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Snowmobile effects on height and live stem abundance of wetland shrubs in south-central Alaska

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ABSTRACT

Snowmobiling is an important recreational activity at higher latitudes and in alpine areas where snow occurs. The Kenai National Wildlife Refuge in south-central Alaska allows snowmobiling access to >500,000 ha between December–April but not until snow depths are ≥50 cm to reduce snowmobile impacts to vegetation. We used a Before-After-Control-Impact experimental design to determine snowmobile effects on height and abundance of live stems of dwarf birch (*Betula nana*), shrubby cinquefoil (*Dasiphora fruticosa*) and sweet gale (*Myrica gale*) at snow depths ≥50 cm and <50 cm. We traversed 50x2-m transects with 10 snowmobile passes, taking snow depth measurements before and after treatments in January 2012 (≥50 cm) and April 2012 (<50 cm). Vegetation was measured in September 2011 and August 2012. Data were analyzed with general linear mixed effects models. Snowmobile traffic compacted snow by >40%. Dwarf birch was the most intolerant of snowmobiles with ≥7% decline in mean height ($p \leq 0.05$) and ≥28% decline in mean live stem abundance ($p \leq 0.02$). Shrubby cinquefoil was the most resilient as plant height was unaffected and mean live stem abundance declined by 20% only when snow was <50 cm ($p = 0.01$). Mean height of sweet gale was also unaffected at both snow depths but mean live stem abundance declined by ≥ 15% regardless of snow depth ($p \leq 0.04$). When snowmobiles did affect height or live stems, the impacts were greater in all three species at snow depths <50 cm. In contrast, both vegetative metrics for all three species remained the same or increased in the control group. Snow depths ≥50 cm reduce snowmobile impacts to wetland shrubs but did not entirely eliminate them. Thinning snowpack in a rapidly warming climate suggests more damage to vegetation is likely where snowmobiling occurs.

Management implications: Land managers may specify a minimum snow depth to protect vegetation from the physical damage of snowmobiles and their indirect effects through degradation of the subnivean environment. Snow depths ≥50 cm observed in our study reduced the negative effects of snowmobile traffic on three wetland shrub species but did not eliminate them. Snowmobiling as a winter recreational activity is likely to decrease in the foreseeable future in a warming climate. However, declining snowmobile opportunity does not necessarily translate to declining impacts in fact, the opposite may be true at least in the near term. Our data suggest snowmobiling over poor snowpack likely means more vegetation damage. We recommend partial openings when snow depth in the regulated area varies above and below 50 cm over large areas. The development of a maintained trail system, rather than open access, is an alternative way to reduce landscape-scale impacts.

1. Introduction

The use of snowmobiles has been a growing recreational activity in North America since at least the 1950s. There are now >1.1 million snowmobiles registered in the United States and 543,000 in Canada, collectively generating $35 billion annually from expenditures on equipment, clothing, accessories, and winter vacations (ISMA 2020). Most snowmobiles are used for recreational pursuits, but they can promote a certain use and appreciation of wilderness areas (Mullet et al., 2017) and are commonly used as a utility vehicle for trappers, hunters and others (Simpson, 1987). However, snowmobile activity can also affect wildlife and vegetation during winter when resources are seasonally limited and environmental conditions are severe (Wanek, 1971; Boyle & Samson, 1985; Burkowski et al., 2006; Neumann &

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Merriam, 1972; Seip et al., 2007).

Most studies that have addressed the impacts of snowmobiling on vegetation were conducted in the 1970s. These studies came in the wake of a dramatic increase in snowmobile manufacturing for outdoor recreation and increased concern from public land managers over their potential effects on plants and wildlife (Butler 1970; Dustin & Schneider, 2004). However, snowmobile models of the 1970s were much slower and heavier and lacked the efficiency and maneuverability of the lighter and faster snowmobiles of today. The ecological effects of contemporary snowmobile models have not been well studied. Such information is important for public land management, as well as for educating snowmobilers about responsible and compatible use of their recreational vehicles on public and private lands.

Snowmobiling can have direct and indirect effects on vegetation. Direct impacts occur when snowmobile skis and tread contact or crush individual plants (typically woody species) protruding above or just beneath the snow surface, which may result in physical damage. Plant tissue damaged by direct contact with snowmobiles can inhibit stem growth and cause plant mortality (Wanek, 1971, Neumann & Merriam, 1972; Wanek & Schumacher, 1975). Indirect effects of snowmobile traffic on plants are manifested through compaction of the snow. Depending on its density and depth, undisturbed snow provides a subnivean environment that is typically warmer than above-snow temperatures (Marchand, 1996). At an average depth of 20 cm, Pesant et al. (1985) found that temperatures beneath undisturbed snow in their experimental area rarely fell below -1 °C. Snow depths ≥50 cm provide stable temperatures to protect underlying vegetation from the colder temperatures above the snow (Marchand, 1982). The subnivean environment therefore provides a protection zone for plants against the harsh winter elements above the snow, in some cases providing high enough temperatures for cell division to occur (Kimball & Salisbury, 1974).

However, the temperature gradient and thermal insulation of snow beneath the surface can be drastically reduced by snow compaction caused by snowmobiles (Wanek, 1971, Neumann & Merriam, 1972). Neumann and Merriam (1972) found that the specific gravity of snow doubled below the surface and tripled at the surface following snowmobile traffic, effectively increasing thermal conductivity below and at the surface by four and nine times, respectively. These changes to the insulative properties of compacted snow may ultimately expose underlying vegetation to potential frost-related damage (Marchand, 1996) and reduce soil temperatures, which decreases stored food reserves in plants and may prevent them from growing the following spring (Bolduc et al., 1977). Snowmobile-compacted trails also generally melt slower than undisturbed areas because of changes in snow structure that reduce its water retention capacity (Neumann & Merriam, 1972). These effects can significantly reduce the capacity of snow to slow runoff and thawing during snowmelt, which has been found to slow early season plant growth, reduce total dry biomass, and reduce species composition (Neumann & Merriam, 1972; Foresman 1973; Wanek, 1974; Keddy et al., 1979; Pesant et al., 1985).

Wetlands in south-central Alaska, U.S.A., are important resources for many wildlife species (Schwintzer, 1979; Renecker & Schwartz, 1997; Collins, 2002; Ladyman, 2003). They are also known to assist in regulating the global carbon budget (Panikov & Gorbenko, 1992; Christensen et al., 1999; Ives et al., 2011; Oechel et al., 2000). However, mostly open wetland landscapes are widely used by snowmobilers to access trapping and hunting sites, and remote cabins, as well as for recreational riding (Mullet, 2014). Wetland shrubs are likely more susceptible to direct physical damage by contact with traversing snowmobiles and indirect damage caused by snow compaction because they tend to protrude above the snowpack while depending on subnivean conditions to reduce frost-related damage. These effects can reduce photosynthetic support structures (e.g., stems) of plants, potentially reducing growth and longevity which may have cascading effects on wetland plant community composition and ecological processes.

Here, we examine the effects of snowmobiles on three common wetland shrubs in south-central Alaska that are also circumboreal in distribution: dwarf birch (*Betula nana* L.), shrubby cinquefoil (*Dasiphora fruticosa* [L.] Rydb. ssp. *fruticosa ssp. floribunda* [Pursh] Kartesz) and sweet gale (*Myrica gale* L.). Dwarf birch and shrubby cinquefoil are facultative wetland species, whereas sweet gale is an obligate wetland species (NRCS 2020). Our study objectives are (1) to test how snow depth influences the effects of snowmobiling on these three species; (2) to verify whether a predetermined snow depth of ≥50 cm is adequate to protect these three species from snowmobile-related impacts; and (3) to better understand snow depth as a buffer against snowmobile-related impacts and a metric that managers can use to minimize those impacts.

2. Methods

2.1. Study area

We conducted our study within the 805,000-ha Kenai National Wildlife Refuge (KNWR), located on the western Kenai Peninsula in south-central Alaska, USA (Fig. 1). The KNWR consists of diverse subarctic ecosystems, including lowland wetlands, boreal forests and alpine tundra. The Kenai Lowlands are vegetated by white spruce (*Picea glauca*) and black spruce (*P. mariana*) forests with a mixture of aspen (*Populus tremuloides*), Alaska birch (*Betula neoalaskana*), and an extensive network of wetlands and peatlands dominated by dwarf birch, shrubby cinquefoil, sweet gale, bog rosemary (*Andromeda polifolia*), marsh labrador tea (*Ledum palustre*), sedges (*Carex* sp.), and various moss species.

Temperatures at this latitude (60−61° N) rarely exceed 26 °C in summer or drop below −18 °C in winter, although winter temperatures of −30 °C do occur (PASX National Weather Station; https://mesowest.utah.edu/). During this study, we used 30 Natural Resources Conservation Service (NRCS) aerial snow markers to monitor snow depth throughout KNWR. Mean snow depth for the winters between 2009 and 2012 (December–April) was 39.9 cm (SD = 11.63) in wetland areas (unpubl. data). Mean snow depth in wetlands across months ranged from 54.4 cm (SD = 41.49) in December to 7.5 cm (SD = 11.63) in April.

The KNWR is mandated by the 1980 Alaska National Interest Lands Conservation Act (ANILCA) to allow snowmobiling for traditional activities (Sections 1110(a) and 811(b)). The KNWR actively manages snowmobile use to reduce its effects on vegetation by prohibiting their use above treeline (~500 m above sea level) in the Kenai Mountains and by restricting their use between 01 December–30 April "only when snow depth is sufficient to protect underlying vegetation and terrain" (KNWR Comprehensive Conservation Plan 2010; Section 3.3.6.7; p 3–5). No standard snow depth to protect underlying vegetation has been specifically defined by the KNWR's Comprehensive Conservation Plan or the Refuge Manager; however, an arbitrary snow depth of ≥50 cm is generally considered acceptable (A. Loranger, KNWR manager, pers. comm.). To date, no study exists to assess whether ≥50 cm of snow is sufficient to protect underlying vegetation, including wetland shrubs. Wetland shrub species are a specific concern because high winds in these exposed, flat areas in KNWR can cause snow depth to vary considerably over space and time and because they provide an open, unimpeded landscape for snowmobiling (Mullet, 2014; Mullet et al., 2017).

2.2. Hypotheses

A particular threshold of snow depth may play an important role in protecting woody vegetation from damage by snowmobiles. Marchand (1982) found that snow depths ≥50 cm provide stable temperatures to protect underlying vegetation from the colder temperatures above the snow. Furthermore, snow depths ≥50 cm could also protect many shrubs from direct damage by snowmobile traffic as a physical buffer from direct contact with skis and tread.

The height and number of live stems (hereafter referred to as abundance) on a given plant are indicators of plant health (Sachs, 2006)

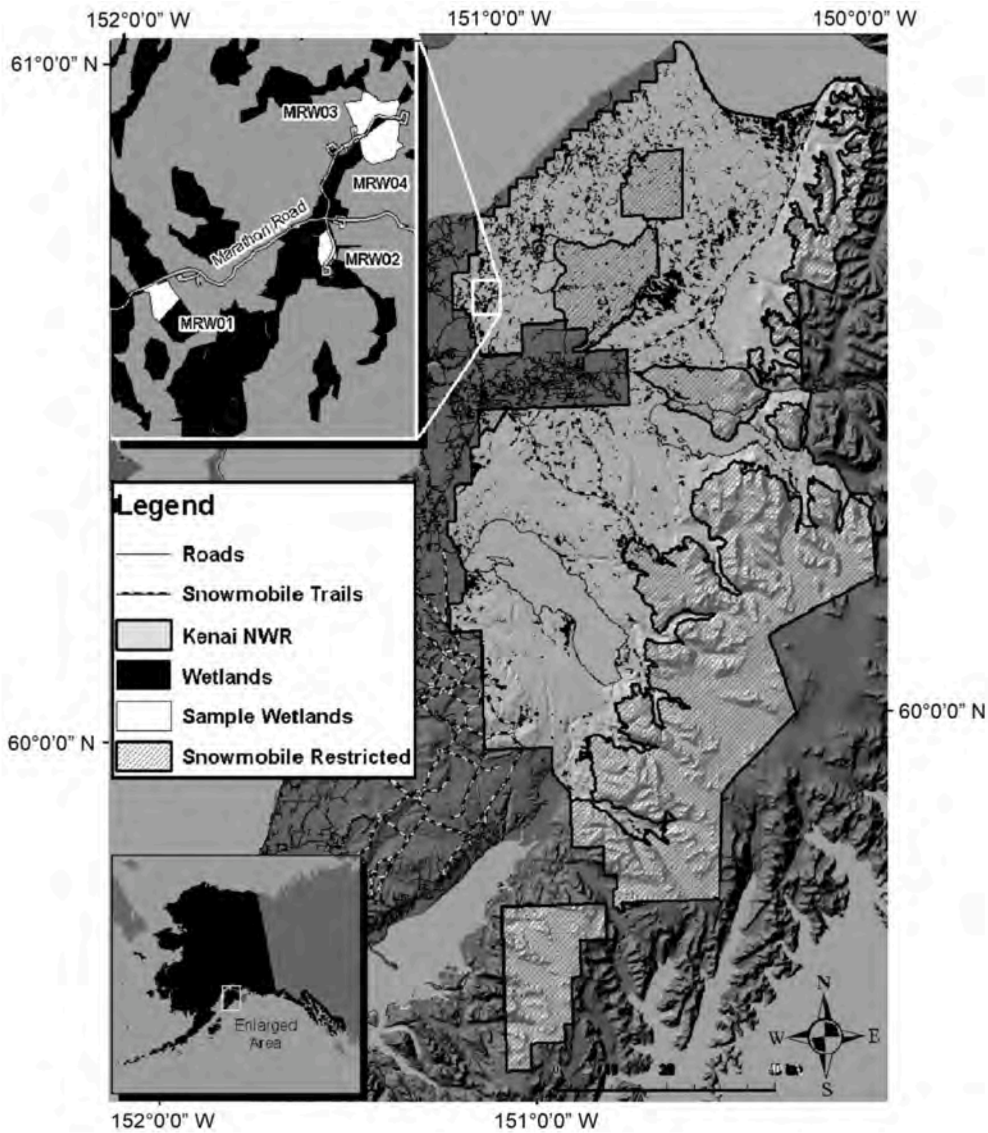

Fig. 1. Location of study area on the Kenai National Wildlife Refuge, Alaska, in relation to the distribution of wetlands, roads, established snowmobile trails, and snowmobile restricted areas. Snowmobile traffic is not restricted to established trails.

as well as a measure of potential impacts to direct and indirect effects of snowmobile traffic (Wanek, 1971; Neumann & Merriam, 1972; Wanek & Schumacher, 1975). We hypothesized that shrub height and live stem abundance would be significantly reduced after snowmobile traffic at snow depths <50 cm and, in keeping with the KNWR's snowmobile policy, that these impacts would be less or non-existent at snow depths ≥50 cm.

2.3. Sampling design

We used a Before-After-Control-Impact (BACI) design to test our hypotheses (Smith, 2002). We conducted our experiment during September 2011–August 2012 in four wetlands (W01, W02, W03, and W04) along Marathon Road in the northwest corner of the KNWR, adjacent to the City of Kenai (Fig. 1). In early September 2011, we established sample plots in all four wetlands where each plot consisted of three transects: one control and two treatments (Treatment 1 = snow depth ≥50 cm and Treatment 2 = snow depth <50 cm). Transects were 50 m long, 2 m wide, and placed 1 m apart. The four experimental wetlands were restricted from public snowmobiling prior to and during our study and consisted of shrubs common in wetlands where snowmobiling is permitted on KNWR. Therefore, we assumed our study sites were undisturbed by any previous snowmobile activity and representative of other wetlands where snowmobiling occurs.

We measured the height and counted the number of live stems on 30 individual plants of each species within each sample plot transect. Even though plants were unevenly distributed along transects, we ensured that the plants sampled were (1) not clustered in any one location, (2) located throughout the transect being sampled, and (3) distinguishable as a single plant. Additionally, because hummocks may alter the depth and distribution of snow, we controlled for this by selecting wetlands and sample plots without hummocks to ensure snow depth was reasonably homogeneous across transects.

We used a meter stick to measure the height of each plant to the nearest centimeter from the base to the tallest terminal bud. We counted all live stems on each plant. We defined a live stem as a stem with living tissue, the presence of leaves, and/or terminal flowers or fruiting bodies branching from the main stem. We marked each plant with a colored zip-tie and ribbon of the same color with an identification number placed at the base of the plant. This color-coded numbering system ensured that the same plants were measured and counted in August 2012 after winter treatments.

During winter, we measured snow depth at 5-m intervals for each control and treatment transect prior to snowmobile traverses and then again directly after snowmobiles traversed treatment transects. Snowmobile traverses consisted of a single snowmobile driven back and forth across the length and width of treatment transects 10 times. This number of traverses was consistent with the average number of daily snowmobile passes on snowmobile trails used to access wetlands in the KNWR during a pilot study conducted over winter 2010–2011. We conducted all snowmobile traverses with a 2009 Ski-Doo Skandic® at a rate of 2 km/h. This commonly-used recreational and utility model is 1.15 m wide from ski-to-ski, with a track width of 0.6 m and dry weight of 326 kg. The rider weighed approximately 100 kg.

2.4. Statistical analysis

The aim of our study was to determine the effects of snowmobile traffic at snow depths ≥50 cm and <50 cm on three wetland shrub species as measured by the parameters of plant height and live stem abundance. Log-transformed plant height and live stem abundance for all species were normally distributed (Shapiro-Wilks, $p > 0.100$, $\alpha = 0.05$). We graphed and compared within-treatment differences using 95% confidence intervals (CI). We determined how these differences compared with control and between treatment groups by testing a set of *a priori* general linear mixed effects models (GLMM) using the "nlme" package in program R (Pinheiro et al., 2013).

We built our BACI GLMMs based on the predictors of 'Time' (i.e., Before and After snowmobile traverses) and 'Treatment' (i.e., Control, Impact: ≥50 cm of snow, and <50 cm of snow). In BACI study designs, a significant effect of ecological impacts appears via the interaction between time and treatment; thus we tested for an effect of snowmobile traffic at snow depths of ≥50 cm and <50 cm on plant height and live stem abundance by including the interaction between 'Time' and 'Treatment' (Eq. (1)). All models included the random effects of 'Site' (i.e., W01, W02, W03, W04; Eq. (1)):

$$y_i = b_0 + b_1(\text{Time}) + b_2(\text{Treatment}) + b_3(\text{Time} * \text{Treatment}) + \text{Site} + e_i \quad (1)$$

Model and test results with $\alpha \leq 0.05$ were considered significant.

3. Results

We conducted our experiment during the period (28 December 2011–22 April 2012) when snowmobiling was allowed on the KNWR. At the time KNWR opened to snowmobiling, snow depth at the Kenai Municipal Airport (12 km from study area) was 46 cm. Treatment 1 was traversed on January 23, 2012 when mean snow depth on each transect measured ≥50 cm. Treatment 2 was traversed on April 17, 2012 when mean snow depth measured <50 cm. The study area was completely snow free on April 26, 2012.

3.1. Snow compaction

Uncompacted snow depth at the time of Treatment 1 (January 23, 2012) averaged 51.5 cm (SE = 1.30, n = 56) among all four wetlands, ranging from 32 to 60 cm. Uncompacted snow depth among all wetlands at the time of Treatment 2 (April 17, 2012) averaged 33.8 cm (SE = 1.07, n = 56), ranging from 16 to 54 cm.

Snow depth on control plots mirrored treatment plot values for all four wetlands. Snow depth on control plots at the time of Treatment 1 averaged 51.8 cm (SE = 2.00, n = 28), ranging from 32 to 67 cm; snow depth at the time of Treatment 2 averaged 33.6 cm (SE = 1.31, n = 28), ranging from 6–45 cm.

For Treatment 1, snow depth before snowmobile traverses averaged 51.2 cm (SE = 1.70, n = 28) with a range of 35–67 cm. Snow depth following snowmobile traverses averaged 32.8 cm (SE = 1.50, n = 28) with a range of 17–45 cm. Snow measuring ≥50 cm deep was compacted by 18.4 cm, on average, following snowmobile traverses, resulting in a 44% reduction in overall snow depth (t = 6.83, p = 0.00).

For Treatment 2, snow depth before snowmobile traverses averaged 33.9 cm (SE = 1.72, n = 28) with a range of 16–54 cm. Snow depth following snowmobile traverses averaged 22.4 cm (SE = 1.40, n = 28) with a range of 7–36 cm. Consequently, snowmobile traverses over snow depths <50 cm compacted snow by 11.6 cm, on average, resulting in a 41% reduction in overall snow depth (t = 6.11, p = 0.00).

3.2. Species-specific vegetative responses to snowmobile treatment

We measured plant height and live stem abundance before winter snowmobile traverses in early September 2011, following the growing season. Vegetation was remeasured following snowmobile traverses in late August 2012. For each transect, we sampled a total of 150 dwarf birch in five sample plots among all four wetlands (W01 = 1 [30], W02 = 2 [60], W03 = 1 [30], W04 = 1 [30]); 90 shrubby cinquefoil plants in three sample plots among two wetlands (W01 = 1 [30], W04 = 2 [60]); and 90 sweet gale plants in three sample plots among three wetlands (W01 = 1 [30], W02 = 1 [30], W04 = 1 [30]).

Mean heights of all three species in control transects did not change during the study period (Fig. 2). Similarly, mean heights of shrubby cinquefoil and sweet gale did not change as a result of snowmobile traverses whether in snow <50 cm or ≥50 cm in depth (shrubby cinquefoil $p \geq 0.45$, sweet gale $p \geq 0.24$; Table 1). However, mean height of dwarf birch differed before (95% CI: 31.5–35.3) and after snowmobile traverses (95% CI: 27.9–30.9), declining 7% in snow ≥50 cm and 12% in snow <50 cm (Fig. 2). Notably, the decline in height of dwarf birch was more significant than that of the control group when snowmobile traverses were applied on both treatment groups of snow depths ≥50 cm (p = 0.05) and <50 cm (p = 0.02) while differences in heights of sweet gale and shrubby cinquefoil were not different from control at both snow depths (p > 0.10) (Table 1).

In contrast, mean live stem abundance of shrubby cinquefoil and sweet gale in the control group increased between sample periods. However, mean live stem abundance of dwarf birch did not change (Fig. 3). Following snowmobile traverses, mean live stem abundance of dwarf birch and sweet gale differed as a result of snowmobile traverses at both snow depths <50 cm and ≥50 cm ($p \leq 0.04$) (Table 2). Dwarf birch live stem abundance decreased by 28% at snow depths ≥50 cm and by 31% at snow depths <50 cm (Fig. 3), whereas sweet gale live stem abundance decreased by 15% at snow depths ≥50 cm and by 33% at snow depths <50 cm (Fig. 3). Mean count of shrubby cinquefoil live stems did not change in snow depths ≥50 cm following snowmobile traverses (p = 0.21) (Table 2) but did decrease by 20% at snow depths <50 cm following snowmobile traverses (p = 0.01) (Table 2). Although differences in living stem counts were only notable for dwarf birch and sweet gale at snow depths ≥50 cm, all three species exhibited significant reductions in living stems at snow depths <50 cm ($p \leq 0.01$) (Table 2). All control groups exhibited an increase in live stems (Fig. 3).

4. Discussion

Our results indicate that snowmobile traffic at snow depths <50 cm and ≥50 cm has negative effects on dwarf birch, shrubby cinquefoil, and sweet gale, three common woody shrub species growing in wetlands on the Kenai Peninsula. Snow depths ≥50 cm appeared to reduce impacts of snowmobile traverses to the height of sweet gale and the height and live stems of shrubby cinquefoil, but did not appear to protect the height of dwarf birch or the live stems of dwarf birch and sweet gale. Dwarf birch height and live stem abundance were also negatively affected by snowmobile traverses at snow depths <50 cm. Although the heights of sweet gale and shrubby cinquefoil remained unaffected, there were significant reductions in live stem abundance.

Dwarf birch was the most sensitive of the three species to 10 snowmobile traverses regardless of snow depth, whereas shrubby cinquefoil

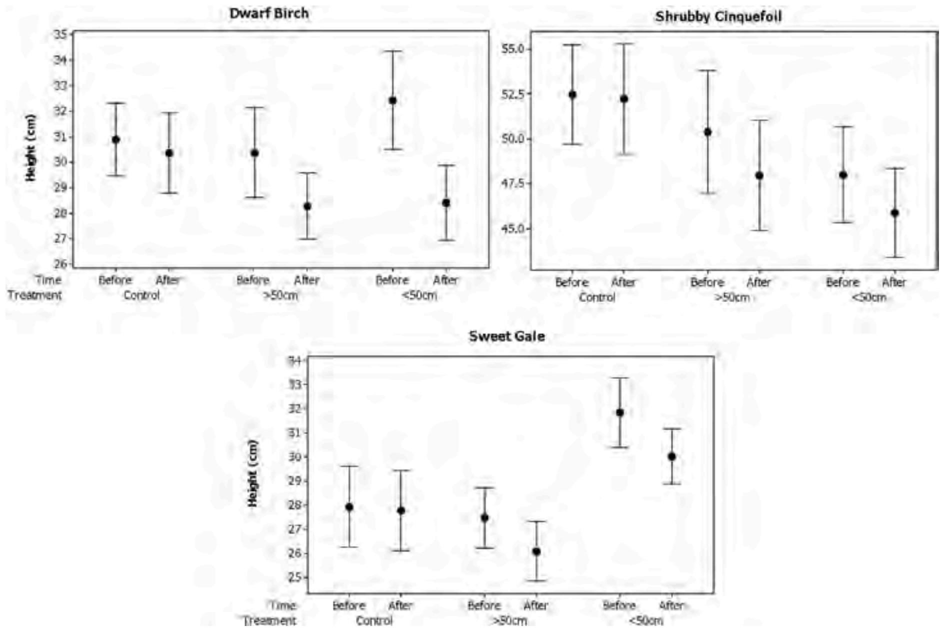

Fig. 2. Mean plant heights (with 95% confidence intervals) of three woody wetland shrub species without snowmobile traverses (control) and before and after 10 snowmobile traverses at snow depths ≥50 cm and <50 cm.

Table 1
Parameter estimates from general linear mixed-effects modeling of measured plant height on three woody wetland shrub species before and after 10 snowmobile traverses at two snow depths (≥50 cm, <50 cm). An "X" indicates the interaction between time (Pre- and Post-snowmobile traverses) and treatment (snow depths ≥50 cm and <50 cm) exhibited in a Before After Control Impact design (BACI) (Smith, 2002). * denotes significant effect (α = 0.05).

Parameter	Estimate	SE	t-value	p-value
Dwarf Birch (df = 888)				
Intercept	31.07	1.79	17.31	0.00*
Pre- vs Post-snowmobile	−0.53	1.06	−0.50	0.62
Control vs ≥ 50 cm	−0.51	1.06	−0.49	0.63
Control vs < 50 cm	1.53	1.06	1.45	0.15
Pre- vs Post-snowmobile X Control vs ≥ 50 cm	−3.06	1.55	−1.98	0.05*
Pre- vs Post-snowmobile X Control vs < 50 cm	−3.50	1.50	−2.34	0.02*
Shrubby Cinquefoil (df = 532)				
Intercept	52.48	2.69	19.50	0.00*
Pre- vs Post-treatment	−0.27	2.03	−0.13	0.90
Control vs ≥ 50 cm	−2.07	2.03	−1.02	0.31
Control vs < 50 cm	−4.47	2.03	−2.20	0.03*
Pre- vs Post-treatment X Control vs ≥ 50 cm	−2.18	2.87	−0.76	0.45
Pre- vs Post-treatment X Control vs < 50 cm	−1.86	2.87	−0.65	0.52
Sweet Gale (df = 539)				
Intercept	27.92	1.24	22.52	0.00*
Pre- vs Post-treatment	−0.16	0.99	−0.16	0.88
Control vs ≥ 50 cm	−0.44	0.99	−0.45	0.65
Control vs < 50 cm	3.92	0.99	3.96	0.00*
Pre- vs Post-treatment X Control vs ≥ 50 cm	−1.28	1.40	−0.91	0.36
Pre- vs Post-treatment X Control vs < 50 cm	−1.64	1.40	−1.17	0.24

was more resilient to snowmobile disturbance, especially at snow depths ≥50 cm. All three species exhibited negative effects to snowmobile traffic at snow depths <50 cm. In contrast, vegetative metrics within the control group remained within the same confidence interval from year to year with marginally increasing live stem abundance and marginally decreasing plant height. We believe the latter may simply be an artifact of remeasuring these plants two weeks earlier in 2012 than in 2011.

We observed that dwarf birch and sweet gale did not protrude above the snowpack at either snow depth prior to snowmobile traverses. All plants of both species remained covered by snow following snowmobile traverses over snow ≥50 cm (mean = 51 cm) in depth. Although dwarf birch is known to be resistant to cold temperatures and frosting (de Groot et al., 1997), results suggest that thermal changes as a result of snow compaction caused by snowmobile may have exceeded the physiological limits of this species (and perhaps sweet gale). Although this effect was not addressed in our study, results support others that found snowmobile-induced changes to the subnivean environment slows plant growth and reduces living tissue (i.e., live stems), typically due to frost-related damage (Foresman et al., 1973; Pesant et al., 1985; Wanek, 1974).

All three species exhibited significant reductions in live stems following snowmobile traffic at snow depths <50 cm. We noted that 5−10 marked shrubby cinquefoil plants protruded above the snowpack (<50 cm) in all three wetlands where it was present prior to treatment and were in direct contact with the snowmobile during traverses. Conversely, dwarf birch and sweet gale plants remained buried in the snowpack prior to snowmobile traverses at snow depths <50 cm. Yet 10−20 marked plants of both species protruded above the snowpack following treatments in all experimental wetlands where they were present, suggesting they came in contact with the snowmobile during treatment. During post-treatment counts of live stems the following summer, we observed ~13% of marked shrubby cinquefoil plants within <50 cm treatment transects had noticeable abrasions on the main stems; furthermore, all three species exhibited broken stems similar to findings by Wanek (1971), Neumann and Merriam (1972), and Wanek and Schumacher (1975).

These are not trivial findings. The average snowmobiler in North America rides 1788 km per year (ISMA 2020). Even one pass of a snowmobile can dramatically affect plants and snow. Neumann and Merriam (1972) observed that almost 80% of tree saplings experienced trunk abrasions or stem loss from a single pass of a snowmobile compared to 10% of saplings in control transects that showed an unknown, but likely natural, form of damage (e.g., weathering, browsing). Similarly, Keddy et al. (1979) found that snow depth was reduced 57% after a single snowmobile pass.

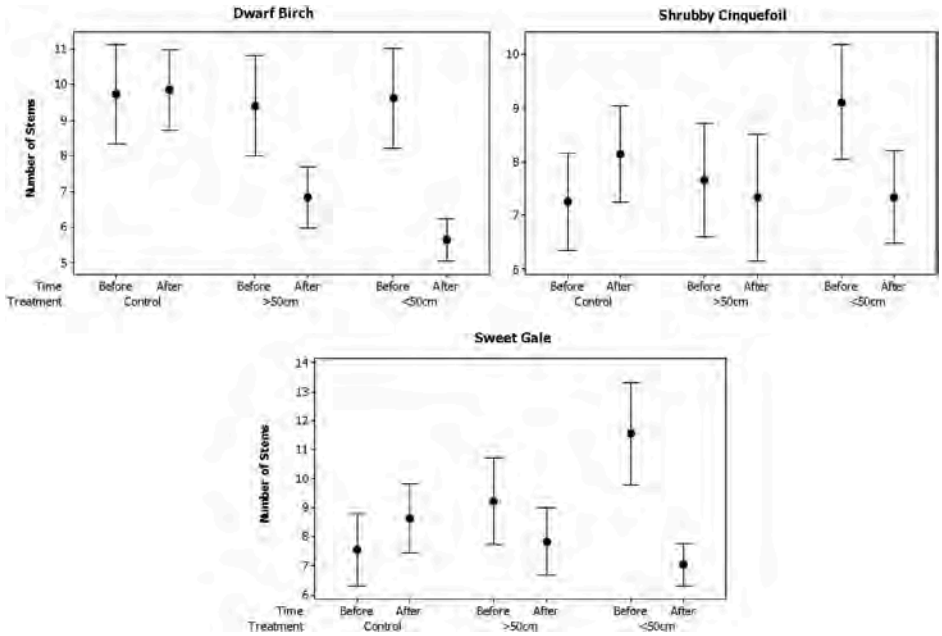

Fig. 3. Mean live stem counts (with 95% confidence intervals) of three woody wetland shrub species without snowmobile traverses (control) and before and after 10 snowmobile traverses at snow depths ≥50 cm and <50 cm.

Table 2
Parameter estimates from general linear mixed-effects modeling of live stems counted on three woody wetland shrub species before and after 10 snowmobile traverses at two snow depths (≥50 cm, <50 cm). An "X" indicates the interaction between time (Pre- and Post-snowmobile traverses) and treatment (snow depths ≥50 cm and <50 cm) exhibited in a Before After Control Impact design (BACI) (Smith, 2002). * denotes significant effect (α = 0.05).

Parameter	Estimate	SE	t-value	p-value
Dwarf Birch (df = 888)				
Intercept	9.56	1.02	9.41	0.00*
Pre- vs Post-snowmobile	0.13	0.81	0.16	0.88
Control vs ≥ 50 cm	−0.31	0.81	−0.39	0.70
Control vs < 50 cm	−0.11	0.81	−0.13	0.90
Pre- vs Post-snowmobile X Control vs ≥ 50 cm	−2.68	1.18	−2.27	0.02*
Pre- vs Post-snowmobile X Control vs < 50 cm	−4.11	1.15	−3.57	0.00*
Shrubby Cinquefoil (df = 532)				
Intercept	7.26	1.05	6.92	0.00*
Pre- vs Post-snowmobile	0.89	0.69	1.29	0.20
Control vs ≥ 50 cm	0.40	0.69	0.58	0.56
Control vs < 50 cm	1.86	0.69	2.70	0.01*
Pre- vs Post-snowmobile X Control vs ≥ 50 cm	−1.21	0.97	−1.25	0.21
Pre- vs Post-snowmobile X Control vs < 50 cm	−2.66	0.97	−2.73	0.01*
Sweet Gale (df = 539)				
Intercept	7.54	1.82	4.14	0.00*
Pre- vs Post-snowmobile	1.08	0.85	1.30	0.21
Control vs ≥ 50 cm	1.69	0.85	1.98	0.05*
Control vs < 50 cm	4.00	0.85	4.70	0.00*
Pre- vs Post-snowmobile X Control vs ≥ 50 cm	−2.47	1.21	−2.05	0.04*
Pre- vs Post-snowmobile X Control vs < 50 cm	−5.56	1.21	−4.61	0.00*

On the KNWR, snowmobiling occurs at varying intensities on 48% of 36,000 ha of wetlands (Mullet, 2014). Many peatlands on the Kenai Lowlands are drying in response to a 55% decrease in available water since 1968, with concomitant invasion by woody shrubs and black spruce (Berg et al., 2009; Klein et al., 2005). Annual exposure to snowmobile traffic over a landscape this vast is likely altering wetland communities important to many organisms and ecological processes, even as they are responding to a rapidly warming climate (Berg et al., 2009; Ives et al., 2011).

Snowmobiling as a winter recreational activity is likely to decrease in the foreseeable future as climate change-related warming increases (Perry et al., 2018). Certainly, this is highly likely on the Kenai Peninsula, where snow is forecasted to decrease at lower elevations (where most residents live) and the winter recreational season is expected to decrease by ½ to 1 day annually through 2059 (Hayward et al., 2017). A reduction in snowpack due to warmer winters may naturally restrict snowmobile access to certain areas. However, declining snowmobile opportunity does not necessarily translate to declining impacts; in fact, the opposite may be true at least in the near term. Multiple snowmobile accidents in New Hampshire, for example, were linked to "early season" riding conditions in mid-winter, when there is normally a solid snow base (Shamel, 2020). Our data suggest snowmobiling on thin snowpack likely means more damage to vegetation.

4.1. Management implications

Managers of public lands open to snowmobile activity are typically responsible for protecting environmental health within their jurisdictions. Ensuring that snowmobiling occurs at snow depths to adequately protect vegetation from direct physical damage and their indirect effects through the degradation of the subnivean environment is an important mitigation measure. On a conservation unit as large as the KNWR, the manager typically relies on the observations of staff and other backcountry stakeholders (e.g., a local recreational snowmobile club) to make informed decisions on where and when to open the KNWR to snowmobiling (A. Loranger, KNWR manager, pers comm.). Although snow distribution can be monitored reasonably well with remote-sensed imagery (Lindsay et al., 2015), only in the last decade has the KNWR begun to monitor snow depth using NRCS aerial snow markers. Snow depth across the area that KNWR opens for snowmobiling ranges considerably based on latitude and elevation. Additionally, the snowpack among wetlands can vary by 53 cm on any given month between December and April (NRCS snow marker data 2009–2012) making it difficult to assume that one snow depth would protect all vegetation across a heterogeneous landscape.

Since 1976, the KNWR has closed the entire season (December–April) only three times, along with several years of partial openings, late openings, and/or early closings due to insufficient snow depth (<50 cm). In recent years, partial openings in designated zones have been used more frequently as snowpack varies considerably over the 130-km latitudinal span (in contrast, elevations range ~500 m from sea level to treeline). We recommend partial openings when snow depth in the regulated area varies above and below 50 cm over large areas. The development of a maintained trail system, rather than open access, is an alternative way to reduce landscape-scale impacts.

It is evident that snow depths ≥50 cm observed in our study reduced the negative effects of snowmobile traffic on dwarf birch, shrubby cinquefoil, and sweet gale but did not eliminate them. We found that snowmobile traffic reduced the photosynthetic structures (i.e., live stems) of these species and, consequently, reduced their ability to make and store food that is important for growth, reproduction, and overall longevity. We consider our study design and its results a conservative representation of snowmobile activity on these three wetland shrubs.

CRediT authorship contribution statement

Timothy C. Mullet: Methodology, Validation, Writing - review & editing, Investigation, Formal analysis, Data curation, Writing - original draft, Visualization, Project administration. **John M. Morton:** Methodology, Validation, Writing - review & editing, Resources, Supervision, Funding acquisition.

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