated between May and June 1984. The Marden L7 roller-chopper has a drum length of 2.2 m and a drum diameter of 0.62 m, yielding a water-filled weight of 3.6 tonnes. A series of metal blades welded to the drums, and parallel to the axis, are capable of severing the stems of woody plants up to 15 cm in diameter (Schindler et al. 2004). Because of the spacing of the blades, vegetation is severed into pieces about 20 cm long, and the roller-chopper creates a series of parallel grooves in the soil surface about 10 cm deep and 15 cm wide, depending on soil texture. These grooves are designed to trap water and seeds and therefore hasten revegetation. Cost of this method at the time of treatment (1984) was about AUD 33 ha^{-1}, or AUD 86 ha^{-1} in 2020 dollars.

Plant measurements

We used the step-point method (Everson & Clarke 1987), a form of the point-intercept method, to record plant species cover, soil surface cover and to calculate plot-level plant richness. We criss-crossed each plot and recorded each plant by species (< 50 cm tall), bare soil or litter cover found beneath each of 1000 points. Shrubs or groundstorey plants > 50 cm were recorded if their canopy was located directly above a point. Using these data, we calculated total plant (litter, or bare soil) cover as the percentage of points where a plant, litter or bare surfaces was recorded. Plant richness was calculated as the total number of plant species recorded using step-pointing plus any additional plants found on the plots. Measurements were made before treatment (1984), 3 years post-treatment (1987) and 10 years post-treatment (1994).

Statistical analyses

We used a split-plot ANOVA to examine the effects of the three treatments, three time periods, and their interactions, on shrub density, plant richness, grass cover, forb cover, bare soil cover and litter cover. Our model had two strata. The first stratum examined time effects (n = 3); pre-treatment, early recovery (3 years post-treatment) and late recovery (10 years post-treatment). The second stratum examined treatment effects (n = 3) and their interaction with time. Analyses were undertaken in Genstat 19.1 (VSN International). The residuals were checked for equal variance and normality with Levene's test prior to analyses, but did not require transformation. Significant *post-hoc* differences in means were examined using Tukey's LSD test. We examined potential differences in groundstorey plant species assemblages among years, treatments, and their interaction using permutated, non-metric multivariate analysis of variance (PERMANOVA; Anderson 2017) using the Bray-Curtis similarity matrix (Gauch Jr 1973) and the same model structure as used in the univariate analyses. We then used Indicator Species Analysis, with the 'indicspecies' package in R (De Caceres & Legendre 2009) to identify those species that were indicative of different years or treatments.

Results

Shrub density and population structure

Shrub composition varied among sites, with low and moderate density sites dominated by *Dodonaea viscosa* (99% by density), with a few scattered *Acacia aneura*, whereas the high density site supported a greater diversity of shrubs including *Eremophila sturtii*, *Acacia* spp., *Grevillea striata*, *Senna artemesioides*, *Senna eremophila* and *Hakea leucoptera*. *Dodonaea viscosa* comprised 85% of shrubs, by density, at the high-density site.

Ten years after treatment (Table 1), average shrub cover of each site was lowest at the high-density (11%), intermediate at the low-density (28%) and greatest at the moderate-density site (46%). On the untreated (control) plots, shrub density declined naturally over the 10 years by an average of 51%, 26% and 8% at high, low, and moderate density site, respectively (Fig. 1).

The effectiveness of roller-chopping for reducing woody plant density varied among sites and times (Fig. 1). For example, at the low-density site both the single and double treatments significantly reduced total shrub density ($F_{2,18}$ = 4.52, P = 0.026), and this reduction persisted until 10 years after removal. At the high density site, total shrub density declined from 9,583 shrubs ha^{-1} in the control plots to 6,375 shrubs ha^{-1} under the single treatment, with a significant reduction to 3,049 shrubs ha^{-1} under the double treatment ($F_{2,18}$ = 22.1, P < 0.001). Under moderate density, however, we found no effect of roller-chopping on total shrub density (P = 0.18), and this was consistent across time. There were no significant time by treatment interactions for any of the three sites.

The size distribution of shrubs also varied with treatment across sites. Under low density, shrubs were moderately right-skewed with some very large (> 4 m high) shrubs on the control plots but left-skewed with more smaller shrubs (< 25 cm high) persisting in the absence of any removal treatment a decade after treatment (Fig. 2). Under moderate density, the distribution of shrub sizes was relatively symmetrical within the control plots, with some small and some large shrubs, and a median height of 100-150 cm, but highly skewed to smaller size classes under both single and double treatments 10 years later. On the control plots under high woody density site, size classes of *Dodonaea viscosa* were skewed to smaller size classes with a median pre-treatment height of 50-100 cm. This remained relatively unchanged 10 years after treatment (Fig. 2). The median heights of shrubs at low and moderate density sites declined from height classes of 150 to 250 cm in the controls, to the 50 to 100 cm class under the double treatment. At the high-density site however, median shrub heights remained unchanged under the single treatment (100 to 125 cm) and increased (125 to 150 cm) under the double treatment. Over all sites, both roller-chopper treatments (single, double) resulted in highly skewed populations dominated by generally short (<25 cm tall) shrubs in the long term (Fig. 2).

Groundstorey plant community

Over all sites and treatments, bare soil cover was generally high (55.6 ± 5.5%; mean ± SE) and plant cover sparse (26 ± 5.1%; Table 1). There were no significant differences in total groundstorey plant cover, litter cover or bare soil a decade after treatment on any site or under any treatment (Table 1). When we examined changes in two major plant functional groups (forbs and grasses), we found some effects of treatment and time (Fig. 3). For example, grass cover increased with intensity of treatment at the low-density site only ($F_{2,18}$=11.47, P < 0.001; Fig. 3d), but there was no effect of roller-chopping on forb cover at any site (Fig. 3). There were also some ill-defined temporal effects on both forb and grass cover (Fig. 3d-f), and significant time by treatment interactions for both forb cover ($F_{4,18}$ = 7.72, P = 0.001; Fig. 3a) and grass cover ($F_{4,18}$ = 5.74, P = 0.004; Fig. 3d), but only at the low-density site. These interactions indicated that at the low-density site only, there was 1) no temporal changes in forb cover in the control plots, but greater forb cover at 10 years under the double roller-chopper treatments, and 2) substantially reduced grass cover under both single and double treatments 3 and 10 years after treatment (Fig. 3d).

We also detected some effects of roller-chopping on species richness, with significantly lower richness on control than treated plots at moderate ($F_{2,18}$ = 4.55, P = 0.025) and high ($F_{2,18}$ = 5.03, P = 0.018) density sites, but no treatment effects under low density (Fig. 1d-f). There were also some effects of time since removal, but these were inconsistent across different sites. For example, there were no temporal differences in richness at moderate and high-density sites, but at low-density sites, average plot richness declined over time ($F_{2,9}$ = 177.5, $P < 0.001$; Fig. 1d).

When we examined the effects of roller-chopping on plant composition we found two main effects. First, plant composition on treated (single, double) plots was significantly different from that on control plots, but only at low (pseudo $F = 2.68$, P-perm = 0.002) and moderate (pseudo $F = 2.60$, P-perm = 0.004) density sites (Fig. S2). Second, there were significant differences among years, particularly between the pre-treatment Year 0 and 10 years after treatment (Fig. S2). We found no obvious species that were strong and consistent indicators of different times or treatments (Table S1). However, perennial grasses such as *Eragrostis dielsii, Aristida jerichoensis* var. *jerichoensis, Aristida contorta, Enneapogon avenaceous* and *Eragrostis* spp. tended to be strong indicators of both low and moderate density sites, particularly 10 years after treatment (Table S1).

Discussion

Marked increases in woody plant encroachment in open woodlands, savanna and grasslands over the past century have intensified the use of multiple, generally physical, methods to control woody plants in order to reinstate the original grassland vegetation (Scifres et al. 1985) which sustains pastoral enterprises (Blanco et al. 2005). Our study showed that the effectiveness of roller-chopping was strongly site specific, with significant reduction in shrub density at sites of high and low initial shrub densities, but not at the moderate density site, and with no clearly defined effect due to different treatment intensity (i.e., single or double roller configurations). Consistently, however, the effectiveness of roller-chopping for removing mature shrubs from all sites was to shift a shrub community with an even distribution of sizes to one dominated by many shorter shrubs, either by stimulating seed fall and recruitment, or recovery (resprouting) of existing severed shrubs. In addition, roller-chopping had some effects on groundstorey plants, such as changes in plant composition, generally increasing forb cover and reducing grass cover. Strong temporal changes in plant composition were likely driven by shifts in rainfall among years. Furthermore, shrub densities declined naturally by 11 to 46% over the decade-long study in the absence of any treatment (control sites), a phenomenon that was likely associated with increasing competition for resources, and potentially, drying climatic conditions during the study period, particularly at the high density site (Bureau of Meteorology 2019). Furthermore, our study provides empirical evidence that treatment effectiveness is generally short-lived, with either single or double treatment configuration failing to sustain viable control over a decade. Further, our study was conducted more than three decades ago under climatic conditions that are different from current conditions. Modern responses to roller-chopping may well differ from those experienced three decades ago. Overall, our results suggest that a one-off roller-chopper treatment is unlikely to restore woody encroached grasslands.

Effectiveness of roller-chopping is site specific and short lived

Grazing, fire, herbicides and mechanical methods have all been used to control woody encroachment, but with variable success (e.g., Moore & Walker 1972; Gonzalez 1990; Harland 1992; Robson 1995; Booth et al. 1996; Adema et al. 2004; Schindler et al. 2004). We found that the effectiveness of roller-chopping for removing shrubs was highly site specific, consistent with a global synthesis that indicated strongly nuanced effects dependent on soil type, woody plant traits, and removal method (Ding & Eldridge 2019). For example, in our study, the effectiveness of removal varied with the pre-treatment encroachment status. Contrary to prediction, the greatest density decline was at the site with the greatest initial density, which seems at odds with the notion that heavily encroached sites are relatively stable and resistant to disturbance (Bestelmeyer et al. 2018). However, most shrubs at the densest site were short (50-100 cm high) and likely to be more susceptible roller-chopping. Smaller shrubs would also likely carry a smaller seed load, and support a lower level of recruitment a decade after treatment. By comparison, the moderate-density site comprised more medium-sized shrubs (100-150 cm high), which would have been more resistant to mechanical disturbance. Equally, *Dodonaea viscosa* might have reprouted more rapidly following treatment (Hodgkinson 1998), resulting in no overall treatments effect. Furthermore, we found that the effectiveness of roller-chopping dampened with increasing time since treatment, with any significant suppressive effect lasting only 3 years in one of the three sites examined (*sensu* Archer & Predick 2014; Ding & Eldridge 2019). This finding is partly consistent with the results of global studies reporting marked reductions (60%) in shrub cover in the first few years following treatment (e.g., Tanner et al. 1988; Aguilera & Steinaker 2001; Blanco et al. 2005). Yet unlike our study, few studies have tracked changes in woody plant density over time frames longer than 3 years, so short-term studies reporting the success of roller-chopping in woody encroachment management, such as those reported above, may provide an overly optimistic perspective of its long-term efficacy. We acknowledge that our study used only a one-off treatment. Follow-up treatment, using further mechanical methods or herbicide, may well prove more effective in providing a longer-term control of woody plants, and to be effective, follow-up treatment would need to occur within 10 years of initial treatment.

Despite site differences, removal effectiveness is likely to be driven most by treatment method (Archer et al. 2011; Ding et al. 2020). The main effect of roller-chopping is to prune plants by chopping plants into similar-sized fragments ~ 20 cm long, not necessarily at ground level. We expected this action to be more effective under the double treatment, but our hypothesis (Hypothesis 3) was upheld only at the high-density site, which supported both a greater richness and density of woody species. The overall insignificant effect of treatment configuration (single *cf.* double) could be due to species-specific differences in stem flexibility, bark thickness or susceptibility to cutting, with very little difference in susceptibility even when treated twice. For example, *Acacia aneura*, has thick bark at the sapling (shrub-like) stage, which might have mediated against physical chopper effects (Schubert et al. 2016). The other common shrub species, *Senna eremophila, Eremophila sturtii* and *Eremophila latrobei* ssp. *glabra*, are relatively short plants with thin flexible stems that would have been less susceptible to shearing and cutting. The regionally widespread *Dodonaea viscosa* is however moderately susceptible to mechanical control (Harland 1992; Robson 1995; Eldridge & Robson 1997; Daryanto 2013), with a variable response to roller-chopping due to its high ability to resprout from basal shoots (Hodgkinson 1998; Nano & Clarke 2011).

No long-term legacy effects on groundstorey richness or cover

Roller-chopping has been widely used as an effective way to increase plant production (Kunst et al. 2012), with increasing plant cover shown in a number of studies worldwide such as Argentina (Passera et al. 1992) and the United States of America (Willcox & Giuliano 2010). In our study, we found that roller-chopping increased grass cover, but only at the site with low density of shrubs. Moreover, treatment effects on composition were mixed, with treated plots differing from control sites, at low and moderate density sites, but not at the high-density site. These variable effects of roller-chopping on plant community composition (Watts & Tanner 2003) are likely due to difference in climatic conditions across the sites, particularly given that high density site received, on average, about 30% more rainfall than the other sites. Our data also indicate a general increase in forb cover over time, irrespective of treatment. The failure to increase grass cover, the primary goal of most shrub removal treatments, could be due to the time lag between removal and plant response (North et al. 2005). For example, herbaceous species can take some years to respond to reductions in competition and greater access to resources following the removal of the woody overstorey (Allegretti et al. 1997; Ansley et al. 2006). Such lagged responses could be further dampened by the rapid re-establishment of shrubs at our sites, resulting in no net groundstorey response. Mixed responses could also relate to the different effects that shrubs have on groundstorey plants, which would depend upon trade-offs between facilitation (e.g. shading, hydraulic lifting; Caldwell et al. 1998) and competition (e.g. resource competition; Munzbergova & Ward 2002). Grasses are frequently sown as part of the roller-chopper treatments in order to increase pastoral production (Aguilera & Steinaker 2001). Although grasses were not sown at our study sites, prolific grass growth following shrub removal could increase the effectiveness of control by increasing competition between grasses and shrub recruits. Future studies should examine the usefulness of planting grasses as part of any shrub control program.

In summary, we showed that shrub suppression by roller-chopping was mixed, with little evidence of long-term effects on surface cover or plant community composition in our study. Despite the widespread use of roller-chopping as a vegetation management tool in the

Americas, there is little evidence that it provides long-term benefits in managing shrubs in Australia's semi-arid woodlands. Our long-term study also reinforces the view that the effectiveness of shrub control is relatively short lived, and unlikely to be sustained over a decade. Encroachment, however, is likely to intensify globally in drylands as carbon dioxide levels increase under predicted climate changes for global drylands (Huang et al. 2016). This will likely place further pressure on pastoralists as they attempt to sustain their grazing enterprises on a declining grassland base. We repeat the call made by Eldridge & Soliveres (2015) for more studies of cost-effective, ecologically appropriate and environmentally sensitive techniques for managing woody encroachment that meet the needs of conservation and production-based systems.

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Table 1. Mean (± SE) cover of plants, litter and bare soil (%) across the three sites with different initial shrub density and three treatments 10 year after removal. There were no significant treatment effects for any attributes or site.

Site	Treatment	Plant cover (%)		Litter cover (%)		Bare soil cover (%)	
		Mean	SE	Mean	SE	Mean	SE
Low	Control	15.6	5.4	26.1	1.0	58.3	4.5
	Single	20.3	5.9	30.1	3.5	49.5	9.1
	Double	20.4	5.6	27.7	2.3	51.9	7.6
Moderate	Control	52.6	2.4	0	0	47.0	2.0
	Single	48.3	6.7	0	0	51.3	6.3
	Double	45.0	3.1	0	0	54.5	2.8
High	Control	8.2	4.8	25.4	3.7	62.6	7.6
	Single	11.9	5.7	22.8	1.5	62.4	3.9
	Double	11.7	6.0	23.2	0.6	63.1	5.3

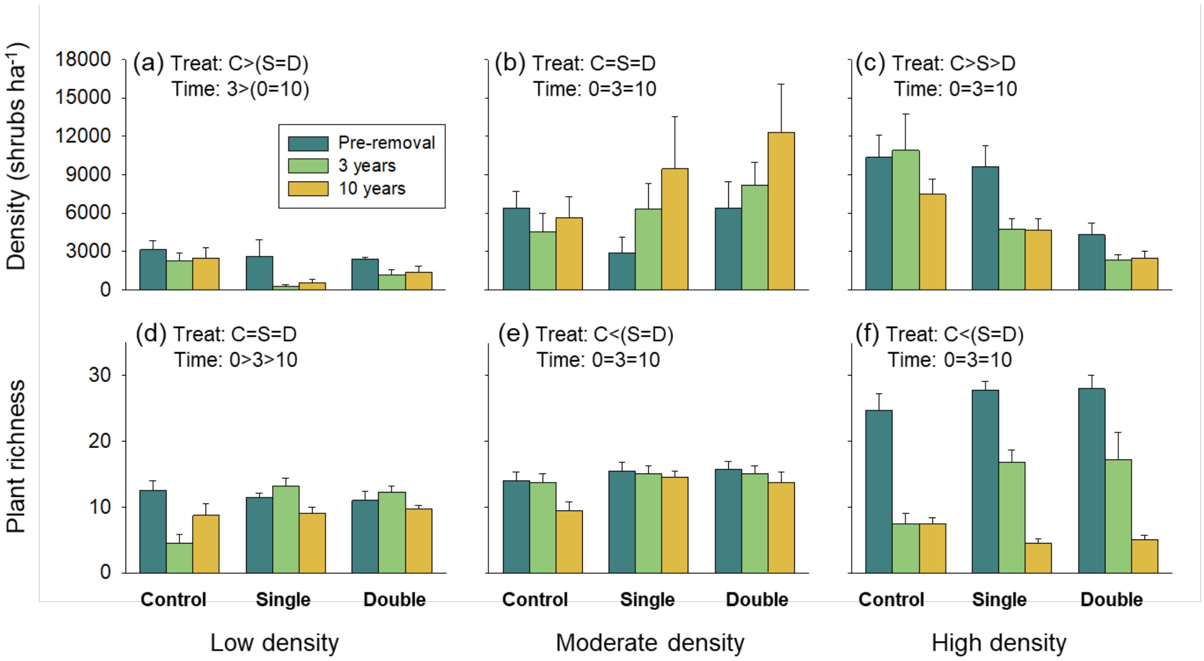

Figure 1. Mean (± SE) shrub density (shrubs ha^{-1}) and plant richness (number of plant species) on control (C), single (S) and double (D) plots prior to treatment in 1984 (0), and 3- and 10-years post-treatment for sites with different initial shrub density.

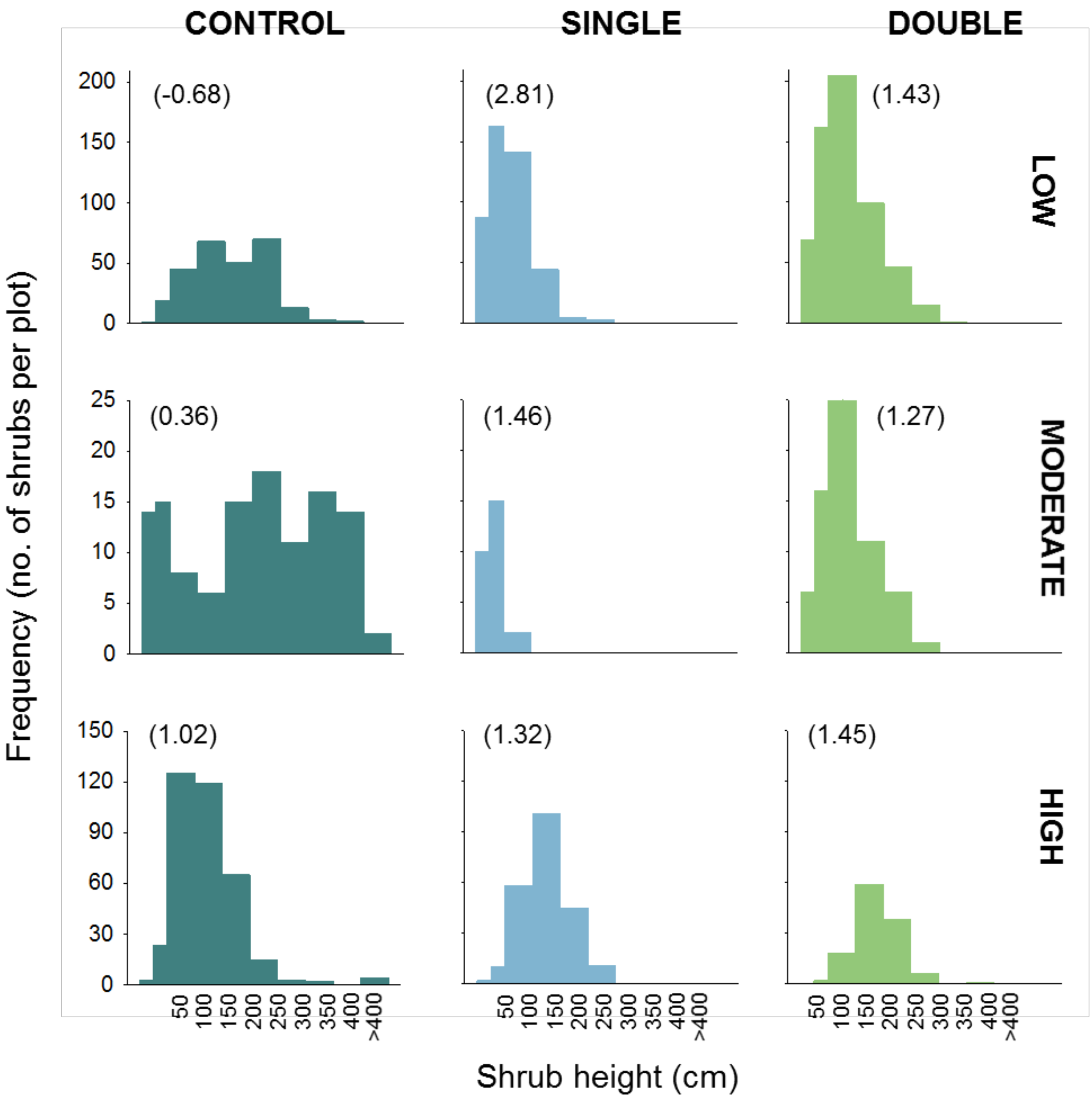

Figure 2. Frequency distribution of *Dodonaea viscosa* heights (cm) 10 years after removal for the three treatments at the three sites with different initial shrub density. Skewness values shown in parentheses.

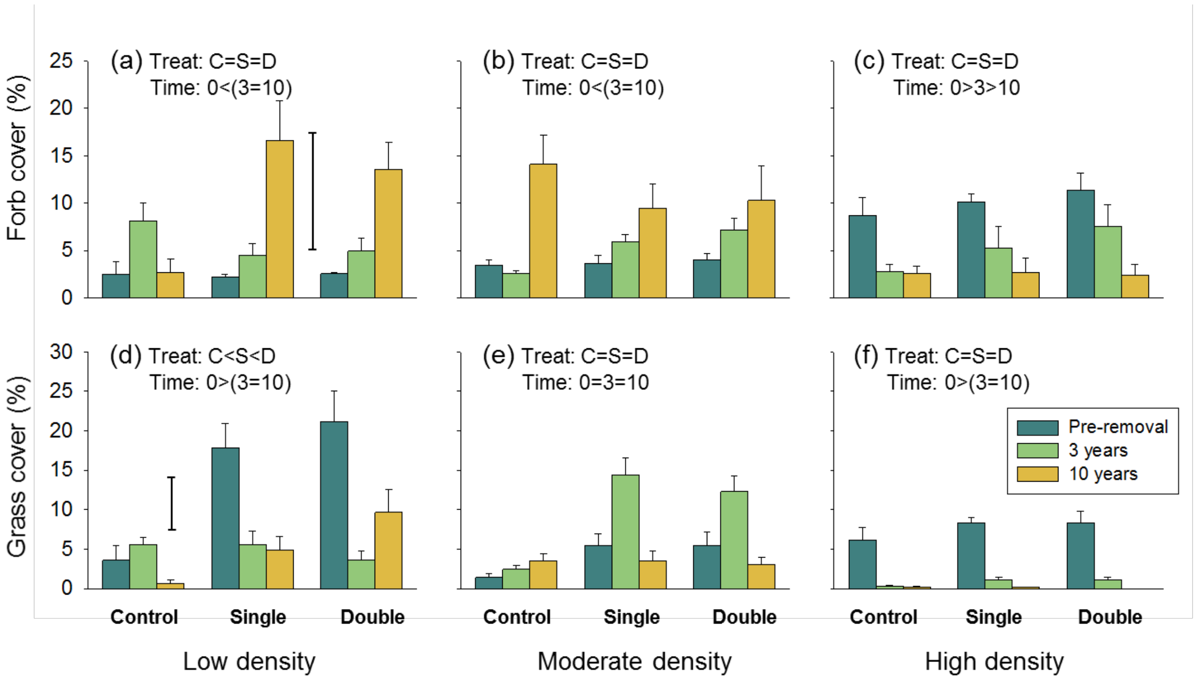

Figure 3. Mean (± SE) forb cover (%) and grass cover (%) on control (C), single (S) and double (D) plots prior to treatment in 1984 (0), and 3- and 10-years post-treatment for sites with different initial shrub density. Vertical bars on (a) and (d) indicate the 5% LSD for the Treatment by Time interaction.