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RESEARCH ARTICLE

Is the removal of aboveground shrub biomass an effective technique to restore a shrub-encroached grassland?

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Encroachment of woody plants into grasslands is a global phenomenon that has substantial impacts on pastoral productivity and ecosystem services. Over the past half century, pastoralists and land management agencies have explored various options to control woody plants in order to improve ecosystem services in shrub-encroached grasslands. We examined the effectiveness of controlling the encroachment of the shrub *Caragana microphylla* into grassland in Inner Mongolia, China. We cut and removed all of the aboveground biomass from 450 shrubs, predicting that the effectiveness of this technique to control shrubs would depend on shrub morphology. Specifically, we expected that larger shrubs with more biomass would be more difficult to kill by cutting than smaller shrubs. A year after treatment, we found that cutting killed only 11% of the 450 treated shrubs, and of these, three-quarters of the locations that they occupied reverted to grasses and one-quarter to bare soil. Shrubs that survived the cutting treatment produced more stems and leaf biomass, and therefore had a greater leaf to stem ratio. Shrubs that died after cutting had a lower crown area and basal area, and less stem biomass than shrubs that resprouted within 12 months of cutting. There were no effects of shrub height on the fate of treated shrubs. Cutting had no effect on understory plant cover or richness, but reproductive plants were taller under shrubs that were not cut. Overall, our study showed that removing aboveground shrub biomass by cutting is an ineffective technique for "restoring" the original grassland community unless shrubs are very small. Strategic targeting of small shrubs would be a more effective technique for controlling the spread of *C. microphylla* in the long term.

Key words: ***Caragana microphylla*, encroachment, grassland condition, mechanical removal**

Implications for Practice

- Removal of the aboveground biomass of *Caragana microphylla* shrubs by cutting is a relatively ineffective technique for managing shrub densities if the aim is to "restore" the original grassland community.
- The value of cutting depends on whether soil hummocks supporting shrubs provide greater short-term production for grazing.
- Land managers wishing to control *C. microphylla* by cutting (e.g. mowing) should concentrate on sites with small shrubs where treatment is more effective.

Introduction

Woody encroachment is a global phenomenon characterized by an increase in the cover and/or density of woody plants at the expense of herbaceous species, often grasses (Van Auken 2000). The causal mechanisms of encroachment are multifaceted, and relate to changes in fire regimes, overgrazing by domestic livestock, land use disturbance, and increasing concentrations of atmospheric CO_2 (Van Auken 2000; Eldridge et al. 2011; Archer & Predick 2014). At a global scale, woody encroachment is thought to affect a large area of the world's drylands, a biome that supports about 40% of the global human population, many of whom rely on pastoral production for their livelihoods (Pravalie 2016). Over the past half century, practitioners have invested substantial funds to manage the effects of woody encroachment in the Americas, Australia, and Africa (Paynter & Flanagan 2004; Noble & Walker 2006; Isaacs et al. 2013; Archer & Predick 2014). For example, the Restore New Mexico Program aims to reverse economic loss caused by woody encroachment (Zavaleta et al. 2001; Hamilton et al. 2004). Control of woody plants is often motivated by the need to increase pastoral production and therefore farmer livelihoods, though other reasons can be to alter habitat for threatened plants and animals or to reduce the risk of wildfire (Huggett et al. 2008). Removal is based on the often perverse assumption that shrubs and herbaceous plants

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are incompatible, and that removal of woody plants is necessary to increase pastoral production (Eldridge et al. 2013).

The physical removal of woody plants is a popular and widely used technique for reducing woody plant density and cover (Archer et al. 2011). A wide range of physical techniques have been used, with variable success. For example, blade (root) plowing is used in Australia to reduce extensive stands of native shrub species such as *Eremophila* and *Dodonaea* (Robson 1995). In the Americas, physical methods such as roller-chopping have been trialed to reduce the density and cover of woody plants (Adema et al. 2004). Although different woody plant management techniques can be applied singularly or with other techniques, results to date suggest that one-off treatments are generally short lived (Archer et al. 2011). Results might also depend on the type of treatment. For example, mechanical treatments that covered the severed roots of the shrub *Eremophila sturtii* have been shown to be more effective at killing shrubs than those that leave the roots exposed (Wiedemann & Kelly 2001). In China, some pastoralists have experimented with mowing shrubs in the expectation that this will reduce shrub growth rate and stimulate the growth of perennial grasses. However, to our knowledge, we know of no studies that have specifically tested the efficacy of such cutting treatments and whether the effectiveness of cutting varies with differences in shrub attributes such as size. Results might also depend on the type of treatment. For example, mechanical treatments that cover the severed roots of the shrub *Eremophila sturtii* have been shown to be more effective at removal than those that leave the roots exposed (Wiedemann & Kelly 2001).

The response of woody plants to different treatments depends on the identity of the species and environmental conditions. The success of any woody plant removal program, therefore, will depend on the mechanisms by which plants reduce the effects of herbivory to maximize survival and growth under different disturbance and environmental regimes (Meloche & Diggle 2001). These include diverting resources from the production of reproductive structures, which are carbohydrate expensive, to defense structures such as thorns (Zhang et al. 2006) or increases in anti-herbivore leaf phenols (Simms & Rausher 1987), resprouting from epicormic buds, or reestablishing from the soil seed bank (Götmark et al. 2016). Plants that invest in the production of multiple stems may be shorter (Midgley 1996; Paula & Pausas 2011), but removal of aboveground material could stimulate resprouting species to produce more shoots per individual than occurred prior to disturbance (Hermann et al. 2012). This has been observed in the conspecific *Caragana korshinskii* where total removal of aboveground material stimulated long side shoots, allowing shrubs to maximize vertical structure as quickly as possible in order to escape further herbivory (Fang et al. 2006*a*). Finally, larger shrubs may be able to allocate more resources to roots to sustain high growth rates (Paula & Pausas 2011). Thus, larger shrubs are likely to have a greater root to shoot ratio, allowing them to resprout more easily after defoliation or physical disturbance because they can more readily allocate resources to aboveground compartments.

Caragana microphylla Lam. is a perennial xerophytic shrub from the family Fabaceae, and currently occupies more than 5 million ha of China's northern grassland (Zhang et al. 2006; Peng et al. 2013*a*). Although *microphylla* is a natural component of these grasslands, the cover and abundance of this plant has increased markedly over the past half century. Considerable research suggests that encroachment of *Caragana* results from overgrazing by domestic livestock, which reduces competition for soil moisture from perennial grasses (Hester et al. 1996; Zhang et al. 2018), and increases in atmospheric CO_2 concentrations (Xiong et al. 2003; Christensen et al. 2004). Once established, *Caragana* is relatively resistant to grazing (Xiong et al. 2003), leading to its widespread persistence. Encroachment is enhanced by the fact that *Caragana* is highly temperature- and drought-tolerant, and therefore has the capacity to rapidly increase in density under adverse conditions (Cao et al. 2000; Chen et al. 2015). Although encroachment of *C. microphylla* into grasslands could provide shelter for livestock and increase landscape-level biodiversity by facilitating understory plants (Liu 1991), the grazing value of the previously grass-dominant steppe for livestock has declined (Xiong et al. 2003; Xiong & Han 2005; Peng et al. 2013*b*). The presence of *Caragana* also increases the difficulty of hay production by mowing (Liu 1991). Young *C. microphylla* plants can be controlled by fire, which will also reduce bud formation on mature plants (Li & Jiang 1994; Lin & Bai 2010). However, current government policy prevents the widespread use of fire or mechanical methods to control to remove shrubs.

In this study, we examined the effectiveness of controlling the encroachment of *C. microphylla* by removing the aboveground compartment of the shrubs by cutting. Specifically, we asked whether shrub density can be reduced by removing the aboveground biomass and thus whether cutting is a potential technique for managing the encroachment of *C. microphylla* into *Leymus chinensis* (Trin.) Tzvel and *Stipa grandis* P. Smirn grassland. A potential state-and-transition model for *C. microphylla* suggests a transition from State A (shrubland) to State B (bare soil) with removal of aboveground shrub biomass (Fig. 1) and a further transition to State C (grassland) dominated by grasses and/or forbs triggered by removal of the competitive effects of the shrubs. Equally likely, however, is a transition to State D (recovering shrubland) depending on the extent of shrub recovery. The question of what determines shrub survival after biomass removal by cutting is poorly known. This lack of information limits our capacity to recommend cost-effective management options to control shrubs in grasslands or to reduce their density. We expected that the effectiveness of cutting would vary with shrub morphology (Fang et al. 2006*b*). For example, taller plants and those with a greater basal area and more biomass would be more likely to resprout after cutting because they can allocate resources to recover from disturbance (Massi & Franco 2016) or overcompensate with greater bud growth, such as occurs with bitterbrush (*Purshia tridentata*) a dryland shrub (Bilbrough & Richards 1993). In contrast, smaller shrubs with smaller canopies and less biomass might be expected to be more susceptible to cutting because resources would be rapidly depleted by cutting, and shrubs would be less likely to resprout (Fig. 1).

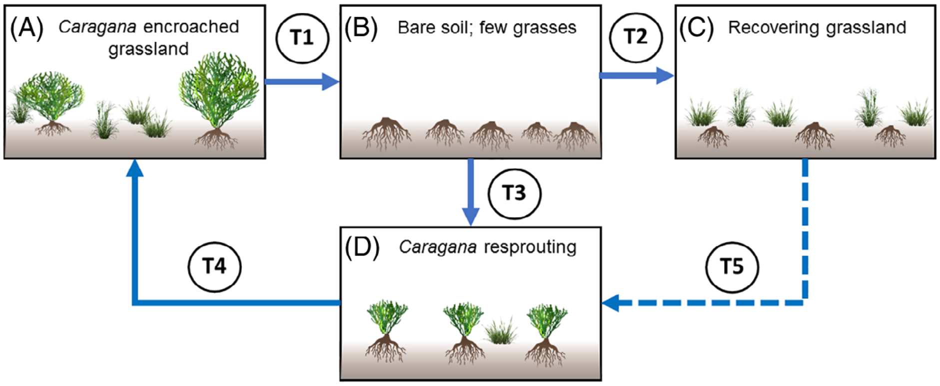

Figure 1. Conceptual model of the potential states and transitions within a *Caragana microphylla* encroached grassland–shrubland matrix. The state-and-transition model captures potential scenarios that might arise after all aboveground material is removed from the encroaching shrubs by cutting. In our model, numbers indicate transitions and letters indicate states. The starting position in our model is an encroached grassland (State A) with scattered but diminishing grasses. Both the understory shrub environment and the interspaces likely vary in plant composition depending on shrub size and abiotic conditions, and, as suggested in our study, in the heights of plants with reproductive structures. Transition 1 is achieved by shrub biomass removal, leading to a predicted temporary state (State B), which, in our study, shifted rapidly to State D within 12 months due to the resprouting ability of *Caragana*. Few plants shifted to State C (Transition 2), which is likely driven by rainfall and a relaxation of grazing intensity. Based on previous studies, we would expect State C to move to State D (Transition 5) with overgrazing and increased atmospheric CO_2 (Xiong et al. 2003; Zhang et al. 2006), but the time frame is likely variable. Transition 4 is likely to occur over less than a decade in the absence of other interventions.

Specifically, we tested whether the extent to which cut shrubs (State B; Fig. 1) transition (via Transition 2) to State C (grasses present, shrubs absent) or State D (via Transition 3, shrubs reprouting with sparse grasses), and posit that larger shrubs would resprout (Transition 3) whereas smaller shrubs would succumb to cutting (Transition 2). We tested our prediction by comparing differences in size-related plant traits between individuals that either survived or died following the cutting treatment. We then compared the pretreatment, size-related traits of plants that either died or survived (resprouted) to test our hypothesis that larger shrubs were more resistant to the removal of their aboveground biomass.

Methods

Study Site

This study was carried out in the typical steppe of Inner Mongolia, China (44.372°N, 44.147°E), a central region of the Eurasian steppe (Bai et al. 2008). Winters are cold and dry (average daily temperature −22°C) and summers mild and humid (average 19°C) with an average annual rainfall of about 290 mm, 60–80% falling in the growing season (June–September). The soil is predominantly a calcareous chestnut soil (Calcic Chernozem) according to the IUSS Working Group WRB (2006) and the slopes are <1%. The plant community is dominated by the perennial tussock grasses *Stipa grandis* and the perennial rhizomatous grass *Leymus chinensis* (Bai et al. 2004). A more detailed description of the plant community and response of dominant species to grazing at this site is given in Liu et al. (2011). The area also shows evidence of encroachment by the thorny leguminous shrub *Caragana microphylla* due to half a century of overgrazing and intense landuse change. *C. microphylla* now occurs in many places within a matrix of grass and shrub patches (Peng et al. 2013*a*).

In 2017, we established the experiment in a 67 ha grassland site with a uniform distribution of *C. microphylla* shrubs. The site was moderately grazed prior to livestock exclusion fencing. In July 2017, we randomly selected fifty 100-m^2 plots (each 10 m × 10 m) within this site and marked their location. Within each plot we marked the position of every *C. microphylla* shrub and its hummock (the slightly elevated area around each plant) and, for each shrub, measured the height, crown diameter, and basal diameter in two directions, and counted the number of stems before cutting off all of the aboveground material from each shrub. Shrub density averaged 906 ± 55 shrubs/ha (mean ± SE) and cover was 5.9 ± 0.6%. In July 2018, 12 months after shrub biomass removal, we relocated the plots and individual shrubs, and made the same measurements as prior to biomass removal. Shrubs were recorded as resprouted or dead on bare soil or dead with grasses. Mean shrub density in July 2018 was 802 ± 53 shrubs/ha and cover 4.7 ± 0.5%. For each shrub, we separated leaf material, new stems, and old stems, and dried the material until constant weight, then weighed the material.

To assess understory vegetation, we randomly selected 20 of the plots where shrubs had been cut, and an additional 20 control plots where shrubs had not been cut. Within each of these plots we measured total plant cover, and the height of up to five vegetative (without reproductive structures) and reproductive plants within two microsites: under shrub canopies and in the open.

Statistical Analyses

We tested for differences in shrub attributes and understory plant attributes (e.g. plant cover, richness) before and after cutting using linear models. For shrub attributes, our model had 50 blocks (plots) and two treatments (before and after biomass removal), and we tested the effect of biomass removal using the block by treatment residual term. Analyses were similar for understory plant attributes except that the model was a split-plot with two strata, the first examined Treatment (cutting vs. control), and the second Microsite (shrub vs. open) and its interaction with Treatment. Differences in mean values were compared using least significant difference testing. Analyses were conducted after testing for normality and homogeneity of variance (Levene's test) using the Minitab statistical software. The leaf to stem ratio was calculated based on biomass.

Results

We recorded a total of 450 shrubs in our study site across an area of 5 ha (90 plants/ha). Of the 450 shrubs, 89% (401 shrubs) regrew. Most (84%, 377) of the 401 shrubs regrew completely, and the remaining 24 exhibited partial regrowth. Hummocks with dead shrubs either reverted to bare soil (12) or were colonized by grasses (37; Fig. 2). We also recorded an additional 16 new shrub recruits across the 5-ha sites measured.

Effects of Shrub Biomass Removal Treatment on Shrub Attributes

Twelve months after biomass removal, surviving shrubs, that is those showing partial or complete regrowth, had markedly different morphologies compared with pretreatment. For example, surviving shrubs were 16% shorter ($F_{[1,399]} = 31.9$, $p < 0.001$), had 67% smaller crown areas ($F_{[1,399]} = 31.9$, $p < 0.001$), 64% smaller basal area ($F_{[1,399]} = 31.9$, $p < 0.001$), less total biomass ($F_{[1,399]} = 31.9$, $p < 0.001$), and stem biomass ($F_{[1,399]} = 31.9$, $p < 0.001$; Fig. 3). Our shrub treatment also stimulated the production of stems by 124% ($F_{[1,399]} = 31.9$, $p < 0.001$), total shrub leaf biomass by 84% ($F_{[1,399]} = 31.9$, $p < 0.001$), and, consequently, increased the leaf:stem ratio by 178% ($F_{[1,399]} = 31.9$, $p < 0.001$; Fig. 3).

Do Shrub Attributes Explain Their Susceptibility to Biomass Removal?

Shrubs growing on hummocks that had either reverted to bare soil or grass tended to have fewer stems per plant ($F_{[3,446]} = 14.59$, $p < 0.001$). Shrubs growing on hummocks reverting to bare soil tended to have lower crown ($F_{[3,446]} = 11.11$, $p < 0.001$) and basal areas ($F_{[3,446]} = 12.02$, $p < 0.001$) while those that reverted to grasses tended to have significantly less stem ($F_{[3,446]} = 6.10$, $p < 0.001$) and total biomass ($F_{[3,446]} = 6.70$, $p < 0.001$) than those that either resprouted totally or partially following treatment (Fig. 4). There were no apparent effects of shrub height ($p = 0.13$) or leaf:stem ratio ($p = 0.29$) on the fate of shrubs to the cutting treatment (Fig. 4).

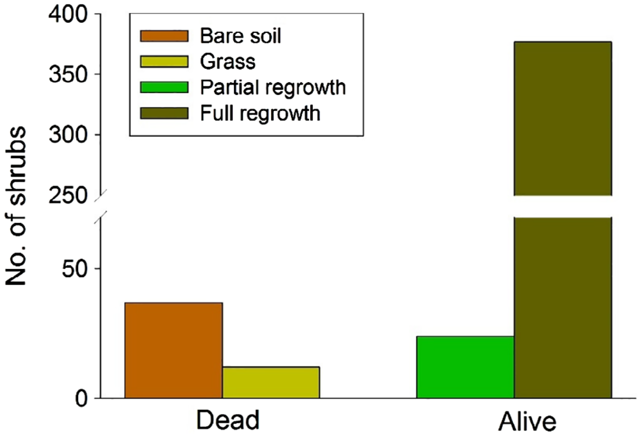

Figure 2. The number of *Caragana microphylla* shrubs recorded 12 months after the shrub cutting treatment.

Effects of Cutting on Understory Plants

We found no effect of cutting on either plant cover or plant richness ($p > 0.08$), but plant cover ($F_{[1,18]} = 24.2$, $p = 0.001$) and richness ($F_{[1,18]} = 18.2$, $p < 0.001$) were significantly lower, overall, beneath shrubs than in the interspaces (Fig. 5). The heights of vegetative plants did not vary with treatment or microsite ($p > 0.33$). The height of reproductive plants, however, was significantly greater under uncut shrubs than under cut shrubs, irrespective of microsite (treatment by microsite interaction: $F_{[1,18]} = 6.89$, $p = 0.017$; Fig. 5). Plant attributes were consistently twice as variable under shrubs than in the open across both treatments. Plant richness was more variable under shrubs, but only at cut sites (Table 1). There was little variability in the heights of vegetative and reproductive plants in relation to cutting treatment or microsite.

Discussion

In our study, cutting killed only 11% of treated shrubs, and only 6% of hummocks where shrubs were treated reverted to grasses. A one-off removal of the aboveground biomass of *Caragana microphylla* shrubs was not an effective method to meet our management objective of controlling shrubs and promoting grass recovery. The tendency of *C. microphylla* to recover after the removal of all aboveground biomass (e.g. through grazing) is likely related to its ability to resprout, and perhaps fix nitrogen. The ability to produce nitrogen may increase the tolerance of *C. microphylla* to herbivory as it resprouts, as has been shown in N-producing forbs and grasses (Watson & Ward 1970). *C. microphylla* is known to resprout from subsurface shoots and axial tillers in response to shoot removal (Fang et al. 2006*b*).

Removal of stems and leaves of *Caragana* will likely reduce growth rates, given the strong links between measures of leaf gas exchange rate (such as net photosynthetic rate, stomatal conductance, and transpiration rate) and the relative growth rate of *Caragana* spp. (Ma et al. 2016). Further, a greater root to shoot ratio should allow plants to absorb water and

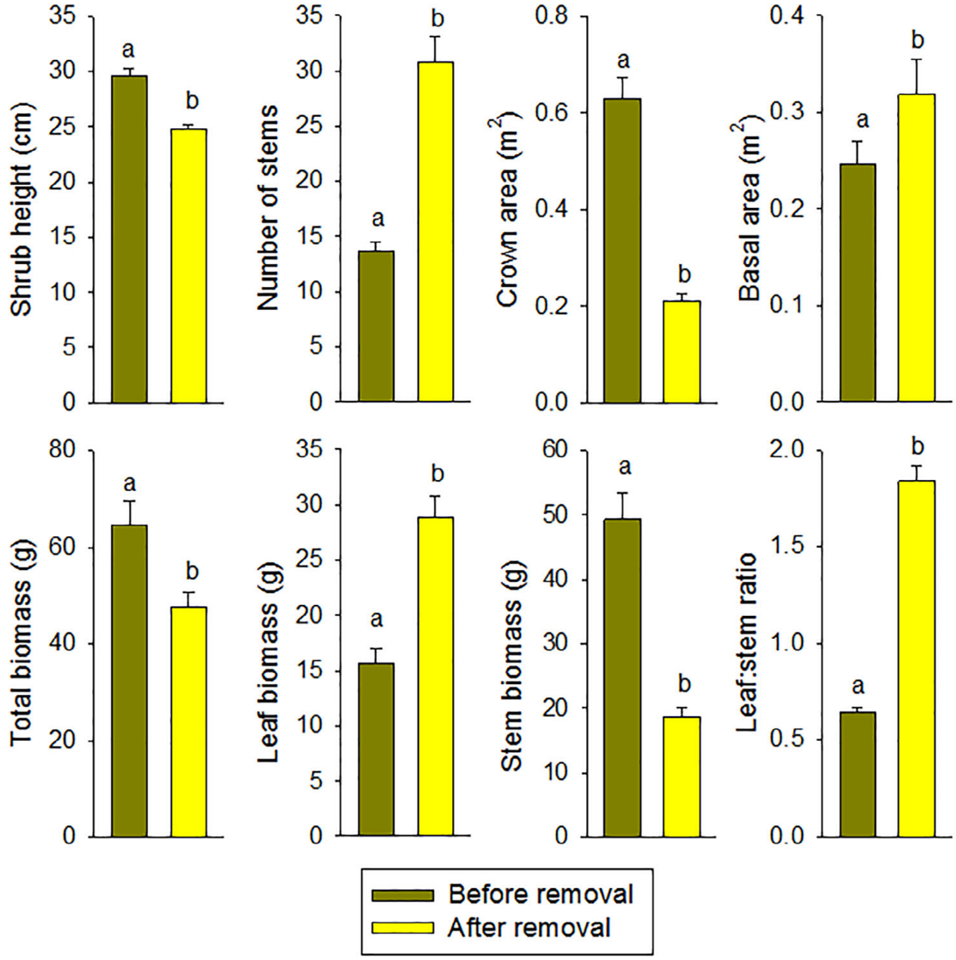

Figure 3. Mean (+SE) of different attributes of *Caragana microphylla* shrubs before and after the removal of aboveground shrub biomass. Different superscripts indicate a significant difference in the mean values at $p < 0.05$.

nutrients more efficiently, but this has been shown not to be the case in *C. microphylla*. Vegetation removal by cutting or herbivory may allow shrubs to invest more resources in defenses against stem removal, thereby retarding the growth of individual plants, particularly young plants (Zhang et al. 2006). An alternative mechanism to account for resprouting following biomass removal could be related to reduced levels of biological control from herbivorous insects that are removed when the plant is defoliated.

Many methods of shrub control such as root plowing or roller-chopping involve substantial soil disturbance, and this physical disturbance typically initiates resprouting by activating the growth of epicormic buds (Wiedemann & Kelly 2001; Fulbright et al. 2013). In our study, however, removal of the aboveground shrub biomass involved little or no soil disturbance. Cutting is more likely to maintain the integrity the soil surface, with fewer effects on surface litter and therefore soil seed banks than treatments that disturb the surface (Eldridge & Robson 1997). Notwithstanding the lower levels of disturbance compared with root plowing (e.g. Daryanto & Eldridge 2010; Smith et al. 2013), cutting was not an effective method for either removing shrubs or improving understory plant cover and richness.

Our results indicated that the effectiveness of shrub cutting was greater for smaller plants with shorter stems and less biomass. Smaller plants are likely younger, suggesting two things. First, control is more effective on younger, smaller plants that will be more difficult to detect if they are below the size of grasses. Pastoralists therefore need to be vigilant to detect small plants before they reach a size that is unresponsive to physical removal. Second, larger shrubs would need to be controlled by alternative methods, which might include herbicide, or may require follow-up treatment of smaller resprouting individuals. However, we found no evidence to suggest any effect of plant height on the fate of treated plants. This could be due to the fact that there were no clear allometric relationships between height and other size measurements, suggesting that height might not be a good indicator of shrub age, given that the shoots can assume a pronounced prostrate habit.

Shrubs support a range of important ecosystem services such as habitat provision, carbon sequestration, and nutrient cycling (Eldridge et al. 2011; Daryanto et al. 2019). A recent global

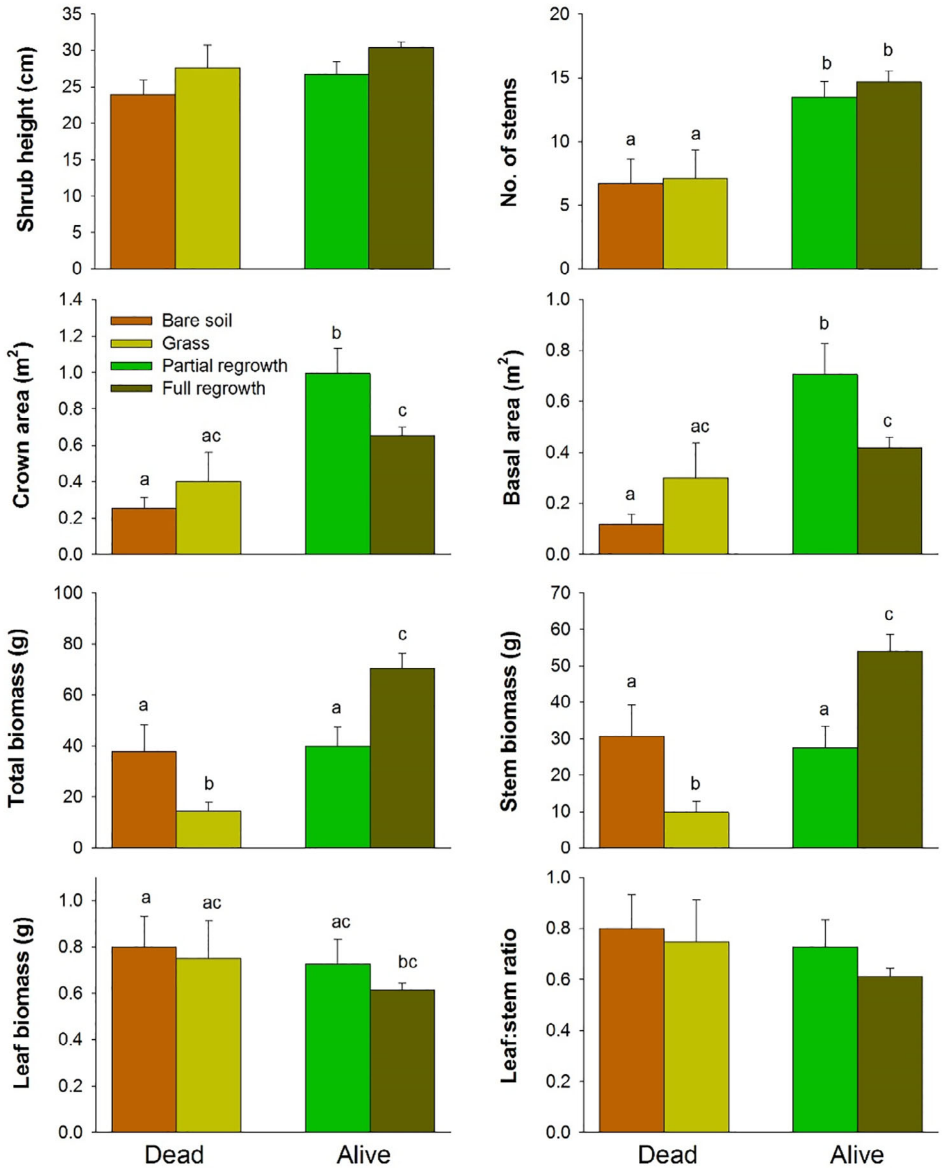

Figure 4. Mean (+SE) values of attributes of *Caragana microphylla* shrubs in relation to their fate after cutting. Different superscripts indicate a significant difference in the mean values at $p < 0.05$. There were no differences in leaf:stem ratio or shrub height among the four fate classes.

meta-analyses of shrub removal showed that increases in forage production were relatively short-lived (Daryanto et al. 2019). Persistence of *C. microphylla* after cutting, therefore, does not necessarily mean that this treatment is entirely ineffective for either pastoral production or biodiversity conservation given potential short-term benefits of either increases in production or plant diversity. The extent to which *C. microphylla* competes with or facilitates understory species is poorly known (Zhang et al. 2018). Although shrubs are known to compete with understory protégé species for resources, they also enhance species richness via positive (facilitatory) interactions by ameliorating environmental conditions and protecting protégé species from grazing (Smit et al. 2009; Soliveres et al. 2016). The ability of shrubs to facilitate understory protégé species might increase with shrub age, and therefore size (Zhao et al. 2007). Thus, shrubs resprouting after complete removal of all aboveground material will likely be less effective at facilitating protégé species; many of which are likely palatable to livestock. Physical removal therefore may produce unintended consequences by reducing the capacity of shrubs to facilitate pastorally important understory species.

Our study is based on an assessment of understory locations of individual shrubs and their paired interspaces. Despite not sampling at broader spatial scales (e.g. patches of shrubs, communities), the state-and-transition model identifies the likely scenarios that might emerge at these larger spatial scales. Scaled-up results suggest that within 12 months, State B moves to State D (Transition 3), which is characterized by a substantial

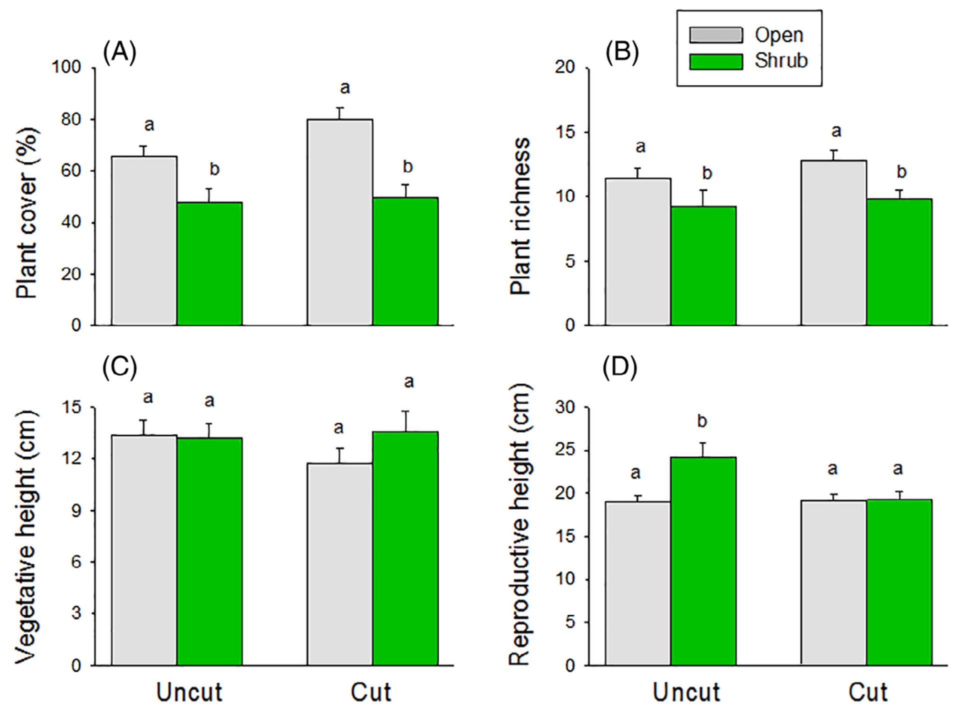

Figure 5. Mean (+SE) values for selected attributes of understory plants in the open and beneath the canopy of *Caragana microphylla* shrubs for both uncut (control) and cut treatments. Different superscripts indicate significant differences at $p < 0.05$.

Table 1. Mean variability (coefficient of variation %) in understory plant cover (%), plant richness (number of species), and heights (cm) of vegetative and reproductive plants in the open and beneath shrubs for sites ($n = 10$) where shrubs were either treated (cut) or untreated (uncut).

	Uncut		*Cut*	
Attribute	*Open*	*Shrub*	*Open*	*Shrub*
Plant cover (%)	16.4	31.2	18.9	36.9
Plant richness (number of species)	20.4	24.0	23.1	44.9
Height of vegetative plants (cm)	23.1	28.4	21.2	19.1
Height of reproductive plants (cm)	13.5	15.8	11.5	22.1

number of resprouting shrubs, with few shrubs (8%) reverting to the preferred State C (Fig. 1). Our results also suggest that Transition 2 (State A to State C) is highly dependent upon shrub traits, and likely restricted to shrubs with smaller crowns and basal area, less biomass, and fewer shoots per shrub. Given the short duration of our study, we can only speculate upon the potential transition to State D (Transition 5). State D is likely to be relatively transient, with movement from State C to A (via D) occurring relatively rapidly, and exacerbated by overgrazing, which removes competition from perennial grasses (Hester et al. 1996; Zhang et al. 2018). Our results also suggest that progression to State D has no significant effects on understory plant cover or richness, at least in the short term. However, we found some evidence that reproductive plants might be affected by shrub cutting, if a decline in height is indicative of fewer inflorescences and therefore a reduced potential to produce viable seed (McGrath et al. 2010). Our data also indicate lower heterogeneity in plant attributes with shrub cutting, which could lead to long-term declines in ecosystem functions. Overall, therefore, any decision to remove shrubs will be highly context-dependent, varying with societal goals for shrublands and/or the need to maintain a healthy, productive and diverse plant community. Land managers, therefore, need to be cognizant of the many values of *C. microphylla* before undertaking control methods designed to increase grass production.

Acknowledgments

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