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Original Contribution

Can Co-Grazing Waterfowl Reduce Brainworm Risk for Goats Browsing in Natural Areas?

Katherine M. Marchetto,[1] Morgan M. Linn,[1] Daniel J. Larkin,[2] and Tiffany M. Wolf[1]

[1] *Veterinary Population Medicine, 225 Veterinary Medical Center, University of Minnesota, 1365 Gortner Ave., St. Paul, MN 55108*
[2] *Department of Fisheries, Wildlife, and Conservation Biology, University of Minnesota, 135 Skok Hall, 2003 Upper Buford Circle, St. Paul, MN 55108*

Abstract: Goats browsing in woodlands, whether for livestock production goals or vegetation management (e.g., targeted grazing to control invasive plants), are at risk of meningeal worm (*Parelaphostrongylus tenuis*) infection. Indeed, up to 25% incidence has been observed in goats employed in vegetation management. Infection, which occurs via the consumption of an infected gastropod intermediate host, is potentially deadly in goats. We experimentally tested whether co-grazing with waterfowl could reduce goats' exposure via waterfowl consumption of gastropods. Gastropods were sampled in a deciduous woodland before and after the addition of goats alone, goats and waterfowl, or a control with no animal addition. We found that goats browsing on their own increased the abundance of *P. tenuis* intermediate hosts; however, when goats co-grazed with waterfowl, these increases were not observed. Importantly, waterfowl did not significantly affect overall gastropod abundance, richness, or diversity. Thus, waterfowl co-grazing may effectively reduce goat contact with infectious gastropods without detrimentally affecting the gastropod community. While co-grazing goats with waterfowl may decrease their *P. tenuis* exposure risk, additional research is needed to confirm whether waterfowl can actually lower *P. tenuis* incidence.

Keywords: ecological restoration, *Parelaphostrongylus tenuis*, targeted grazing, terrestrial gastropods

INTRODUCTION

Invasive plants can have highly detrimental impacts on ecosystem health, including biodiversity loss (Flory and Clay 2009; Pyšek et al. 2012), disease spillover to native hosts (Malmstrom et al. 2005), and increases in vector-borne and zoonotic diseases (Civitello et al. 2008; Allan et al. 2010; Reiskind et al. 2010; Stone et al. 2018; Wei et al. 2020). In addition to widely adopted methods of invasive plant control, such as applying herbicide, cutting, or burning (Kettenring and Adams 2011), interest has grown in the use of livestock grazing or browsing for vegetation management (Richardson 2014; Derner et al. 2017). Targeted grazing, a method that controls grazing timing, duration, and intensity for specific vegetation manipulation goals (Bailey et al. 2019), has been found to reduce undesirable plant abundance in a meta-analysis (Marchetto et al. 2021). Targeted grazing using goats has become increasingly common for a variety of reasons, including their

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Correspondence to: Katherine M. Marchetto, e-mail: march313@umn.edu

preference for woody vegetation and ability to traverse hilly terrain (Hart 2001; Richardson 2014). In addition, one-third of goat producers in the U.S. report that weed control is a very important reason for them to raise goats (USDA 2010). However, using livestock for invasive plant management could expose working animals to new health risks, as they are translocated between natural areas with different biota, trophic interactions, and diseases. Furthermore, while most general goat operations (e.g., for meat production) do not involve the frequent moves associated with using goats for targeted grazing, they may nonetheless expose animals to similar natural habitats. This is reinforced by 43% of U.S. goat producers relying entirely on weeds and/or browse to feed their goats (USDA 2010).

Goats browsing in natural areas in North America are at risk of contracting a potentially deadly nematode parasite (brainworm or meningeal worm, *Parelaphostrongylus tenuis*) of white-tailed deer (*Odocoileus virginianus*). *Parelaphostrongylus tenuis* has little effect on its definitive host, white-tailed deer (Anderson 1972), so infection prevalence can be as high as 90%, with larval shedding in feces occurring in 50–60% of infected individuals (Cyr et al. 2014). However, the consequences of infection can be severe in incidental hosts, including goats, sheep, alpacas, and llamas. In incidental hosts, *P. tenuis* larvae aberrantly migrate through the spinal cord and brain, causing neurological damage that can lead to partial paralysis or death (Lankester 2002). Goats and other ungulates are exposed to *P. tenuis* following inadvertent consumption of terrestrial gastropods, within which the parasite completes two life stages before becoming infectious (Anderson 1963). *Parelaphostrongylus tenuis* incidence in livestock varies greatly annually (Keane et al., *in revision*), but can reach up to 15%-22% of a goat herd in a high-prevalence year (Guthery et al. 1979; Still Brooks 2016).

A novel means to reduce the risk of *P. tenuis* exposure in goats browsing in natural areas could be to reduce the abundance of gastropod intermediate hosts by co-grazing goats with waterfowl, such as ducks and geese. A widely known example of using waterfowl to control undesired gastropods is the use of ducks to control pest snails in irrigated rice fields (Teo 2001). Waterfowl have also been shown to reduce the abundance of snail intermediate hosts for parasites such as schistosomes (Ndlela and Chimbari 2000) and the liver fluke *Fasciola hepatica* (Samson and Wilson 1973). Additionally, the use of guinea hens to control gastropod intermediate hosts of *P. tenuis* has been suggested but not evaluated (Still Brooks 2016).

Gastropod consumption by waterfowl could also be ecologically beneficial if non-native gastropod species are disproportionately eaten. Non-native gastropods can have detrimental effects on native or endangered plant species, more so than for non-native plants (Joe and Daehler 2008; Hahn et al. 2011; Blattmann et al. 2013; Shiels et al. 2014). In addition, one non-native slug species, *Deroceras reticulatum*, has been shown to harm native plants in Midwestern woodlands (Hahn et al. 2011). This species is also a known intermediate host of meningeal worm, so reductions in its abundance could both aid native plants and reduce meningeal worm exposure in goats foraging in natural areas.

We experimentally tested the effects of waterfowl and goats, goats alone, or no livestock addition on *P. tenuis* intermediate host abundance in a deciduous woodland where goats were used to control the invasive shrub common buckthorn (*Rhamnus cathartica*). We hypothesized that co-grazing waterfowl with goats would decrease *P. tenuis* intermediate host abundance, which would be beneficial from an ecosystem health perspective. A secondary potential benefit we expected to observe was waterfowl reduction of non-native gastropod abundance. Countering these potential benefits, we hypothesized that waterfowl addition would also decrease total gastropod abundance, richness, and diversity, which would be generally undesirable from a conservation perspective.

MATERIALS AND METHODS

Study site: The study took place at the University of Minnesota's Rosemount Research and Outreach Center in Rosemount, MN (USA). The site is a mesic hardwood forest, with an overstory consisting primarily of *Celtis occidentalis* (hackberry), *Ulmus americana* (American elm), *Fraxinus pennsylvanica* (green ash), *Rhamnus cathartica* (common buckthorn), *Acer negundo* (boxelder), *Prunus serotina* (black cherry), *Populous tremuloides* (trembling aspen), and *Quercus rubra* (northern red oak). The site has a continental climate, with cold winters and warm summers. Average temperatures in the winter, spring, summer, and fall are -5°, 15°, 22°, and 2 °C respectively (MNDNR 2021). Average precipitation in winter, summer, spring, and fall is 8.5, 30, 28, and 13.6 cm, respectively (MNDNR 2021). The management area containing the study site has approximately 0.035 deer ha^{-2} (D'Angelo and Giudice 2016), which is considered a low deer density for the region (Russell et al. 2001). This site was also a location where goats were being used for targeted grazing on a temporary, seasonal basis to control the invasive shrub, *Rhamnus cathartica.*

Experimental design: The experiment consisted of a control area with no animal additions and two treatments: goats only or goats + waterfowl. Waterfowl were added to the goats + waterfowl treatment before the goats to pretreat the area (33 days pretreatment in 2019, 20 days in 2020), and co-grazed with the goats in the goats + waterfowl treatment. Waterfowl additions began on August 18, 2019 and September 10, 2020. Eleven geese and six ducks were used to pretreat the area in 2019, with one goose lost to predation and the addition of five ducks concurrent with addition of goats. Thirteen geese were used in 2020. All animals were removed from the site on October 1 in 2019 and October 12 in 2020. This yielded waterfowl stocking rates of 1.57 animal unit months (AUM) per hectare in 2019 and 0.88 AUM/ha in 2020. Average goat stocking rates were 0.78 AUM/ha during the study. A detailed accounting of the AUM/ha calculations can be found in Table S1. Goats comprised a variety of breeds, ducks were Anconas, and geese were primarily Toulouse and Emdens. The experimental procedure was reviewed and approved under the University of Minnesota IACUC protocol 1802-35546A.

Gastropod sampling. Gastropods were sampled before and after the addition of waterfowl and goats, one day after a rain event on both occasions. Sampling occurred within three days of waterfowl addition and animal removal from the site. Gastropod populations are highly spatially clumped (Cameron and Pokryszko 2005), so we sampled at multiple evenly spaced locations along transects and aggregated the data for each transect and time point. Three transects were randomly located within each treatment area, each with three quadrats separated by 7 m. Different quadrat locations (separated by 2 m) were sampled before and after animal additions to avoid carryover effects of the previous sampling. At each sampling location, all litter and the top 2 cm of soil were removed from square, 40.6-cm × 40.6-cm quadrats and brought back to the lab for sorting through a series of sieves (Coppolino 2010). Large pieces of detritus were examined in the field, and any gastropods found thereon were retained. Samples were stored in plastic bags at 4°C, with a moist paper towel to prevent drying and attract slugs. Only live gastropods were counted. A dichotomous key for terrestrial gastropods of Wisconsin and surrounding states was used to identify snail specimens (Nekola 2000). Slugs were identified using Burch (1962). Voucher specimens are stored at the Bell Museum of Natural History in St. Paul, MN. Data are available at https://doi.org/10.13020/pz48-e352.

Statistical analysis. All analyses were performed using the statistical software R (R Development Core Team 2019). Quadrat samples were aggregated by transect and sampling time prior to analysis. Univariate response data were analyzed using generalized linear mixed-effects models with the *glmmTMB* package (Brooks et al. 2017). Univariate responses analyzed were counts of intermediate hosts, non-native gastropods, and all gastropods; gastropod species richness; and gastropod Shannon diversity. There is some uncertainty regarding which gastropod species are intermediate hosts of *P. tenuis*; in two instances *P. tenuis* has been observed in specimens only identified to genus, *Cochlicopa* sp. and *Strobilops* sp. (Platt 1989; Cyr et al. 2014). Therefore, we performed two analyses for intermediate host numbers, a conservative test comprising only species that have conclusively been identified as intermediate hosts and a more liberal test that included *Cochlicopa lubricella* and *Strobilops aeneus,* two species identified at our sites that may serve as intermediate hosts. Only one non-native species, *Deroceras reticulatum,* was found at our site during sampling. *Deroceras reticulatum* is a slug and a known *P. tenuis* intermediate host (Parker 1966). Treatment, timing, their interaction, and year were used as fixed effects in all univariate response models, with transect as a random intercept to account for spatial non-independence associated with nested sampling. Poisson errors generally fit the data best, with the exception of Shannon diversity (Gaussian) and the more inclusive count of intermediate hosts (negative binomial). Wald chi-square tests were used to determine the significance of model terms (Fox and Weisberg 2019), with post-hoc tests to compare levels of the treatment × timing interaction using the *emmeans* package (Lenth 2020).

Differences in gastropod community composition among treatment groups were visualized with non-metric multidimensional scaling (NMDS) ordination using the *vegan* package (Oksanen et al. 2019). The *betadisper* function in *vegan* was used to confirm the homogeneity of dispersions among treatment groups. To test whether treatments significantly differed in gastropod composition, we used multivariate generalized linear models (GLMs) using the *mvabund* package (Wang et al. 2020), followed by similarity percentage (SIMPER) analysis in *vegan* to identify which gastropod species contributed most to compositional differences between groups. The multivariate GLM used the species-by-site community matrix as the response, and included as fixed effects treatment, timing, treatment × timing interaction, year, and transect, with a negative binomial error distribution.

Across all analyses, we were most interested in identifying significant interactions between livestock treatment (control, goats, or goats + waterfowl) and timing (before vs. after treatment). A significant main effect of livestock treatment alone would indicate that treatment areas differed consistently throughout the experiment, whereas a significant effect of timing would indicate a seasonal influence across livestock treatments. In contrast, a significant interaction between treatment and timing would indicate that livestock treatments differed in the rate of change between sampling times, beyond the effects of pre-existing site differences or seasonality alone.

RESULTS

Seventeen species of terrestrial gastropods were identified during sampling (Table S2). Five of these species are known *P. tenuis* intermediate hosts, and two additional species, *C. lubricella* and *S. aeneus*, are potential hosts. A total of 971 individuals were collected, of which 16% were known intermediate hosts—increasing to 31% when *C. lubricella* and *S. aeneus* are considered to be intermediate hosts. *Vallonia costata*, *V. pulchella*, *C. lubricella*, and *D. reticulatum* were the most abundant species.

Abundance of *P. tenuis* intermediate hosts differed between livestock treatments over time (Figure 1A; Table 1, treatment × timing interaction: $p = 0.002$). The abundance of *P. tenuis* intermediate hosts was significantly higher *after* goats browsed the site in comparison to controls (post-hoc test: $p = 0.02$). While co-grazing goats with waterfowl did not lower intermediate host abundance compared to controls (post-hoc test: $p = 0.23$), co-grazing with waterfowl did prevent the increase in intermediate host abundance observed when goats browsed alone. Using a less conservative definition of intermediate hosts (i.e., including *C. lubricella* and *S. aeneus*), did not qualitatively affect these patterns (Table S3; Figure S1).

There was a marginally significant effect of the interaction between livestock treatment and timing on non-native gastropod abundance (i.e., abundance of *D. reticulatum*, an intermediate host) (Figure 1B, Table 1; $p = 0.085$). This was driven by a reduction in *D. reticulatum* abundance when goats were co-grazed with waterfowl compared to controls (post-hoc test: $p = 0.047$); *D. reticulatum* abundance was similar between goat-only and control treatments (post-hoc test: $p = 0.98$).

Livestock treatment had a significant effect on overall gastropod abundance (Figure 2; Table S4; $p < 0.0001$), but not species richness ($p = 0.42$) or Shannon diversity

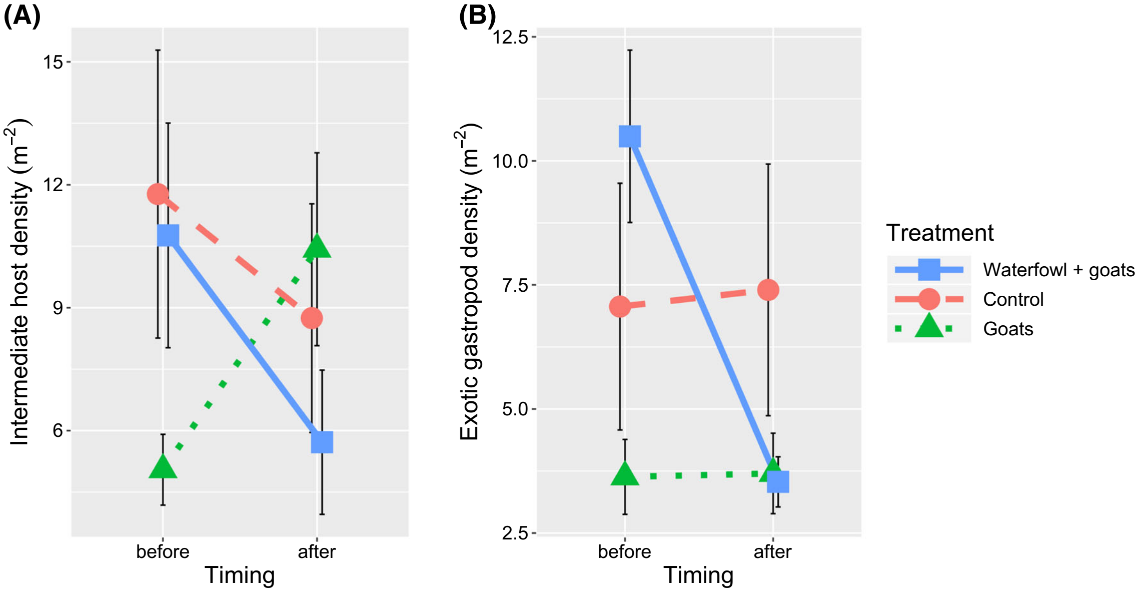

Figure 1. Effects of treatments on **A** meningeal worm (*Parelaphostrongylus tenuis*) intermediate host density and **B** non-native gastropods. At the study site, the only non-native gastropod species observed was the slug *Deroceras reticulatum*, an intermediate host of *P. tenuis*. Bars denote standard errors.

Table 1. Analysis of deviance and post-hoc interaction tests for generalized linear mixed-effects models of meningeal worm (*Parelaphostrongylus tenuis*) intermediate host abundance and non-native gastropod abundance. Transect was used as a random effect in the models; the error family was Poisson. $^{*}p < 0.05$; $^{**}p < 0.01$.

	Intermediate hosts				Non-native gastropods			
	Chi. Sq	Df	*P*-value		Chi. Sq	Df	*P*-value	
Treatment	0.31	2	0.856		7.70	2	0.021	*
Timing	0.91	1	0.340		1.17	1	0.279	
Year	1.26	1	0.261		3.76	1	0.052	
Treatment × Timing	12.52	2	0.002	**	4.93	2	0.085	
Post-hoc tests for treatment × timing Interaction								
	Estimate	t-ratio	*P*-value		Estimate	t-ratio	*P*-value	
control vs. goat	−1.02	−2.51	0.018	*	−0.01	−0.02	0.983	
waterfowl vs. control	−0.49	−1.23	0.229		−1.10	−2.09	0.047	*

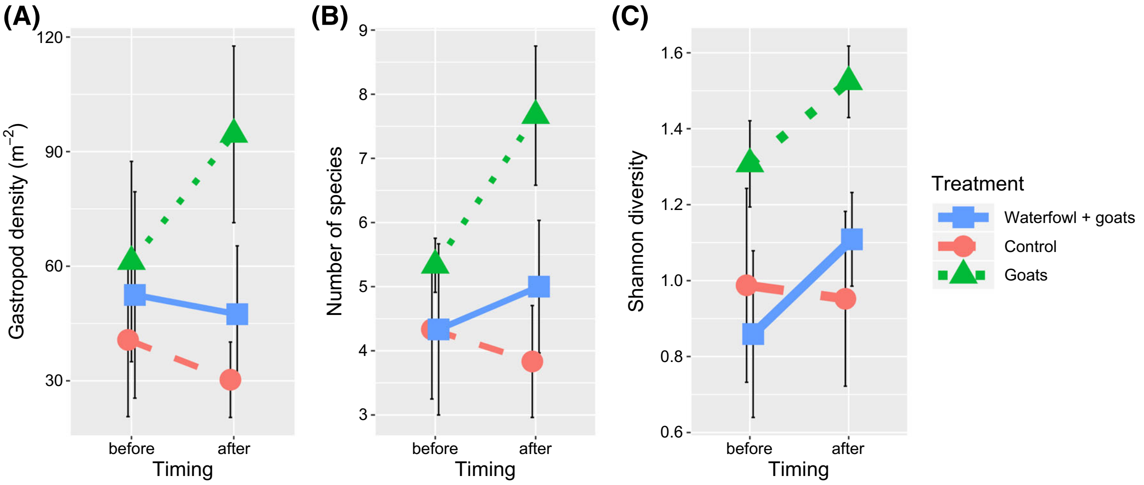

Figure 2. Effects of treatments on gastropod **A** density, **B** species richness, and **C** Shannon diversity. Bars denote standard errors.

($p = 0.60$). Specifically, gastropod abundance was higher in goat than control treatments (post-hoc test: $p < 0.001$) but similar between control and goat + waterfowl treatments (post-hoc test: $p = 0.29$).

While gastropod species richness and Shannon diversity were not significantly altered by the addition of livestock, multivariate analysis revealed significant differences in community composition with livestock treatments (Figure 3; Table 2; $p = 0.032$). Control transects showed similar community composition over time (little movement in ordination space), whereas livestock-treated transects showed higher turnover in community composition (larger movements in ordination space; Figure 3). Based on SIMPER analysis, overall differences in community composition before and after animal additions were most driven by differences in abundance of *Vallonia pulchella* and *V. costata* (Table S5). Specifically, 87% of the difference in control transects over time was driven by increases in *D. reticulatum* and *C. lubricella* and decreases in *V. pulchella* and *V. costata*. In the goat transects, 84% of the difference in transects over time was driven by increases in *V. pulchella*, *V. costata*, and *C. lubricella*, while *Nesovitrea electrina* decreased in goat transects. Finally, 84% of the difference in goat + waterfowl transects over time was driven by increases in *Zonitoides arboreus* and *V. pulchella* as well as decreases in *D. reticulatum* and *V. costata*. Of these species, *D. reticulatum* and *Z. arboreus* are confirmed *P. tenuis* intermediate hosts and *C. lubricella* is a possible host (Parker 1966; Platt 1989).

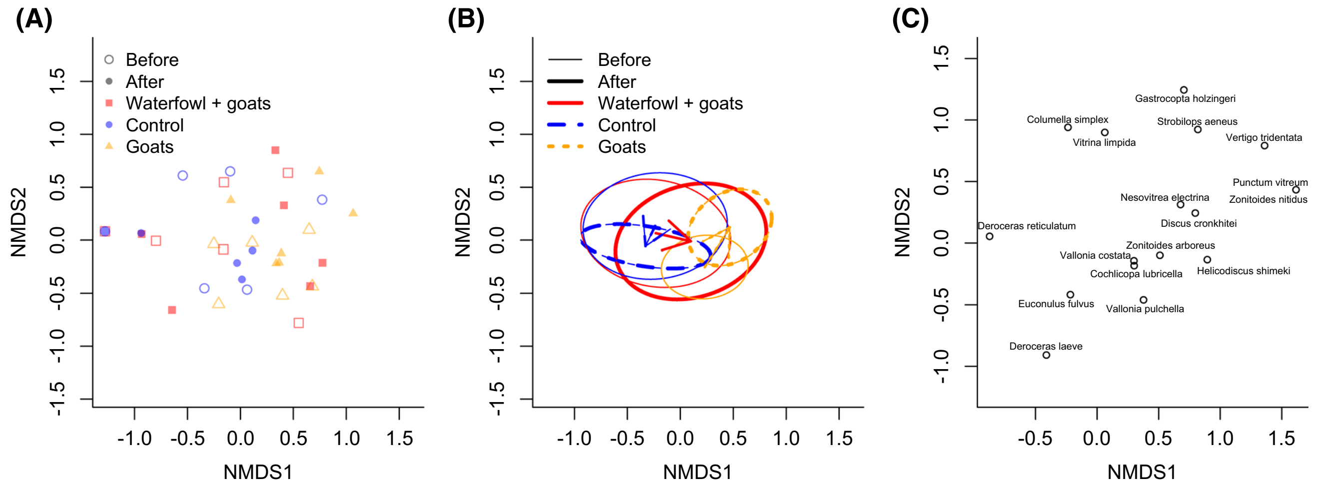

Figure 3. Non-metric multidimensional scaling plots of gastropod community composition showing **A** individual transects, **B** ellipses representing one standard deviation around the centroid for groups shown in panel A, and **C** the position of gastropod species in ordination space. The arrows in panel B show a change in the composition of each centroid before and after livestock treatment. The stress of the NMDS ordination is 0.15.

Table 2. Multivariate generalized linear model for gastropod community composition. *$p < 0.05$; **$p < 0.01$.

	Residual DF	DF difference	Deviance	*P*-value	
Intercept	35	–	–	–	
Treatment	33	2	65.39	0.042	*
Timing	32	1	18.96	0.416	
Transect	24	8	231.31	0.001	***
Year	23	1	70.81	0.001	***
Treatment × Timing	23	2	49.53	0.032	*

Discussion

Co-grazing goats with waterfowl appeared to prevent the increase in *P. tenuis* intermediate host abundance that was observed when goats alone grazed a deciduous woodland. There was also a marginal reduction in non-native gastropod abundance in goat + waterfowl treatments compared to controls. Contrary to our expectations, overall gastropod abundance, richness, and diversity were unaffected by co-grazing waterfowl with goats. Goat-only treatments were associated with an increase in total gastropod abundance but not gastropod richness or diversity. Livestock treatments were also associated with differences in gastropod community composition. These results have implications for potential parasite-infection risk-mitigation strategies for goats foraging in natural areas, including those used for targeted grazing to control invasive plants, an increasingly popular land-management strategy. Furthermore, targeted grazing by goats, both with and without the addition of waterfowl to reduce *P. tenuis* infection risk, did not have detrimental impacts on terrestrial gastropod communities.

Increases in the abundance of intermediate hosts, and gastropods generally, following browsing by goats (absent waterfowl) were unexpected. We hypothesized that browsing by goats would lead to fewer gastropods, as decreases in plant density should be associated with drier, warmer ground-level conditions. However, some terrestrial gastropod species are attracted to ungulate feces (Garvon and Bird 2005), which may explain increased gastropod abundance in areas browsed only by goats. These increases were not observed when goats co-grazed with waterfowl. From a disease risk standpoint, the timing of gastropod attraction and consumption matters for *P. tenuis* exposure in goats. With our study design, we are unable to differentiate whether waterfowl decreased intermediate hosts throughout their time on-site or if they mainly removed gastropods that colonized in response to the addition of goats and their feces. If the former, then pretreatment with waterfowl could decrease initial host abundance and thus exposure risk for goats. We did not determine how long gastropod abundance remained elevated following goat browsing.

From the standpoint of terrestrial gastropod conservation, we found that neither targeted grazing by goats nor co-grazing of goats with waterfowl reduced gastropod abundance, richness, or diversity. This contrasts with findings from intensive production grazing systems, where livestock grazing can negatively affect terrestrial gastropods (Baur et al. 2007; Boschi and Baur 2007). Invasive plants are also known to affect terrestrial gastropod abundance and diversity—either positively or negatively depending on circumstances (Stoll et al. 2012; Ruckli et al. 2013). For instance, the presence of the invasive plant *Impatiens glandulifera* (ornamental jewelweed) modifies forest microclimates in ways that increase terrestrial gastropod abundance, with common gastropod species increasing more than rarer species (Ruckli et al. 2013). Conversely, invasion by *Fallopia japonica* (Japanese knotweed) reduced overall gastropod abundance (Stoll et al. 2012). In particular, large and long-lived species were most likely to be negatively affected. Thus, in some systems, targeted grazing could have indirect effects on gastropod communities via effects on plant species density and composition.

Our results suggest that co-grazing waterfowl with goats could potentially be used to mitigate the exposure of goats to *P. tenuis*, but additional research is needed. In particular, further work that covers more habitat types and occurs over longer time scales would enable stronger inferences. Gastropod intermediate hosts of *P. tenuis* vary in abundance in different habitat types and at different times of year (Kearney and Gilbert 1978; Cyr et al. 2014). While our study was conducted at a time hypothesized to be most important for *P. tenuis* infection in goats (late summer and early fall), other seasons when gastropods are active could still be important for transmission (Still Brooks 2016; Lankester 2018).

In addition, we addressed *potential* exposure of goats in terms of intermediate host availability. Direct tests of actual *P. tenuis* exposure through immunological assays—and the effectiveness of waterfowl for reducing such exposure—are needed. At this time, no antemortem immunological assay had been validated for *P. tenuis* exposure in goats, although diagnostic research and development may allow direct tests of exposure risk in the future. Current disease management recommendations to limit *P. tenuis* infection in livestock include limiting the contact of livestock with gastropod intermediate hosts, but the exact relationship between gastropod intermediate host abundance and risk is unknown and subject to several modifying factors. These factors include white-tailed deer density, *P. tenuis* incidence and larval shedding rates in white-tailed deer, weather conditions, and species of intermediate hosts present (Lankester and Peterson 1996; Lankester 2001, 2018; Vanderwaal et al. 2015).

While the goats used in this experiment work full time on plant management activities across numerous locations, which logistically complicates a waterfowl co-grazing strategy, goats feeding on natural browse that are managed within one property could be better targets for this strategy. For instance, 95% of goat operations in the US remain on land owned by the operation (USDA 2010). Some logistical hurdles to implementing co-grazing of goats with waterfowl include rounding up the waterfowl when it is time to move to a new browsing location, the inability to use bodies of water as natural boundaries to contain waterfowl (as can be done for goats), and differences in fencing needs for goats vs. waterfowl. Waterfowl are also at greater risk of predation than goats, with geese being generally less vulnerable than ducks.

While goats can be exposed to wildlife parasites when browsing in natural areas, it is worth noting that the reverse may occur, with domestic species transmitting parasites or other pathogens to wildlife. For instance, *Mycobacterium bovis*, a pathogen of cattle, has spilled over into several wildlife species, including white-tailed deer, in which it has become endemic, now complicating its control in cattle (Palmer 2008; VerCauteren et al. 2018). Domestic sheep and goats have also been identified as sources of diseases that have been responsible for population declines in wildlife, including *Mycoplasma ovipneumoniae* (Kamath et al. 2019) and likely chronic wasting disease (Cassmann et al. 2021). Domestic and wild ruminants are known to share parasite species (Winter et al. 2018), but it is often difficult to demonstrate transmission events across the livestock-wildlife interface (Morgan et al. 2006). Thus, it is equally important to consider the health of goats used in natural areas because of the potential for pathogen transmission in either direction.

Vegetation management using goats occupies the nexus of several key challenges in eco-health. The use of targeted goat browsing can reduce the abundance of targeted invasive plants and increase plant species richness (Marchetto et al. 2021), but the trophic linkages present in woodlands expose domestic goats to a potentially deadly wildlife parasite. Manipulating these trophic interactions by introducing waterfowl can prevent the increase in intermediate hosts of the parasite observed when goats browse alone, without negative conservation consequences for terrestrial gastropods. Further applied research is needed to investigate the viability of this novel approach to disease management for domestic livestock employed in natural areas.

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