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REVIEW ARTICLE

The effectiveness of using targeted grazing for vegetation management: a meta-analysis

Katherine M. Marchetto[1,2], Tiffany M. Wolf[1], Daniel J. Larkin[3]

The use of targeted grazing to control undesired plants as a component of ecological restoration is gaining in popularity, but there is considerable uncertainty among land managers about the effectiveness of this approach. We synthesized existing literature on the use of livestock (ruminants, swine, and equids) to control undesired plants using a meta-analysis to address questions about the effectiveness of the approach. Seventy studies matched our inclusion criteria; these comprised 86% peer-reviewed journal articles and 14% gray literature. Studies were conducted in 17 countries but highly concentrated in the United States and Europe. Cattle, goats, horses, and sheep were used for vegetation management in the studies. Most target plant species were nonnative perennial forbs. Median study duration was 3 years, with a maximum of 10 years. We found that, overall, the use of targeted grazing significantly reduced undesired plants and significantly increased plant species richness. However, several important questions remain. In particular, further research is needed to differentiate temporary defoliation from actual plant mortality, to separate the contributions of native versus nonnative species to gains in plant species richness, and to address longer term outcomes following grazing cessation.

Key words: browsing, ecological restoration, invasive species, livestock, prescribed grazing, species richness

Implications for Practice

- Use of targeted grazing for managing invasive and undesired plant species is a rapidly growing area of restoration practice.
- Targeted grazing by livestock can reduce the abundance of undesired plant species. To not just temporarily suppress but kill and remove undesired species may require sustained efforts over multiple years. More research is needed to determine how long effects persist after cessation of grazing.
- Increases in plant species richness were often observed with targeted grazing; however, this apparent benefit requires further investigation, as the contributions of native versus nonnative species to richness gains were rarely differentiated.

Introduction

Invasive species have negative effects on biodiversity and ecosystem services and interfere with meeting restoration goals (Norton 2009; Funk et al. 2013). Consequently, billions of dollars are spent on invasive plant control annually (Pimentel 2011). Much of this money is spent on control measures such as use of herbicide, cutting, and burning, and most scientific studies of control effectiveness have focused on these methods (Kettenring & Adams 2011). However, interest in alternative vegetation control methods, including livestock grazing, is growing not just in rural areas, where it has been a longstanding element of rangeland management, but in suburban and urban environments as well (Richardson 2014; Derner et al. 2017). Landowner and restoration practitioner interest in targeted grazing has grown for a variety of reasons, including an aversion to herbicide use, a perception of environmental friendliness, lower demand for human labor than other control practices, and ease of use on slopes or other difficult terrain (Richardson 2014). Due to its burgeoning popularity and the relatively scant information that is available about outcomes, land managers and other stakeholders are calling for more research into the use of livestock grazing to control invasive plants and more evaluation of how grazing outcomes compare to those of other control methods (Neary et al. 2012).

Currently, there is debate about the appropriateness of grazing livestock in natural areas. Opponents point to documented negative impacts caused by overgrazing and the harmful effects of invasive or overabundant native ungulates on plant communities (Fleischner 1994; Beschta et al. 2013; Batchelor et al. 2015). A meta-analysis of grazing impacts in Australia linked grazing

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[1]Veterinary Population Medicine, University of Minnesota, 225 Veterinary Medical Center, 1365 Gortner Avenue, St. Paul, MN 55108, U.S.A.
[2]Address correspondence to K. M. Marchetto, email march313@umn.edu
[3]Department of Fisheries, Wildlife, and Conservation Biology, University of Minnesota, 135 Skok Hall, 2003 Upper Buford Circle, St. Paul, MN 55108, U.S.A.

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as a whole with detrimental effects on plant community structure and function, but not plant species richness (Eldridge et al. 2016). Nonnative herbivores, particularly ungulates, facilitate increases in nonnative plant richness and abundance (Parker et al. 2006; Oduor et al. 2010). In addition, invasive ungulates are linked to plant species losses, particularly on islands (Courchamp et al. 2003). Even overly abundant native ungulates can be a concern for plant biodiversity. For example, overabundance of native white-tailed deer, *Odocoileus virginianus*, in North America has negative effects on native understory plants and facilitates spread of invasive species (Knight et al. 2009).

Conversely, proponents of livestock grazing in natural areas argue that carefully controlled grazing can help meet restoration goals, such as reductions of undesired plants, without the negative effects associated with uncontrolled grazing (Svejcar et al. 2014). This type of grazing is referred to as "targeted" or "prescribed," terminology that also encompasses browsing of woody vegetation in the literature and present study (Holst & Allan 1996; Launchbaugh & Walker 2006). Targeted grazing focuses on manipulating livestock density, grazing duration, and grazing timing with the explicit goal of achieving a particular outcome, such as the removal of an invasive plant (Bailey et al. 2019). This method has had notable successes in reducing invasive plant abundance (e.g. Goehring et al. 2010) and increasing plant species diversity (e.g. Hickman et al. 2004), but results have been mixed. For example, goats used in targeted grazing to control invasive shrubs can also damage desirable native shrubs (Rathfon et al. 2014).

The targeted grazing literature focuses on the importance of grazing with the proper stocking density or intensity, with the right frequency, and at the right time of year (e.g. DiTomaso et al. 2008; Rathfon et al. 2014; James et al. 2017). High stocking densities for shorter amounts of time are generally recommended to increase consumption of targeted plants (Bailey et al. 2019). Complementary use of multiple livestock species, particularly ones with different feeding styles (e.g. sheep that graze on low-growing vegetation paired with goats that browse on higher canopy layers), has also been suggested to have more even effects on plant species across different functional groups (Walker et al. 2006). Multiple grazing sessions in 1 year or repeated treatments over multiple years have been recommended for reducing targeted plant species (Launchbaugh & Walker 2006). However, there is not always agreement on optimal grazing methods (Briske et al. 2011*b*) and the right time to graze depends on characteristics of the target plant species or other management goals (Launchbaugh & Walker 2006). For instance, one might want to graze at a particularly vulnerable growth phase of an undesired plant species (ideally when desired plants will be less susceptible to grazing effects) or before an undesired species has been able to produce seed (Bailey et al. 2019).

To systematically evaluate the current evidence for targeted grazing's effectiveness, we synthesized the results of available studies through a meta-analysis. Prior quantitative literature syntheses on use of livestock grazing for conservation either do not focus specifically on targeted grazing (Stahlheber & D'Antonio 2013), only examine one target species (James et al. 2015), or use tallying of studies with and without significant effects (vote counting) rather than a more rigorous analytical approach (Briske et al. 2011*a*). We collected and analyzed existing studies in a meta-analysis to yield comprehensive information about the robustness of using livestock for plant management across multiple habitat types and target plant species. Our systematic review also provides a snapshot of the relevant research that has been performed and identifies knowledge gaps to be filled by future studies.

We hypothesized that prescribed livestock grazing would lead to reductions in targeted, undesired plant species, but that this effect would lessen over time as plants recovered following grazing. We also hypothesized that the effects of livestock grazing on plant community richness would be smaller in magnitude than the effects on individual target species and sensitive to when measurements were taken (e.g. immediately after grazing vs. the following year when there has been time for recruitment from the seed bank). We also expected to find that there were significant reductions in overall plant abundance immediately after grazing, but that plant abundance would rebound after grazing ceased. Finally, we anticipated that multiple, consecutive years of grazing would amplify short-term effects, whether positive or negative.

Methods

Search Method

The literature search was conducted in two phases, with the second search performed using additional terms to make the search more comprehensive and incorporate newly available studies. The first database search targeted articles published through November 2018. Web of Science, Scopus, and Biosis were searched with the Boolean search terms: (goat* OR sheep OR cattle OR horse* OR pig* OR mule* OR burro* OR donkey*) AND (brows* OR graz*) AND (invas* OR exotic OR alien OR introduc* OR noxious) AND plant*. The database Agricultural and Environmental Science was searched using the following string of main subjects: ("Invasions" OR "Introduced species") AND (("Grazing (rotational))" OR ("Grazing") OR ("Browsing")) AND (("Livestock") OR ("Ungulates")). These searches yielded 1,853 studies, with some duplicates.

"Gray literature" collections (agency reports and other publications outside of scientific journals) were also included in this first search, using simpler search terms (e.g. "targeted grazing") and the following online resources: National Technical Reports Library, US Government Publications, US Forest Service TreeSearch, Department of Interior Catalog, USDA ARS, OpenGrey, and Open Dissertations. These searches included studies published through December 2018, and resulted in over 1,200 works that were individually examined for suitability. Some works located in this manner were duplicates or theses and dissertations that were also available as peer-reviewed journal articles. Ultimately, only three gray-literature works were added from these sources. In comparison, search of traditional scientific databases was fairly effective for identifying gray literature, at least for conference proceedings. Fewer than 10% of studies were added opportunistically (not following the reproducible search methods described above); these included two recent theses.

To ensure the thoroughness of our search effort, the Web of Science, Scopus, and Biosis searches were updated with the additional terms "cow," "non-native," "nonnative," "weed," "non-indigenous," and "nonindigenous." The Agricultural and Environmental Science database search was also repeated with the original search terms to check for new studies. These searches included studies published through July 2020. The *revtools* package in R (Westgate 2019) was used to identify 475 nonduplicated studies through these additional database searches, which were then examined for suitability. A second gray-literature search resulted in 350 additional works between 2018 and 2020. See online version for a diagram summarizing sample size information across all search methods (Fig. S1).

We used the program Rayyan to sort accepted and rejected studies from the database searches (Ouzzani et al. 2016); see below for acceptance criteria. This allowed us to tag each reference with searchable inclusion or rejection decisions and other custom notes (see Table S1 for enumerated reasons for database entry rejection).

Across all of our search methods, we identified 70 studies in the English language that fulfilled our criteria. A full list of studies used in the meta-analysis can be found in the online supplement. Specifically, we selected papers that represented (1) manipulative experiments with (2) appropriate controls for purposes of our study that (3) reported the effects of prescribed/targeted livestock grazing on plants. Examples of inappropriate controls would be studies where plots grazed by one livestock species were compared to plots grazed by a different livestock species, or plots that were subjected to an additional treatment like burning, without data on original plot conditions or separate spatial control plots. Most of the retained studies reflected the explicit goal of reducing the abundance of one or more target plant species, but studies were also included in the analysis that had broader goals for plant species richness and diversity. Experiments that placed exclosures in habitually grazed areas were excluded, both because they represented habitual grazing rather than a targeted approach and because livestock densities were often unknown or coarsely estimated. The areas being grazed were limited to relatively natural areas (no areas where plants were managed as a crop), but we did include grazed rangelands or pastures where targeted grazing was performed to manage a specific undesired species. Grazing had to be closely controlled, thus papers examining impacts of feral livestock were not included. Studies with simulated grazing by clipping were also excluded. In addition, studies that combined grazing with other management techniques without a full factorial design, such that the specific effects of grazing could not be isolated, were not considered. One author (KMM) performed the screening methods.

Dataset Construction

There were two general categories of information that we recorded from studies: effects on undesired focal plant species targeted for removal and effects on overall plant community diversity and abundance. In some cases, multiple response variables within these larger categories were recorded from single studies, for example, when studies examined effects on multiple target species or overall community effects were measured in multiple ways. Some studies compared multiple livestock treatments, including different livestock species, stocking rates, or treatment times. Information about grazing methodology was recorded for each paper, including number of grazing events per year, total days grazed per year, stocking rate in animal units (AU ha^{-1} yr^{-1}, where 1 AU = 1 cow, or approximately 450 kg of total animal mass), and the time of year when grazing occurred.

Two factors that we evaluated reflected how data were collected. Studies measured responses after varying lengths of time following cessation of grazing, including immediately after grazing ended, 1 year later, 2 years later, or some combination thereof. We did not include every year of data from multi-year datasets, but focused on *immediate* within-year effects, *carry-over* effects the following year, and *cumulative* effects at the end of the experiment after multiple years of treatment (following Verhoeven et al. 2020). Another variable that differed between studies was how comparisons were made to ungrazed controls. Some studies used comparisons over time, where the control condition was the state of the experimental plot before grazing occurred (temporal control). In other cases, comparisons were made over space, where the control was a separate plot that was not subjected to grazing (spatial control). Lastly, some papers used both approaches (spatiotemporal control).

Log response ratios (*ln*[treatment mean/control mean]) were used as a measure of effect size. This was done because we wanted to include as many studies as possible, but many studies contained no meaningful replication (e.g. only one treatment area and one control area). Studies often had low sample sizes due to the difficulty of fencing large paddocks and moving groups of animals. Restricting the study pool can bias meta-analyses (Gurevitch et al. 1992), so we opted for inclusivity through use of a broadly applicable response metric. When summary data were not tabulated, numeric values were extracted from figures using DataThief III (Tummers 2006).

Statistical Analysis

We separately examined three response variables: effect sizes for undesired target plants, effect sizes for plant community richness and diversity, and effect sizes for general plant abundance (percent cover, density, and biomass of desirable or neutral species). Effect sizes from multiple studies, along with corresponding predictor variables (e.g. livestock species), were analyzed together in meta-analyses, which were performed using generalized estimating equations (GEEs) using the *geepack* package in R version 3.5.2 (Halekoh et al. 2006; R Core Team 2018). GEEs account for multiple, nonindependent responses per study by clustering responses by a factor, in this case originating study (i.e. citation). The resulting parameter estimates and standard errors are population-averaged by cluster rather than individual response (observation). This is advantageous for cases where it is not possible to extract estimates of variance for each

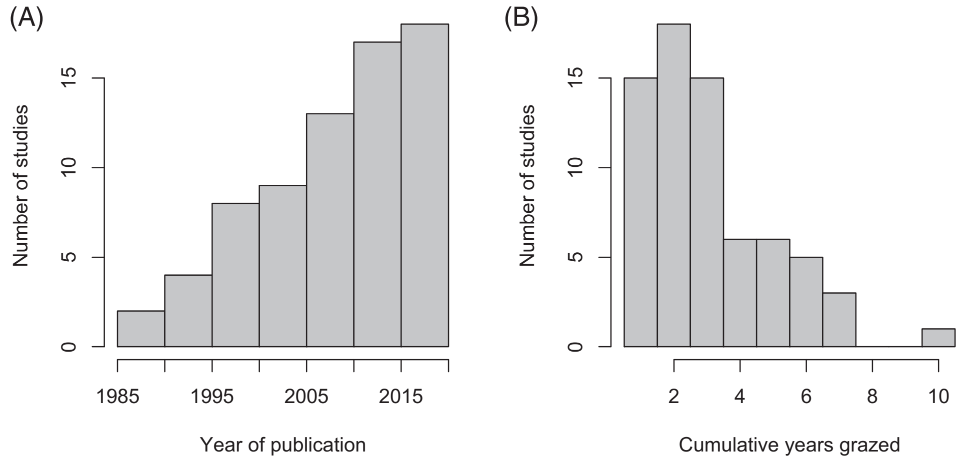

Figure 1. Number of included studies by (A) year of publication and (B) grazing duration.

observation in a meta-analysis (Larkin et al. 2019), which complicates separation of within- and between-study variation (Gurevitch et al. 2018).

The explanatory variables of interest in our models were livestock species, whether or not data were measured within the year grazing occurred, the number of years of grazing, the method used for controls (temporal and/or spatial), and the interaction between number of years of grazing and the method used for controls. This interaction was examined due to observations made during data collection that, while spatial and temporal controls often produced similar results, there were situations in which their use led to different inferences within the same study. Two additional types of models were also run. One was a single-predictor model used to evaluate effects on undesired species based on when data measurement occurred: within the year grazing occurred, 1 year later, or 2 years later. This was done to estimate absolute effect sizes for each measurement timing. Lastly, intercept-only models (without any explanatory variables) were constructed for all response variables to estimate mean effects of targeted grazing across studies.

Results

Dataset Description

Interest in quantifying the effects of livestock grazing on undesired plants and the potential benefits for native plant communities has grown in the last 35 years (Fig. 1A). We identified a total of 70 suitable studies, of which 86% were peer-reviewed journal articles and 14% were from the gray literature. While we identified studies from 17 countries, most were conducted in the United States or Europe (Fig. S2), and within the United States, studies were concentrated in the west (Fig. S3).

The dataset encompasses a variety of grazing strategies. The median amount of time plots were grazed was 3 years and the maximum was 10 years (Fig. 1B). In most instances grazing only occurred once per year (61% of studies); however, in one case five grazing sessions occurred in a single year. The median length that plots were grazed each year was 24 days, with a range of 1–365 days (Fig. S4A). Plots were grazed for 1 week or less 32% of the time, and grazed for 1 month or less 61% of the time. The median stocking rate was 0.337 AU ha^{-1} yr^{-1} (range 0.025–2.5 AU ha^{-1} yr^{-1}; Fig. S4B). Information about the duration and intensity of grazing is provided to summarize information about the methods used in the primary studies, but it is difficult to draw inferences about these factors, which are expected to vary with weather, geographical location, habitat type, and livestock species (Holechek 1988). In 58% of cases, grazing was completed within one season, as when grazing only happened in the summer; 42% of the time grazing occurred in more than one season. It was most common for grazing to occur in summer (39%), but only slightly more than spring (35%; Fig. S5). Grazed plots had a median size of 0.4 ha (range: 6.25 m^2–901 ha).

Monitoring approaches varied considerably between studies. Most studies (55%) were only monitored in the same year that grazing occurred, 22% were only monitored 1 year after grazing, and 23% were monitored both the year of grazing and 1 year later. Only a single study included monitoring 2 years after grazing. Fewer than half of studies used spatiotemporal controls (39%), 49% used only spatial controls, and 13% used only temporal controls.

The dataset includes studies that used cattle, goats, sheep, horses, or combinations thereof for vegetation control. Sheep were most commonly used (35%) and horses were least commonly used (2%, two studies) (Fig. 2A). Studies took place in forests, forest edges, savannas, shrublands, grasslands, wetlands, and roadsides. Sixty percent of control efforts occurred in grasslands (Fig. 2A). Notably, only treatments including goats were used in forests (one study combined goats and sheep), although other species were used along forest edges (Fig. 2A).

When livestock were used to target a specific undesired plant species, 52% of the targeted species were forbs, 30% were grasses, 14% were shrubs, and 5% were vines (Table 1). Each species of livestock was associated with control for a particular

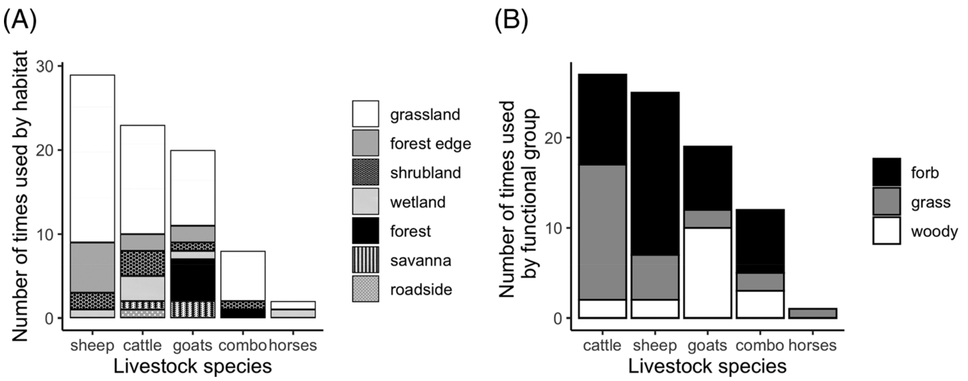

Figure 2. The number of instances that a particular livestock species was used (A) in a given habitat and (B) to control a certain functional group of undesired plants. "Combo" refers to multiple livestock species being grazed together in the same plots.

plant functional type, although there was substantial crossover: sheep were more commonly used against forbs, goats against woody plants, and cattle against grasses (Fig. 2B). Most of the targeted plant species were considered undesirable because they were invasive and nonnative in the area where they were being controlled (73%). In other cases, native species were targeted because they were aggressive, poisonous to other livestock species, or generated high fuel loads in wildfire-prone areas. Most focal plant species were perennial (82%) and most were only targeted in one study (84%). Leafy spurge (*Euphorbia esula*) was targeted in the greatest number of studies; other focal species addressed by multiple studies were medusahead (*Taeniatherum caput medusae*), yellow star thistle (*Centaurea solstitialis*), cheatgrass (*Bromus tectorum*), spotted knapweeds (*Centaurea maculosa* and *C. stoebe*), and common reed (*Phragmites australis*).

Percent cover, density, and biomass were the three most common response variables used to measure livestock grazing impacts on target species; height, reproduction, survival, and growth were also recorded (Fig. 3). Species richness was the most common measure of the effects of grazing on overall plant community composition, but diversity indices, percent cover, biomass, and density of nontarget species were also reported. In most cases, *total* rather than *native* species richness was reported; thus, additional, nontarget, nonnative—or otherwise undesirable—species may have contributed to richness measures.

Meta-Regressions

Fifty-two studies contributed to the primary model for the effects of livestock grazing on undesired focal plants. The intercept-only model shows that targeted grazing of livestock significantly reduced undesired target plants overall (Fig. 4). Cattle, sheep, and goats all significantly reduced focal undesired plants ($p < 0.0001$, Table S2, Fig. 4), but the effects of horses and livestock combinations were not significant ($p \geq 0.64$). Undesired plants were most reduced immediately after grazing and showed recovery 1 or 2 years after grazing ($p < 0.01$ for both). A model examining the effects of only measurement time on undesired

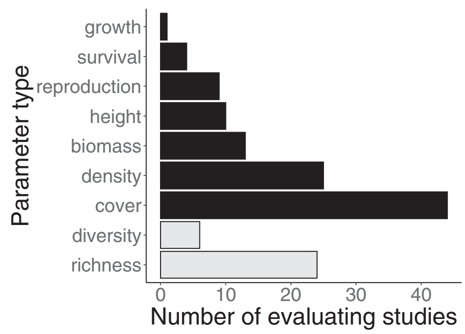

Figure 3. The number of studies evaluating different response parameters. Black bars represent parameters used to describe either an effect on a single focal plant species or multiple plant species, whereas light gray bars represent community-level parameters.

plants showed that targeted grazing effects were no longer significant 1 year after grazing occurred ($p > 0.05$, Fig. S6). The same model showed significantly more target plants in grazed plots 2 years after grazing compared to controls; however, this is based on only two effect sizes from a single study (Fig. S6). There were no significant main effects of either the number of years that plots were grazed ($p = 0.23$) or the control comparison method (temporal or spatial; $p = 0.33$).

Community-level targeted grazing effects can be described either by effects on plant richness and diversity or by effects on general plant abundance. Overall, grazing led to increases in plant community richness and diversity ($p < 0.001$; Fig. 5) and increasing years of grazing were associated with further increases in plant community richness ($p < 0.05$; Table S3). There were not significant differences in plant richness with respect to whether measures were performed immediately or 1–2 years later ($p > 0.05$). There was no overall, significant effect of targeted grazing on general plant abundance (Fig. 5, Table S4). Plant abundance did increase significantly between the year when plots were grazed and 1–2 years after grazing ceased ($p < 0.001$). Sheep, cattle, and combination treatments led to significant reductions in general plant abundance

Table 1. Plant species in the dataset targeted for control using livestock grazing ordered by number of studies. There were 45 plant species targeted across 51 studies. In addition to invasive status, species were also considered undesired due to being poisonous to other livestock or contributing to fuel loads in wildfire-prone areas. A: Aggressive, I: Invasive, F: Fire risk, T: Toxic, E: Exotic, N: Native, A: Annual, P: Perennial.

Scientific Name	*Common Name*	*Number of Studies*	*Invasive*	*Nativity*	*Functional Group*	*Annual or Perennial*	*Reference*
Euphorbia esula	Leafy spurge	7	I	E	Forb	P	Lacey and Sheley (1996); Lym et al. (1997); Olson and Wallander (1998); Taylor et al. (2005); Cornett et al. (2006); Seefeldt et al. (2007); Rinella (2013)
Taeniatherum caput medusae	Medusahead	6	I	E	Grass	A	DiTomaso et al. (2008); Robertson (2012); Davy et al. (2015); Stonecipher et al. (2016); James et al. (2017); Davy and Rinella (2019)
Centaurea solstitialis	Yellow star thistle	4	I	E	Forb	A	Wallace et al. (2008); Goehring et al. (2010); Robertson (2012); Davy et al. (2015)
Bromus tectorum	Cheatgrass	3	I	E	Grass	A	Diamond et al. (2012); Schmelzer et al. (2014); Decker (2018)
Centaurea maculosa	Spotted knapweed	2	I	E	Forb	P	Olson et al. (1997*b*); Sheley et al. (2004)
Centaurea stoebe	Spotted knapweed	2	I	E	Forb	P	Rinella (2013); Mosley et al. (2016)
Phragmites australis	Common reed	2	I	E,N	Grass	P	Silliman et al. (2014); Volesky et al. (2016)
Acroptilon repens	Russian knapweed	1	I	E	Forb	P	Rinella (2013)
Artemisia tridentata	Big sagebrush	1	F	N	Shrub	P	Decker (2018)
Brachypodium pinnatum	Heath false brome	1	A	N	Grass	P	Warda et al. (2016)
Brachypodium rupestre	False brome	1	A	N	Grass	P	Catorci et al. (2014)
Bromus hordeaceus	Soft brome	1	I	E	Grass	A	Davy and Rinella (2019)
Carthamus lanatus	Saffron thistle	1	I	E	Forb	A	Grace et al. (2002)
Centaurea biebersteinii	Spotted knapweed	1	I	E	Forb	P	Williams and Prather (2006)
Chrysanthemum leucanthemum	Ox-eye daisy	1	I	E	Forb	P	Olson et al. (1997*a*)
Delphinium nuttallianum	Two-lobed larkspur	1	T	N	Forb	P	Pfister et al. (2010)
Elaeagnus umbellata	Autumn olive	1	I	E	Shrub	P	Webb et al. (2011)
Elytrigia atherica	Couch grass	1	A	N	Grass	P	Lagendijk et al. (2017)
Erodium sp.	Filaree	1	I	N,E	Forb	A	Davy and Rinella (2019)
Genista scorpius	Scorpion broom	1	A	N	Shrub	P	Valderrabano and Torrano (2000)
Gutierrezia sarothrae	Broom snakeweed	1	T	N	Forb	P	Ralphs et al. (2007)
Hedera helix	Common ivy	1	I	E	Vine	P	Ingham and Borman (2010)
Heracleum mantegazzianum	Giant hogweed	1	I	E	Forb	P	Andersen (1994)
Lepidium latifolium	Perennial pepperweed	1	I	E	Forb	P	Williams et al. (2002)
Lepidium perfoliatum	Clasping pepperweed	1	I	E	Forb	A	Diamond et al. (2012)
Leymus racemosus	Mammoth wildrye	1	A	N	Grass	P	Zhang et al. (2011*b*)
Lythrum salicaria	Purple loosestrife	1	I	E	Forb	P	Kleppel and LaBarge (2011)
Melilotus officinalis	Yellow sweet clover	1	I	E	Forb	A,P	Scasta et al. (2019)
Mimosa pudica	Sensitive plant	1	I	E	Forb	A,P	Ajorlo et al. (2014)
Molinia arundinacea	Purple moor grass	1	A	N	Grass	P	Probo et al. (2017)
Onopordum illyricum	Illyrian thistle	1	I	E	Forb	P	Holst and Allan (1996)
Persicaria perfoliata	Mile-a-minute	1	I	E	Forb	A	Girard-Cartier and Kleppel (2015)
Phalaris arundinacea	Reed canary grass	1	A	N	Grass	P	Hillhouse et al. (2010)
Poa bulbosa	Bulbous bluegrass	1	I	E	Grass	P	Decker (2018)
Potentilla recta	Sulfur cinquefoil	1	I	E	Forb	P	Mosley et al. (2017)

Table 1. Continued

Scientific Name	*Common Name*	*Number of Studies*	*Invasive*	*Nativity*	*Functional Group*	*Annual or Perennial*	*Reference*
Quercus gambelii	Gambel oak	1	F	N	Shrub	P	Decker (2018)
Reynoutria japonica	Japanese knotweed	1	I	E	Forb	P	Brabec and Pysek (2000)
Rosa multiflora	Multiflora rose	1	I	E	Shrub	P	Rathfon et al. (2014)
Rubus armeniacus	Himalayan blackberry	1	I	E	Shrub	P	Ingham (2014)
Rumex obtusifolius	Broad-leaved dock	1	I	E	Forb	P	Sakanoue et al. (1995)
Sisymbrium altissimum	Tall tumble mustard	1	I	E	Forb	A	Diamond et al. (2012)
Smilax sp.	Greenbriar	1	A	N	Vine	P	Boggs et al. (2012)
Urochloa maxima	Guinea grass	1	I	E	Grass	P	Ramirez-Yanez et al. (2007)
Urochloa mutica	Buffalo grass	1	I	E	Grass	P	Williams et al. (2005)

($p < 0.05$), but the effect of goats was not significant ($p = 0.059$).

Discussion

We found that, across a variety of habitats and livestock species, targeted grazing generally had beneficial effects, significantly reducing undesired plant species and leading to small but significant increases in plant community richness and diversity. We did not observe an overall significant effect on neutral/desired plant abundance, but the sample size for this sub-analysis was only nine studies. While there was high variability in outcomes, and exceptions to these general patterns, our findings provide support for the use of targeted grazing as a vegetation management tool for ecological restoration. These results are in contrast with a meta-analysis of studies examining the effects of grazing in general on vegetation—as opposed to studies conducted with the explicit goal of controlling undesired plants (Stahlheber & D'Antonio 2013). Still, both the present study and Stahlheber and D'Antonio (2013) found increases in plant species richness, which Stahlheber and D'Antonio (2013) linked to increases in both native and nonnative plant species.

It should be noted that our inferences are constrained by the available data, which are notably sparse with respect to certain key response variables and monitoring approaches. A majority of studies only conducted monitoring in the same year that grazing treatments occurred, and the most commonly measured response variable was percent cover. A short-term drop in percent cover is indicative of defoliation but not necessarily mortality. Plants can tolerate substantial damage (Zhang et al. 2011*a*; Tito et al. 2016), and even overcompensate and exhibit increased reproduction in the face of herbivory (Paige & Whitham 1987). Across all studies in the dataset, the effects of grazing treatments on target plants did not remain significantly different from controls 1 year after grazing ceased. However, individual studies did find that grazing effects on target plants remained significantly different from controls 1 year after treatment (e.g. Cornett et al. 2006; Ingham 2014; Nolden 2019). These outcomes are not uncommon for plant management methods generally, such as mowing or herbicide use (Petrov & Marrs 2000; Simmons et al. 2007). Only a single study in the meta-analysis examined effects 2 years after grazing ended. Longer-term studies of outcomes should be a priority for future research. In addition, for projects seeking to not just suppress but eliminate target plants, measuring parameters like density, survival, and reproduction is necessary to determine whether livestock are actually killing target species and their potential offspring.

Plant species richness was the response variable most commonly used to assess grazing effects at the community level. While a few studies differentiated richness of native or otherwise desirable plant species (e.g. Castillo et al. 2006; Cornett et al. 2006; DiTomaso et al. 2008), most papers only reported total species richness. This lack of a specific focus on native vegetation responses is common not just in targeted grazing studies, but in invasive plant management studies more broadly (Kettenring & Adams 2011). Undesirable changes in vegetation, such as increases in invasive species or other disturbances, can result in neutral effects or even increases in total richness (Powell et al. 2013). Furthermore, control of a dominant invasive plant can result in increased abundance of subordinate invasive species, or "secondary invasions" (Pearson et al. 2016). Thus, it is critical that evaluation of management outcomes extend beyond measures of total richness to address changes in desirable (e.g. native) versus undesired (e.g. invasive) species. Based on the present dataset, we are unable to determine the extent to which increases in richness and abundance associated with grazing were due to native plant recovery versus release of undesired species.

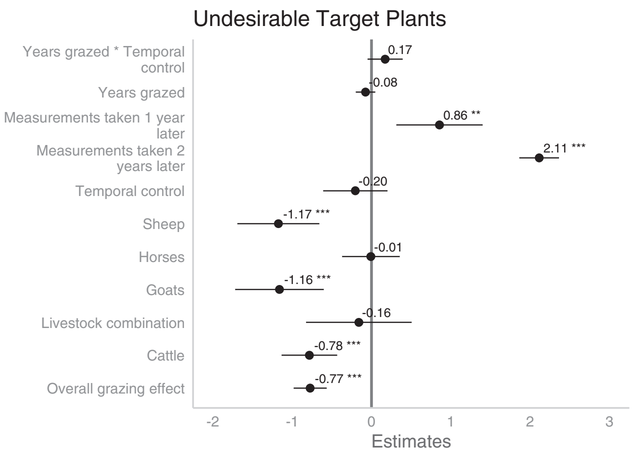

Figure 4. Forest plot of generalized estimating equation models for undesirable focal plants (mean estimate ±95% CI). Model includes 52 studies, with a maximum of 27 effect sizes from any given study. Positive values indicate an increase in undesired plants, while negative values indicate a decrease. The variables "measurements taken 1 year later" and "measurements taken 2 years later" are in comparison to measurements recorded within the year of treatment. The model includes log response ratios from all applicable parameter types: percent cover, density, biomass, height, reproduction, survival, and growth. The overall grazing effect represents an intercept-only model that estimates the mean effect of grazing treatments across studies. ** $p < 0.01$, *** $p < 0.001$.

We were surprised to find that grazing for multiple consecutive years did not significantly improve control of undesired species. One explanation for this may be site selection bias (Reid et al. 2018). Sites subjected to multiple years of control may have had particularly challenging, recalcitrant problems with undesired plants that led managers to continue grazing longer than if the invasion had been easier to manage. Managed systems are complex, and interactions between plant traits, livestock behavior and management, and environmental conditions may impede undesired plant control. Undesired species may be difficult to eliminate due to legacy effects, their persistence in seed banks or dispersal from the surrounding landscape, or insufficient competition from desirable plants (Davies & Sheley 2007; Brown et al. 2008; Lankau et al. 2014; Passos et al. 2017). While more years of grazing did not improve undesired plant control, we did find that increasing years of consecutive grazing did significantly increase plant species richness across studies in our analysis.

Across the dataset, the method that studies used for controls (comparison to the initial state of experimental plots or comparison to a separate ungrazed control) did not significantly influence outcomes. However, some individual studies found that, while grazing did not reduce the abundance of undesired target

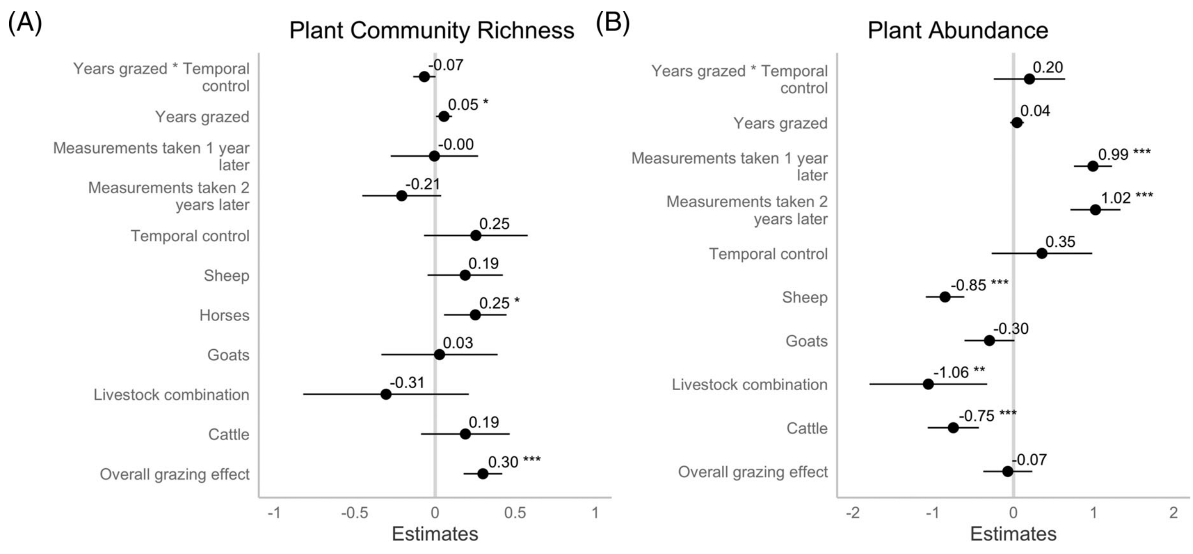

Figure 5. Forest plot for generalized estimating equation models for effects on (A) plant community richness and (B) plant abundance (mean estimate ±95% CI). Some papers reported effects on native plant richness, but most papers reported effects on plant species richness without differentiating native from nonnative species. Richness data came from 25 studies, with a maximum of 24 effect sizes from any given study. Abundance data came from 10 studies, with a maximum of 22 effect sizes from any given study. Positive values indicate an increase in plant community richness and abundance, while negative values indicate a decrease. The overall grazing effect represents an intercept-only model that estimates the mean effect of grazing treatments across studies. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

species within plots over time, grazing did prevent the increases in undesired plants that were observed in control plots (Cornett et al. 2006; Lagendijk et al. 2017), that is vegetation deteriorated less with grazing. This nuance would not have been detectable without spatiotemporal controls, which were utilized by 39% of studies in the dataset.

The majority of studies included in the meta-analysis used traditional animal–plant functional group pairings (cattle and horses to control grasses, sheep to control forbs, and goats to control woody plants). However, a considerable proportion of studies did include nontraditional pairings. Counter to conventional wisdom, many of these pairings resulted in significant reductions of the targeted plant species, e.g. using goats to control the invasive grass *Phragmites australis* (Silliman et al. 2014) or intensive cattle grazing to control the forb *Gutierrezia sarothrae* (Ralphs et al. 2007). Landscapes are often invaded by multiple exotic species (Kuebbing et al. 2013), so synthesizing existing targeted grazing research across both traditional and less traditional animal–plant pairings can shed light on the use of targeted grazing for restoration under the complex scenarios with which land managers commonly contend.

While it would have been ideal to perform separate meta-analyses for each target plant species, sample sizes would have been very small (≤7 studies), limiting statistical power and the ability to examine predictors, such as livestock species or years of grazing. A single species meta-analysis was performed to examine effects of grazing (and other methods) on medusahead control (James et al. 2015), the second most-represented target species in our meta-analysis. Overall, we found tremendous diversity in which plant species were evaluated as targets of control, with 84% of species only being targeted in a single study.

While our analysis did not evaluate the effects of grazing relative to other plant control methods, broad comparisons can be made to past syntheses. In general, studies on invasive species control involve short treatment periods and small treatment areas. For instance, >50% of invasive plant control studies applied control methods for ≤1 year (Kettenring & Adams 2011), whereas the livestock grazing studies in our meta-analysis continued treatments for a median of 3 years. In addition, <9% of invasive plant control studies treated areas >0.1 ha (Kettenring & Adams 2011), while the targeted grazing studies we examined had a median treatment area of 0.4 ha. The greater duration and spatial extent of targeted grazing studies is likely due to livestock treatments being more feasible and less expensive to apply over longer time periods, or to larger areas, than labor-intensive methods like herbicide or cutting. For example, Svejcar et al. (2014) argued that livestock grazing is one of only a few viable methods for reducing fuel loads for wildfire prevention at a landscape level. The increased treatment duration in the targeted grazing studies could also be related to the expectation that multiple years of grazing are required to kill undesired perennials, which can be killed more quickly with herbicides.

As is a common theme in restoration and invasive species research, longer-term monitoring is critically needed for decision-making (Matthews & Spyreas 2010; Trowbridge et al. 2017; Reis et al. 2021). While some experimental manipulations were maintained for many years, almost all studies only measured the effects of livestock grazing immediately or up to 1 year after treatments ended. In fact, only one study included measures taken 2 years after grazing, and in that case one of the grazing treatments had almost twice the undesired plant cover as the ungrazed control, although the difference was not statistically significant in the primary study (DiTomaso et al. 2008). It is critical that additional, longer-term monitoring be performed to determine whether this outcome was anomalous or indicative of a more prevalent pattern.

Managers should also be careful to evaluate the potential for unintended consequences before performing management activities. For example, livestock are often used to promote plant diversity in calcareous grasslands (Butaye et al. 2005), but increasing numbers of grazing events in a season can negatively affect native bees (Hopfenmüller et al. 2020). Similarly, conservation grazing on heathlands can have mixed effects on insects, such as butterfly species, depending on the successional characteristics of their host plants (WallisDeVries et al. 2016).

Targeted livestock grazing shows promise for reducing undesired plants while potentially increasing overall plant species richness, in contrast to the general use of grazing that may favor invasive species (Stahlheber & D'Antonio 2013). However, more research is needed to document the effects of targeted livestock grazing across a greater variety of ecological and management contexts and over longer time horizons, and to ensure that gains in species richness are of desirable, rather than invasive or otherwise detrimental plant species.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Reasons that studies were rejected for inclusion in the meta-analysis.
Table S2. Generalized estimating equation model for undesired focal plants.
Table S3. Generalized estimating equation for effects on neutral or desirable plant community richness and diversity.
Table S4. Generalized estimating equation for effects on neutral or desirable plant abundance.
Figure S1. Diagram showing meta-analysis search sample sizes.
Figure S2. Number of studies located in each country.
Figure S3. Number of studies located in each state of the United States.
Figure S4. (A) Numbers of days grazed per year, and (B) stocking rates used in the studies included in the meta-analysis.
Figure S5. Instances when grazing occurred at least partially in each season for the studies in the meta-analysis.
Figure S6. Single covariate generalized estimating equation model for the effect of when data were measured on the estimated effect on target, undesired plants.

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