Bark-stripping of common buckthorn by goats during managed browsing on bur oak savannas

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Abstract Goats are being used increasingly to manage woody invasive plants in woodland habitats, but their specific impacts on those plants over a period of time during active, periodic browsing has not been documented. This study investigated bark-stripping by goats browsing on common buckthorn in savanna habitats (75 goats/hectare, 5 to 7 days), focusing on possible size-selective feeding and the cumulative effects of repeated, periodic browsing over a 3-year period. When surveyed after the first browsing period, bark was stripped selectively on buckthorn stems 20 to 60 mm in diameter. Approximately 60% of all stripped stems were completely girdled, but only 14–17% of stems were bark-stripped. After five browsing periods, 66% of standing stems displayed bark stripping and 39% were completely girdled. Buckthorn densities were reduced by 90% compared to the first browsing period, the decline resulting mostly from consumption of foliage and terminal shoots of small (< 20 mm) buckthorn and bark-stripping resulting in top-kill in intermediate-sized (20–60 mm) plants. Large buckthorn (> 60 mm) were largely unimpacted by goats. Relatively few (28%) seedling buckthorn were browsed by goats, although > 90% of 2nd-year plants were browsed. Buckthorn can be managed in part via goat browsing, but repeated, periodic browsing over 3 to 6 years may be necessary to produce a significant reduction in plant abundance, and other techniques will be needed to eliminate large, seed-producing plants.

Keywords Goats · European buckthorn · Bark stripping · Selective feeding · Managed browsing · Savanna

Introduction

Domestic goats (Capra hircus L.) have long been used to manage undesirable vegetation (Taylor 1992; Popay and Field 1996; Hart 2001; Rathfon et al. 2021). Their willingness to consume and tolerate a diversity of plants often makes goats a top choice among various livestock for vegetation management (Popay and Field 1996; Hart 2012). Recently, the ability of goats to feed aggressively on invasive woody shrubs has produced new and dramatically expanding agricultural and business opportunities using goats to manage unwanted vegetation (Hart 2001; Jenner 2013; Fernandez 2012; Nolden 2020). Goats can defoliate woody invasive plants and strip bark from their stems (Hart 2001, 2012; Goetsch et al. 2010; Manousidis...
et al. 2016), although they may require several years of repeated, managed browsing to suppress most woody shrub species (Gipson 2005). A recent study (Nolden 2020) suggests that using goats as the only management technique will not produce rapid control or complete eradication of woody shrubs.

Savanna habitats, especially remnant patches, are prone to invasion by woody shrubs due to their high edge-to-size ratio, frequent use by fruit- and seed-eating birds, and removal of fire and large ungulates (O’Connor 2006; Harrington and Kathol 2009). The invasion and dominance of savannas by woody invasives (e.g., buckthorns \( Rhamnus \) spp., honeysuckles \( Lonicera \) spp.) is especially concerning, given the importance of these habitats to numerous threatened, endangered, and special-concern species and the significant loss (> 90% decline from 1890s to present) of savanna habitat in some regions (MN DNR 2006). Buckthorn is especially problematic as the most frequently reported invasive plant in these regions and likely one of the most ecologically and economically damaging non-native plants (Zouhar 2011; Schuster et al. 2020; Russell et al. 2020).

Common or European buckthorn (\( Rhamnus cathartica \) L.) is not native to North America, but it has invaded and spread into a diverse array of wildlands and disturbed habitats (Zouhar 2011). Its rapid growth rate and strong competitive abilities have enabled it to dominate native plant communities in forests, woodlands, savannas, prairies, and wetlands (Bisikwa 2005). It can grow as a short, bushy shrub or as a tree reaching > 8 m in height (Farrar 1995). When mature, female plants can produce thousands of black, ripened fruits by early autumn, which can be dispersed to new habitats by fruit-eating birds or fall to the ground and contribute to a seed bank of up to 5000 seeds/m\(^2\) (Qaderi et al. 2009), where they can remain viable for up to 6 years (Goodwin 1943).

When cut, girdled, or otherwise damaged, buckthorn responds with vigorous and abundant sprouting either immediately below the damaged stem area or from the root crown (Bisikwa 2005; Moriarty 2005). Girdled large stems may require more than one year to top-kill, with repeated removal of sprouts often required to kill plants completely (Heidorn 1991). Buckthorn seedlings tend to have reduced mortality rates from herbivory and other factors compared to other shrub species (Kollmann and Grubb 1999), but they lack the ability to sprout if they are top-killed (Boudreau and Wilson 1992).

Goats readily consume buckthorn, even dense stands of plants growing in difficult terrain (Hart 2012; Jenner 2013). Even while providing effective control of heavy invasions of non-native shrubs, goats can have neutral to positive effects on the native herbaceous layer (Rathfon et al. 2021). Consequently, using goats to help restore savannas is becoming commonplace on both public and private lands (Nolden 2020).

Scientific assessments of the impact of goat browsing (from here forward defined as including defoliation, terminal shoot removal, and bark stripping) on woody plants have been undertaken in many ecosystems around the world (e.g., Perevolotsky et al. 1998; Arévalo et al. 2007; Dostálek and Franti 2008; Jáuregui et al. 2009; Papachristou and Platis 2011; Manousidis et al. 2016; Randriamalala et al. 2016; Nolden 2020; Russell 2020). Managed goat browsing can produce significant increases in dead and top-killed woody invasives (Papachristou and Platis 2011; Nolden 2020) and improve plant community diversity (Dostálek and Franti 2008; García et al. 2012). However, the process by which goats kill invasive buckthorn is documented only through anecdotal observations (Nolden 2020). No scientific studies have examined the specific impacts of goat browsing on buckthorn (either individual plants or populations), or directly measured these impacts over a period of time. Consequently, the objective of this study was to assess the impact of initial and repeated browsing by goats on invasive European buckthorn within a ridgetop oak savanna complex in the blufflands of southeastern Minnesota. Specifically, it was hypothesized that (1) goats would exhibit size-selective feeding (bark stripping) on buckthorn plants where the top foliage was out of reach of goats, and that (2) repeated browsing over 3 years would significantly suppress buckthorn densities through a combination of defoliation, terminal bud removal, and girdling with subsequent sucker (or basal sprout) browsing.
Methods

Study site

Garvin Heights Park and Overlook (44° 02' 04" N, 91° 39' 05" W), jointly owned and maintained by the City of Winona, MN, and Winona State University, consists of a patchy distribution of bur oak savannas and dry bluff prairies bordered by oak-hickory and maple-basswood forests. All habitats were invaded by Tatarian honeysuckle (*Lonicera tatarica* L.) and common buckthorn prior to the 1980s, with subsequent efforts (e.g., cutting, chemical treatment, prescribed fire) made to control invasive shrubs only within the dry bluff prairie and a small section of savanna nearest a public overlook. Savannas and prairies at Garvin Heights have a WSW aspect and a slope of approximately 20°. Two savanna parcels (Parcel 1 [0.75 hectare]—savanna only; Parcel 2 [0.61 hectare]—mixed savanna and prairie) with differing management histories (Table 1) were present at Garvin Heights. No management activities had been undertaken in Parcel 1 after woody invasives became established. In contrast, woody invasives in Parcel 2 were cut and chemically treated in 1992 and prescribed burns were conducted in 1994 and 2006.

At Garvin Heights, the savanna buckthorn population consisted of scattered, mature, plants (including fruit-bearing females) that were 6 to 11 m tall, and an abundant understory of younger plants ranging from seedlings to plants that were several years old. Most buckthorn exhibited the single-stem, tree-like growth form.

As part of the long-term site management plan, an idealized species list was generated for the target, post-reclamation plant community desired within the savannas and prairies at Garvin Heights (Table S1). That list combined a site-specific herbarium species search along with recent on-site surveys and a professional assessment of the site by a local seed supplier. The list includes two species of trees, four shrubs, nine grasses, and 65 savanna and/or prairie forbs. Invasive species are not included in this list, although it is acknowledged that those species likely

| Table 1 | Management history and buckthorn sampling design and assessment on two Garvin Heights parcels |
|---------|--------------------------------------------------------------------------------------------|
|         | Management/sampling | Parcel 1 | Parcel 2 |
|         |                      | Savanna   | Savanna/prairie |
| Parcel management history | Goat browsing 2016–2019 | Woody invasives cut/chemically treated 1992 |
|                      | Woody invasives cut/chemically treated 1992 | Prescribed burns 1994, 2006 |
|                      | Goat browsing 2016–2019 | Goat browsing 2016–2019 |
|                      | Woody invasives cut/chemically treated 2017 | Woody invasives cut/chemically treated 2017 |
| Buckthorn sampling design | Random plot surveys 2014 densities, size distribution, aging (all sizes of buckthorn) | Random plot surveys 2016, densities, 1st/2nd-year plants |
| & assessment | Belt transect surveys 2016, densities, stems > 5 mm diam | Bark stripping surveys 2016, number, extent, size distrib |
|                     | Bark stripping surveys 2016, number, extent, size distrib | Bark stripping surveys 2016, number, extent, size distrib |
|                     | Random plot surveys 2016, densities, browsing damage, 1st/2nd-year plants | Random plot surveys 2016, densities, 1st/2nd-year plants |
|                     | Random plot surveys 2019, densities of live stems > 5 mm diam | Random plot surveys 2019, densities, 1st/2nd-year plants |
|                     | Bark stripping surveys 2019, number, extent, size distrib., fate | Random plot surveys 2019, densities, 1st/2nd-year plants |

Bark-stripping of common buckthorn by goats
will not be completely eradicated from the site during the restoration process or during subsequent management. This list is intended to serve only as a guide during the restoration and management process, not as a final goal against which project success will be measured.

Pre-browsing assessments

In 2016, a 3-year project was initiated to restore invaded savanna and prairie habitats within Garvin Heights Park via a combination of goat browsing (contracted from Diversity Landworks LLC, La Crescent, MN; https://www.diversitylandworks.com) and cutting and treatment with chemical herbicide (Table 1). Prior to beginning restoration, the buckthorn population in Parcel 1 was assessed in two different ways (Table 1; no assessments were made in Parcel 2). In September 2014, six replicate plots (each 2 m × 4 m) were selected at random using coordinate grids and all buckthorn plants (seedling through mature plants) within the plots were counted, measured (mm, basal stem diameter), and cut at ground level and aged via annual growth rings. In August 2016, densities of seedling and 2nd-year buckthorn were assessed with 40 replicate plots (0.1 m²) randomly selected using grid coordinates of the parcel. Seedlings and 2nd-year plants were tallied separately.

Treatment with goats

To begin restoration, buckthorn in Parcels 1 and 2 were first subjected to goat browsing in 2016. Timing of the five browsing periods conducted during this project were determined by the contractor, based on buckthorn browse availability and/or regrowth between successive browsings. Plants in Parcel 1 were treated only by browsing throughout the entire, 3-year project period. Plants in Parcel 2 were first browsed by goats, but after the initial browsing all buckthorn were cut and chemically treated (cut-stump treatment with triclopyr [Garlon 4 Ultra]). Goat browsing continued in Parcel 2 for the remainder of the study period even after buckthorn was removed. For this study, savanna habitats within Parcels 1 and 2 were used to examine the effects of an initial, single period of goat browsing on buckthorn, with Parcel 1 also used to assess the cumulative effects of five periods of goat browsing on buckthorn. No data were collected from Parcel 2 after the effects of the initial browsing were assessed. During each browsing period, 35 to 80 goats (the same number of goats were used in both parcels during a given browsing period) were confined to the parcel by portable electrified fencing for a period of 5 to 7 days (period varied slightly between parcels during a given browsing period to achieve equivalent browsing pressures [goats/hectare/day], given the slight area difference between parcels), under the direct supervision of contractor personnel.

Effects of first browsing

Immediately following the first period of goat browsing during October/November 2016, buckthorn densities, size distributions, and browsing damage were assessed in the savannas of Parcels 1 and 2 (Table 1). Stem densities of larger buckthorn (5 to 150 mm stem diameter) in Parcels 1 and 2 were assessed with short (10–20 m) belt transects and small (2 m²) plots, respectively. Belt transects (n = 12) were used in Parcel 1 where buckthorn was larger and more dispersed, whereas plots (n = 13) were used in Parcel 2 where higher stem densities made transects impractical. Replicate transects or plots were selected at random using coordinate grids within each habitat. If this process selected for adjoining plots or transects, a different coordinate grid was chosen to ensure that clones or shoots of the same plant were not being sampled in multiple plots or transects. Plot boundaries were delineated with a collapsible plot frame, and belt transects were sampled with a meter tape and metric measuring rod following the King procedure (Brower et al. 1997).

Densities of and browsing damage (i.e., missing foliage and/or terminal shoots) to small buckthorn (1st-year seedlings and 2nd-year plants) were assessed in 40 random plots (0.1 m², selected via a site grid) in Parcel 1 after the first browsing period. Seedlings and 2nd-year plants were tallied separately, and the proportions of plants that were browsed in each age group were determined for each plot.

In addition to consuming buckthorn foliage within reach, goats stripped and consumed bark from buckthorn and other shrubs/trees within the Garvin Height parcels. Consequently, evidence of bark stripping was used as an indicator of browsing damage to buckthorn. All buckthorn stems within plots and belt transects were categorized as browsed or not browsed, and
individual browsed stems (those within plots and transects, plus 150 to 220 additional plants per parcel) also were assigned to five different categories based on the extent of bark-stripping damage: bark stripping covering 1 to 25% of the stem’s circumference, 26 to 50, 51 to 75, 76 to 99, and 100%.

To assess buckthorn size distributions and possible size-selective bark stripping by goats, stem diameters of bark-stripped and non-bark-stripped buckthorn in Parcels 1 and 2 were measured with a dial caliper (nearest mm) at a height (50 to 75 cm above ground level) consistent with the height of most bark stripping. The goal was to measure 300 and 500 plants within each parcel to obtain a representative size distribution for both bark-stripped and non-bark-stripped stems.

Effects of multiple browsings

After the final (fifth) browsing for the project, the effects of goats on buckthorn density, possible size-selective bark stripping, and potential for long-term buckthorn control were assessed in Parcel 1 (Table 1). Densities of live buckthorn > 5 mm stem diameter were assessed in replicate plots (each 20 m², n = 30) arranged in three parallel transects along the top, middle, and bottom of the hillslope, respectively. Diameters of 806 plants were measured as described above to determine size distributions of bark-stripped and non-bark-stripped plants, and the extent of bark-stripping damage (% of circumference in five categories as above) was assessed by examining 486 plants with evidence of bark-stripping. Thirty, 1-m² plots (randomly selected via a site grid) were used to assess densities of 1st-year seedlings and 2nd-year plants within Parcel 1. Unlike after the initial browsing, no attempt was made to differentiate browsed and non-browsed plants. Finally, diameters were measured for 368 individual buckthorn plants > 5 mm stem diameter that fell into one of four possible fate categories: (1) entirely dead due to complete girdling/bark stripping by goats, (2) top-killed by complete girdling/bark stripping by goats, but with live basal sprouting, (3) partial girdling/bark stripping by goats, but tops still living, and 4) no bark stripping by goats and tops alive.

Analyses

After initial goat browsing, buckthorn in Parcels 1 and 2 were compared to assess possible differences in plant density and size between parcels, and to examine possible size-selective feeding by goats. Buckthorn densities and stem diameters were compared between parcels with Mann–Whitney tests, and diameter size distributions were compared between sites with a contingency table after grouping measurements into 10-mm size categories. Within both parcels, stem diameters and diameter size distributions were compared between bark-stripped and non-bark-stripped buckthorn stems with Mann–Whitney tests and contingency tables, respectively, to determine if goats exhibited size-selective feeding within individual parcels. Similarly, diameters and size distributions of bark-stripped stems were compared between parcels to determine if goats fed on similar-sized buckthorn in habitats where buckthorn populations may have different age/size distributions.

After five browsings by goats, densities, mean sizes, and size distributions of buckthorn in Parcel 1 were compared to data gathered after the initial browsing in Parcel 1 only, and size distributions of buckthorn in different fate categories were assessed. Densities and mean sizes of buckthorn were compared after first and fifth browsings with Mann–Whitney tests, and size distributions were compared with a contingency table test. Similar comparisons also were made between live and dead buckthorn and bark-stripped and non-bark-stripped buckthorn after the fifth browsing. Separate single-factor analysis of variance tests were used to compare diameters of buckthorn among the bark-stripped categories (% of circumference), and among the four fate categories described above.

Results

Pre-browsing assessments

Two years prior to initial goat browsing, the buckthorn population in Parcel 1 displayed an average density of 30 plants/m² (standard deviation = 3 plants/m²). Plant basal stem diameters ranged from 1 to 150 mm, and plant ages ranged from 1st-year seedlings to a 42-year-old female tree (Fig. 1a, b). The population was
dominated (85% of 710 plants surveyed) by plants 3 years old or younger, with only 3% of individuals ≥ 6 years old. Mature, fruit-bearing plants were 40 to 150 mm in diameter, and all were 14 years old or older. For later comparison to post-browsing density assessments of larger (≥ 5 mm stem diameter) buckthorn, pre-browsing densities of this size grouping (representing 34% of total stems assessed) were estimated as 10.2 (2.1 standard deviation) stems/m² (Fig. 2).

Two months prior to goat browsing, densities of young buckthorn were highly variable within Parcel 1. Seedling densities exceeded 100 plants/m², whereas 2nd-year plant densities were an order of magnitude lower (Table 2).
Effects of first browsing

Goats had a noticeable effect on buckthorn in both Parcels 1 and 2 after their initial browsing, reducing foliage within ~ 1.5 m of the ground. During browsing, goats consumed most of the buckthorn leaves and stem tips within easy reach. To reach higher forage, goats either propped their front feet up against larger stems or forced plants toward the ground by using their legs and bodies to bend flexible stems. In addition to consuming foliage, goats stripped bark from stems of buckthorn and other shrubs and saplings (Fig. 3). Overall densities of standing buckthorn (> 5 mm stem diameter) were reduced by 80% compared to densities assessed two years prior to the initial browsing (Fig. 2). Buckthorn seedlings and 2nd-year plants were still abundant after browsing, with > 25% of seedlings and > 90% of 2nd-year plants displaying evidence of browsing (Table S1). Post-browsing seedling densities were 70% lower than pre-browsing estimates, whereas pre- and post-browsing densities of 2nd-year plants were similar.

Although buckthorn populations on the two savanna parcels at Garvin Heights differed significantly both in density ($U_{13,12} = 156$, $P < 0.0001$; Fig. 2) and stem diameter ($U_{83,324} = 27.068$, $P < 0.0001$; Fig. 4a), goats exhibited similar size-selective bark stripping on buckthorn stems in both habitats after a single browsing (Fig. 4b, c). In general, goats selectively stripped bark from stems 20–49 mm in diameter (54.4% of all buckthorn) when available, selecting against stems < 20 mm (43.4% of all buckthorn) and > 60 mm (2.2% of all buckthorn) in diameter. Similar, low proportions of stems were bark-stripped (17% and 14%, $U_{13,12} = 58$, $P = 0.145$) in both habitats, with goats bark stripping selectively on significantly larger stems than those left unstripped in both habitats (mean ± SD; Parcel 1: bark stripped 32 ± 11 mm, unstripped 28 ± 16 mm, $U_{251,232} = 38.027$, $P < 0.0001$; Parcel 2: bark stripped 19 ± 4 mm, unstripped 13 ± 3 mm, $U_{177,147} = 2956$, $P < 0.0001$). Bark-stripped stems differed significantly in size between parcels ($U_{232,177} = 4753$, $P < 0.0001$; Fig. 4b, c), directly corresponding to differences in sizes of stems available in the two parcels (Fig. 4a).

The majority (> 60%) of buckthorn stems that were bark stripped by goats were completely girdled in both savanna parcels after the first browsing (Fig. 5a). The extent of bark stripping did not differ between parcels ($X^2_4 = 0.72$, $P = 0.949$). Since complete girdling should either kill or top-kill buckthorn stems, and 14–17% of stems experienced some degree of bark stripping, the initial browsing by goats in the two savanna parcels potentially either top-killed or completely killed 9–11% of buckthorn within the parcels.

Table 2 Densities for seedling and 2nd-year buckthorn in a bur oak savanna (Parcel 1) pre-browsing and after one and five browsings. Goat browsing rates are shown after one browsing

|                | Seedlings | Percent browsed | 2nd-year plants | Percent browsed |
|----------------|-----------|-----------------|-----------------|-----------------|
|                | Density (number/m$^2$) |              | Density (number/m$^2$) |              |
| Pre-browsing   | 126.5 ± 113.1 | –               | 13.5 ± 14.8 | –               |
| After one browsing | 36.3 ± 37.9 | 28.0 ± 40.9 | 15.8 ± 17.7 | 90.2 ± 28.9 |
| After five browsings | 58.6 ± 47.8 | –               | 12.8 ± 16.5 | –               |

Mann–Whitney $U$ 812, $P = 0.012$; $U$ 623, $P = 0.787$
Effects of repeated browsings

After five browsings conducted over a 31-month period, dead and top-killed buckthorn were common in Parcel 1, and overall densities of standing buckthorn (>5 mm stem diameter) were reduced by 90% compared to densities assessed after the initial browsing ($U_{30,13} = 390, P < 0.0001$) and by 98% compared to densities assessed two years prior to the initial browsing (Fig. 2). Many buckthorn were lying dead on the ground, apparently knocked down and killed by browsing goats. The proportion of buckthorn stems bearing evidence of bark stripping was nearly 4X that observed after the initial browsing (66% versus 17%), but one-third of buckthorn stems still standing remained unstripped after five browsings. The proportion of stems in most various bark-stripping categories nearly doubled and differed significantly after five versus one browsing ($X^2 = 49.4, P < 0.001$; Fig. 5b), whereas the proportion of completely girdled plants declined by more than one third. However, 39% of all buckthorn stems had been completely girdled by goats after five browsings, compared to 11% after the initial browsing. After five browsings, buckthorn with
stem diameters < 20 mm represented only 8% (65 of 820 stems measured) of standing stems.

In contrast to larger buckthorn, densities of seedling and 2nd-year buckthorn were not reduced after multiple browsing periods (Table 2). Seedling densities after five browsings were 60% higher than after the initial browsing, a significant increase. Densities of 2nd-year plants were not significantly different when compared to densities immediately after the initial browsing period.

Mean (± SD) stem diameters of bark stripped (32 ± 13 mm) and unstripped (33 ± 16 mm) buckthorn did not differ significantly (U\(_{299,152} = 22,630, P = 0.472\)) after five browsings. Likewise, there were no significant differences in stem diameters among % bark-stripping categories (ANOVA \(F_{4,295} = 1.14, P = 0.333\)). However, significant size-selective bark stripping was still evident after five browsings (X\(^2_{5} = 43.2, P < 0.001\)), with goats selectively stripping bark on stems 20–49 mm while rejecting a majority of stems < 20 mm and > 50 mm (Fig. 6). However, stem diameters differed significantly among fate categories (ANOVA \(F_{3,364} = 35.65, P < 0.0001\), with dead and top-kill/basal sprouting buckthorn on average 30–40% smaller than either unstripped or incompletely girdled stems (Fig. 7a). A large proportion (30–45%) of these unstripped or incompletely girdled stems were > 50 mm in diameter (Fig. 7b), too tall for goats to browse foliage and too large for goats to bend or push over.

Discussion

This study had five important findings related to goat browsing on buckthorn after either a single browsing period or after repeated browsings. First, goats exhibited size-selective feeding when stripping bark from buckthorn stems. Second, goats girdled approximately 60% of the stems strip barked, but a large majority of stems were not stripped during an initial browsing. Third, repeated browsing reduced densities of buckthorn > 5 mm stem diameter by 98% by killing the abundant, smaller buckthorn within the population. Fourth, goats browsed on seedling and 2nd-year buckthorn, but did not reduce their densities after five browsings. Finally, goats did not kill most large (> 60 cm diameter) buckthorn, as they were unwilling or unable to strip bark from larger stems.

Size-selective bark stripping by goats on buckthorn was evident after both an initial period of browsing and after five periods of browsing. Goats stripped bark and girdled buckthorn stems primarily within the 20–50 mm diameter range, which comprised the majority of buckthorn present on the savanna sites. Smaller (< 20 mm diameter) plants were seldom bark stripped even though they represented > 40% of buckthorn present; observations suggested that small stems were not stiff enough for easy gnawing, and goats could straddle and bend these plants to access foliage and terminal buds. Larger stems were less frequently bark stripped, likely the result of decreased bark palatability in older or larger trees/shrubs (Bergström 1992; Gill 1992a). Similar, size-selective bark stripping on young tree stems has been observed in red deer (Cervus elaphus) in Sweden (Månsson and Jarnemo 2013).

Over 60% of buckthorn stems stripped by goats during the initial browsing session were completely girdled, producing at least top-kill (if not complete kill) of those plants. This magnitude of girdling via bark stripping by browsing wildlife can result in rapid
death of browsed woody trees and shrubs (e.g., Michael 1987; Akashi and Nakashizuka 1999). With only 14–17% of stems bark stripped after initial goat browsing, possibly only 11% of total buckthorn stems in the Garvin Heights savannas faced death or top-kill from bark stripping. However, since most bark stripping was focused on stems 20–60 mm in diameter, goats potentially girdled 25–30% of buckthorn stems within that size group. Killing or suppressing this proportion of buckthorn after a single browsing period is significant, as buckthorn in this size group often represent the majority of fruiting stems in buckthorn populations (Delanoy and Archibold 2007). If this result is typical, and goats continue this level of bark-stripping effort during additional repeated browsings, significant reductions in reproductive output of buckthorn can be achieved.

After five browsing episodes, goats reduced buckthorn stem densities by 98% compared to densities assessed two years prior to the initial browsing. This likely was achieved through a combination of girdling and killing of stems 20–60 mm in diameter and bending and defoliating plants with stem diameters < 20 mm. Buckthorn stems < 20 mm in diameter declined from 43% of the population immediately after the initial browsing to only 8% after five browings, suggesting that goats were very successful at defoliating and killing the smaller stems, similar to the effects of other browsers on smaller woody plants (Gill 1992b; Akashi and Nakashizuka 1999; Horsley et al. 2003; Royo et al. 2010; Faison et al. 2016). In addition, continued bark stripping during repeated browsing sessions left only one-third of buckthorn stems unstripped after five browsings. Such cumulative bark stripping is typical when young woody stems are subjected to intense feeding pressure from wild ungulates, often when alternative foods are limited or unavailable, or when additional fiber is needed in the diet (Gill 1992a). However, unlike wild ungulates, observations during the current study suggest that goats were never food- or nutrition-limited, consuming a combination of buckthorn foliage, branch tips, and bark when first released into a savanna parcel and...
continuing to do so for the duration of each browsing period. By defoliating buckthorn < 20 mm in diameter and stripping bark from larger stems, goats were successful in killing the majority of buckthorn that were present initially within the savanna habitat.

Densities of very small buckthorn (seedling and 2nd-year plants, < 0.5 mm stem diameter) were not reduced by goat browsing. Although pre-browsing seedling density estimates were > 3X greater than densities immediately after the first browsing, the decline in density cannot be attributed to goat browsing. The probability of buckthorn seedlings surviving their first growing season can be < 30% (Zouhar 2011), and with < 30% of seedlings exhibiting browsing damage, the likelihood of goats causing a significant decline in seedling density is remote. Densities of 2nd-year plants remained stable and those of seedlings actually increased slightly after five browsings, an expected outcome based on the presence of an abundant seedbank and shade release from a reduced canopy post-browsing (Schuster et al. 2020).

Goat contractors usually remove goats from habitats before ground-level browse becomes the only food option (K. Johnson, Diversity Landworks LLC, personal communication), to prevent goats from ingesting eggs of harmful parasites (Hart 2001). Conditions for germination of the buckthorn seedbank improved as densities of intermediate-sized (5–60 mm stem diameter) buckthorn were reduced by goats during repeated browsing (Hart 2012; Schuster et al. 2020). A similar increase in seedling buckthorn density was observed in a nearby savanna parcel (not part of this study), where buckthorn had been removed by cutting/treating followed by attempted control of new growth via prescribed burns and propane weed torches. It appears that goats were not effective against very young buckthorn (either by choice or due to removal of goats by graziers prior to consumption–see above), only browsing on it heavily once it grows beyond the seedling stage. If a buckthorn seedbank is present, or if large buckthorn remain and continue to produce seeds, periodic goat browsing will be necessary to keep the plants in check until the seedbank is depleted and/or the mature buckthorn are removed.

Repeated managed browsings by goats over a period of three years had little to no effect on larger (> 60 mm stem diameter) buckthorn within the Garvin Heights savanna. Goats were unable to access foliage or terminal buds (usually 3 m or more aboveground) on these plants, and were unwilling or unable to strip bark from these larger stems. Even though large buckthorn represented only slightly more than 2% of the buckthorn population in the Garvin Heights savannas, this size group included the major berry- and seed-producers within the population. Inability of goats to feed on large buckthorn was expected, as goat contractors generally recommend felling or otherwise pretreating large buckthorn prior to goat browsing (Hart 2012; Nolden 2020; K. Johnson, Diversity Landworks LLC, La Crescent, MN, personal communication). Because goats likely are ineffective on large buckthorn, using goats along with other practices to control woody invasives would improve the chance of successful management (Nolden 2020).

Management implications

Managed browsing with goats proved to be an effective tool for suppressing established populations of common buckthorn within bluffland savannas in southeastern Minnesota. Suppression was accomplished through (1) direct consumption of foliage and terminal shoots on small buckthorn (< 20 mm stem diameter) that goats could reach or bend over, and (2) bark-stripping of intermediate-sized (20–60 mm) stems that often resulted in complete girdling and eventual top-kill. Girdled and top-killed plants often produced basal sprouts, which goats readily browsed, leading ultimately to complete plant death.

Although goats were successful at killing most buckthorn with stem diameters between 5 and 60 mm, they were ineffective against both seedling buckthorn and plants with stem diameters > 60 mm. Prior to using goats to manage buckthorn, all large plants should be felled or chemically treated to eliminate ongoing seed production. If a substantial buckthorn seedbank is present, goat browsing will open up the habitat and likely accelerate seed germination (Radosevich et al. 2007; Schuster et al. 2020), favorably leading to more rapid depletion of the seedbank than might occur under shaded conditions (Hart 2012). However, during that depletion process that could last from 2 to 6 years (Zouhar 2011), periodic goat browsing will be needed to cull plants as they reach browsable sizes. Managing buckthorn and other woody invasives using goats will be a many-year
undertaking, and landowners should be fully aware that additional control methods will be necessary to successfully suppress and control undesirable vegetation like buckthorn.

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Availability of data and material Data available from the first author.

Declaration

Conflicts of interest The author declare that they have no conflict of interest.

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