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Targeted Browsing with Goats for Eastern Redcedar (Juniperus Virginiana L.) Control

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TARGETED BROWSING WITH GOATS FOR EASTERN REDCEDAR (*JUNIPERUS VIRGINIANA* L.) CONTROL

BY

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This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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> And God said, "Let the land produce living creatures according to their kinds: the livestock, the creatures that move along the ground, and the wild animals, each according to its kind." And it was so. God made the wild animals according to their kinds, the livestock according to their kinds, and all the creatures that move along the ground according to their kinds. And God saw that it was good.
>
> Then God said, "Let us make mankind in our image, in our likeness, so that they may rule over the fish in the sea and the birds in the sky, over the livestock and all the wild animals, and over all the creatures that move along the ground."
>
> – Genesis 1:24-26

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ABSTRACT

TARGETED BROWSING WITH GOATS FOR EASTERN REDCEDAR (*JUNIPERUS VIRGINIANA* L.) CONTROL

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As eastern redcedar (ERC) (*Juniperus virginiana* L.) grassland encroachment progresses, all potential control methods should be explored in the interest of Great Plains grassland health and longevity. Targeted browsing with goats has been proven as an effective control method on some juniper species; however, little is known about its ability to control ERC. These studies intend to mend knowledge gaps of how targeted browsing with goats control ERC by causing tree death without chemicals or machinery. The first study is two 3x3 Latin squares comparing protein-supplemented diets. The second study is a randomized complete block design of five 0.224 ha sites over two years, each with four replicate paddocks. Trees of five height classes were tagged (n = 820) and measured before and after browsing. The objectives were to quantify and to characterize targeted browsing with goats as ERC biological control in terms of 1) the efficacy of ruminally undegradable protein (RUP) supplementation to aid goats in detoxifying plant secondary metabolites (PSM) when browsing ERC bark and foliage, 2) browsing in relation to tree height, and 3) subsequent tree mortality. We hypothesized that 1) RUP protein supplemented goats will defoliate and debark ERC more than the control, 2) goats will debark ERC > 100 cm tall and defoliate ERC < 100 cm tall, and 3) debarked ERC will more frequently be killed than defoliated ERC. Supplementation did not (P > 0.05) increase browsing compared to the control. Unlike previous pen feeding trials that studied select fed tree parts, we investigated goat behavior on whole ERC. In the field study, tree height was correlated positively with debarking and negatively with defoliation ($P < 0.001$). The resulting mortality was positively correlated with the taller, debarked trees ($P < 0.001$), and sites with less deciduous browse appeared to have more debarking suggesting that juniper should ideally be the only woody component when applying targeted browsing. The results of both studies have practical implications for herdsman and landowners including suggested stocking rate, considerations for site vegetation, expected juniper mortality, and recommendations for future research.

Chapter 1. Literature Review

Eastern redcedar (ERC) (*Juniperus virginiana* L.) encroachment on grasslands decreases forage production and threatens wildlife habitat (Limb et al., 2010). The ERC is a native species east of North America's 100th meridian (Van Haveneke and Read, 1976), however due to fire suppression and planting in shelterbelts it has steadily moved westward and established on the Great Plains (Donovan et al., 2018). The result is a devastating grassland ecosystem imbalance (Fogarty et al., 2022; Limb et al., 2010). Mechanical removal is a popular solution but compounds environmental damage with erosion (Bailey et al., 2019). Natural control of woody encroachment like prescribed fire and grazing are of increasing interest. While burning faces some social- and weather-related obstacles, goats under targeted browsing have been shown to consume chemically defended juniper while other herbivores may avoid it. Unfortunately, little is known about targeted browsing as a potential alternative or integrated ERC control method. The aim of this literature review is to examine relevant aspects of ERC grassland invasion and ERC control with targeted browsing with goats.

Eastern Redcedar Growth and Establishment on the Great Plains

Historically, frequent fires and diverse (e.g., bison, elk, pronghorn, and deer) large herbivore grazing and/or browsing prevented woody establishment on central U.S. tallgrass prairies and forest meadows (Arend, 1950; Bragg and Hulbert, 1976; Hintze et al., 2021; O'Connor et al., 2020); however, urbanization brought fire suppression and shelterbelt planting to the region creating fuel litter buildup, elevating wildfire risk, and supplying a seed source that facilitates woodland conversion in a matter of decades (Bidwell et al., 2008; Bragg and Hulbert, 1976; Donovan et al., 2018). Beginning in

1916, early National Park Service policies implemented widespread fire suppression (van Wagtendonk, 2007), and ERC shelterbelts were and continue to be planted to protect human interests, inadvertently becoming a seed source for rapid woody conversion of grasslands of the Great Plains and western states (Donovan et al., 2018) (Figure 1-1). A fierce competitor, ERC adapts easily to a variety of sites because it is drought tolerant and grows rapidly (Axmann and Knapp, 1993).

Eastern redcedar encroachment threatens grassland sustainability, productivity, and biological diversity (Bidwell et al., 2008). For example, when not controlled, juniper invasion catalyzes rangeland water quality decline by degrading watershed quality through bare soil erosion or the site eventually requires ERC mechanical control, causing soil disturbance (Bidwell et al., 2008). Furthermore, establishment of ERC occurs quickly, a stand of 200 trees per acre can increase as much as 57% over 10 years (Engle and Stritzke, 1992). Eastern redcedar grows more rapidly with increasing age and consequential trunk diameter. For example, linear regression indicates that for every 0.69 cm diameter increase of trunk, ERC height will increase by 19.94 cm for each year of age (Owensby et al., 1973). As ERC canopy cover and density increases, competition for sunlight and water increases, decreasing forage production and grazer access to vegetation; consequentially, pasture stocking must be reduced to meet cattle nutritional needs, decreasing overall profitability (Hintze et al., 2021). Eastern redcedar invasion has a generally negative impact on grassland wildlife. Eastern redcedar may displace desirable food and cover plants essential for wildlife prosperity, depending on the site, vegetative cover, and ERC density (Rollins and Armstrong, 1994). Endangered and grassland obligate species like the greater and lesser prairie chicken, which require prairie for habitat (Bidwell et al., 2008) suffer greatly. Conversely, some habitat generalists feed on juniper and juniper berries, like the white-tailed deer, although it provides only marginal browse (Rollins and Armstrong, 1994).

Widespread Invasion

New rangeland monitoring data confirms that intact grassland is being lost to woody encroachment at nearly the rate of grassland conversion to agriculture (Jones et al., 2020); furthermore, over 43.7 million hectares of the Western U.S. have seen woody plant increases since 1999, now equivalent to 2.3 times the size of Nebraska in area (Jones et al., 2020; Natural Resources Conservation Service, 2021). Therefore, juniper saplings should be suppressed at early developmental stages to minimize the possibility of woodland establishment (Utsumi et al., 2010) and encroachment on native prairie rangeland. Since ERC relies on seed dispersal to reproduce, the distance between intact grasslands and ERC encroached lands should be monitored (Twidwell et al., 2021). Around 90% of ERC sapling recruitment occurs within 91.4 m of mature seedbearing trees, that is trees at least six years old and 1.5 meters tall (Owensby et al., 1973), and only 5% of seeds deposited more than 182.9 m recruit (Fogarty et al., 2022). A reproductively mature female ERC can produce up to 1.5 million seeds per year (Holthuijzen et al., 1987), and seed germination usually takes place within two years of dispersal (Holthuijzen and Sharik, 1984). Seed dispersal is most commonly facilitated by birds consuming seeds and depositing them through droppings. Despite woody encroachment traditionally being seen as a slow driver of undesirable change, it is now causing collapse at the largest level of terrestrial organization: the biome (Twidwell et al., 2021) (Figure 1-3). At this widespread rate of invasion and scale, Twidwell et al. (2021)

asserts that range managers must prioritize integrated management (i.e., combining control methods) to defend grassland biodiversity.

Grassland Management and Eastern Redcedar Control

Complete ERC encroachment reversal is a difficult achievement, as large-scale conversion from woody-invaded prairie to intact grassland has not yet been documented; additionally, control methods should be applied before substantial resource degradation (Twidwell et al., 2021). Woody management can include mechanical, pyric (i.e., prescribed fire or prescribed burning), chemical (i.e., herbicide), biological control (e.g., targeted browsing, targeted grazing), or any combination of methods, known as integrated management. Twidwell et al. (2021) defines five stages of ERC encroachment (Figure 1-2) as “Intact” (a treeless grassland with no incoming seed), “Dispersal” (treeless grassland compromised by incoming seed), “Recruitment” (early successional brush; reproductively immature seedlings present), “Encroachment” (spread of mature reproducing plants), “State Transition” (ecological state has transitioned to woody dominance).

Mechanical

Mechanical juniper control is relatively straightforward and includes hand cutting, grubbing, dozing, chaining, shearing, and roller chopping. These methods are a way of removing aboveground vegetation and, in theory should be entirely effective since ERC does not resprout (Ortmann et al., 1998). Mechanical ERC control is a common method with 75%, 59%, and 30% of Missouri landowners employing hand removal, mowing, and bulldozing, respectively (Morton et al., 2010). Despite its relative popularity, mechanical control is also often expensive and requires gentle terrain (DiTomaso, 2000) while exposing land to the risk of erosion (Bailey et al., 2019). Twidwell et al. (2021) recommends mechanical applications like hand cutting or haying at the “Recruitment” stage to prevent saplings from reaching reproductive maturity and heavy machinery and chemical applications to target large, mature ERC in “Encroachment” and “State Transition” stages. DiTomaso (2000) asserts that mechanical control is best used on small woody populations or on the fringes of a large infestation.

Pyric

Prescribed fire is an effective grassland management tool to control small ERC but is not widely utilized by landowners. If the juniper trunk below the lowest bud is girdled mechanically or with fire, then the roots usually die from lack of top growth (Arend, 1950). However, burning limitations exist based on weather, location, and land ownership (Hintze et al., 2021). Owensby et al. (1973) demonstrated this in the northern Kansas Flint Hills where fire controlled 89% of seedlings less than 61 cm, 83% of small trees 61-183 cm, and 39% of medium trees greater than 183 cm. The Flint Hills are a notable example of how frequent privately owned grassland burning can control ERC (Morton et al., 2010). Ortmann et al. (1998) found that burning mortality was inversely proportional to height with 88%, 60%, 35%, and 10% mean mortality for ERC trees <100 cm, 100-200 cm, 200-300 cm, and >300 cm, respectively. Late spring (April 15-May 1) is recommended for ERC control since ERC leaf water content is lowest in the spring, and earlier burning reduces grass forage production (Engle et al., 1987; Launchbaugh and Owensby, 1978). Using late spring burning, Owensby et al. (1973) found that fire controlled 83% of trees < 183 cm tall and 89% of seedings, but was less effective on 39% of ERC trees > 183 cm tall. Although it appears landowners recognize the threat of ERC encroachment, they do not yet identify prescribed burning with ERC control (Morton et al., 2010). A more proactive approach, suggested by Twidwell et al. (2021), calls for prescribed fire as early as the “Dispersal” stage as it is the only management tool able to prevent seed germination and seedling emergence on an intact grassland compromised by ERC seeds. Burning works to reduce system vulnerability to encroachment by consuming seeds dropped in the grass before they can germinate, thus depleting the seedbank, and can also be integrated with targeted browsing or mechanical removal during more advanced encroachment stages to reduce site exposure and sensitivity to woody transition (Twidwell et al., 2021).

Chemical

Land managers can combine techniques through integrated approaches such as applying herbicide or cutting after a burn. Alone, managers consider cutting or herbicide application too expensive and economically risky for use on low-productivity rangelands, but preceding these tools with broadcast fire may increase ERC mortality and lower secondary removal costs by about half from $0.15 per tree for herbicide alone to $0.08 per tree for herbicide following broadcast fire (Bernardo and Engle, 1990; Ortmann et al., 1998). In a series of rigorous experiments, Buehring et al. (1971) found that 4-amino-3,5,6-trichloropicolinic acid, commonly known as picloram, was a more effective herbicide in controlling ERC than 2,4-D, 2,4,5-T, fenuron, fenac, dicamba, paraquat, endothal, monuron TCA, amirole, NH_4SCN, or dichloroprop. Although herbicides are the primary method of weed control in most rangeland systems, private landowner perspective holds herbicide use in great concern (12% of survey respondents strongly opposed) for ERC control (DiTomaso, 2000; Morton et al., 2010).

Socio-Cultural Considerations

While prehistoric fires and nomadic bison grazing quickly killed or subdued invading seedlings before they could establish into the "Recruitment" stage (Twidwell et al., 2021), modern private land ownership without a collective conservation mindset has led to a fragmented prairie landscape and unseated the central role of fire and grazing as beneficial, natural disturbances promoting biodiversity (Freese et al., 2014). The result is grasslands managed by agronomic practices rather than ecological principles (Morton et al., 2010) that does not interrupt the woody encroachment stages, increasing vulnerability to woody transition (Twidwell et al., 2021). Despite skepticism and distrust from agricultural producers towards widely implementing grassland conservation practices, recreational and productive land uses could benefit from ecosystem services (Morton et al., 2010). There is a distinct challenge to find common ground for both groups by protecting delicate grasslands and ensuring that agricultural income is not jeopardized. While there are tradeoffs for every grassland management tool, one example of biological control such as targeted browsing, provides a unique and adaptable approach to ERC control that may support both agricultural and conservation land uses.

Targeted Browsing

Targeted grazing/browsing is viewed as environmentally friendly and uniquely adaptable in integrated management that controls undesirable plants by causing biological disturbance during vulnerable life stages. Targeted browsing rests on the grazing management principles of stocking rate (i.e., the number of animals per unit of area over time), distribution, species of livestock, and season of grazing towards a specific goal (Bailey et al., 2019). Launchbaugh (2006) describes targeted grazing as a skillful combination of the understanding of animal behavior and plant responses to form a livestock-based ecosystem service. Grazing can be applied or removed whenever needed, leaves no chemical residue, and often improves range biodiversity while converting plant biomass into profitable products like meat, milk, and fiber (Bailey et al., 2019). The regenerative force of livestock grazing, along with fire, are among the oldest vegetation management tools (Launchbaugh, 2006). Targeted browsing goats for juniper control is suggested for defoliating short, immature saplings (Lyons et al., 2009; Twidwell et al., 2021), although little data supports these recommendations as with many ecosystem management assessments observed by Carpenter et al. (2009). Twidwell et al. (2021) advocates for commitment to repeated targeted browsing in combination with mechanical methods during the ERC “Recruitment” stage to keep saplings from reaching reproductive maturity if the seed bank cannot be controlled with prescribed fire. Of domestic livestock, goats may be best suited for ERC control with their narrow mouths and dexterous lips.

The best display of the success of targeted browsing is its evolution into a business. Entrepreneurs are hired to use small ruminant livestock to browse fire breaks and noxious weeds (Frost et al., 2012). An advantage to using small ruminants, such as goats or sheep, for targeted grazing is that they can be applied in some urban settings or in nearly every weather condition while other control methods may not be feasible. Targeted browsing goats is a suggested tool to suppress woody species seedling development (Launchbaugh, 2006) and extend the effectiveness of other management options such as fire (Utsumi et al., 2010). Overall, landowners view targeted grazing positively because according to a survey of Missouri landowners, 68% of respondents perceive grazing as a legitimate land use and grassland management tool (Morton et al., 2010). More research is needed to determine the herbivory intensity needed to achieve a biologically significant decline in juniper sapling survival rates (Utsumi et al., 2010).

While livestock overgrazing can damage range health by congregating near water sources and cripple preferred plant productivity when allowed to re-graze pastures, carefully applied targeted browsing is an invaluable management tool to control unwanted plants (Bailey et al., 2019; Vallentine, 2001). By utilizing the aforementioned principles, managers can encourage undesirable plant consumption during vulnerable life cycle stages (Bailey et al., 2019). To illustrate the significance of carefully timed grazing, Owensby et al. (1973) studied increasing cattle stocking rates on ERC populations. Researchers found that when grazed by cattle under an increasing stocking rate during the ERC growing season (May-October), ERC invasion rate declined 6.3 trees per acre per additional animal unit month (AUM) added and by 13.8 trees per acre per additional AUM the following year. Under dormant season grazing, however, ERC declined a mere 2.3 trees per acre per additional AUM.

Stocking Rate and Browsing Tendencies

Targeted browsing can be manipulated through stocking rate to alter diet selection. Heavier stocking rate forces herbivores to practice diet mixing, switching between preferred and chemically defended forages (Provenza et al., 2007; Shaw et al., 2006). This technique of combining heavy stocking rate and high stocking density (the number of animals per area) by rotating animals daily was effective in creating high utilization of big sagebrush by sheep (Shaw et al., 2006). It should be noted, however, under undefined “heavy” stocking pressure, desirable fodder for browsing wildlife will likely disappear before juniper does, so strategic timing and stocking could minimize goat damage on desirable species (Rollins and Armstrong, 1994). To compare impacts of heavy and light stocking rates of goats in the Chihuahuan desert, Mellado et al. (2003) used rates of heavy (1.5 ha per goat) and light stocking (15 ha per goat) and found that overstocking goats caused them to alter diet selection to include more resinous, toxic, and course species than light stocking. In turn, this pattern greatly reduced grass and shrub cover as well as pushing the animals to a lower nutritional plane (Mellado et al., 2003). For effective juniper control, Riddle et al. (1996) recommends year-round undefined "moderate" stocking rates and "frequent" applications of goats on infested pastures. In addition, the authors go on to suggest temporarily increasing goat numbers on "heavily" juniper-infested pastures during winter months when plant secondary metabolite (PSM) chemical defense concentrations are lowest and juniper is most palatable (Riddle et al., 1996). Plant secondary metabolites are discussed in detail in the "Eastern Redcedar Browsing Resistance" section. Nelle (1997) emphasizes the effectiveness of goats in pruning back small juniper and reducing the number of seedlings, noting that brush control alone is not the solution the juniper problem. In fact, Nelle (1997) claims that the use of goats against larger trees is uneconomical and not environmentally sound.

The Impact of Tree Height on Browsing

Juniper sapling size and age appear to have an impact on debarking and defoliation intensity as younger, shorter, trees are more likely to be defoliated and older, taller, trees are more likely to be debarked. Generally, young plants are highly digestible and nutritious, and they become less so as the seasons and plant maturity advance. Furthermore, plants are vulnerable to damage and additional energy expenditure in the spring as the come out of dormancy. Therefore, the critical time to apply targeted browsing when a plant is vulnerable to debarking and defoliation (Launchbaugh, 2006).

Such appears to apply to one-seed junipers as mixed species browsing goats and sheep at a high-density stocking rate (110 AUD/ha) is associated with an increased browsing frequency of short (< 50 cm tall) one-seed juniper saplings with a high defoliation (67-100% of branches defoliated) (Utsumi et al., 2010). Spring browsing trials were more likely to yield branch mortality, bark girdling, and branch stripping since saplings are susceptible when resuming growth after the dormant season (Utsumi et al., 2010). Older, taller one-seed juniper saplings suffered heavy branch debarking, possibly because they offered more bark that was easier to reach and less chemically defended than mature leaves (Utsumi et al., 2010). Conversely, younger, smaller one-seed juniper saplings potentially contain lower levels of chemical defenses in their leaves and tend to have more frequent heavy (67-100% of branches defoliated) use by herbivores (Campbell and Taylor, 2007; Utsumi et al., 2010). In addition, redberry juniper shoot regrowth post-fire is poorly defended by PSM for up to 11 months until defensive levels are comparable to mature tissue (Campbell and Taylor, 2007). Estell et al. (2014) found that one-seed juniper saplings had lower terpenoid concentrations during stages when their growth rate was higher, potentially because the plant was allocating more carbon for active tissue growth than defensive compounds. There is limited quantitative data available to link juniper mortality or slowed growth to debarking or defoliation browsing injury sustained by saplings.

Browsing Herbivores

Eastern redcedar bark and foliage PSM can impact the suitability of livestock species used, season of use, and age of tree to which the targeted browsing is applied, which can be addressed by targeted grazing principles. Goats have proven themselves effective in controlling woody species and are sometimes described as “nature’s herbicide” (Nelle, 1997) because of their digestive architecture. Goats have narrow mouths with dexterous prehensile lips in addition to a relative capability to detoxify tannins and terpenes often found in shrubs (Launchbaugh, 2006). Since the term “grazing” can be vague and misleading to describe ruminant feeding, ruminants can be divided in to three categories: grass/roughage eaters, intermediate feeders, and concentrate selectors (Hofmann, 1988). Goats are considered intermediate feeders, which are adapted to digest both roughage (e.g., cell wall) and concentrate (e.g., cell contents) plants and possess large parotid salivary glands and livers relative to their body size (Hofmann, 1988). The salivary glands are important for concentrate digestion as saliva serves as a fermentation buffer fluid against tannins, and the liver detoxifies toxins like PSM, among other key metabolic functions (Hofmann, 1988). Goats are known as highly selective mixed feeders and have a great preference for cell contents and a limited ability to utilize cellulose (Hofmann, 1988). When used in conjunction with other control methods such as mechanical means and fire, goats can aid in juniper control (Riddle et al., 1996). Campbell and Taylor (2007) advise that prescriptive herbivory has tremendous potential as effective follow-up treatment in juniper control if the PSM barriers to browsing can be overcome.

Supplementation Considerations

Plant secondary metabolites negatively affect protein utilization of ruminal microbes (Oh et al., 1967) and gas production (Frutos et al., 2004; Oh et al., 1967), while increasing fecal nitrogen and liver amino acids needed for tannin neutralization (Illius and Jessop, 1995). Furthermore, depending on which mechanism is dominant, the type of protein supplement fed to goats consuming one-seed juniper, ruminal degradable protein (RDP) or ruminal undegradable protein (RUP), may be very important (Utsumi et al., 2009). Rumen undegradable protein would be available to rumen microbes, while RUP that bypasses the rumen may increase amino acids available to the hindgut and liver for PSM detoxification (Estell et al., 2018).

Rumen undegradable protein appears to allow goats to have more moderate intake long-term by bypassing breakdown in the rumen, making it more available for tannin detoxification. Goats browsing one-seed juniper fed an 12.5% CP RDP supplemented diet containing soybean mean consumed more juniper than goats fed 12.5% CP RUP containing fish meal or 5% CP control diets in the summer, while in the winter the RUP group utilized more juniper than the RDP supplement group (Utsumi et al., 2009). Since goats with high initial intake had the greatest declines in ingestion in subsequent seasons, this suggests that adding RDP to diets could induce a short-term spike in juniper preference followed by a longer term aversion if the period of high intake is associated with a high dose of PSM, outweighing the short-term benefits (Utsumi et al., 2009). RUP inclusion, in contrast, appeared to encourage a more moderate response that seemed to allow animals to reach more successful regulation of PSM, avoiding conditioned aversions (Utsumi et al., 2009). The protein-PSM interactions are a significant difference between RDP and RUP supplementation as RDP is more easily bound by juniper tannins than the escape protein in RUP; therefore, animals fed RDP will likely have less protein available for PSM detoxification and be more sensitive to seasonal PSM changes in the foliage (Utsumi et al., 2009). Selecting the proper protein source could be crucial in controlling variation in intake for goats browsing on juniper.

For goats in biological control programs where high juniper consumption is required, tannins may negatively affect the animals’ nitrogen balance; therefore, protein supplementation may be more important than energy supplementation to maintain a nutritional balance and increase juniper intake (Campbell et al., 2007; Pritz et al., 1997). Utsumi et al. (2009) found that voluntary one-seed juniper intake is greatly impacted by the amount and type of protein in the diet and by seasonal changes in PSM concentrations. However, in the fall when one-seed juniper PSM concentrations peak, protein supplementation does not appear effective at overriding adverse effects on intake (Utsumi et al., 2009). Breed, as well as species, can impact a small ruminant’s affinity to metabolize PSM. When compared with Angora goats, Spanish meat-type goats were found to have a higher juniper intake, indicating that Spanish breed goats are better adapted to and have a better ability to tolerate or detoxify the negative consequences of juniper (Pritz et al., 1997; Riddle et al., 1996). Goats appear to be more capable of consuming juniper and increasing juniper intake in reaction to dietary protein levels than sheep (Utsumi et al., 2009). Although polyethylene glycol supplementation was shown to increase one-seed juniper intake in sheep and goats (Utsumi et al., 2013), it was not considered for this project since it can be considered too expensive for practical application in rangeland settings (Bailey et al., 2019).

The manner in which animals experience phenolics and tannins, two types of PSM, could be affected by level and type of dietary protein and therefore, the potential exists to manipulate voluntary intake (Utsumi et al., 2009). Therefore, a key idea emerges that animal-to-forage ratios and forage availability can be used to manipulate juniper utilization through heavy stocking rates (110 AUD/ha) and high stocking density with small ruminants. In mixed species browsing with sheep and goats, goats appear to increase juniper intake when forage is restricted to exploit the benefits of diet mixing, while sheep were less likely to alter their feeding patterns to include more juniper, leaving less grass for co-grazed goats (Utsumi et al., 2010). Diet mixing is useful for ruminants because microbial activity in the reticulo-rumen dictates digestion and interruptions in microbial fermentation of digesta, like volatile oils present from juniper in the diet, can slow the rate of passage and consequentially reduce forage intake (Schwartz et al., 1980).

Eastern Redcedar Browsing Resistance

As noted above, junipers employ diverse biochemical defenses to resist and avoid grazing pressure to survive. Grazing resistance is "the relative ability of plants to survive and grow in grazed plant communities" (Briske, 1996). Resistance can be divided into avoidance and tolerance mechanisms. Avoidance qualities reduce the likelihood or severity at which autotrophs will be grazed, such as morphological characteristics, mechanical deterrents, and biochemical defenses (Bailey et al., 2019; Briske, 1996). Certain avoidance mechanisms that increase with grazing intensity are known as inducible defenses, but there is little evidence to support the effectiveness of this response to deter grazing (Briske, 1996; Rhoades, 1985). Conversely, tolerance mechanisms increase plant regrowth after being grazed through “the availability and source of residual meristems and physiological processes capable of promoting growth following defoliation” (Briske, 1996).

Several studies have shown that goats will consume juniper species (Animut et al., 2004; Bisson et al., 2001; Dietz et al., 2010; Ellis et al., 2021; George et al., 2010; Miller and Scott, 2021; Pritz et al., 1997), but intake is limited because of aversive post-ingestive feedback caused by monoterpenoids found in the foliage (Frutos et al., 2004; Provenza, 1995; Riddle et al., 1996). Successful targeted browsing programs utilize techniques to encourage voluntary intake of the woody target plant while simultaneously avoiding understory vegetation destruction (Utsumi et al., 2010). Fortunately, exposing goats to juniper or juniper essential oils at weaning (Dietz et al., 2010), preconditioning (Miller and Scott, 2021), protein supplementation (George et al., 2010; Miller and Scott, 2021; Mkhize et al., 2016), individual animal selection (Campbell et al., 2007), seasonal browsing (Riddle et al., 1996), and feeding polyethylene glycol (Decandia et al., 2000; Villalba and Provenza, 2001) are management options that can counteract some of the negative digestive and behavioral reactions to juniper tannins (Decandia et al., 2000; Dietz et al., 2010; Villalba and Provenza, 2001).

Plant Secondary Metabolites

Potentially toxic compounds such as condensed tannins, soluble phenolics, and terpenes in junipers like ERC are broadly called plant secondary metabolites (PSM) (Pritz et al., 1997; Utsumi et al., 2009). Plants can release PSM when grazed by an herbivore or subjected to an abiotic stress such as drought, salinity, or harsh climate (Ahmed et al., 2017). In contrast to primary plant metabolites, secondary metabolites serve no known direct purpose in plant growth, development, and reproduction, although differences between the two are complex (Ahmed et al., 2017). However, some secondary metabolites are lowly palatable to herbivorous mammals through an effective trifecta of inhibitory effects on ruminal microbes (Pritz et al., 1997; Schwartz et al., 1980), harmful impact on liver metabolism (Huston et al., 1994), and negative post-ingestive feedback leading to conditioned taste aversions (Provenza, 1995). Specifically, PSM can negatively affect herbivore digestion by forming bonds with substrates and increase an animal's energy expenditure to neutralize PSM (Ahmed et al., 2017). To illustrate the metabolic cost of neutralization, Illius and Jessop (1995) modeled a ruminant consuming PSM and estimated additional energy needs for detoxification at 1.25-2 times maintenance. Tannins are a group of high molecular-weight compounds that are able to form complexes with proteins (Frutos et al., 2004) rendering the proteins unavailable to an herbivore's body. Tannins are usually classified into two groups, either hydrolysable tannins or condensed tannins, based on their chemical structure (Min and Hart, 2003). Condensed tannins are the most common variety of tannin found in shrubs, trees, and forage legumes (Barry and McNabb, 1999).

Some PSM-herbivore interactions are positive, like those that lower parasite burden and increase intake. For example, sheep and goats have been known to consume tannin-rich plants to lower their gastrointestinal parasite burden (Min and Hart, 2003). Some compounds, such as camphor and cymene in ashe (*Juniperus ashei* J. Buchholz), and redberry (*Juniperus pinchotii* Sudw.) juniper foliage, are positively related to intake (Riddle et al., 1996).

Plant Secondary Metabolite Seasonality

Seasonality affects PSM concentrations of juniper plants, and since PSM concentrations are usually inversely related to herbivory intensity, it is useful to know a species' chemical defense characteristics (Estell et al., 2018). Volatile oil extracted from ERC needles in Texas "has been found to contain mainly sabinene, as well as limonene, a-pinene, y-terpinene, terpinolene, 3-carene, myrcene, 4-ter- pineol, citronellol, elemol, eudesmol, and the aromatic ethers estragole, safrole, methyl eugenol, and elemicin" (Setzer et al., 1992; Vinutha and von Rudloff, 1968), but Setzer et al. (1992) found by comparing results from their ERC leaf oil analysis on trees in Alabama that tree sex and geographical location has an influence on PSM composition and concentrations. Eastern redcedar wood is known to contain mainly cedrene and cedral (Setzer et al., 1992). However, the PSM contents of the bark alone have been given little attention, which could be relevant for applying goats as biological control to girdle ERC. Intuitively, there is a knowledge gap regarding ERC PSM composition and concentration in eastern South Dakota.

In the redberry and ashe juniper, volatile oil concentrations were generally greater during spring and summer and lower in fall and winter with season having a significant effect on individual oil totals (Riddle et al., 1996). In contrast, one-seed juniper (*Juniperus monosperma* (Engelm.) Sarg.) volatile oil concentrations, specifically terpenes, are lowest in the summer, highest in the fall, and intermediate in winter and spring (Estell et al., 2018). Varying levels of PSM concentrations, sapling development stage, and season may impact the probability of a plant being browsed and therefore its vulnerability to control by small ruminant herbivory (Utsumi et al., 2010). Comparing spring and summer browsing by sheep and goats, there appears to be little difference in one-seed juniper utilization except in short ($P < 0.05$ m) saplings, which were branches were heavily browsed at levels of 74.6 ± 6.1% and 51.7 ± 10% for summer and spring, respectively (Utsumi et al., 2010). Spring browsing also reduced ($P < 0.05$) sapling height, diameter, and volume over summer browsing, although there were no differences between seasons for sapling mortality which averaged 5 ± 1.1% across browsing treatments (Utsumi et al., 2010). Branch mortality tended to be higher, and the proportion of debarked branches greater, in spring than summer browsing with branch debarking linearly related to branch mortality and one-seed juniper sapling height and volume decreases (Utsumi et al., 2010).

Conclusion

Eastern redcedar encroachment into Great Plains grasslands is a fast-moving threat to native grassland plants, wildlife, and livestock productivity. A variety of control methods are available to reduce juniper spread including mechanical, pyric, chemical, and biological treatments like targeted browsing. Small ruminant targeted browsing can be an effective, flexible, precision approach to pair with other control treatments, but little is known about its effectiveness against ERC. Goats are intermediate feeders which means their diet is comprised of herbaceous and woody sources. Furthermore, goats, have large salivary glands and livers relative to their body size which allows them to detoxify and utilize potentially toxic PSM that would create conditioned feed aversions in grass/roughage eating species. Some research suggests that protein supplementation can increase juniper intake in goats by offsetting protein lost by PSM-binding in the rumen and by supporting liver detoxification. Stocking rate can be adjusted strategically to encourage diet mixing, which can help herbivores tolerate PSM, leading to increased juniper browsing (defoliation and debarking). Current literature also supports that tree height may be an important predictor of goat browsing, but more research is needed to better understand how tree height can be used to guide targeted browsing management decisions. Juniper tree age, season, and background herbaceous biomass quality and quantity are additional covariates to consider reaching juniper mortality by targeted browsing. Previous studies suggest that juniper branch debarking is important for tree mortality, but there remains a severe lack of research in this area. With the help of grazing management principles and integrated management, woody encroachment may be slowed. The issue of grassland loss is of global interest and concern as threats of woody invasion, desertification, and cropland conversion are felt on each continent. Browsing animals are a natural and vital component of working with, rather than forcing, nature grassland habitat restoration and conservation.

FIGURES

Figure 1-1 An aerial view of eastern redcedar encroachment around a planted shelterbelt seed source. Adapted from *Fogarty et al., 2022*.

Practice	*Woody encroachment stages*				*State transition*	*Components of risk*	
	Intact	*Dispersal*	*Recruitment*	*Encroachment*		*Sensitivity*	Exposure
Prescribed fire	X	X	X	X	X	↓	↓
Hand tool removal			X	X			↓
Haying			X				↓
Goats			X			↓	
Mechanical				X	X		↓
Grazing management						↑↓	

Figure 1-2 Woody control methods and their potential applications during different stages of non-resprouting woody encroachment. Adapted from *Twidwell et al. (2021)*.

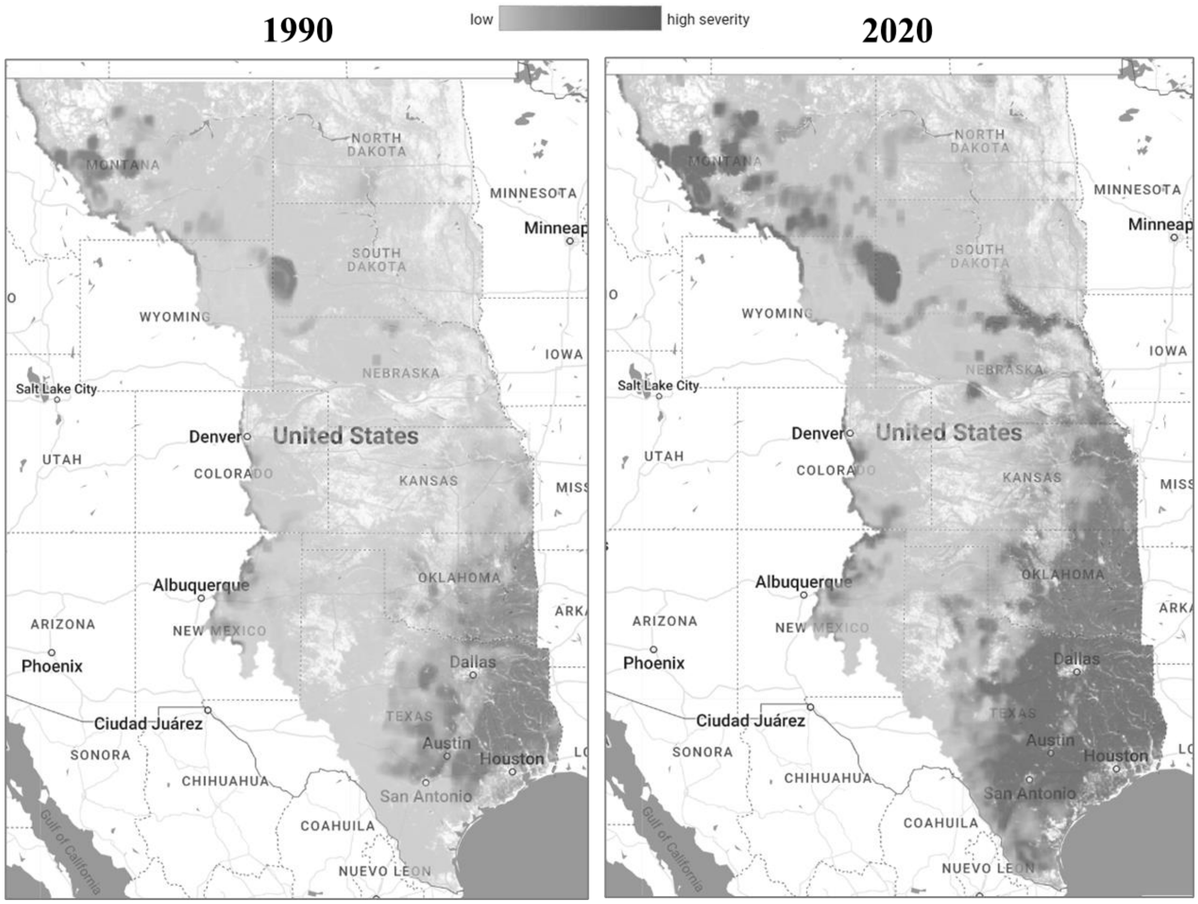

Figure 1-3 The rapid expansion of woody encroachment threatens the sustainability and longevity of grasslands. Illustration adapted from *USDA-NRCS Working Lands for Wildlife (https://rangelands.app).*

Chapter 2. Goat Defoliation and Debarking on Eastern Redcedar (*Juniperus virginiana* L.) with Rumen Undegradable Protein Supplement

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ABSTRACT

Eastern redcedar (ERC) (*Juniperus virginiana* L.) encroachment threatens long-term Great Plains health. Goats browse juniper by defoliation and debarking but are limited by negative post-ingestive feedback from plant secondary metabolites (PSM). Protein supplementation may increase fed juniper foliage intake by offsetting nitrogen loss from PSM-protein binding, but little is known about supplementation of goats browsing whole juniper, mimicking a field setting. Therefore, the objective was to study the effects of rumen undegradable protein (RUP) supplementation and tree height on goat browsing. Experimental design was two 3x3 Latin squares of two diets and three ERC tree height treatments. Within each square, twelve Savannah X Spanish X Boer crossbred 50 ± 3.9 kg does were fixed to a diet for ten days (seven days for adaptation and three days for ERC browsing). Fed diets were control (grass hay and whole corn) and supplemented (grass hay and dried distiller's grain (DDG), an RUP source). Diets were isocaloric and supplemented diet crude protein was fed at 2x maintenance. Each pen (three pens of four goats per diet) was offered two trees from one of three tree height treatments for eight hours daily over three days in a rotation where pens received all tree height treatments. Supplemented RUP did not increase defoliation (P = 0.73), trunk debarking (P = 0.84), or branch browsing (P = 0.74). However, tree height may impact browsing as short (50 cm) trees were more defoliated and 50 and 100 cm trees had more branches browsed than

taller (200 cm) trees (*P* < 0.05). Therefore, for field application relevance, it may be more important for pen studies to measure browsing of whole juniper rather than fed foliage intake. Future pen and/or field studies should explore alternative protein sources, consider tree height in their design, and offer goats whole juniper.

Keywords: Juniper, eastern redcedar, goat, targeted grazing, rumen undegradable protein

Introduction

Eastern redcedar (ERC) (*Juniperus virginiana* L.) encroachment, expedited by shelterbelt planting (Donovan et al., 2018) and fire suppression (Twidwell et al., 2021), is an increasing threat to Great Plains grassland health and longevity through woody transition, decreasing herbaceous biomass through shading and altering the hydrologic cycle, which has negative impacts on ranch profitability and wildlife habitat (Limb et al., 2010; Twidwell et al., 2021). Management of ERC includes mechanical, pyric, chemical, and biological (i.e., targeted browsing with goats). A non-sprouting species, ERC can also be killed by removing or gridling aboveground portions (Arend, 1950).

Of domestic livestock, goats may be best suited for ERC control with their dexterous lips and large salivary glands, which give them better capability to detoxify plant secondary metabolites (PSM) often found in shrubs and trees including ERC (Hofmann, 1988; Launchbaugh, 2006). Targeted browsing goats is suggested for defoliating short, immature juniper saplings (Lyons et al., 2009; Twidwell et al., 2021).

Plant secondary metabolites are lowly palatable to herbivores. Detoxification can increase dry matter intake by 1.25-2 times maintenance (Illius and Jessop, 1995) and impact rumen microbe protein utilization (Oh et al., 1967; Pritz et al., 1997; Schwartz et al., 1980). Since PSM can complex with dietary nitrogen rendering it unavailable in the rumen, concern arises as to whether it negatively impacts a ruminant's nitrogen balance (Frutos et al., 2004). To increase redberry juniper (*Juniperus pinchotii* Sudw.) intake, protein supplementation is often suggested (Estell et al., 2018; Illius and Jessop, 1995; Pritz et al., 1997). However, literature is inconsistent on whether rumen degradable protein (RDP) or rumen undegradable protein (RUP) is more important for goats consuming one-seed (*Juniperus monosperma* (Engelm.) Sarg.) and redberry juniper (Campbell et al., 2007; George et al., 2010; Miller and Scott, 2021; Utsumi et al., 2009). While RDP would be available to rumen microbes, RUP that bypasses the rumen may increase amino acids available to the hindgut and liver for PSM detoxification (Foley et al., 1995; George et al., 2010). Dried distiller's grain (DDG) is a common high RUP protein source in the midwestern U.S. (National Research Council [NRC], 2007). Therefore, supplementing DDG protein at 1.25-2 times maintenance may aid in detoxification and increase browsing of ruminants consuming PSM.

Tree height may be an indicator of PSM content. One-seed juniper saplings had lower terpenoid concentrations during stages of high growth, potentially because more carbon was allocated for tissue growth than defensive compounds (Estell et al., 2014). Under goat browsing, older, taller, one-seed juniper saplings suffered heavy branch debarking, possibly because they offered more bark that was easier to reach and less chemically defended than mature leaves (Utsumi et al., 2010). Study objectives were to assess goat browsing on whole ERC relation to tree height and the effects RUP supplementation. We hypothesized RUP supplementation with DDG at 2x protein maintenance would increase browsing impact to ERC trees with the shorter trees more defoliated and the taller trees more debarked.

Materials and Methods

Experimental Design

Experimental protocols were approved by South Dakota State University (SDSU) Institutional Animal Care and Use Committee (IACUC 2105-025E). The study was conducted at the SDSU Animal Science Beef Breeding Research Unit (44°20'22" N, 96°48’04” W) in Brookings, SD, USA. Eastern redcedar trees were harvested from a 59-ha pasture (44°23’17” N, 96°57’44” W) of U.S. Fish and Wildlife Service land 19 km west of the pen study site.

The experimental design was two 3x3 Latin squares of two diets and three ERC tree height classes as treatment for three days. Diets were control fed a maintenance diet of grass hay and whole corn and supplemented fed a high-RUP diet of grass hay and DDG at 4% of body weight (BW) (Table 2-1). Within each square, twelve Savannah X Spanish X Boer crossbred 50 ± 3.9 kg doe goats were assigned to one diet for a ten-day period (seven days of adaptation and three days of ERC browsing and data collection). Four goats were fixed to each of three pens (9 m^2) per diet based on weight tape estimations ([$Girth^2$·Point-of-Shoulder to Pin]/300) (Moaeen-ud-Din et al., 2006) totaling 24 goats and six pens.

The control diet contained 10% crude protein (CP) whereas the supplemented diet contained 14% CP. Goats were supplied a commercially available trace mineral (MannaPro®) with ad libitum water access. Diets were isocaloric and met or exceed maintenance needs (National Research Council [NRC], 2007) (Table 2-1).

During the three-day data collection period, pens in each square were offered two ERC trees (*n* = 36) from one height class (50, 100, and 200 cm) in a daily rotation such that all height classes treatments were applied to each pen after three days, balancing the Latin square. Trees were cut at the base of the trunk with a hand saw, mounted in tree stands, and offered to goats (Figure 2-1). No more than one hour elapsed between tree harvest and presentation to goats to limit PSM volatilization and leaf water loss, and goats had access to ERC for eight hours. The herd was previously on pasture, and prior ERC exposure is unknown.

Data Collection

Pre-browse data collected on ERC trees included height (ground to top of crown) and average canopy diameter (average of widest points along two perpendicular axes). Post-browse, ERC tree height and canopy measurements were repeated along with browse line height (highest occurrence of debarking or defoliation), trunk debarking (ocular estimate of trunk browsed below browse line), and branch browse (browsed branches below browse line/total branches below browse line · 100). Defoliation was calculated by determining the pre- and post-browse volume assuming the conical shape described by Johnson and Larson (2016):

$$V = \frac{1}{3}\pi r^2 h$$

where *V* is the juniper canopy volume as a function of height, *h*, and ½ canopy diameter, *D* = 2*r*. The difference was then determined a percentage change:

$$\% \Delta V = \left(\frac{(V_1 - V_2)}{V_1}\right)100$$

Data Analysis

Analyses were performed using R Statistical Software (v4.0.3; R Core Team, 2021). Diet and ERC height class were independent variables, and browsing defoliation, debarking, and branch browse were dependent variables. Kruskal-Wallis nonparametric modeling and Dunn's test for means separation were used since data could not be transformed for normality. Significance was declared at $P < 0.05$.

Results

Supplementation of DDG fed at 2x protein maintenance, did not increase goat browsing defoliation, debarking, or branch browse on whole ERC trees ($P > 0.05$, Table 2-2). While results showed no difference in debarking in relation to tree height ($P = 0.30$), shorter (50 cm) trees were more defoliated than taller (100 and 200 cm) trees ($P < 0.01$, Table 2-2). Branch browse had an inverse relationship to tree height. Trees 50 and 100 cm had more branches browsed below browse line than taller (200 cm) trees ($P < 0.01$, Table 2-2).

Discussion

Supplementing goats with a high-RUP protein source at 2x maintenance did not impact browsing on ERC trees. This was unexpected as protein supplementation may aid in PSM detoxification and increase juniper intake (Estell et al., 2018; Illius and Jessop, 1995; Pritz et al., 1997). However, previous literature is inconsistent whether an RUP or RDP source is more essential to increase goat consumption of one-seed and redberry juniper; however, RUP may be preferable as it provides limiting amino acids to support liver detoxification resulting in conservative long-term intake increases while RDP supports rumen microbes resulting in high initial intake sometimes followed by long-term conditioned aversions if PSM-binding cannot be matched (Foley et al., 1995; George et al., 2010). To date, no studies have addressed the response of protein-supplemented goats browsing ERC, which may explain why browsing was not different between treatments. Nevertheless, browsing appears to be influenced by tree height.

Eastern redcedar height could be a significant predictor of goat defoliation and branch browsing. Shorter trees (50 cm) were more defoliated than tall (100 and 200 cm) trees, while 50 and 100 cm trees had more branches browsed compared to 200 cm trees. This aligns with the inverse relationship between defoliation and tree height reported in field studies by Estell et al. (2014) and Utsumi et al. (2009, 2010) on one-seed juniper. Therefore, in order for pen studies to better represent field trials, whole juniper should be utilized.

Future pen studies could benefit by presenting whole trees to goats as it may better capture the browsing impacts in the field. Previous penned goat juniper studies of one-seed and redberry juniper used only clipped leaf and stem tissue, branches, needles stripped from branches, and distilled PSM instead of whole juniper trees (Campbell et al., 2007; Miller and Scott, 2021; Pritz et al., 1997; Utsumi et al., 2010, 2009), presumably to measure intake. When targeted browsing with goats to kill juniper is a part of management goals, foliage intake may be less important than how goats browse (defoliation and debarking), which appears to be strongly correlated to tree height. Further research is needed on whole juniper in controlled pen settings and the amount of foliage and/or bark removed by goat browsing needed to kill ERC.

Implications

It appears that rumen undegradable protein supplementation does not increase goat defoliation and debarking of ERC trees. However, this novel study allowed us to test how goats might browse ERC trees of different sizes. Since all tree heights were debarked about 81%, rather than solely defoliated, this research sheds new light on how goats could be used to control non-sprouting juniper because debarking or girdling should interrupt carbohydrate flow between branches and roots, potentially killing the tree. Previous research and current guidelines suggest that goat targeted browsing should be applied to control immature sapling juniper (< 100 cm) by defoliation (Twidwell et al., 2021); however, this research suggests that goats could control juniper of various heights by debarking, particularly on the trunk. This study was limited as goats might have spent more time browsing than they would in a field setting. However, the strength of our study design included whole juniper unlike previous pen studies where goats were fed needle and branch tree parts. Importantly, this research demonstrates that future studies could benefit from using whole juniper trees to measure browsing, instead of harvested branches and needles to capture intake, because whole juniper illustrates how goats will browse in the field, helping managers reach their goals. Future pen studies should explore alternative protein sources, consider tree height in their design, and offer goats whole juniper to improve targeted browsing as a potential rangeland reclamation and maintenance tool.

TABLES

Table 2-1 Ingredient composition of diets fed to goats browsing eastern redcedar to test the effect of rumen undegradable protein on browsing.

Ingredient	Diet[1]	
	Control	Supplemented
DDG ($g \cdot kg^{-1}$ BW)	-	34
Whole Yellow Corn ($g \cdot kg^{-1}$ BW)	35	-
Brome Grass Hay ($g \cdot kg^{-1}$ BW)	125	125
Mineral-Vitamin Premix[2] ($g \cdot kg^{-1}$ BW)	0.28	0.28
Metabolizable Energy ($Mcal \cdot kg^{-1}$)	2.3	2.3
CP (%)	10	14

[1] Diets were control (no protein supplement) and supplemented (dried distiller's grain [DDG]) are isocaloric and meet or exceed NRC (2007) doe maintenance recommendations.

[2] Mineral-Vitamin Premix composition: Calcium 16.00-19.20%, Phosphorus 8.00-12.00%, Salt 4.80-14.40%, Sodium 4.80-5.75%, Magnesium 1.50%, Potassium 1.50%, Copper 1350-1600 ($mg \cdot kg^{-1}$), Manganese 2750 ($mg \cdot kg^{-1}$), Zinc 5500 ($mg \cdot kg^{-1}$), Selenium 12-14.4 ($mg \cdot kg^{-1}$), Vitamin A 135,900 ($IU \cdot g^{-1}$), Vitamin D_3 13,590 ($IU \cdot g^{-1}$), Vitamin E 217 ($IU \cdot g^{-1}$), Lactic Acid Bacteria 679,500 ($CFU \cdot kg^{-1}$).

Table 2-2 Effect of rumen undegradable protein supplemented and control diets and tree height on goat browsing eastern redcedar trees.

Browsing Variable[1]	Diet[2]			*P*-value
	Control		Supplemented	
Defoliation (%)	62.94 ± 8.6 [a]		66.73 ± 8.6 [a]	0.73
Debarking (%)	81.28 ± 6.4 [a]		82.39 ± 5.7 [a]	0.84
Branch Browse (%)	87.88 ± 5.2 [a]		92.47 ± 2.8 [a]	0.74
	Height Class (cm)			
Browsing Variable	50	100	200	*P*-value
Defoliation (%)	93.27 ± 2.8 [a]	73.21 ± 5.0 [b]	28.02 ± 10.5 [b]	< 0.01
Debarking (%)	75.92 ± 10.0 [a]	90.25 ± 3.97 [a]	79.33 ± 6.63 [a]	0.30
Branch Browse (%)	100.00 ± 0.0 [a]	99.68 ± 0.3 [a]	70.83 ± 5.5 [b]	< 0.01

Values within rows with the same superscripts (a-b) do not differ (*P* > 0.05).

[1] Values are means ± SE of goat browsing on eastern redcedar compared to pre-browse.

[2] Diets are isocaloric and meet or exceed NRC (2007) does maintenance recommendations.

FIGURES

Figure 2-1 Whole eastern redcedar fastened to PVC pipe in wooden tree stands. Photos show 50 cm (a, d), 100 cm (b, e), and 200 cm (c, f) trees pre- and post-browse.

Chapter 3. Targeted Browsing with Goats for Eastern Redcedar (*Juniperus virginiana* L.) Control: Vegetative Composition, Stocking, and Juniper Mortality

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ABSTRACT

Eastern redcedar (ERC) (*Juniperus virginiana* L.) encroachment into grassland ecosystems, facilitated by shelterbelt planting and fire suppression threatens the long-term health of the Great Plains grasslands. Goats browse (defoliate and debark) juniper tree trunks and branches. Since ERC do not resprout, trunk girdling may kill the tree, making targeted browsing with goats a potential ERC control tool; however, little field experimentation exists. The objective was to investigate how goats browse ERC of different heights and the impact on tree mortality. A randomized complete block design was used with five sites comprised of four replicate paddocks browsed two consecutive summers. Up to ten ERC in five height classes (< 50, 51-100, 101-150, 151-200, and 201-250 cm) were permanently tagged in each paddock and browsing measurements and forage disappearance were recorded. Juniper height was negatively related with defoliation ($y = -0.28x + 72.1$; $R^2 = 0.39$; where x = plant height in cm) and positively related with debarking ($y = 0.12x$; $R^2 = 0.29$; where x = plant height in cm). Defoliation by volume reduction (%) was highest on trees < 100 cm tall and the greatest percentage of the trunk was debarked on trees > 100 cm tall. On sites with less deciduous browse, ERC 151-250 cm had more ($P = 0.003$) browned foliage and higher ($P = 0.01$) mortality than shorter, 51-100 cm juniper. Sites with more deciduous browse had less debarking and mortality; therefore, ERC debarking and mortality success with targeted browsing with goats will most likely depend on site plant community composition where juniper should be the only woody component. Targeted browsing with goats could be an effective ERC site pre-treatment when integrated with prescribed fire or other control.

Keywords: *Eastern redcedar, targeted browsing, goat, woody encroachment, juniper mortality*

Introduction

Eastern redcedar (ERC) (*Juniperus virginiana* L.) encroachment, expedited by fire suppression (Twidwell et al., 2021) and shelterbelt planting (Donovan et al., 2018), is a long-standing threat to the health and longevity of the Great Plains. Although ERC is the eastern-most native juniper species in North America (Van Haveneke and Read, 1976), its presence in rising numbers on South Dakota grassland is undesirable for a number of reasons including its role in increasing fuel load for wildfires (Animut et al., 2004), decreasing pasture forage production and biodiversity by shading (Engle et al., 1987; Ortmann et al., 1998), and competition for water resources (Hintze et al., 2021; Miller et al., 2019; Treadwell et al., 2021). Approximately 43.7 million hectares of the Western U.S. have seen woody plant increases since 1999, equivalent to 2.3 times the size of Nebraska in area (Jones et al., 2020; Natural Resources Conservation Service, 2021). Eastern redcedar encroachment has a generally negative impact on grassland wildlife and may displace desirable food and cover plants essential for wildlife prosperity, depending on the site, cover, and density of ERC (Rollins and Armstrong, 1994). This threatens endangered species like the greater and lesser prairie chicken, which require prairie for habitat (Bidwell et al., 2008). Therefore, it is necessary to control encroached juniper populations on grasslands.

Several management options exist for controlling or suppressing ERC numbers including mechanical, pyric (e.g., prescribed fire), chemical (i.e., herbicidal), and biological (e.g., targeted grazing) techniques. A non-sprouting species, both large and small ERC can be killed with mechanical removal (e.g., shearing, chopping) below the lowest bud (Owensby et al., 1973; Twidwell et al., 2021), but heavy machinery often cause severe soil disturbance and compaction and decrease water infiltration (Miller et al., 2019). Chemical herbicide applications can also be used to control larger ERC, but they are less publicly accepted, less economical, and less effective than other forms of control (Morton et al., 2010; Twidwell et al., 2021). Prescribed fire can be used at all stages of encroachment from seed dispersal to woody state transition, but more intense fire is needed to kill larger juniper (Twidwell et al., 2021). Additionally, prescribed burning somewhat limited by weather factors and barriers to landowner adoption (Treadwell et al., 2021). Biological control by targeted browsing with goats is an emerging juniper control method that has been briefly explored on one-seed (*Juniperus monosperma* (Engelm.) Sarg.), ashe (*Juniperus ashei* J. Buchholz), and redberry (*Juniperus pinchotii* Sudw.) juniper (Animut et al., 2004; Bisson et al., 2001; Dietz et al., 2010; Ellis et al., 2021; George et al., 2010; Miller and Scott, 2021; Pritz et al., 1997), yet there remains a knowledge gap around targeted browsing for ERC control.

Targeted browsing with goats is recommended for immature juniper as a means to suppress saplings before they reach reproductive maturity of > 150 cm tall (ERC females can produce 1.5 million seeds per year) (Lyons et al., 2009; Owensby et al., 1973; Twidwell et al., 2021), although little data supports that immature juniper is the optimal height for goat targeted browsing. Goats appear to prefer juniper seedlings and regrowth with some selectivity between tree species and sex (Treadwell et al., 2021). Simulated browsing of needle-leaf juniper saplings found that defoliation to the root level killed 80% of trees, 1 cm above root level killed 52%, and defoliation of half of the foliage killed 15% (Lyons et al., 2009). Tree height is also often considered an important factor in targeted browsing, but there is insufficient data to determine how browsing affects juniper mortality.

Older, taller, one-seed juniper saplings suffered heavy branch debarking, possibly because they offered more bark that was easier to reach and less chemically defended than mature leaves (Utsumi et al., 2010). Conversely, younger, smaller, one-seed juniper saplings potentially contain lower levels of chemical defenses in their leaves and tend to have more frequent heavy (67-100% of branches defoliated) use by herbivores (Campbell and Taylor, 2007; Utsumi et al., 2010). Utsumi et al. (2010) investigated whole tree defoliation as a function of volume change and debarking as a function of branches debarked (%) and found mortality (%) two years post-browse significantly greater under heavy (1.1 AUD·100 m^2) goat and goat-sheep mixed browsing than the non-browsed control. The mean whole tree mortality was around 5% (density 500-533 juniper·ha^{-1}) (Utsumi et al., 2010); however, there is limited quantitative data to link juniper mortality or slowed growth to trunk debarking or defoliation browsing injury sustained by saplings. Additionally, environmental covariates such as juniper density, goat stocking rate, herbaceous forage, and juniper PSM are often overlooked, yet they could influence targeted browsing, and subsequently juniper mortality (Bailey et al., 2019).

The objectives of this study were to 1) describe the relationship between ERC tree height on goat defoliation and debarking levels, 2) develop a comprehensive understanding of influences of real-life site-specific factors, such as background herbaceous biomass quantity, stocking rate, and ERC tree density on browsing intensity, and 3) assess how defoliation and debarking impact ERC tree survival and subsequent browsing intensity leading to tree mortality. We hypothesize that shorter (< 100 cm) trees will be more defoliated and taller (> 100 cm) trees will be more debarked and that browsing intensity to be inversely related to background vegetation quantity and quality, and ERC density while directly related to stocking rate. Finally, we anticipate that debarking (% of trunk debarked below the browse line) will be directly related to tree death as reported in Campbell et al. (2007) and Utsumi et al. (2010). Season was initially considered, but due to spatial and temporal constraints, it was excluded in the second-year replication and focus was applied to the most important identified covariates.

Materials and Methods

Site Description

The study site was located in Southeast Gregory County, SD, USA (43°02’42” N, 98°33’12” W) and consisted of about 15 ha of reclaimed farmland (farmed early 1900’s) composed of grasses (smooth bromegrass [*Bromus inermis* Leyss.], Kentucky bluegrass [*Poa pratensis* L.], big bluestem [*Andropogon gerardii* Vitman]), forbs (sweetclover [*Melilotus officinalis* (L.) Lam.], Canada thistle [*Cirsium arvense* L.], heath aster [*Symphyotrichum ericoides* L.]), and woody species (eastern redcedar, chokecherry [*Prunus virginiana* L.], American elm [*Ulmus americana* L.]). Elevation was around 450 m ASL, and the area had an average of 100-150 frost-free days (Natural Resource Conservation Service [NRCS], 2022) with a mean annual temperature from the years 2000-2022 of 10° C (National Weather Service [NWS], 2022). Mean annual precipitation 2000-2022 is 620 mm (NWS, 2022). The two main soil types are Onita silt loam and Wendte silty clay (NRCS, 2022). Onita silt loam soils are moderately well-draining soils mainly found in central and south-central South Dakota as well as parts of north-central Nebraska and eastern Wyoming (National Cooperative Soil Survey, 1997a). Wendte silty clay soils are found in central and south-central South Dakota and sometimes in north-central Nebraska with slow permeability and a rare flooding (National Cooperative Soil Survey, 1997b). The moderate stocking paddocks were located mainly on Onita silt loam soils, while the low and high stocking paddocks are located mainly on Wendte silty clay soils (NRCS, 2022). Chokecherry, cotoneaster (*Cotoneaster lucidus* Schltdl.), plum (*Prunus domestica* L.), Mongolian cherry (*Prunus pumila* L.), and hansen hedge rose (*Rosa rugosa* Thunb.) were planted near Site C on July 1, 1996, ERC, green ash (*Fraxinus pennsylvanica* Benth.), hackberry (*Celtis occidentalis* L.), Midwest crab apple (*Malus baccata* L.), chokecherry, apricot (*Prunus armeniaca* L.), Mongolian cherry, and plum were planted near Site A June 9, 1997, and bur oak (*Quercus macrocarpa* Michx.), ERC, chokecherry, plum, Mongolian cherry, and Midwest crab apple were planted near Sites B and E May 29, 1998. The only juniper control applied at the time of the study was mechanical shredding and chipping of ERC and Russian olive (*Elaeagnus angustifolia* L.) > 100 cm encroaching beyond shelterbelt boundaries in 2014.

Experimental Design

A randomized complete block design was used to explore goat browsing on ERC at five tree height classes (< 50, 51-100, 101-150, 151-200, 201-250 cm tall). Separate experiments were designed on five ERC-encroached sites (Figure 3-1) selected near ~ 25-year-old planted ERC shelterbelts. Each site was blocked into four adjacent, replicate 30 x 18 m (540 m^2) paddocks (with the exception of Site E at 21 x 18 m due to land constraints) (Table 3-1). Stocking rates, ERC density, and forage quantity varied for each site. Targeted browsing with goats was repeated summers 2021-2022. Spanish-crossbred open does and kids, *n* = 79 - 109) at 27.21 - 32.21 kg body weight (BW), were hired from a contract browsing herd raised on Nebraska rangeland, thus the does were not naïve to ERC. Goats were moved through paddocks at consecutive 24-hour shifts and fenced with electric netting (ElectroNet®). Ad libitum commercial salt mineral and fresh water were provided. Experiment protocols were approved by South Dakota State University Institutional Animal Care and Use Committee (IACUC 2105-025E).

Data Collection

In each paddock, up to 10 (minimum 3) ERC tree subsamples from each of the five height classes were tagged permanently with an aluminum tree tag fastened with wire to the lower trunk. Treatment was height class offered cafeteria-style were there was an equal chance of goat selection preference for grazing. In 2021, pre-browse data collected on ERC included tree height (ground to the top of the crown) and canopy diameter (the widest points along two perpendicular axes and averaged). Post-browse, ERC tree height and canopy measurements were repeated along with browse line height (highest occurrence of browsing), trunk debarking (ocular estimate of percentage of trunk browsed below the browse line), and branch browse (percentage of branches defoliated and/or debarked below browse line) (Table 3-2). In 2022, pre- and post-browse ERC data was collected as described above for Sites D and E with the exception of branch girdling (percentage of branches girdled below the browse line) replacing branch browse and the inclusion of trunk girdling below the lowest branch (presence/absence) (Table 3-2). For Sites A, B, and C no 2022 pre-browse ERC data was taken, but post-browse, trunk debarking, and branch girdling were collected (Table 3-2). Defoliation was calculated by determining the pre- and post-browse volume assuming the conical shape described by Johnson and Larson (2016):

$$V = \frac{1}{3}\pi r^2 h$$

where V is the juniper canopy volume as a function of height, h, and ½ canopy diameter, $D = 2r$. The difference was then determined a percentage change:

$$\%\,\Delta V = \left(\frac{(V_1 - V_2)}{V_1}\right)100$$

where % ΔV is the percentage of volume reduction when V_1 is pre-browse volume and V_2 is post-browse volume. After a dormant winter season, ERC tree mortality data was determined with an ocular estimate of browned foliage as a part of all foliage on Sites A, B, and C (%) (Table 3-2).

Herbaceous vegetation cover estimates and biomass clippings were taken randomly with 0.25 m^2 quadrats in triplicate at three locations in each paddock pre- and post-browse: under canopy (UC) of 100% cover by ERC ≥ 200 cm tall, ERC canopy edge (CE) 50% cover by ERC ≥ 200 cm tall, and open grassland (G) with 0% ERC canopy cover (Table 3-2). Biomass samples were dried at 60° C for 72 hours. The current year's growth was then sorted out and weighed ($kg \cdot ha^{-1}$). Weights were pooled by location within paddock for analysis. Biomass disappearance percent change with the volume reduction formula above where V_1 is pre-browse biomass and V_2 is post-browse biomass. Since canopy cover was sparce for UC and CE samples on Site D, all samples were taken as G and otherwise treated the same as other biomass. Adjustments were made to match actual site proportions of UC, CE, and G biomass (Table 3-3).

To assess ERC PSM, fresh bark and foliage samples were collected near Volga, SD, USA (44°23'17" N, 96°57'44" W) from three randomly selected trees at each of the five height classes, below 200 cm, if applicable, as was consistent with observed goat browse lines. Samples were stored at -20 °C for volatile oil extraction. Pooled samples were ground cryogenically in liquid nitrogen and 0.5 g was dissolved in 10 ml methyl alcohol, shaken for 10 minutes, and then allowed to rest undisturbed for one hour. After centrifugation, 8 µl of supernatant was injected into the gas chromatograph – mass spectrometer (GC-MS) and analyzed for calibrated compounds by retention time and peak area (Riddle et al., 1996; Setzer et al., 1992) (Table A-1).

Data Analysis

Juniper Height and Goat Browsing.

Data was analyzed by site. Blocking was done by paddock within site with tagged trees as experimental units. Height class treatment means were used for all analyses except regression. Analyses were performed using R Statistical Software (v4.0.3; R Core Team, 2021). Tree height class treatment was independent while browsing response variables included defoliation, debarking, branch browse, branch girdling, and foliage browning. Forage sampling location in relation to ERC canopy was the independent variable compared to herbaceous biomass production as the dependent variable. Analysis of variance (ANOVA) was conducted, and Fisher's LSD test for means separation was used post-hoc with the Bonferroni correction for statistically significant models (α = 0.05). For models with residuals that could not be transformed for normality, the Kruskal-Wallis non-parametric rank-based test was applied and Dunn's post-hoc test for median separation was applied and adjusted for multiple comparisons using the Bonferroni correction for statistically significant models (α = 0.05).

Linear regression models were fit to identify significant relationships (Pearson's correlation coefficient, expressed *r*(*df*) = *r* statistic; *p* = *p*-value) between ERC height as the independent variable and defoliation and debarking as dependent variables (Figures 3-2, 3, 4, 5). Additionally, regression compared 2021 defoliation, debarking, and juniper height as independent variables and 2022 foliage browning as the response for Sites A, B, and C (Figures 3-6, 7, 8).

Biomass Production and Species Diversity.

Biomass production ($kg \cdot ha^{-1}$) was adjusted to reflect individual site proportions at the under canopy (UC), canopy edge (CE), and grassland (G) sampling locations (Table 3-3). Relative species frequency and cover by species were calculated within each site by sample location within paddock with the following formulas:

$$\%\ Frequency\ (Spp_x) = \left(\frac{\#\ of\ plots\ in\ which\ Spp_x\ occurs}{Total\ \#\ of\ plots\ examined}\right)100$$

$$\%\ Cover\ (Spp_x) = \left(\frac{Total\ cover\ (\%)\ of\ Spp_x}{\#\ of\ plots\ in\ which\ Spp_x\ occurs}\right)100$$

Species frequency, Shannon-Wiener diversity, and Shannon-Wiener evenness were also calculated within sites. Shannon's diversity was based on cover by species and calculated with the following formula:

$$H' = -\sum_{i=1}^{S} P_i \ln P_i$$

where S is the number of recorded species (i.e., species richness), P_i is the proportion of individuals in the *i*th species, and ln is the natural logarithm (Magurran, 2004). Shannon's diversity assumes all species are randomly sampled within a study area and incorporates species richness and evenness (Magurran, 2004).

Shannon's evenness was calculated with the following formula:

$$J' = \frac{H'}{H'_{Max}}$$

where H' is Shannon's diversity and H'_{Max} is the natural logarithm of S (i.e., species richness). Since at maximum diversity (H'_{Max}) species have equal abundances, Shannon's evenness calculates the ratio of observed diversity to maximum (Magurran, 2004).

To assess tree density post-browse after treetops had been browsed, double-sampling was done to create a model for predicting juniper height up to 200 cm from trunk basal diameter. The model excluded ERC > 200 cm tall since tree top browsing was not usually observed above that height. The relationship was determined with simple linear regression and the model was validated with mean squared prediction error (MSPE) compared to mean square error (MSE) (Table 3-4) as described in Misar et al. (2016). Use of this formula for trees > 200 cm tall is considered extrapolation and is not recommended.

Results

Juniper Height and Goat Browsing

Defoliation ($r(811) = .62$) and debarking ($r(811) = .54$) occurrences were moderately correlated ($p < .001$) with juniper height (Figures 3-2, 3). For every cm of tree height, defoliation should decrease by 0.28% and debarking should increase by 0.12% (Figure 3-2, 3).

Trunk gridling was most frequent on ERC 151-200 cm on Site D (Table 3-5). Defoliation by volume reduction (%) was highest on trees < 100 cm tall on all sites on which the variable was measured (A, B, C 2021; D, E 2022 (Table 3-6). Where signficance was found between treatment heights (A, B 2021; A, D 2022), a greater percentage of the trunk was debarked on trees > 100 cm tall (Table 3-6). The percentage of branches browsed (i.e., defoliation and/or debarking) and branches girdled (i.e., complete branch girdling) was also higher on trees < 100 cm tall for signficance sites (A, C 2021 and D 2022) (Table 3-6). It is recommended that branch girdling be used over branch browse to quantify goat damage leading to mortality since branch browse is too broad, encompassing any amount of defoliation and/or debarking while branch girdling measures only the proportion of branches receiving complete girdling at the base of the branch. Means, standard error, and significance are reported in Table 3-6.

Vegetation Composition

It was observed that Sites A and D had moderate ERC cover and few decideous shrubs while Sites B, C, and E were under dense ERC canopy with high frequencies of planted chokecherry and Russian olive incidental decideous browse, aforementioned in the Site Description, which goats may prioritize over coniferous browse. Categorization by ecological similarities and differences can help illustrate the impact of ERC height and background browse on goat browsing impact.

Herd daily dry mater intake (DMI) was estimated as 3% body weight (BW) for a four-day trial (herd size · 0.03 · BW · 4 days), and estimated percent of intake derived from biomass ([intake for herd/ herbaceous biomass removed] · 100) (Table 3-7). For most sites, biomass disappearance did not meet estimated maintenance DMI requirements (Sites A, B, and C 2021, A, B, and E 2022) (Table 3-7) and may be an indication the goats consumed browse (i.e., coniferous or deciduous), which was not measured in herbaceous biomass clippings. No goat weight loss was observed. Due to smaller paddock size as a result of site constraints, Site E paddocks (0.038 ha) were grazed more heavily than desired, and goats began testing the fences. Therefore, this stocking rate is not recommended. Biomass disappearance exceeded expected intake (Sites C and D 2022) (Table 3-7), on more open, less juniper-dense sites suggesting that without as much browse, goats spent more time than expected grazing, but this cannot be confirmed without observational grazing data collection like that of Utsumi et al. (2010). Site C had the lowest juniper density and Site D was the only site without deciduous browse (Table 3-9).

Biomass clipped UC, CE, and G locations within each paddock pre- and post-browse were compared using one-way ANOVA and LSD with the exception of Site D, which was clipped at G locations only due to a lack of canopy cover to take UC and CE. Both methods allow for an amount of error that could help explain some biomass intake variability. There was no significant difference ($P > 0.05$) between biomass weight reductions for any 2021 site (Table 3-8). In 2021 on Site A, pre-browse G biomass (g) was greater ($P = 0.006$) than CE and UC, and post-browse G biomass weight was higher ($P = 0.028$) than UC (Table 3-8). Site A 2021 mean biomass removal was 70.31 ± 2.4% across locations. In 2022, mean biomass removal was 66.24 ± 7.0%, and no biomass differences were found pre- or post- browse or in biomass removal between locations (P = 0.11, 0.09, 0.62 for UC, CE, and G, respectively) on Site A (Table 3-8).

In 2021, Site B pre-browse biomass locations were all different with G being greatest and UC least ($P < 0.001$) (Table 3-8). Post-browse biomass showed that G and CE were greater ($P = 0.001$) than UC (Table 3-8), and mean biomass removal was 44.45 ± 2.8% across locations. Similarly, in 2022 Site B mean biomass removal was 60.96 ± 9.7%, and G and CE were greater ($P = 0.003$) than UC pre-browse, but not post-browse ($P = 0.09$) (Table 3-8). Biomass removal was greater ($P = 0.003$) in G and CE locations than UC (Table 3-8).

On Site C, 2021 pre-browse G biomass was greater ($P = 0.012$) than UC, but post-browse biomass showed no significant difference ($P = 0.262$) between the three locations (Table 3-8). Site C 2021 mean biomass removal was 72.43 ± 1.7% across locations. In 2022, G biomass was greater ($P = 0.03$) than UC pre-browse while post-browse biomass and biomass removal not different (P = 0.13, 0.85) between locations (Table 3-8). Mean biomass removal was 58.30 ± 4.8%.

Site D mean biomass removal was 76.27 ± 1.6%, and locations could not be compared since canopy cover was sparse; thus, only the G location was sampled (Table 3-8). Site E mean biomass removal was 64.15 ± 4.5%. Pre- and post-browse G biomass were greater (P = 0.015, 0.004) than UC, and biomass removal was not different between locations ($P = 0.35$) (Table 3-8).

Mean juniper density ranged 67.25 - 187.72 trees per paddock with a majority being > 100 cm tall on all sites except Site E (Table 3-9). Mean juniper height was measured on Sites A, B, and C and ranged 156.52-197.67 cm tall (Table 3-9). Stocking rates (animal units [AU] per area per unit time) were reached based on average animal weight rather than AU equivalents (i.e., six goats per AU) was variable ranging 97.34-124.00 animal unit days (AUD) per ha on Sites A, B, and C in 2021 and 102.86-157.89 AUD per ha on all sites in 2022 (Table 3-9). Perhaps most telling, however is stocking rate as a ratio of goats per tree. This stocking, which is heavily dependent on paddock juniper density, ranged widely from 0.78-3.26 goats per tree on Sites A, B, and C in 2021 to 0.69-1.98 on all sites in 2022 (Table 3-9). While in-depth research is still needed, when browsing under this study design, goats appeared to browse the most juniper at rates above one goat per tree when little deciduous browse is present. Stocking density (animal weight per unit area) was lower in 2021 at 44,169-52,962 kg per ha on Sites A, B, and C than all sites in 2022 at 48,600-71,621 kg per ha (Table 3-9). Means and standard error of these parameters are displayed individually in Table 3-9.

Herbaceous forage species diversity (H'), evenness (J'), cover (%), and frequency (%) are presented for descriptive purposes in Tables A-2, 3, 4, 5, and 6. Foliage and bark samples were analyzed with GC-MS and revealed that PSM pinene compounds [(1S) (-) α Pinene and (-) β Pinene] appear to be higher in bark than foliage in shorter trees decreasing with increasing height while pinene compounds stayed relatively steady in foliage (Table A-7). Additionally, (-) Limonene was found in foliage but not in bark samples (Table A-7).

Juniper Mortality

Regression was conducted to show the possible relationship between defoliation and debarking with mortality; however, sites performed very differently, so it is difficult to find a conclusive mortality threshold (Figures 3-4, 5, 6 ,7, 8, and 9). Site A and C mortality were correlated with defoliation and Site A only with debarking while Site B had no significant relationships, presumably due to heavy incidental deciduous browse and high ERC density. Results from Site A showed that a 1% increase in defoliation or debarking may lead to a 0.23% and 0.68% increase, respectively, in mortality ($r(155) = .37, .81, p < .001$) (Figures 3-4, 5). Conversely, on Site C data suggests that a 1% increase in defoliation may lead to a 0.60% increase in mortality ($r(152) = .57, p < .001$) (Figure 3-8). It is not likely that defoliation alone increases mortality as Site C suggests, and many short ERC were observed dead outside of browsing paddock indicating that Site C may have experienced disease or other external factors.

Data showed that the relationship between juniper height and mortality of Sites A ($r(155) = .72$; $p < .001$) and C ($r(151) = .63$; $p < .001$) were moderately correlated with a 1 cm increase in juniper height leading to a 0.26% and -0.40% change in foliage browning, respectively, (Figures 3-10, 11). This supports that Site C may have experienced external factors since its shorter trees were defoliated similarly to Site A (Table 3-6). Site B did not show a relationship between juniper height and foliage browning (Figure 3-12)

Eastern redcedar 151-250 cm had more ($P = 0.003$) browned foliage and higher ($P = 0.01$) relative whole tree death occurrences than shorter, 51-100 cm trees on Site A

(Table 3-10) with a site average foliage browning of 33.20% and 42 (tagged) trees dead. No differences were found in tree mortality or foliage browning on Site B (Table 3-10), and the site average foliage browning was 7.81% with 13 (tagged) trees killed. Trees < 50 cm on Site C had more browned foliage and higher relative whole tree death occurrence than taller height classes ($P < 0.001$) (Table 3-10). Site C average foliage browning was 38.09% with 45 (tagged) trees killed.

Discussion

Juniper Height and Goat Browsing

These data support that goats tend to defoliate short (< 100 cm) juniper and debark tall (> 100 cm) juniper, which has been shown by previous research (Estell et al., 2014; Lovreglio et al., 2014; Mellado et al., 2003; Treadwell et al., 2021; Utsumi et al., 2010), but are contradictory to management recommendations (Lyons et al., 2009; Twidwell et al., 2021) that targeted browsing with goats should be used on short, immature saplings for their defoliation browsing. Previous research of branch debarking showed positive correlations to branch death (Estell et al., 2018; Utsumi et al., 2010), but in the interest of juniper removal, we support connections between trunk debark girdling and tree death (Purohit et al., 2001; Utsumi et al., 2010). Since debarking as it is more related to tree death, we recommend that targeted browsing with goats should be applied to ERC juniper 100-250 cm tall. Future research should first quantify debarking needed to achieve tree death of different juniper species and the associated stocking rates, with consideration to available background forage, before integrated management can be properly assessed (Utsumi et al., 2010).

Vegetation Composition

Individual site characteristics are undoubtably the most ambiguous factors and the most difficult to control, therefore, it is important that future browsing and grazing studies include vegetative sampling and note environmental characteristics. Beginning with herbaceous forage, biomass clipping from 2021 trials showed no differences in biomass disappearance between UC, CE, and G sampling locations suggesting that goats do not discriminate between grazing under ERC canopy and open grassland. Biomass quantification is important for monitoring vegetative production and relative utilization when assessing goat application sites pre- and post-browse, thus, background herbaceous vegetation seasonality was a prominent factor in these studies (Treadwell et al., 2021). With that in mind, consideration should be given to deciduous browse present on a site. The combination of non-juniper forage and browse will likely drive herbivore behavior (Utsumi et al., 2010).

Since less forage was removed than anticipated daily intake (3% BW) on Sites A (2021, 2022), B (2021, 2022), C (2021) and E (2022), ERC was conclusively included in the diet at a notable rate. Heavy dietary ERC inclusion supports the assertions of Walker (1994) that when given access to diverse pasture, goats become highly selective and comprise their diet of 30, 10, and 60% grass, forbs, and woody shrubs, respectively. Future studies should include grazing observation scans similar to Shaw et al. (2006) and Utsumi et al. (2010) to confirm juniper browsing activity. Multispecies browsing of goats with cattle can increase carrying capacity of ERC-invaded rangeland by expanding forage use to include woody plants contributing to grass decreases (Hintze et al., 2021). Multispecies browsing can yield a 20% increase in ranch carrying capacity and a 17% reduction in per animal fixed costs, presuming no capital improvements to include the additional species (Walker, 1994). It is well established that juniper browsing is a learned behavior, either through herd mates or preconditioning, so a herd's previous experience should not be overlooked when implementing juniper targeted browsing with goats (Bisson et al., 2001; Dietz et al., 2010; Estell, 2010; Iason, 2005; Miller and Scott, 2021; Provenza, 1995; Provenza et al., 2007, 2003; Shaw et al., 2006; Treadwell et al., 2021; Villalba et al., 2004).

Site A performed most closely to hypotheses and showed the best debarking response suggesting that more investigation should be done to the combination of goat stocking rate (goats per tree) and the amount of deciduous browse on a browsing site. Campbell et al. (2007) identified the goats per tree ratio stocking as a "critical element" in managing juniper with goats. Site B may have been more lowly affected by browsing (i.e., defoliation, debarking, girdling) likely due to three primary factors: juniper density, goat stocking rate, and herbaceous biomass production. High juniper density is important to targeted browsing as it lowers the goat:tree ratio thus lowering the likelihood that a given tree will be browsed heavily, if at all. From Utsumi et al. (2010), it is known that increasing this ratio with higher numbers in goat-only herds decreases the suppressive impact of background herbaceous vegetation on browsing and stimulates diet mixing. Thus, stocking rate determination based on factors like juniper density and site forage, outlined by Treadwell et al. (2021), should be a research priority. Furthermore, this research establishes that ERC PSM vary by juniper height and between foliage and bark, supporting Utsumi et al. (2010, 2006) that heavy stocking can help equalize browsing distribution and that chemical defenses vary across a site. Finally, Site C provided contradictory data with excessive mortality of short ERC, including ERC outside of the browsing paddock indicating possible disease or impact from browsing wildlife as deer bedding sites were observed on Site C. Relative occurrence of whole tree death ([dead trees/total trees] • 100) averaged 33.20%, 7.81%, and 38.09% of ERC trees in Sites A, B, and C, respectively compared to 5% one-seed juniper mortality ([dead trees/total tress] • 100) found by Utsumi et al. (2010) under heavily stocked (1.1 AU/0.01 ha/day) goat browsing.

Based on this knowledge, the authors suggest that successful targeted browsing with goats should be planned as a prescription for the site dependent on site forage (particularly deciduous browse), site juniper (i.e., height and density), and goat herd constraints. This is supported by the relative ecological similarities between Sites A & D (i.e., open canopies, lower juniper density, marginal deciduous browse) and Sites B, C, and E (i.e., dense canopies with heavy juniper numbers, thick deciduous browse) and their similar ERC mortality performance.

Biological Juniper Control

Treadwell et al. (2021) outlines stocking and herd planning for targeted browsing with goats and highlights the importance of juniper density because heavy canopy will lower forage production (juniper content in the diet should not be forced to exceed 60% for extended periods). Furthermore, Bidwell et al. (2008) advises that juniper control must take a multifaceted approach of natural ecological processes (i.e., prescribed fire) and human made (i.e., mechanical). Targeted browsing with goats in particular deserves consideration as an ERC management tool to control taller (100-250 cm) ERC saplings through debarking when applied at a high stocking rate on sites with little deciduous browse during the season when ERC plant secondary metabolites are least potent. Estell et al. (2014) supports that PSM are higher in foliage than in bark, and also found an inverse relationship between herbivory and terpenoid concentration in short juniper. Similarly, Utsumi et al. (2010) found that debarking was greatest on one-seed juniper in the spring because PSM was higher in the leaves. Besides season, GC-MS analysis of ERC foliage and bark of varying tree heights supports Setzer et al. (1992) that individual trees and sites also vary greatly. Setzer's samples were comprised mainly of safrole and methyl eugenol while these studies found the main components to be (1S) (-) α Pinene and (-) β Pinene. Little research has been conducted on juniper bark PSM.

Study observations support Rollins & Armstrong (1994) who note that heavy stocking will cause vegetation to be consumed before juniper, so strategic timing and stocking could minimize goat damage on desirable species. Furthermore, Mellado et al. (2003) warns managers that prolonged high density browsing of toxic browse reduces grass and shrub cover while pushing animals to a lower nutritional plane.

While these studies reflect the reality of variable juniper age structure and site characteristics, they do possess limitations. The field studies lack adaptation periods, although no significant differences were noted between earlier and later-browsed paddocks, and these data are largely reliant on juniper height as a predictor of age (and therefore, PSM content), but it should be noted that this measure is variable and dependent on environmental factors (e.g., precipitation). Due to the exploratory nature of this research, sites varied greatly, making comparisons difficult but providing a broad assessment of relevant characteristics (e.g., forage production, juniper density, juniper canopy cover, and deciduous browse). Deciduous browse should be quantified and considered an important factor drying goat herbivory. Finally, steps should be taken in site selection to observe browsing wildlife (e.g., deer) use and disease presence.

Unlike mechanical and chemical ERC control, targeted browsing with goats is more sustainable as it yields outputs (e.g., meat, milk, feeder kids) instead of consuming inputs alone. Introducing breeding goats can help offset some of the costs of controlling woody species while diversifying an operation, often a recommended risk-management tool (Hintze et al., 2021). Furthermore, multi-species grazing of goats with cattle or sheep has been explored (Animut et al., 2004; Hintze et al., 2021; Utsumi et al., 2010) with success as grass-roughage eaters will compete with goats for incidental forage encouraging goats to browse. However, careful parasite management should be implemented when co-grazing goats, sheep, and/or cattle rotations. It could be argued that pyric control also contributes non-financial outputs in terms of nutrient cycling and plant community diversity promotion (O'Connor et al., 2020). Furthermore, levels of PSM were lower in juniper regrowth after fire than 11 months later in redberry and also in juvenile one-seed juniper (Campbell et al., 2007; Estell et al., 2014), contradicting the general theory that PSM levels are highest in growing tissue. On the other hand, targeted browsing's preference towards damage to taller trees could help prepare a site for prescribed burning. Targeted browsing may extend the effectiveness of other management options such as fire (O'Connor et al., 2020; Utsumi et al., 2010) and Hintze et al. (2021) found that integration of a goat breeding operation with prescribed patch-burning had a mean net present value of $16,000 more than traditional grazing management. Additional costs of targeted browsing with goats can include the herd (if breeding, purchase one buck for every 35 does), veterinary care (vaccinations may cost

$2 per head per year), feed, labor (if breeding, estimated 3 hours per head per year), and a livestock guardian dog (LGD) (purchase price may be $1,000 with $500 in yearly maintenance) to minimize losses (Hintze et al., 2021). Llamas and donkeys can also guard herds (Launchbaugh, 2006). Goat reproduction rates range 130-180%, thus a sustaining number of kids can be retained as herd replacements or sold providing additional income (Hintze et al., 2021). Equipment that may be needed for targeted browsing goats could include a truck and trailer, portable electric net fencing, a fencer (≥ 5,000 V for goats, ≥ 3,000 V for sheep), step-in posts, water and mineral troughs, a water source, and a pruner and/or saw to clear fence lines (Launchbaugh, 2006). Goats should have access to shade on hot days, and if an LGD is used, consideration should be given to the type of predators on site and nearby human activity or busy roads. To minimize predator attacks, keep animals on small open hills away from creeks (Launchbaugh, 2006). Grazing sites should move at least every three days to avoid overgrazing. Overgrazing is often mistaken for removing a majority of the biomass from a site but is more accurately defined as an issue of grazing timing, depleting plant resources by re-grazing plants in regrowth (compensatory growth) (Bailey et al., 2019). Future studies should build on this strong foundation and explore integrated management, particularly browsing and prescribed burning.

Winter targeted browsing is a topic of exploration since PSM levels may be lower. In a pen study, Utsumi et al. (2009) found that one-seed juniper intake was highest on winter juniper for goats supplemented with rumen undegraded protein (RUP) ($P < 0.05$) when PSM levels were intermediate but also noted that intake is variable with protein supplementation and previous juniper experience. Riddle et al. (1996) compared

Angora and Spanish-type goat redberry and ashe juniper intake and found that Spanish consumed more ($P < 0.05$) juniper than Angora except in the winter when intake was similar between breeds ($P \geq 0.05$) indicating that PSM are lower in the winter. Finally, George et al. (2010) explains that winter browsing is often effective because preferred deciduous browse is dormant, but RUP supplementation is recommended to offset PSM-protein binding intake depression and to maintain body condition.

Implications

Eastern redcedar encroachment must be managed, or it will progress until the land loses profitability (Treadwell et al., 2021), and current targeted browsing guidelines recommend applying goats to defoliate short, immature saplings (Twidwell et al., 2021). However, our ERC studies suggest that since taller juniper are more likely to be debarked than shorter juniper, and that debarking is highly correlated with juniper mortality, targeted browsing with goats may be most effective for killing juniper when applied to debark tall (100-250 cm) juniper. Since burning mortality is inversely related to height (Ortmann et al., 1998), and goat browsing juniper mortality is directly related to height, moderate stocking (one goat per juniper) with goats could be effectively paired with prescribed burning. These findings add greater weight to the benefits of including goats in multi-species browsing to increase carrying capacity on woody-encroached rangelands since targeted browsing could be most effective if the forage background effect, particularly deciduous browse, could be suppressed by grazers. Diversifying with breeding goats produces salable outputs, potentially increasing ranch resiliency and profitability while restoring plant communities. Thus, this management style has implications for alleviating the land-social poverty cycle. This comprehensive assessment of nearly every relevant angle of the complex system of targeted browsing gives land and livestock managers a clearer understanding and practical tools to implement targeted browsing with goats for juniper control, which is unfolding in strong impact implications for the sustainability of global grasslands and livestock agriculture.

TABLES

Table 3-1 Goat browsing site grazing periods, paddocks, and paddock size to study biological eastern redcedar control in south-central South Dakota, USA.

Site	2021 Browsing Period	2022 Browsing Period	Paddocks	Days per Paddock	Paddock Size (m^2)
A	June 14-17	June 5-8	4	1	30x18
B	July 26-30	July 10-13	4	1	30x18
C	October 7-10	July 22-25	4	1	30x18
D	-	June 9-12	4	1	30x18
E	-	June 13-16	4	1	21x18

Table 3-2 Goat browsing data collected 2021-2022 on five sites to study browsing impact and how site-specific characteristics influence the efficacy of eastern redcedar targeted browsing with goats in southeast Gregory County, South Dakota, USA. Sites A, B, and C were browsed June, July, and October, respectively, in 2021, and Sites A, B, C, D, and E were browsed June, July, July, June, and June, respectively, in 2022. Tagged trees exclude dead or missing trees. An “x” indicates that the variable was collected and “-“ indicates that the variable was not collected.

2021			
Data Collected	A	B	C
Defoliation (%)	x	x	x
Debarking (%)	x	x	x
Branches Browsed (%)	x	x	x
Herbaceous Biomass pre- and post-browse (g/0.25 m^2)	x	x	x
Tagged Trees	159	181	154

2022					
Data Collected	A	B	C	D	E
Defoliation (%)	-	-	-	x	x
Debarking (%)	x	x	x	x	x
Branches Girdled (%)	-	x	x	x	x
Trunk Girdling (Yes/No)	x	x	x	x	x
Foliage Browning (%)	x	x	x	-	-
Herbaceous Biomass pre- and post-browse (g/0.25 m^2)	x	x	x	x	x
Tagged Trees	112	165	103	150	174

Table 3-3 Eastern redcedar (ERC) estimated actual canopy cover proportions (%) to adjust biomass location means for actual herbaceous biomass as a factor for targeted browsing with goats. Samples were taken under 100% ERC canopy (UC), at 50% canopy edge cover (CE), and 0% ERC cover open grassland (G) for all sites except Site D where there was not sufficient UC and CE to sample. Sites A, B, and C were browsed June, July, and October, respectively, in 2021, and Sites A, B, C, D, and E were browsed June, July, July, June, and June, respectively, in 2022.

	Actual Sample Location Proportion (%)		
Site	UC	CE	G
A	40	10	50
B	50	10	40
C	10	10	80
D	0	10	10
E	40	10	50

Table 3-4 Eastern redcedar height (cm) prediction by basal trunk diameter (mm) model regression validation statistics. A dataset (*n* = 382) was split evenly into a prediction model (where “x” is basal trunk diameter and “y” is actual juniper height) and a validation model (where “x” is the predicted juniper height and “y” is the actual juniper height).

Item	Prediction Model	Validation Model
	Actual Height (cm) to Basal Diameter (mm)	Predicted Height (cm) to Basal Diameter (mm)
Mean Square Error (MSE)	287.55	393.48
Mean Square Prediction Error (MSPE)	1.51	2.06
Equation	$y = -0.08x^2 + 7.57x + 1.45$ $R^2 = 0.91$, $n = 191$, $P < 0.05$	$y = 0.003x^2 + 0.25x + 25.30$ $R^2 = 0.985 n = 191$, $P = < 0.05$

Table 3-5 Comparison of eastern redcedar trunk girdling relative frequency by goats below the lowest branch for Sites A, C, D, and E browsed June, July, June, and June 2022, respectively. Site B (browsed July) did not have sufficient trunk girdling observations. Analysis is ANOVA[1] or Kruskal-Wallis[2] tests. Values are means ± SE and same superscripts (a-b) do not differ significantly (*P* > 0.05).

Trunk Girdled	Height Class (cm)					
	< 50	51-100	101-150	151-200	200-250	*P*-value
			Site A[2]			
N (%[3])	0 (0.00[a])	0 (0.00[a])	0 (0.00[a])	2 (12.50[a])	1 (2.78[a])	0.53
			Site C[2]			
N (%[3])	0 (0.00[a])	0 (0.00[a])	0 (0.00[a])	2 (5.00[a])	1 (3.13[a])	0.53
			Site D[1]			
N (%[3])	0 (0.00[a])	4 (10.00[a])	7 (20.83[a])	13 (60.00[b])	1 (5.00[a])	< 0.001
			Site E[1]			
N (%[3])	0 (0.00[a])	0 (0.00[a])	2 (5.00[a])	1 (2.5 [a])	2 (5.63[a])	0.52

[3]Relative percentage (girdled trees / total trees) *100

Table 3-6 Goat defoliation, debarking, branch browsing, and branch girdling of eastern redcedar of five height classes (< 50, 51-100, 101-150, 151-200, 201-250 cm) 2021-2022. Defoliation is volume reduction from pre- to post-browse (%), debarking is trunk surface area (ocular estimation) debarked (%), branches browsed is branches with defoliation and/or debarking below the browse line (%), branches girdled is branches with complete girdling (circumference bark removal) out of all branches below the browse line (%). Sites A, B, and C were browsed June, July, and October, respectively, in 2021, and Sites A, B, C, D, and E were browsed June, July, July, June, and June, respectively, in 2022. Statistics are ANOVA[1] or Kruskal-Wallis[2] tests. Values are means ± SE and same superscripts (a-c) do not differ significantly (*P* > 0.05) for a given site and year.

	2021		
	Browsing		
Height class (cm)	Defoliation (%)	Debarking (%)	Branches Browsed (%)
	----------Site A[1]----------		
< 50	73.21 ± 5.7[a]	0.13 ± 0.1[a]	75.35 ± 3.7[ab]
50-100	70.90 ± 4.4[a]	0.18 ± 0.2[a]	84.60 ± 5.5[a]
101-150	44.63 ± 6.7[b]	10.65 ± 7.4[b]	75.89 ± 6.6[ab]
151-200	22.09 ± 6.4[bc]	61.54 ± 9.9[b]	69.25 ± 5.4[ab]
201-250	17.34 ± 3.2[c]	70.88 ± 12.0[b]	53.63 ± 6.3[b]
P-value	< 0.001	< 0.001	< 0.001
	----------Site B[1]----------		
< 50	57.23 ± 2.5[a]	0 ± 0.0[a]	28.43 ± 4.3[a]
50-100	37.06 ± 5.7[b]	0 ± 0.0[a]	39.00 ± 12.9[a]
101-150	13.91 ± 0.8[c]	2.40 ± 2.4[ab]	50.62 ± 13.4[a]
151-200	9.00 ± 3.7[c]	2.57 ± 1.5[ab]	46.79 ± 14.4[a]
201-250	13.70 ± 2.7[c]	10.80 ± 3.7[b]	33.45 ± 10.6[a]
P-value	< 0.001	< 0.001	0.66
	----------Site C[1]----------		
< 50	74.54 ± 4.3[a]	0 ± 0.0[a]	64.81 ± 6.1[a]
50-100	84.77 ± 1.9[a]	0 ± 0.0[a]	83.13 ± 4.4[a]
101-150	27.68 ± 5.6[b]	2.35 ± 2.2[a]	48.78 ± 11.3[ab]

151-200	6.60 ± 3.3[c]	10.65 ± 3.3[a]	24.00 ± 8.3[b]
201-250	3.80 ± 3.8[c]	11.24 ± 4.1[a]	21.37 ± 5.4[b]
P-value	< 0.001	0.05	< 0.001

2022

Height class (cm)	Browsing	
	Debarking (%)	Branches Girdled (%)
	---Site A[1]---	
< 50	0.00 ± 0.0[a]	No Data
50-100	3.33 ± 3.2[a]	
101-150	36.49 ± 5.2[b]	
151-200	19.88 ± 11.5[ab]	
201-250	4.86 ± 3.1[a]	
P-value	0.003	
	---Site B[2]---	
< 50	0.00 ± 0.0[a]	0.00 ± 0.0[a]
50-100	0.16 ± 0.16[a]	0.67 ± 0.67[a]
101-150	2.55 ± 2.55[a]	1.13 ± 1.13[a]
151-200	0.00 ± 0.0[a]	0.00 ± 0.0[a]
201-250	0.00 ± 0.0[a]	0.00 ± 0.0[a]
P-value	0.53	0.53
	---Site C[1]---	
< 50	0.00 ± 0.0[a]	0.00 ± 0.0[a]
50-100	2.11 ± 1.2[a]	0.00 ± 0.0[a]
101-150	1.94 ± 1.9[a]	0.72 ± 0.7[a]
151-200	12.09 ± 7.0[a]	3.06 ± 1.8[a]
201-250	5.73 ± 4.9[a]	7.26 ± 4.7[a]
P-value	0.30	0.15

2022

Height class (cm)	Browsing		
	Defoliation (%)	Debarking (%)	Branches Girdled (%)
	---Site D[1]---		
< 50	63.68 ± 4.6[a]	0.00 ± 0.0[a]	0.00 ± 0.00[a]
50-100	42.38 ± 4.4[b]	11.20 ± 4.3[ab]	6.85 ± 3.2[a]
101-150	31.95 ± 3.7[bc]	40.06 ± 3.0[abc]	22.04 ± 0.8[ab]
151-200	25.23 ± 5.5[bc]	58.95 ± 9.9[ac]	40.42 ± 9.3[b]
201-250	18.28 ± 0.3[c]	72.71 ± 20.6[c]	24.07 ± 9.4[ab]
P-value	< 0.001	< 0.001	< 0.001
	---Site E[1]---		
< 50	53.50 ± 9.7[a]	0.00 ± 0.0[a]	0.00 ± 0.0[a]
50-100	52.28 ± 6.3[a]	0.03 ± 0.0[a]	0.00 ± 0.0[a]
101-150	37.3 ± 5.5[ab]	5.32 ± 3.5[a]	1.4 ± 1.4[a]
151-200	28.07 ± 8.3[ab]	9.23 ± 4.5[a]	3.1 ± 2.0[a]
201-250	14.66 ± 3.7[b]	9.23 ± 4.5[a]	1.71 ± 0.6[a]
P-value	< 0.001	0.30	0.30

Table 3-7 Goat targeted browsing for eastern redcedar control dry matter intake (DMI) estimated as 3% body weight (BW) and site herbaceous biomass disappearance. Sites A, B, and C were browsed June, July, and October, respectively, in 2021, and Sites A, B, C, D, and E were browsed June, July, July, June, and June, respectively, in 2022. Values are means (± SE).

2021

	Site		
Factor	A	B	C
Herbaceous biomass disappearance (kg · 0.056 ha^{-1})	70.82 ± 16.5	46.11 ± 11.2	63.04 ± 16.8
Herd size	109	79	98
Mean goat BW (kg)	27.21	31.31	32.21
Estimated DMI for herd per day (kg)	88.98	74.20	94.70
Estimated DMI from biomass (%)	79.89	62.41	66.57

2022

	Site		
Factor	A	B	C
Herbaceous biomass disappearance (kg · 0.056 ha^{-1})	49.90 ± 7.4	51.90 ± 11.5	99.85 ± 25.4
Herd size	96	95	95
Mean goat BW (kg)	28.35	31.00	31.00
Estimated DMI for herd per day (kg)	81.65	88.35	88.35
Estimated DMI from biomass (%)	61.11	58.74	113.02

2022

	Site	
Factor	D	E[1]
Herbaceous biomass disappearance (kg · 0.056 ha^{-1})	101.27 ± 5.1	25.74 ± 5.6
Herd size	96	96
Mean goat BW (kg)	28.35	28.35
Estimated DMI for herd per day (kg)	81.65	81.65
Estimated DMI from biomass (%)	124.03	31.5

[1]Site E paddocks were 0.038 ha due to land constraints

Table 3-8 Herbaceous biomass (kg·ha^{-1}) dry weights (adjusted proportionally by canopy cover, refer to Table 3-4) from 0.25 m^2 quadrats clipped in triplicate at three locations for each of four replicate paddocks per blocked site in relation to eastern redcedar (ERC) to account for encroachment biomass loss: under 100% ERC canopy (UC), at 50% canopy edge (CE), and 0% ERC open grassland (G). Samples were pooled by location within paddocks and analysis consisted of one-way analysis of variance. Values are means ± SE and same lettered superscripts (a-c) do not differ significantly (ANOVA; P > 0.05) for a given site and year.

			2021				*P*-value		
Site	Month	Location	Pre-Browse (kg·ha^{-1})	Post-Browse (kg·ha^{-1})	Difference (kg·ha^{-1})	Difference (%)	Pre-Browse	Post-Browse	Difference
A	June	UC	211.48 ± 131.6^a	43.64 ± 16.5^a		67.25 ± 10.8^a	< 0.001	0.01	0.47
		CE	128.08 ± 32.7^a	39.88 ± 9.1^a		63.05 ± 9.1^a			
		G	1159.93 ± 247.6^b	151.33 ± 29.8^b	**1264.64 ± 294.43**	80.63 ± 10.4^a			
		Total	**1499.49 ± 330.9**	**234.85 ± 36.5**					
B	July	UC	215.77 ± 19.1^a	126.43 ± 26.8^a		38.07 ± 16.7^a	< 0.001	< 0.001	0.58
		CE	148.03 ± 23.0^a	86.36 ± 16.4^a		40.32 ± 11.0^a			
		G	1205.65 ± 91.8^b	533.24 ± 59.9^b	**823.42 ± 199.1**	54.97 ± 5.6^a			
		Total	**1569.45 ± 341.8**	**746.03 ± 142.8**					
C	October	UC	89.43 ± 21.1^a	23.23 ± 4.1^a		71.45 ± 6.2^a	< 0.001	< 0.001	0.94
		CE	114.78 ± 5.4^a	29.27 ± 6.4^a		74.58 ± 5.1^a			
		G	1333.57 ± 98.2^b	359.49 ± 108.1^b	**1125.80 ± 299.5**	71.26 ± 10.8^a			
		Total	**1537.79 ± 410.6**	**411.99 ± 111.1**					

Site	Month	Location	2022 Pre-Browse (kg·ha^{-1})	Post-Browse (kg·ha^{-1})	Difference (kg·ha^{-1})	Difference (%)	*P*-value Pre-Browse	Post-Browse	Difference
			2022						
		UC	331.64 ± 85.2^{a}	103.12 ± 21.2^{a}		56.06 ± 17.0^{a}			
A	June	CE	136.83 ± 32.9^{a}	27.12 ± 8.7^{a}		73.56 ± 13.3^{a}	< 0.001	0.001	0.62
		G	811.23 ± 61.0^{b}	258.37 ± 50.1^{b}		69.09 ± 4.6^{a}			
		Total	**1279.71 ± 200.4**	**388.62 ± 68.0**	**891.09 ± 132.4**				
		UC	189.05 ± 60.7^{a}	128.90 ± 26.5^{ab}		22.58 ± 14.5^{a}			
B	July	CE	178.17 ± 35.3^{a}	27.12 ± 8.7^{a}		84.52 ± 4.6^{a}	< 0.001	0.005	< 0.001
		G	922.21 ± 137.2^{b}	206.70 ± 40.1^{b}		75.79 ± 6.8^{a}			
		Total	**1289.43 ± 246.2**	**362.72 ± 52.0**	**926.71 ± 205.0**				
		UC	194.22 ± 22.0^{a}	84.56 ± 23.8^{a}		57.74 ± 9.1^{a}			
C	July	CE	277.39 ± 26.4^{a}	105.58 ± 13.4^{a}		62.28 ± 1.4^{a}	< 0.001	< 0.001	0.85
		G	2691.32 ± 184.9^{b}	1189.72 ± 331.1^{b}	**1783 ± 454.0**	54.88 ± 12.7^{a}			
		Total	**3162.93 ± 818.9**	**1379.87 ± 364.9**					
D[1]	June	G **Total**	**2344.14 ± 96.7**	**535.83 ± 33.3**	**1808.31 ± 91.9**	-	-	-	-
		UC	240.07 ± 43.2^{a}	62.69 ± 4.3^{a}		71.15 ± 5.2^{a}			
E	June	CE	119.78 ± 16.5^{b}	37.07 ± 7.0^{a}		66.38 ± 8.3^{a}	< 0.001	< 0.001	0.35
		G	737.22 ± 107.6^{c}	320.01 ± 53.0^{b}		54.92 ± 8.9^{a}			
		Total	**1097.06 ± 189.0**	**419.77 ± 90.3**	**677.29 ± 100.0**				

[1]Site D juniper profile was not considered dense enough for canopy cover to have a significant impact on herbaceous biomass, so all samples were taken as open grassland

Table 3-9 Targeted browsing with goats for eastern redcedar (ERC) control site ERC density, stocking rate (animal unit day [AUD] and goats per tree), and stocking density. Browsing was applied daily (24 hours each) to four replicate 0.056 ha paddocks[1] per site. Sites A, B, and C were browsed June, July, and October, respectively, in 2021, and Sites A, B, C, D, and E were browsed June, July, July, June, and June, respectively, in 2022. Values are means (± SE).

	Site		
Browsing factor	A	B	C
ERC density (trees · paddock[1])	93.44 ± 16.9	187.72 ± 21.0	67.25 ± 10.5
Average ERC height (cm)	160.28 ± 18.2	197.672 ± 12.0	156.52 ± 22.2
ERC density < 100 cm tall (trees · paddock^{-1})	46.44 ± 16.6	43.25 ± 5.3	32.00 ± 7.9
ERC density > 100 cm tall (trees · paddock^{-1})	47.00 ± 3.6	144.25 ± 39.6	35.25 ± 8.1
2021 stocking rate (AUD · ha^{-1})	116.79	97.34	124.00
2021 stocking rate (goats · tree · paddock $^{-1}$)	2.36 ± 0.2	0.78 ± 0.3	3.26 ± 0.7
2021 stocking density (kg · ha^{-1})	52,962	44,169	56,368
2022 stocking rate (AUD · ha^{-1})	102.86	117.80	117.80
2022 stocking rate (goats · tree · paddock $^{-1}$)	0.95 ± 0.3	1.98 ± 0.2	1.39 ± 0.3
2022 stocking density (kg · ha^{-1})	48,600	52,589	52,589

	Site	
Browsing Factor	D	E[1]
ERC density (trees · paddock[1])	130.75 ± 68.1	163 ± 30.4
ERC density < 100 cm tall (trees · paddock^{-1})	37.25 ± 19.6	91.50 ± 23.0
ERC density > 100 cm tall (trees · paddock^{-1})	93.50 ± 48.8	71.50 ± 13.6
2022 stocking rate (AUD · ha)	102.86	157.89
2022 stocking rate (goats · tree · paddock $^{-1}$)	1.27 ± 0.4	0.69 ± 0.2
2022 stocking density (kg · ha^{-1})	48,600	71,621

[1]Site E paddocks measured 0.038 ha due to land constraints

Table 3-10 Eastern redcedar average foliage browning, and relative frequency of whole tree mortality compared at five height classes (< 50, 51-100, 101-150, 151-200, 201-250 cm) after 24 hours of targeted browsing with goats in June (A), July (B), and October (C) 2021. ANOVA or Kruskal Wallis (Site B only) tested the effect of height class on foliage browning. Values are means ± SE and same lettered superscripts (a-c) do not differ significantly (*P* > 0.05) for a given site.

	Height Class (cm)					
Variable	< 50	51-100	101-150	151-200	200-250	*P*-value
			Site A			
Foliage Browning (%)[1]	24.07 ± 8.0[ab]	4.20 ± 2.9[b]	18.77 ± 9.2[ab]	63.19 ± 16.9[a]	71.85 ± 14.8[a]	0.003
Dead Juniper [N (%[2])]	6 (23.81[ab])	1 (3.13[b])	4 (13.49[ab])	12 (56.94[a])	18 (50.95[ab])	0.01
			Site B			
Foliage Browning (%)[1]	15.97 ± 8.4[a]	7.31 ± 5.4[a]	2.53 ± 2.5[a]	4.62 ± 4.0[a]	5.64 ± 2.6[a]	0.338
Dead Juniper [N (%[2])]	6 (15.63[a])	2 (5.00[a])	1 (2.50[a])	1 (2.50[a])	2 (5.00[a])	0.405
			Site C			
Foliage Browning (%)[1]	91.42 ± 5.5[a]	49.06 ± 13.4[ab]	27.47 ± 14.8[b]	10.15 ± 4.8[b]	4.65 ± 2.4[b]	< 0.001
Dead Juniper [N (%[2])]	31 (81.94[a])	9 (32.14[b])	4 (20.00[b])	2 (5.00[b])	1 (2.78[b])	< 0.001

[1]Average percentage of individual tree foliage that turned brown in May 2022. Determined by ocular estimate 0-100%.
[2]Relative percentage (dead trees / total trees) *100

FIGURES

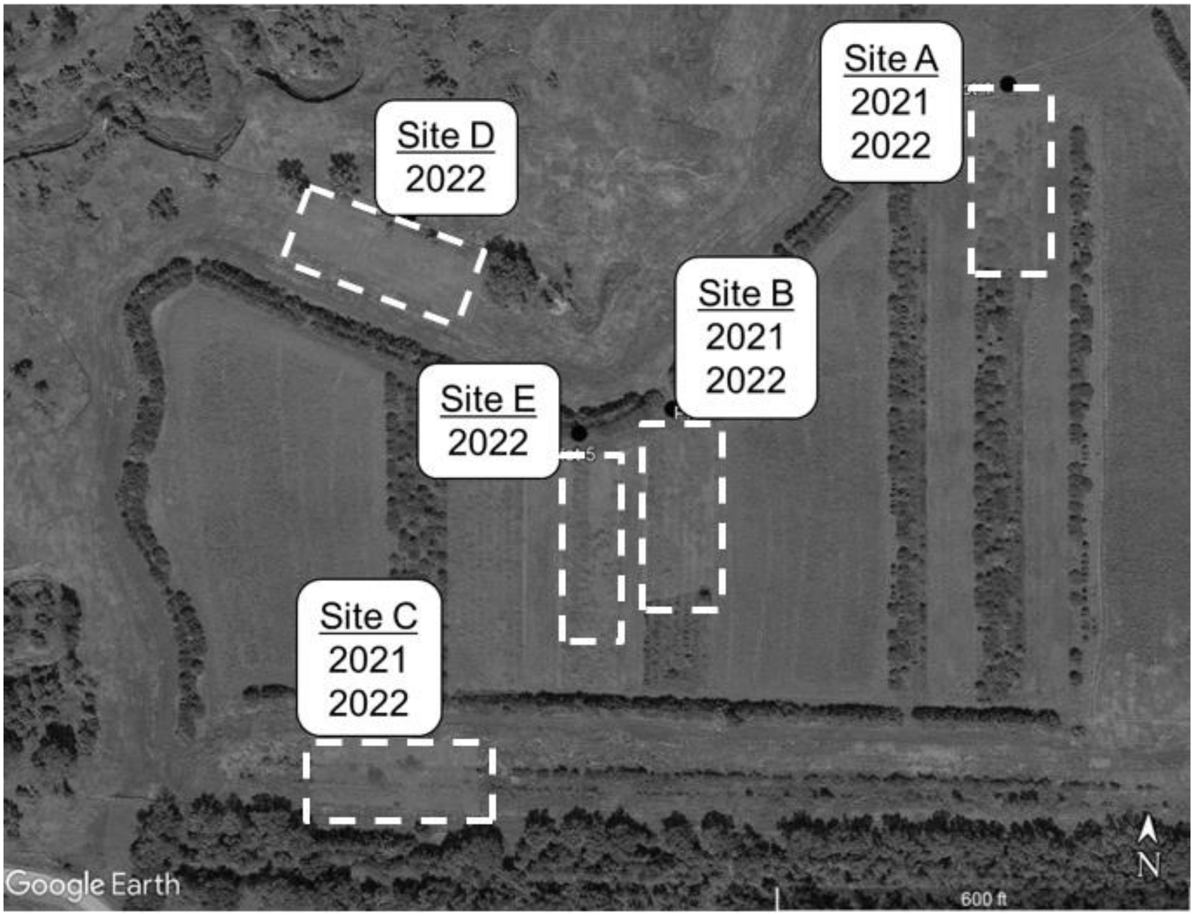

Figure 3-1 Eastern redcedar targeted browsing with goats site locations in southeast Gregory County, SD, USA (43°02’42” N, 98°33’12” W). Sites were browsed as follows: A (June 2021, 2022), B (July 2021, 2022), C (October 2021, July 2022), D (June 2022), and E (June 2022).

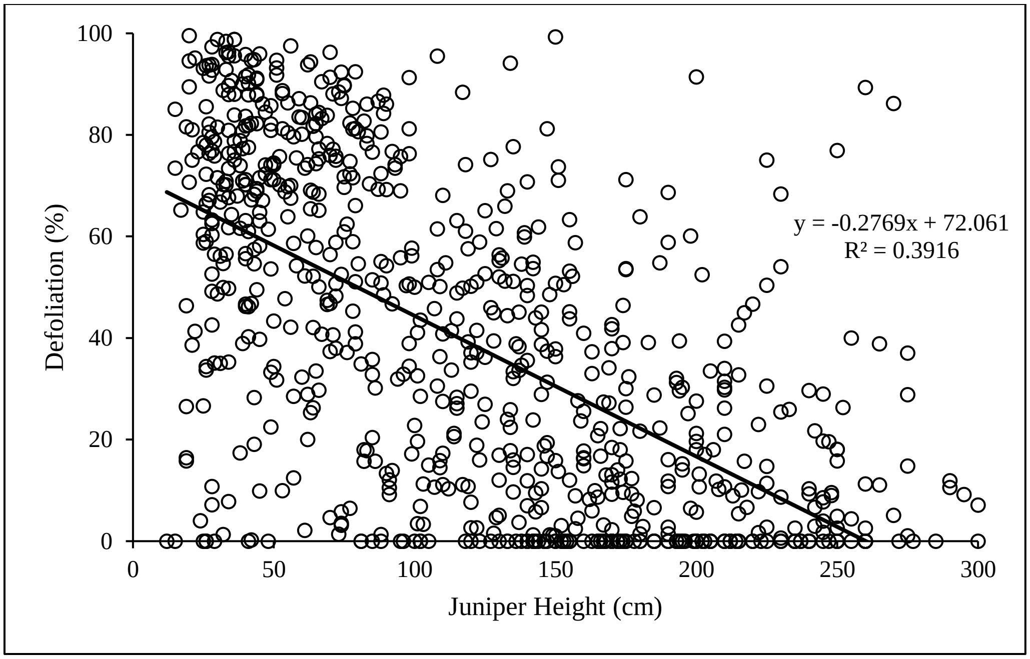

Figure 3-2 Eastern redcedar height and goat defoliation (*n* = 812) from five browsing sites 2021-2022.

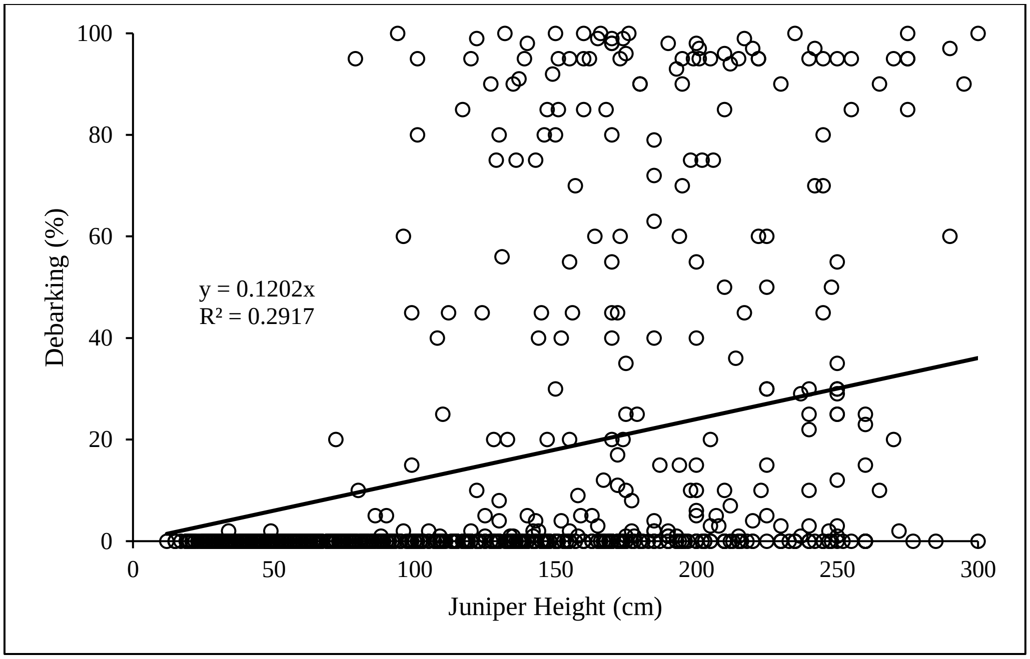

Figure 3-3 Eastern redcedar height (cm) and trunk debarking (%) by goats (*n* = 812) from five browsing sites 2021-2022.

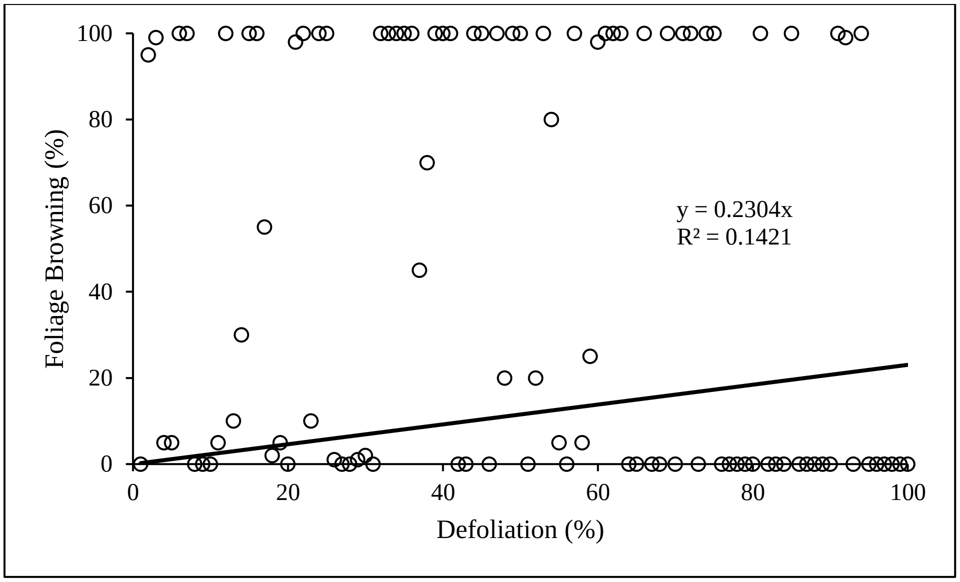

Figure 3-4 Eastern redcedar foliage browning the spring (May 2022) after targeted browsing (June 2021) with goats in relation to defoliation (volume reduction, %) on Site A (*n* = 157).

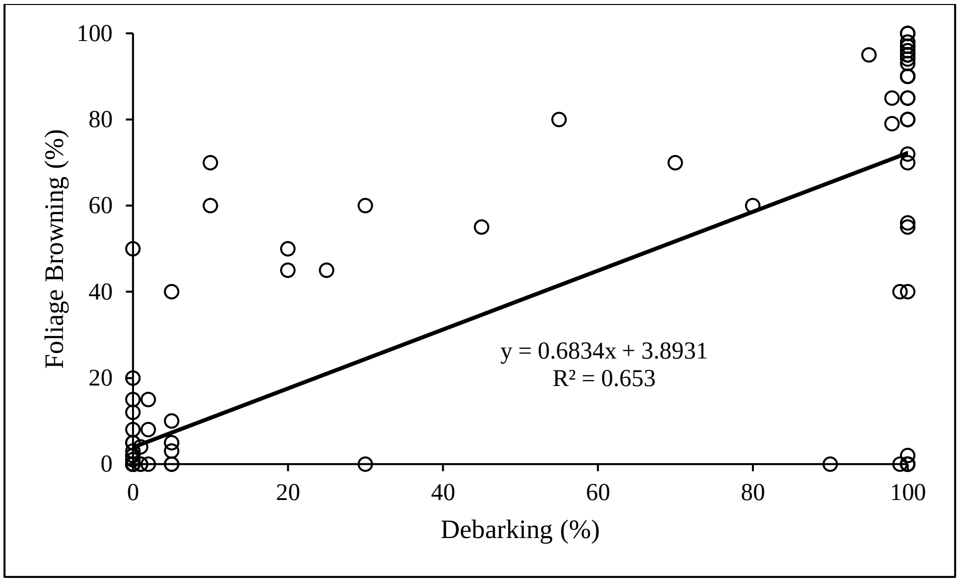

Figure 3-5 Eastern redcedar foliage browning the spring (May 2022) after targeted browsing (June 2021) with goats in relation to debarking (trunk bark removed, %) on Site A (*n* = 157).

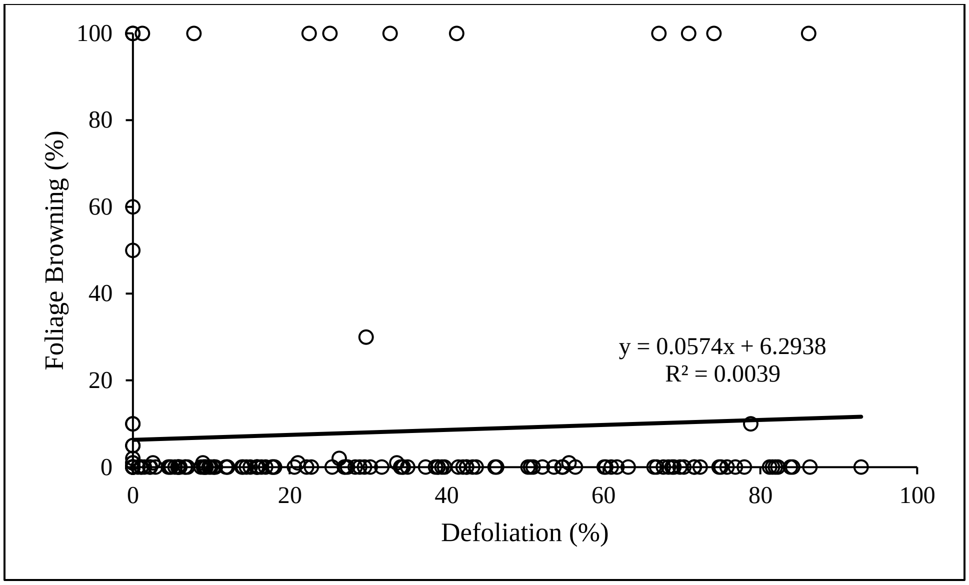

Figure 3-6 Eastern redcedar foliage browning the spring after (May 2022) targeted browsing (July 2021) with goats in relation to defoliation (volume reduction, %) on Site B (*n* = 181).

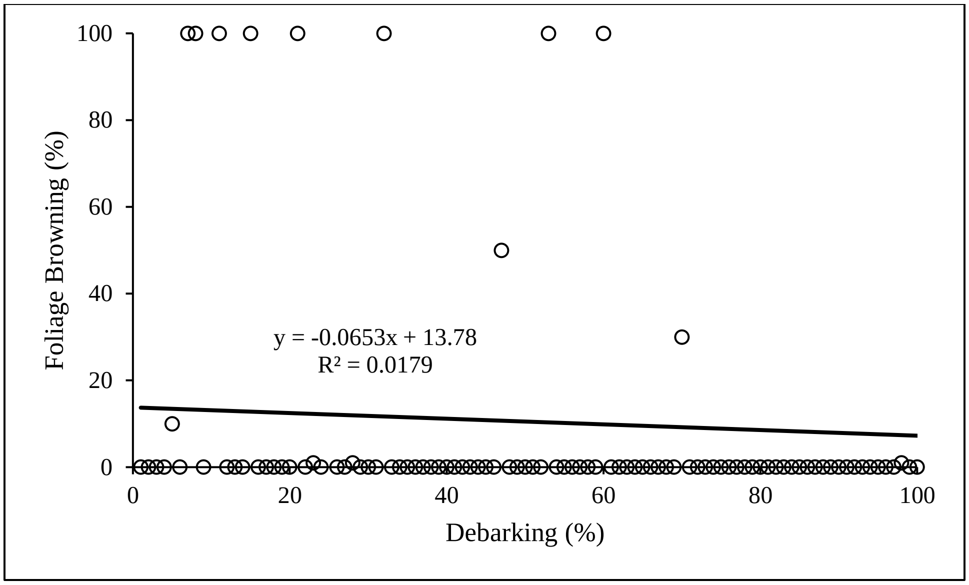

Figure 3-7 Eastern redcedar foliage browning the spring after (May 2022) targeted browsing (July 2021) with goats in relation to debarking (trunk bark removed, %) on Site B (*n* = 181).

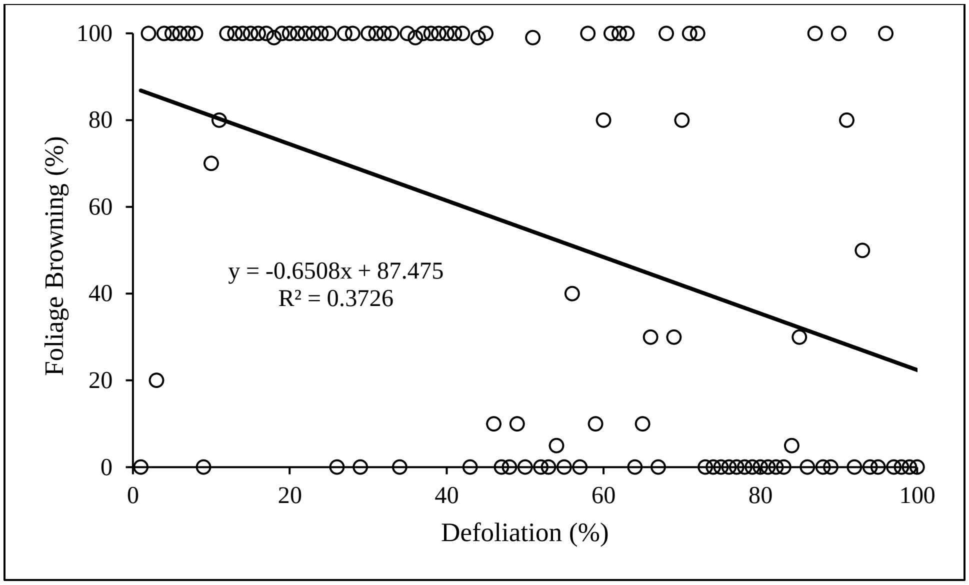

Figure 3-8 Eastern redcedar foliage browning the spring after (May 2022) targeted browsing (October 2021) with goats in relation to defoliation (volume reduction, on Site C (*n* = 154).

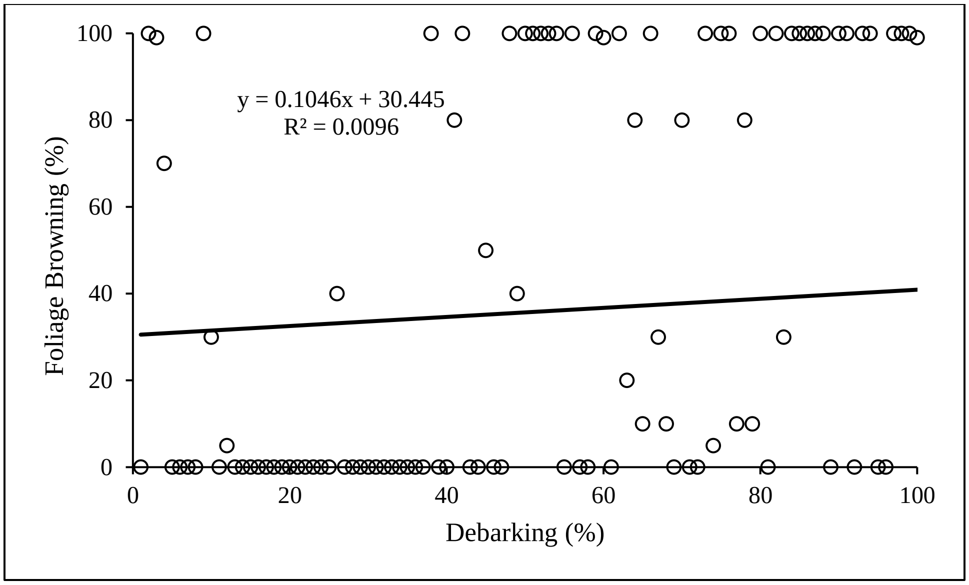

Figure 3-9 Eastern redcedar foliage browning the spring after (May 2022) targeted browsing (October 2021) with goats in relation to debarking (trunk bark removed, %) on Site C (*n* = 149).

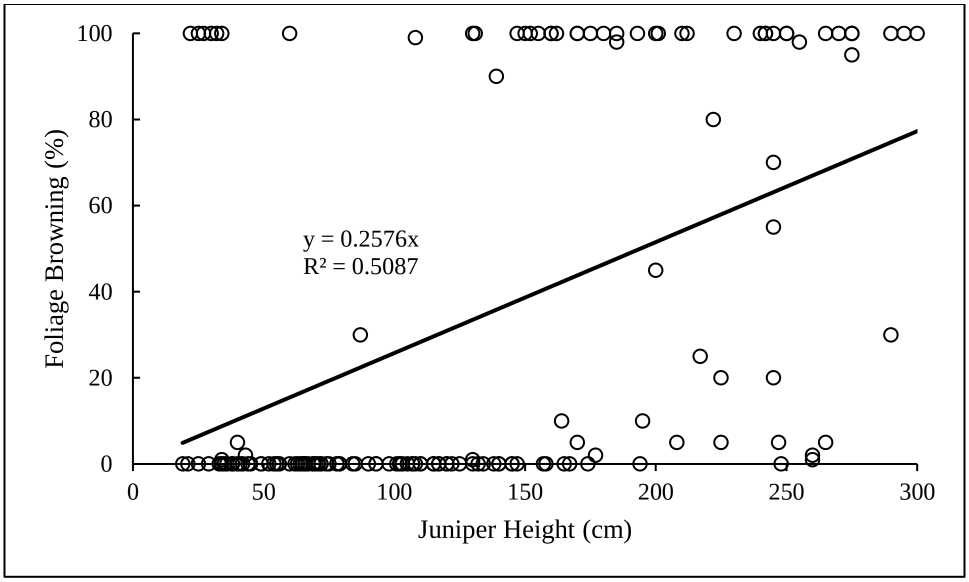

Figure 3-10 Eastern redcedar height (cm) and foliage browning (tree death, %) on Site A (browsed June 2021) (*n* = 157).

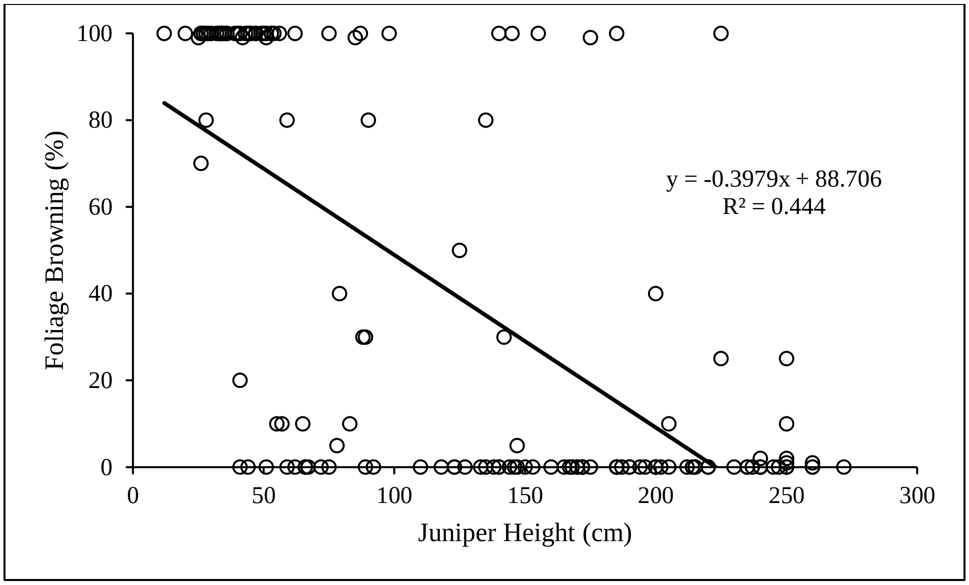

Figure 3-11 Eastern redcedar height (cm) and foliage browning (tree death, %) on Site C (browsed October 2021) (*n* = 149).

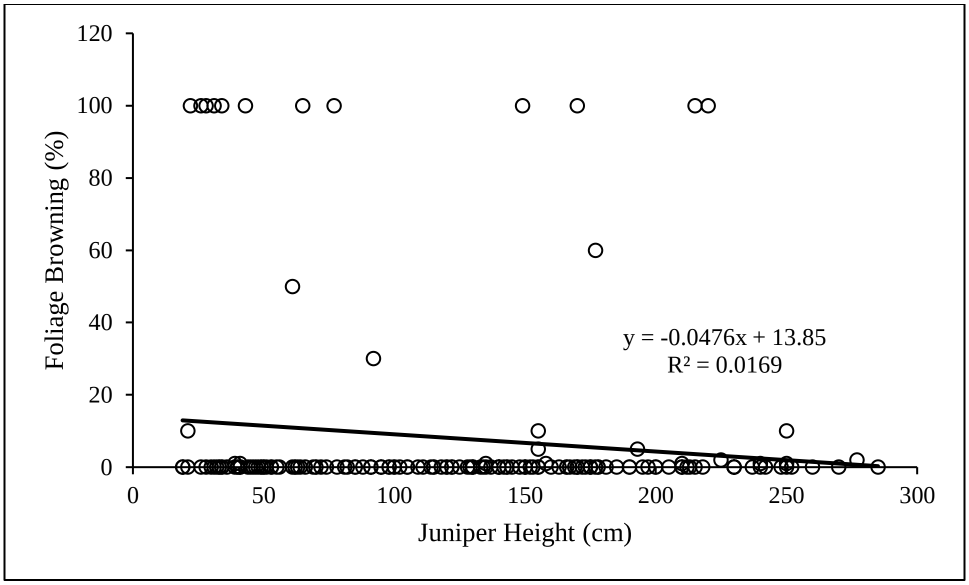

Figure 3-12 Eastern redcedar height (cm) and foliage browning (tree death, %) on Site B (browsed July 2021) (*n* = 181).

APPENDIX

Table A-1 Pure volatile oil compounds and their associate retention time and peak areas for gas-chromograph mass-spectrometry of eastern redcedar foliage and bark.

Compound	Retention Time (min)	Peak Area
(-) Borneol	9.785	18869499
(-) Limonene	7.858	6218242
(-) β Pinene	6.615	13094836
(+) Carvone	10.33	17250718
(+) Terpinen-4-ol	9.851	25150377
(±) Citronellal	9.214	45876814
(±) Camphene	6.027	21917972
(±) Camphor	9.542	10159074
(1R) endo (+) Fenchyl alcohol	9.248	7111886
(1S) (-) α Pinene	5.701	7863900
(1S) (-) β Pinene	6.628	1087284
L Bornyl acetate	10.603	47195185
Linalol	9.026	13053159
Myrcene	6.864	1860848
P Cymene	7.757	8396587
Terpinolene	8.825	1524108
α Terpineol	9.966	12206735

Table A-2 Species richness (S), Shannon-Weiner's species diversity index (H', H' Max), and Shannon-Weiner's evenness (J') on eastern redcedar (ERC) -encroached sites (A-E) browsed with goats 2021-2022. Cover by species was collected under ERC canopy, at the edge of ERC canopy, and open grassland with 0.25 m^2 quadrats in triplicate pre-browse (*n* = 36 quadrats per site).

	2021				2022			
Site	S	H'	H' Max	J'	S	H'	H' Max	J'
A	20	2.46	3.00	0.82	11	1.69	2.40	0.80
B	16	2.31	2.77	0.83	16	2.20	2.77	0.79
C	15	1.69	2.40	0.70	16	2.21	1.20	0.8
D	-	-	-	-	7	1.27	1.95	0.65
E	-	-	-	-	15	2.18	2.71	0.80

Table A-3 Relative frequency and mean cover of species present (ocular cover estimates, triplicate 0.25 m^2 quadrats under eastern redcedar (ERC) canopy, at the edge of ERC canopy, and open grassland pre-targeted browsing with goats) on eastern redcedar (ERC)-encroached sites. Site A was browsed in June 2021 and 2022. Native status to the lower 48 United States (L48) is indicated as native (N) or introduced (I) and life form is graminoid (G), forb (F), shrub (SH), or tree (T). Observation sample size is "N."

2021 *N* = 129					
Common Name	Scientific Name	Life Form	USDA Native Status (L48)	Rel. Freq. (%)	Cover (%)
Smooth bromegrass	*Bromus inermis* Leyss.	G	I	22.48	25.11
Kentucky bluegrass	*Poa pratensis* L.	G	I	15.50	3.45
Big bluestem	*Andropogon gerardii* Vitman	G	N	15.50	4.24
Eastern redcedar	*Juniperus virginiana* L.	T	N	10.08	0.68
Sweetclover	*Melilotus officinalis* (L.) Lam.	F	I	7.75	0.64
Canada thistle	*Cirsium arvense* L.	F	I	5.42	1.31
Chokecherry	*Prunus virginiana* L.	SH	N	5.42	0.76
Indiangrass	*Sorghastrum nutans* L.	G	N	4.65	0.97
Unknown shrub		SH		4.65	4.73
Wild indigo	*Baptisia australis* L.	SH	N	3.10	0.65

Canada wildrye	*Elymus canadensis* L.	G	N	2.33	1.00
Heath aster	*Symphyotrichum ericoides* L.	F	N	1.55	0.60
American elm	*Ulmus americana* L.	T	N	0.78	1.5
Black medic	*Medicago lupulina* L.	F	I	0.78	0.10
Canada goldenrod	*Solidago canadensis* L.	F	N	0.78	8.00
Catnip	*Nepeta cataria* L.	F	I	0.78	0.40
Common dandelion	*Taraxacum officinale* F.H. Wigg.	F	I, N	0.78	0.20
Annual ragweed	*Ambrosia artemisiifolia* L.	F	N	0.78	0.01
Switchgrass	*Panicum virgatum* L.	G	N	0.78	0.10
Unknown tree		T		0.78	0.10

2022

N = 127

Common Name	Scientific Name	Life Form	USDA Native Status (L48)	Rel. Freq. (%)	Cover (%)
Smooth bromegrass	*Bromus inermis* Leyss.	G	I	28.35	11.31
Kentucky bluegrass	*Poa pratensis* L.	G	I	15.75	1.36
Chokecherry	*Prunus virginiana* L.	SH	N	12.60	1.38
Sweetclover	*Melilotus officinalis* (L.) Lam.	F	I	10.24	0.20
Big bluestem	*Andropogon gerardii* Vitman	G	N	9.45	0.64

Canada thistle	*Cirsium arvense* L.	F	I	7.09	2.70
Little bluestem	*Schizachyrium scoparium* (Michx.) Nash	G	N	3.15	1.50
Common Milkweed	*Asclepias syriaca* L.	F	N	3.15	0.43
Eastern redcedar	*Juniperus virginiana* L.	T	N	2.36	0.53
American elm	*Ulmus americana* L.	T	N	1.57	0.50
Indiangrass	*Sorghastrum nutans* L.	G	N	1.57	0.10
Wild indigo	*Baptisia australis* L.	F	N	1.57	0.55
Catchweed bedstraw	*Galium aparine* L.	F	N	0.79	0.10
Field bindweed	*Convolvulus arvensis* L.	F	I	0.79	0.30
Sideoats grama	*Bouteloua curtipendula* (Michx.) Torr.	G	N	0.79	0.10
Troublesome sedge	*Carex molesta* Mack. Ex Bright	G	N	0.79	0.50

Table A-4 Relative frequency and mean cover of species present (ocular cover estimates, triplicate 0.25 m^2 quadrats under eastern redcedar (ERC) canopy, at the edge of ERC canopy, and open grassland pre-targeted browsing with goats) on eastern redcedar (ERC)-encroached sites. Site B was browsed in July 2021 and 2022. Native status to the lower 48 United States (L48) is indicated as native (N) or introduced (I) and life form is graminoid (G), forb (F), shrub (SH), or tree (T). Observation sample size is "N."

2021 *N* = 164					
Common Name	Scientific Name	Life Form	USDA Native Status (L48)	Rel. Freq. (%)	Cover (%)
Kentucky bluegrass	*Poa pratensis* L.	G	I	18.29	6.32
Sweetclover	*Melilotus officinalis* (L.) Lam.	F	I	15.85	4.30
Smooth bromegrass	*Bromus inermis* Leyss.	G	I	14.02	11.01
Big bluestem	*Andropogon gerardii* Vitman	G	N	12.80	6.34
Canada thistle	*Cirsium arvense* L.	F	I	9.15	0.94
Chokecherry	*Prunus virginiana* L.	SH	N	7.32	6.01
American elm	*Ulmus americana* L.	T	N	6.10	1.05
Heath aster	*Symphyotrichum ericoides* L.	F	N	5.49	2.21
Missouri goldenrod	*Solidago missouriensis* Nutt.	F	N	4.88	2.84

Eastern redcedar	*Juniperus virginiana* L.	T	N	2.44	0.78
Canada goldenrod	*Solidago canadensis* L.	F	N	0.61	4
Common milkweed	*Asclepias syriaca* L.	F	N	0.61	5
Indiangrass	*Sorghastrum nutans* L.	G	N	0.61	0.10
Switchgrass	*Panicum virgatum* L.	G	N	0.61	1.00
Western wheatgrass	*Pascopyrum smithii* (Rydb.) A. Love	G	N	0.61	1.50
Wild bergamot	*Monarda fistulosa* L.	F	N	0.61	0.10

2022

N = 144

Common Name	Scientific Name	Life Form	USDA Native Status (L48)	Rel. Freq. (%)	Cover (%)
Sweetclover	*Melilotus officinalis* (L.) Lam.	F	I	25.00	18.69
Smooth bromegrass	*Bromus inermis* Leyss.	G	I	16.67	11.87
Kentucky bluegrass	*Poa pratensis* L.	G	I	15.97	6.86
Big bluestem	*Andropogon gerardii* Vitman	G	N	11.81	9.85
Canada thistle	*Cirsium arvense* L.	F	I	7.64	1.72
Heath aster	*Symphyotrichum ericoides* L.	F	N	5.56	2.06
Chokecherry	*Prunus virginiana* L.	SH	N	4.86	1.10
Indiangrass	*Sorghastrum nutans* L.	G	N	4.17	6.18

American elm	*Ulmus americana* L.	T	N	2.08	2.42
Missouri goldenrod	*Solidago missouriensis* Nutt.	F	N	1.39	2.25
Western wheatgrass	*Pascopyrum smithii* (Rydb.) A. Love	G	N	1.39	3.50
Common yarrow	*Achillea millefolium* L.	F	N	0.69	0.1
Eastern redcedar	*Juniperus virginiana* L.	T	N	0.69	0.25
Field bindweed	*Convolvulus arvensis* L.	F	I	0.69	1.00
Troublesome sedge	*Carex molesta* Mack. Ex Bright	G	N	0.69	2.00
Unknown shrub		SH		0.69	1.00

Table A-5 Relative frequency and mean cover of species present (ocular cover estimates, triplicate 0.25 m^2 quadrats under eastern redcedar (ERC) canopy, at the edge of ERC canopy, and open grassland pre-targeted browsing with goats) on eastern redcedar (ERC)-encroached sites. Site C was browsed in October 2021 and July 2022. Native status to the lower 48 United States (L48) is indicated as native (N) or introduced (I) and life form is graminoid (G), forb (F), shrub (SH), or tree (T). Observation sample size is "N."

2021 *N* = 101					
Common Name	Scientific Name	Life Form	USDA Native Status (L48)	Rel. Freq. (%)	Cover (%)
Smooth bromegrass	*Bromus inermis* Leyss.	G	I	35.64	12.98
Kentucky bluegrass	*Poa pratensis* L.	G	I	18.81	2.91
American elm	*Ulmus americana* L.	T	N	12.87	2.90
Eastern redcedar	*Juniperus virginiana* L.	T	N	7.92	0.38
Common buckthorn	*Rhamnus cathartica* L.	SH	I	3.96	1.49
Big bluestem	*Andropogon gerardii* Vitman	G	N	2.97	0.63
Canada goldenrod	*Solidago canadensis* L.	F	N	2.97	2.50
Reed canarygrass	*Phalaris arundinacea* L.	G	I	2.97	10.00
Sweetclover	*Melilotus officinalis* (L.) Lam.	F	I	2.97	0.13

Heath aster	*Symphyotrichum ericoides* L.	F	N	1.98	0.50
Scribner's rosette grass	*Dichanthelium oligosanthes* (Schult.) Gould var. *scribnerianum* (Nash) Gould	G	N	1.98	1.00
Yellow foxtail	*Setaria pumila* (Poir.) Roem. & Schult.	G	I	1.98	0.30
American milkvetch	*Astragalus americanus* (Hook.) M.E. Jones	F	N	0.99	1.00
Common dandelion	*Taraxacum officinale* F.H. Wigg.	F	I, N	0.99	0.25
Unknown grass		G		0.99	1.00

2022

N = 127

Common Name	Scientific Name	Life Form	USDA Native Status (L48)	Rel. Freq. (%)	Cover (%)
Smooth bromegrass	*Bromus inermis* Leyss.	G	I	40.00	31.85
Kentucky bluegrass	*Poa pratensis* L.	G	I	20.00	1.29
American elm	*Ulmus americana* L.	T	N	20.00	2.01
Chokecherry	*Prunus virginiana* L.	SH	N	6.67	1.77
Sweetclover	*Melilotus officinalis* (L.) Lam.	F	I	5.56	0.96
Heath aster	*Symphyotrichum ericoides* L.	F	N	2.22	0.50
Barnyard grass	*Echinochloa crus-galli* L.	G	I	1.11	5.00
Canada goldenrod	*Solidago canadensis* L.	F	N	1.11	2.00

Eastern cottonwood	*Populus deltoides* W. Bartram ex Marshall	T	N	1.11	0.50
Missouri goldenrod	*Solidago missouriensis* Nutt.	F	N	1.11	1.00
Annual ragweed	*Ambrosia artemisiifolia* L.	F	N	1.11	0.10

Table A-6 Relative frequency and mean cover of species present (ocular cover estimates, triplicate 0.25 m^2 quadrats under ERC canopy, at the edge of ERC canopy, and open grassland pre-targeted browsing with goats) on eastern redcedar (ERC)-encroached sites. Sites D and E were browsed in June 2022. Native status to the lower 48 United States (L48) is indicated as native (N) or introduced (I) and life form is graminoid (G), forb (F), shrub (SH), or tree (T). Observation sample size is "N."

Site D *N* = 59					
Common Name	Scientific Name	Life Form	USDA Native Status (L48)	Rel. Freq. (%)	Cover (%)
Smooth bromegrass	*Bromus inermis* Leyss.	G	I	61.02	27.50
Kentucky bluegrass	*Poa pratensis* L.	G	I	11.86	1.94
Eastern redcedar	*Juniperus virginiana* L.	T	N	10.17	0.37
Sweetclover	*Melilotus officinalis* (L.) Lam.	F	I	10.17	2.28
Canada goldenrod	*Solidago canadensis* L.	F	N	3.39	1.75
Heath aster	*Symphyotrichum ericoides* L.	F	N	1.70	0.50
Woolly verbena	*Verbena stricta* Vent.	F	N	1.70	0.10

Site E

N = 105

Common Name	Scientific Name	Life Form	USDA Native Status (L48)	Rel. Freq. (%)	Cover (%)
Smooth bromegrass	*Bromus inermis* Leyss.	G	I	26.67	7.36
Kentucky bluegrass	*Poa pratensis* L.	G	I	20.00	7.97
Canada thistle	*Cirsium arvense* L.	F	I	12.38	0.80
Little bluestem	*Schizachyrium scoparium* (Michx.) Nash	G	N	9.52	7.26
Sweetclover	*Melilotus officinalis* (L.) Lam.	F	I	7.62	0.17
Chokecherry	*Prunus virginiana* L.	SH	N	6.67	1.51
Big bluestem	*Andropogon gerardii* Vitman	G	N	5.71	0.38
American elm	*Ulmus americana* L.	T	N	1.90	0.1
Heath aster	*Symphyotrichum ericoides* L.	F	N	1.90	1.00
Troublesome sedge	*Carex molesta* Mack. Ex Bright	G	N	1.90	0.75
Western wheatgrass	*Pascopyrum smithii* (Rydb.) A. Love	G	N	1.90	0.80
Catchweed bedstraw	*Galium aparine* L.	F	N	0.95	0.10

Catnip	*Nepeta cataria* L.	F	I	0.95	0.10
Eastern redcedar	*Juniperus virginiana* L.	T	N	0.95	0.50
Missouri goldenrod	*Solidago missouriensis* Nutt.	F	N	0.95	1.00

Table A-7 Concentration (mM) of secondary metabolite chemicals in eastern redcedar foliage and bark at five juniper heights and in mature seed-bearing females near Volga, SD, USA (44°23'17" N, 96°57'44" W) analyzed by gas chromograph-mass spectrometer.

	Height Class (cm)	
	Foliage Concentration (mM)	Bark Concentration (mM)
Chemical	50 cm	
(1S) (-) α Pinene	0.09	0.24
(-) β Pinene	0.06	0.05
(-) Limonene	0.04	-
	51-100 cm	
(1S) (-) α Pinene	-	0.24
(-) β Pinene	0.08	0.004
	101-150 cm	
(1S) (-) α Pinene	-	0.18
(-) β Pinene	0.09	-
(-) Limonene	0.06	-
	151-200 cm	
(1S (-) α Pinene	0.11	0.10
(-) β Pinene	0.07	-
(-) Limonene	0.03	-
	201-250 cm	
(1S) (-) α Pinene	0.06	0.05
(-) β Pinene	0.02	-
(-) Limonene	0.06	-
	Mature Female with Cones	
(-) β Pinene	0.02	0.13
(-) Limonene	0.02	-

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