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Response of vegetation and carbon fluxes to brown lemming herbivory in northern Alaska

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Supplementary Materials

S1 Supplementary Information

In addition to our main experiment, we incorporated predator cues from major predators of lemmings in order to examine the potential for indirect effects of predators on herbivory rates (Beckerman et al., 1997; Schmitz, 2005). These predators include the snowy owl, parasitic jaeger (arctic skua), arctic fox, and ermine (Fauteux et al., 2018a, b). In doing so, we wanted to better understand how the presence of predator cues could impact lemming behavior and thus impact vegetation. We predicted predator cues would elicit a fear response in the lemmings, therefore decreasing the time spent consuming vegetation and altering carbon cycling.

S1.1 Experimental design

We introduced several indirect predator cues to some of the enclosure plot sets to record the effect lemmings in presence of predators may have on vegetation consumption compared to the effect of lemmings alone, without the predator cues. Four of the 10 plot sets had an additional lemming plot to serve as a predator treatment. Once the initial experiment (with the control and no-predator lemming plots) was complete, we placed lemmings in these additional enclosures. Lemmings received a similar resting period between treatments and were presented cues representative of their main predators (fox, jaeger, owl, ermine) one at a time in a random order. After an hour of exposure to a random cue, each lemming had a resting period of approximately one hour and then was introduced to a new predator cue. To create an indirect fox cue, we used urine, a chemical cue known to induce fear and widely used in other studies of the antipredator behavior of rodents (Apfelbach et al., 2005; Borowski and Owadowska, 2001; Dickman and Doncaster, 1984; Fendt, 2006). As a control for predatory urine, we also exposed the lemmings to urine from caribou (an herbivorous ungulate, which is not a predator of lemmings). We measured the urine out in about 200 microliter (10 drops) aliquots, labeled, and placed that amount in individual Eppendorf tubes. We dispensed each of the urine samples from the tubes separately on paper towels in small plastic containers with holes in the lids to provide a scent cue when introduced to the lemmings, but also avoid direct contamination of the tundra with urine from foreign sources. We tested acoustic cues by playing back auditory calls of the snowy owl (Christe, 2015; Suvorov, 2015), parasitic jaeger (Boesman, 2016), and ermine (Free Information Society, 2008). We downloaded the auditory calls onto a mobile phone that we used in the field. For auditory cues, we played the predator call repeatedly three times every 15 minutes for one hour (four playbacks of three calls during each playback). For chemical cues, the urine remained contained in the enclosure for the entirety of the allotted time to prevent an indirect effect on the vegetation and carbon fluxes.

S1.2 Camera footage

After the predatory simulation portion of the experiment, we examined the behavioral responses, or lack thereof, using the time-lapse footage. We examined these video data for noticeable changes in behavior to the different experimental treatments in order to gain insight into the possible effects of the indirect predator cues.

S1.3 Statistical analyses

The same statistical analyses in the initial experiment were applied to the lemming with predator cue plots data to help reveal if predator cues had a different effect on vegetation than the lemming without predator cues plots.

S1.4 Environmental variables

During summer 2018, measurements of the control and lemming plots with predator cues were not significantly different for air temperature (P = 0.492), soil temperature (P = 0.364), and soil moisture (P = 0.291). Due to the substantial spatial heterogeneity of these polygonised tundra ecosystems (because of the presence of continuous permafrost; Zona et al., 2011), predator cue experimental plots were shallower by 2-7 cm and had significantly different thaw depths than control plots (P = 0.011). During summer 2019, measurements of the control and lemming plots with predator cues were not significantly different for air temperature (P = 0.333), soil temperature (P = 0.984), thaw depth (P = 0.144), and soil moisture (P = 0.160).

S1.5 Carbon fluxes

We found no indication that the indirect predator cues we used affected the impact of lemming behavior on carbon fluxes. Direct observations during the experiment showed that lemmings exhibited little or no response to auditory or olfactory predator cues, and even when they did respond, these cues did not affect their feeding behavior long enough to influence carbon fluxes relative to no-predator plots. NEE in treatment plots with and without predator cues had comparable outcomes. Similar to lemming plots without predator cues, lemming plots with cues showed a significant change in NEE values (P = 0.042), and by the end of summer 2018, the effect of brown lemmings' herbivory changed the mean NEE for lemming plots with predator cues from -0.080 ± 0.019 $gC\text{-}CO_2m^{-2}h^{-1}$ to 0.001 ± 0.019 $gC\text{-}CO_2m^{-2}h^{-1}$. However, CH_4 flux values did not significantly differ between treatments (P = 0.079). Measurements from 2019 show that NEE, ER, GPP, and CH_4 flux were all not significantly different between the control and lemming plots with predator cues (NEE P = 0.587, ER P = 0.950, GPP P = 0.737, and CH_4 flux P = 0.863).

S1.6 Hyperspectral surface reflectance and NDVI

Although they trended in the same direction as the NDVI values of the lemming plots without predator cues, the NDVI values for the lemming plots with predator cues were not statistically different from the control plot values during the first summer (P = 0.103). In the second summer, median NDVI values of all plots were similar. During this time, there was no significant difference in NDVI when comparing control plots to lemming plots with cues (P = 0.208).

We did not find a strong indication that indirect predator cues impacted carbon fluxes or lemming foraging behavior, as lemmings continue to eat unless they perceive themselves to be in immediate danger. NEE from the lemming plots with predator cues had the same patterns as the no-predator treatment during both summer seasons. This result was likely due to the lack of fear responses of lemmings toward our auditory or olfactory cues; direct behavioral observations showed that lemmings scarcely paused in their vegetation consumption after encountering cues. This feeding behavior is consistent with a life history oriented toward very quick growth and reproduction and high mortality (Ims and Fuglei, 2005). However, extensive documentation of bank voles, a somewhat closely related rodent species to lemmings, reveals a strong response to olfactory cues from a predatory weasel species (Bleicher et al., 2018; Sievert et al., 2019).

In light of these studies, our findings suggest that brown lemmings may need a much stronger indirect cue to indicate predatory risk, or a direct cue (i.e., an imminent attack), before altering their feeding behavior enough to substantially impact carbon fluxes. There may also be a species difference between bank voles and brown lemmings, in which lemmings are much less risk-adverse than the average *Myodes* species. It is worth noting that the enclosure design may have also provided enough cover and a sense of safety to ease the behavioral response of lemmings to the predatory cues.

	First Quartile	Median	Third Quartile
2018			
Air Temperature	7.08	7.65	7.90
Soil Temperature	2.95	3.15	3.55
Thaw Depth	20.75	22.50	24.25
Soil Moisture	54.20	58.60	65.00
NEE (Before)	-0.09422	-0.07085	-0.05774
NEE (After)	-0.01969	-0.00060	0.01957
CH_4 Flux (Before)	0.03367	0.08756	0.13483
CH_4 Flux (After)	0.07430	0.10798	0.15843
NDVI (Before)	0.4905	0.5705	0.6603
NDVI (After)	0.4730	0.5253	0.5650
2019			
Air Temperature	12.68	13.70	14.88
Soil Temperature	1.63	3.90	4.63
Thaw Depth	18.50	34.00	37.25
Soil Moisture	56.33	63.00	71.53
NEE (Pre-Growing Season)	0.00790	0.01026	0.01404
NEE (Early Growing Season)	-0.04556	-0.04074	-0.03633
NEE (Peak Growing Season)	-0.1182	-0.1168	-0.1057
ER (Pre-Growing Season)	0.04078	0.05325	0.06991
ER (Early Growing Season)	0.06832	0.07968	0.09032
ER (Peak Growing Season)	0.06267	0.06466	0.06575
GPP (Pre-Growing Season)	0.03039	0.04399	0.05936
GPP (Early Growing Season)	0.10468	0.12057	0.13600
GPP (Peak Growing Season)	0.1676	0.1796	0.1830
CH_4 Flux (Pre-Growing Season)	-0.00100	0.01523	0.14569
CH_4 Flux (Early Growing Season)	0.01652	0.03931	0.08447
CH_4 Flux (Peak Growing Season)	0.5968	0.8729	1.9053
NDVI (Pre-Growing Season)	0.2452	0.2515	0.2596
NDVI (Early Growing Season)	0.5447	0.5724	0.5872
NDVI (Peak Growing Season)	0.7031	0.7111	0.7133

Table S1. First quartile, median, and third quartile values for the various data measurements collected from the experimental lemming plots with predator cues during summer 2018 and summer 2019.

S2 Supplementary Figures

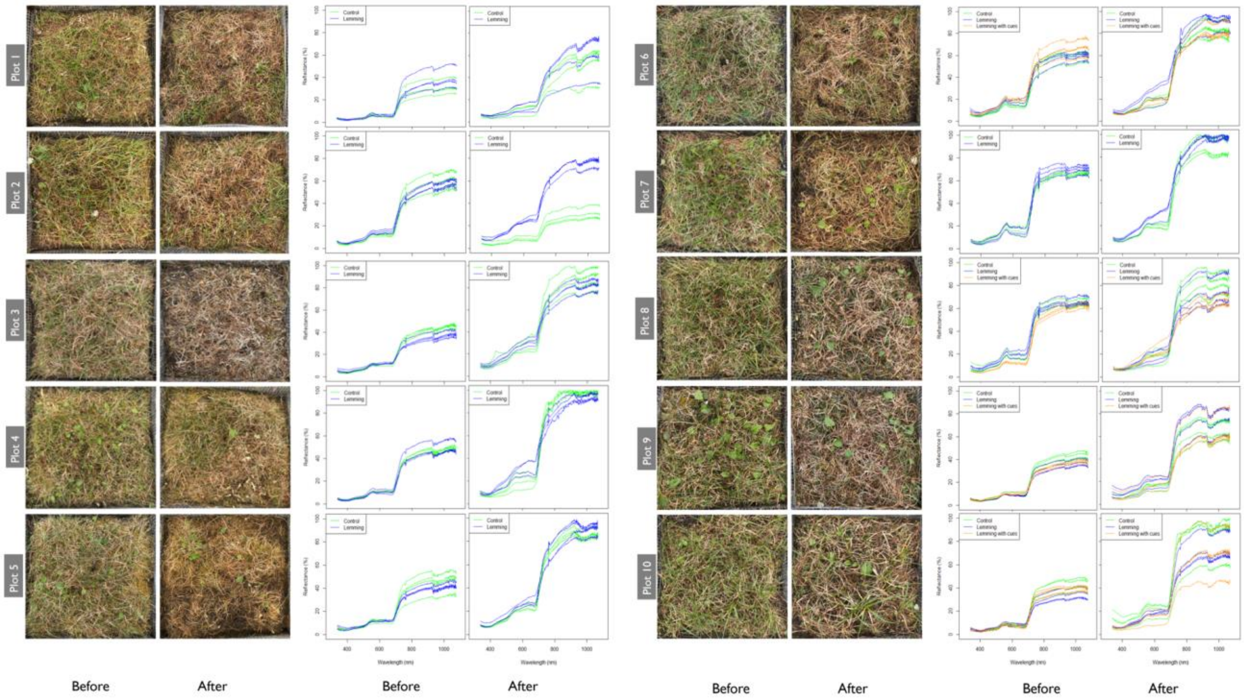
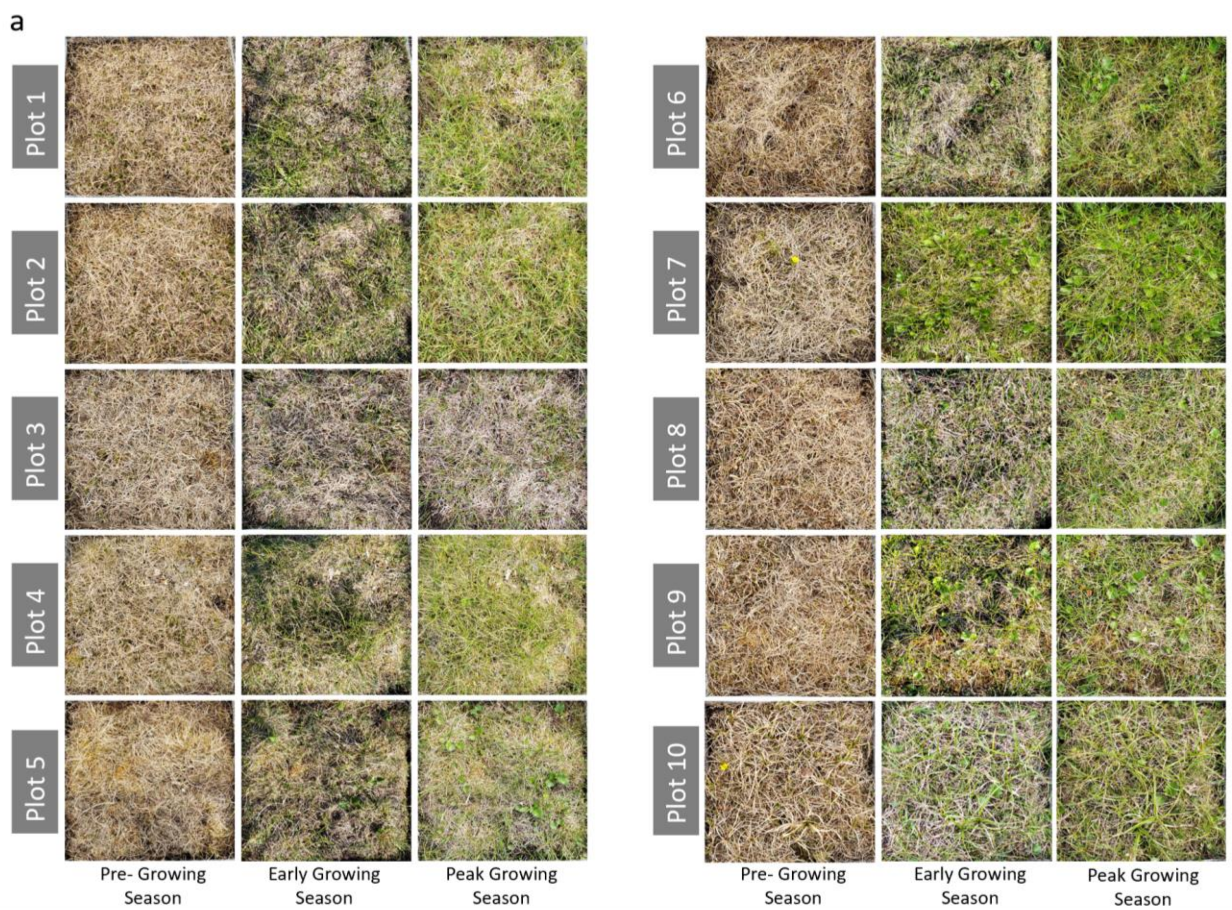


Figure S1. Ground photos and hyperspectral reflectance curves for plot sets with pre-lemming (before) and post-lemming (after) plots (summer 2018). Photos and reflectance curves show the impact one lemming has on each enclosed plot over the 16-hour experiment. The hyperspectral surface reflectance for wavelengths ranging from 338.9-1075.1 nm. Reflectance recorded before and after treatments are shown.



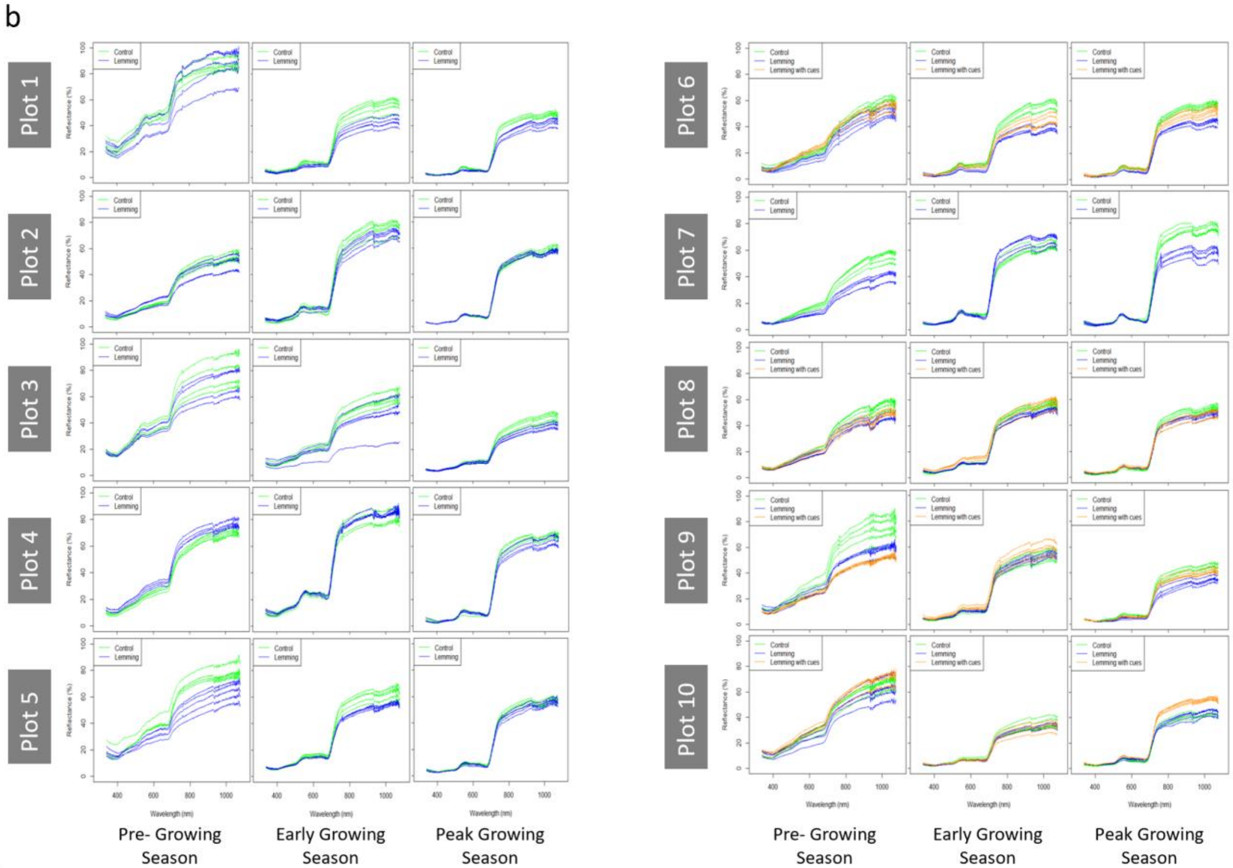


Figure S2. Ground photos and hyperspectral reflectance curves of vegetation during the three rounds of measurements (summer 2019), showing the progressive recovery of vegetation. (**a**) Photos of each plot taken immediately prior to recording measurements for each round, and (**b**) hyperspectral surface reflectance for wavelengths ranging from 338.9-1075.1 nm.

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