WINTER RECREATION IMPACTS TO WETLANDS: A TECHNICAL REVIEW

Prepared for Arapaho-Roosevelt National Forests, White River National Forest, and Black Hills National Forest

Submitted to Steve J. Popovich
Forest Botanist, Arapaho-Roosevelt National Forests

March 18, 2009

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ABSTRACT

In this report, we present a review of the scientific literature as it pertains to the impacts of winter recreation activities on the mountainous ecosystems of the central and southern Rocky Mountains, with an emphasis on the impacts to wetlands, including fens. Winter recreation activities can affect vegetation, soils, and hydrologic regimes, with impacts varying in relation to the intensity, frequency, and extent of disturbance. Impacts are primarily manifested through changes in snowpack conditions such as density, snow water equivalent, and transmissivity to air and water, and through the effects of compaction on thermal profiles. Gradients of intensity of impact exist between activities associated with alpine skiing, such as mechanized grooming, and those associated with nonmotorized recreation like snowshoeing. Winter recreation can have significant impacts to ecosystems and should be incorporated into management and planning of wetland resources.

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Introduction

Wetlands are important resources in the Rocky Mountain region and provide a wide range of ecological functions. Although wetlands occupy a small proportion of the total land area, they are important centers of local and regional biodiversity, providing habitat for many rare taxa (Bedford and Godwin 2003, Wolf et al. 2006, Gage and Cooper 2006). Over 16% of dicot species and 45% of monocot species on the United States Forest Service (USFS) Region 2 sensitive species list occur in wetlands (USFS 2007). Many biogeochemical, physical, and ecological processes occur primarily in wetlands, contributing valuable goods and services such as recreation, groundwater recharge, nutrient removal, and the maintenance of biodiversity (Baron et al. 2002, Boyer and Polasky 2004).

Because of the widespread loss and degradation of wetlands throughout North America (Tiner 1984, Office of Technology Assessment 1984, Patten 1998, Brinson and Malvarez 2002), laws and regulations directed at wetland conservation have been developed. Wetlands are managed by agencies including the US Army Corps of Engineers and the Environmental Protection Agency under section 404 of the Clean Water Act, which regulates the discharge of dredged or fill material into waters of the United States, including wetlands. Wetlands are also the focus of many state and local government regulations (Environmental Laboratory 1987, Tiner 1999).

Within the USDA Forest Service, federal and agency-specific regulations and directives influence the management of wetlands. Executive Orders 11988 (floodplain management) and 11990 (protection of wetlands) of 1977 direct federal agencies to avoid adverse impacts to floodplains if practicable alternatives are available. Guidance on fens is provided by the USFS on a regional basis: USFS Memo 2070/2520-7/2620, *Wetland Protection – Fens*, signed by the Region 2 Director of Renewable Resources on March 19, 2002, emphasizes the protection, preservation, and enhancement of fens. Individual forests may also include specific language pertaining to wetland resources in their Land and Resource Management Plans or other forest planning documents. The Medicine Bow and Routt National Forests' Land and Resource Management Plan describes managing for “the ecological values of unusual plant communities (like alpine tundra), special features (like talus, coves, cliffs, and wetlands) and sites of high biological diversity” (USFS 2001).

A key element of effective wetland management is to understand the anthropogenic impacts that affect wetland structure and function. Wetlands may be deleteriously affected by a wide range of activities, with impacts being either direct, such as the draining of a wetland, or indirect, for example the alteration of hydrologic and sediment regimes due to changes in land use in contributing watersheds (Brinson 1988, Bedford 1999, MacDonald 2000). One general class of potential impacts that are poorly understood originates from winter recreation activities. Driven by demographic and economic shifts, the Rocky Mountain region has seen large increases in winter recreation, forcing land management agencies such as the USFS to address issues of winter recreation in planning and management.

A variety of studies have examined summer recreation impacts on ecosystems. For example, there is an extensive literature addressing the effects of hiking and camping on soils and vegetation (Cole 1995, Marion and Cole 1996, Leung and Marion 1999, Thurston and Reader 2001, Sutherland et al. 2001, Marion and Farrell 2002, Cole and Monz 2003, Cole and Monz 2004). In addition, there is a body of literature detailing disturbance impacts from transportation in far-northern and high-elevation sites (Gersper and Challinor 1975, Challinor and Gersper 1975, Chapin and Shaver 1981, Felix et al. 1992, Kevan et al. 1995, Emers et al. 1995, Harper and Kershaw 1996). However, relatively few studies have examined the potential impacts from winter recreational uses on wetlands in the region. In snow-covered landscapes, activities that affect the distribution and physical characteristics of the snowpack have the potential to affect ecological systems and processes.

Our goal in this report is to provide a review of the available scientific literature on the impacts of winter recreation on the physical characteristics of snow and soils and the resulting ecological impacts to vegetation, fauna, and ecosystem function. Our emphasis is on fens, but we draw upon relevant ecological literature from other wetland and even non-wetland ecosystem types. Geographically, we focus on the mountain environments of the central and southern Rocky Mountains, but address relevant literature from around the world.

Approach

For this report, we conducted a literature review using electronic bibliographic databases available through the Colorado State University library system. Keyword searches on a broad array of topics related to winter recreation, wetlands, snow properties and processes, and winter ecology were done in Web of Science, Science Direct, and Google Scholar. Dissertations and theses were searched using Proquest's Digital Dissertation Database and broad searches for relevant information were made using Google. Citations were managed using Procite v 5. References in the Literature cited sections of particularly relevant papers and reports were identified and added to the Procite database. Over 200 references were added to the database and reviewed as part of the literature search.

Overview of winter recreation activities and their impacts

The nature and severity of impacts vary depending on the activity, as well as the frequency and timing of use. For example, motorized activities, such as grooming for Nordic or alpine skiing and snowmobile use, alter air and snow chemistry through exhaust emissions and fluid leakage (Sive et al. 2003, McCarthy 2007), which are impacts not associated with non-motorized activities such as snowshoeing or cross-country skiing. A single pass of a snow machine has less of an impact on snow properties than multiple passes.

Some effects are common to all activities, most notably snow compaction. However, the amount and extent of impact differs widely. A single narrow ski track is far less likely to significantly affect hydrologic or ecological processes in wetlands then a series of intensely-used snowmobile trails. Although we make generalizations on the relative impacts of different activities, impacts to any specific area will vary in relation to site-specific visitor use and snowpack conditions.

Among winter recreation activities, developed alpine skiing entails the most intense impacts, given the extensive landscape modifications involved in developing and maintaining the infrastructure for ski resorts. Impacts include those associated with the creation of ski runs (tree removal, machine and grading of slopes, etc.), infrastructure and maintenance (access roads, chairlifts, etc.), and operations (grooming, skier use, artificial snow making, etc.). Activities such as the grooming of ski slopes and trails are generally not undertaken until a minimum snow depth occurs; however, this depth is often determined more by safety considerations for the machinery than for ecological reasons (Sanecki et al. 2006a). Artificial snow making increases water and ion concentrations to slopes, which may alter nutrients available for plants. Snow additives, including potentially phytopathogenic bacteria, are often used to enhance ice crystal formation (Rixen et al. 2003), with unknown effects on wetlands. Individually and cumulatively, impacts from alpine skiing operations can be dramatic to plants and soils, including alterations of plant composition and cover and soil physical and chemical properties (Fahey and Wardle 1998, Pickering et al. 2003, Keller et al. 2004, Wipf et al. 2005).

Snowmobiling is common in many National Forests in the region. Impacts to snow characteristics and plant communities have been studied outside the region (Neumann and Merriam 1972, Foresman et al. 1976, Keddy et al. 1979), but data from the southern and central Rocky Mountains ecosystems is lacking. General impacts include those to snow properties, such as changes to thermal regimes from compaction, as well as noise and chemical emissions from exhaust (Ryerson et al. 1977, Olliff et al. 1999, Sive et al. 2003, McCarthy 2007). Because of their significant weight, snowmobile impacts to snow properties occur with low frequency use, even a single pass of a machine (Keddy et al. 1979).

The two primary nonmotorized winter recreation activities are Nordic (cross-country) skiing and snowshoeing. The primary impacts from these activities involve snow compaction. Because of the lower mass of a skier compared to snow machines, impacts are more moderate and dependent on a high frequency of use for significant impact to vegetation and soils to occur.

Visitor use data is collected by the USFS as part of the National Visitor Use Monitoring (NVUM) project and reported in terms of standardized “National Forest visits” in order to provide comparable estimates of visitor use. Winter recreation activities that are assessed include snowmobiling, cross-country skiing, and snowshoeing. In National Forests of Colorado, there are approximately 2,133 miles of groomed winter trails open to snowmobiles, with an available land area of approximately 9,355,419 acres (Bluewater Network 2002). Over 2 million cross-country ski and snowshoe visits and 1.3 million snowmobile visits occur annually in Colorado (Bluewater Network 2002).

Physical properties of snow

Snow is a highly complex material, exhibiting a wide range of physical characteristics depending on its structure. The physical structure of snow is a function of the bonding patterns of water molecules and varies depending on factors such as the air temperature when the snow formed, and the history of freezing and thawing in the snowpack (Halfpenny and Ozanne 1989). Differences in the morphology of snow influences snow's albedo, thermal conductivity, and transmissivity to air and water. In snow-covered landscapes, the direct effects of recreational activities on underlying vegetation and soils is generally limited; rather, the effects are primarily indirect, a function of the altered physical characteristics of the snowpack.

Snow density, defined as the depth of water obtained by melting a unit depth of snow, can vary widely depending on the temperature of the storm, the duration of time since snow fall, and other environmental factors such as wind. Density values in freshly fallen snow vary from ~0.05 if the temperature is -10°C to 0.20 at 0°C, but rapidly increases following deposition due to the effects of the gravitational settling, melting and re-crystallization, and wind packing (Dunne and Leopold 1978). By spring snow densities may range from 0.30 to 0.50. This variability is what makes the estimation of snow water equivalent (SWE) from snow depth measurements unreliable. The effect of human recreational activities on snow density is a primary concern, although the magnitude of impacts varies with intensity and extent. Regular mechanical grooming will have a significantly greater effect than infrequent cross-country skiing.

Winter snow typically undergoes significant morphogenesis during the winter (Colbeck 1982). Melting and recrystallization of snow flakes increases snow grain size, leading to changes in water holding capacity, density, and physical stability. The temporal sequence of storms and the length and meteorological conditions during interludes can create complex stratigraphic variation in snow characteristics. Of particular interest to backcountry skiers and avalanche forecasters, the complex three-dimensional nature of snow packs is highly variable over space and time.

Snow distribution represents the time integration of accumulation and ablation, strongly influencing hydrologic and ecological processes (Deems 2007). Snow layering and compaction influence snow thickness, SWE, temperature profiles, and surface runoff (Xue et al. 2003). In many snow-covered landscapes such as the upper subalpine and alpine tundra, snow redistribution by wind may be a more important factor influencing snow depth than actual precipitation averages. Physiography interacts with wind to create areas with greatly higher or lower snow depths.

The windward sides of exposed ridges in the alpine are generally snow free throughout the winter, exposing sites to the desiccating effects of winds and severely limiting vegetation diversity and cover. In contrast, leeward sides of ridges and depressions can accumulate incredible depths of snow due to drifting effects, remaining snow-covered through most or all of the growing season. These factors are key drivers of ecological form and function in subalpine and alpine environments (Billings and Bliss 1959, Walker et al. 1993, Heegaard 2002).

Snow melting rates are also influenced by factors such as the density and height of woody plants. Snow strongly reflects shortwave radiation, but readily absorbs the long-wave energy given off by objects like trees or structures. Snow in open wetlands receive less long-wave radiation and may persist longer than the same depth of snow in more shaded forests.

Effects on snow properties

Snow compaction results in large increases in snow hardness. Standardized resistance values showed a threefold increase in season-long snow hardness in groomed sites compared to non-groomed sites subject to skiing in the Austrian Alps (Meyer 1993). Working in New Zealand, Fahey et al. (1999) also documented significant increases in snow penetration resistance, but with the effect limited to early in the season.

The effect of different recreation activities upon the amount of snow compaction varies as a function of the force exerted by the passing person or vehicle and the frequency of passes. Snowmobiles weigh significantly more than an individual skier, for example; however, the force exerted per unit area may be comparable, given the narrower track of the skier (Halfpenny and Ozanne 1989). In general, more compaction occurs with an increased number of passes, although the greatest impact is usually from the first pass (Figure 1)(Keddy et al. 1979). Data presented by Keddy et al. (1979) suggest that several passes throughout the winter following snowstorms may cause more overall snow compaction than an equivalent number of passes on a single occasion. The amount of compaction typically is attenuated with increasing depth below the snowpack surface (Halfpenny and Ozanne 1989).

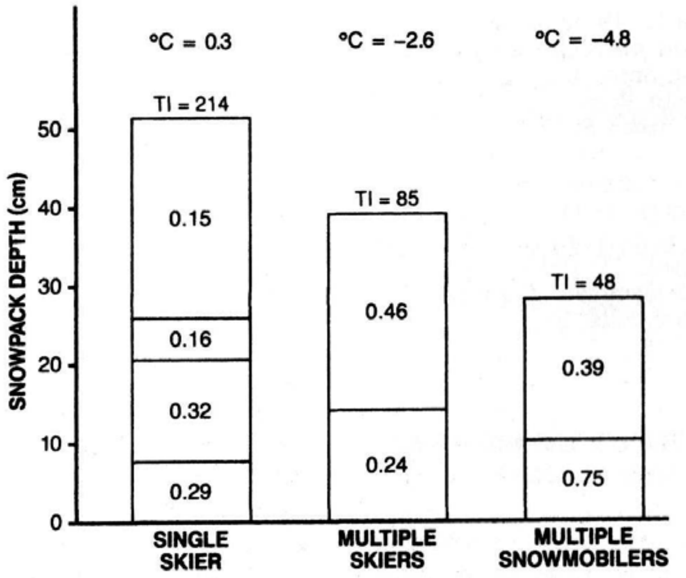

Figure 1. Impacts to snow pack depth, density, and thermal characteristics from winter recreation activities. Reductions in the thermal index (TI) and ground/snowpack interface temperature (along top of figure) and an increase in density (values within bar segments, g/cm^3) are apparent with increasing intensity and frequency of use (source: Halfpenny and Ozanne 1989).

Effects on thermal regimes

Snow compaction due to winter recreation activities strongly affects snow thermal characteristics. Increases in snow density can alter the thermal regime of underlying soils (Keddy et al. 1979, Fahey and Wardle 1998, Fahey et al. 1999). Thermal conductivity, defined as the rate at which heat energy passes through a given area, increases in proportion to the square of snow density (Kattelmann 1985, Fahey et al. 1999, Balland and Arp 2005). Temperature gradients were reduced by the passage of snowmobiles, extending subfreezing temperatures deep into soil profiles in studies in Wisconsin and Quebec (Figure 2) (Neumann and Merriam 1972, Pesant 1987).

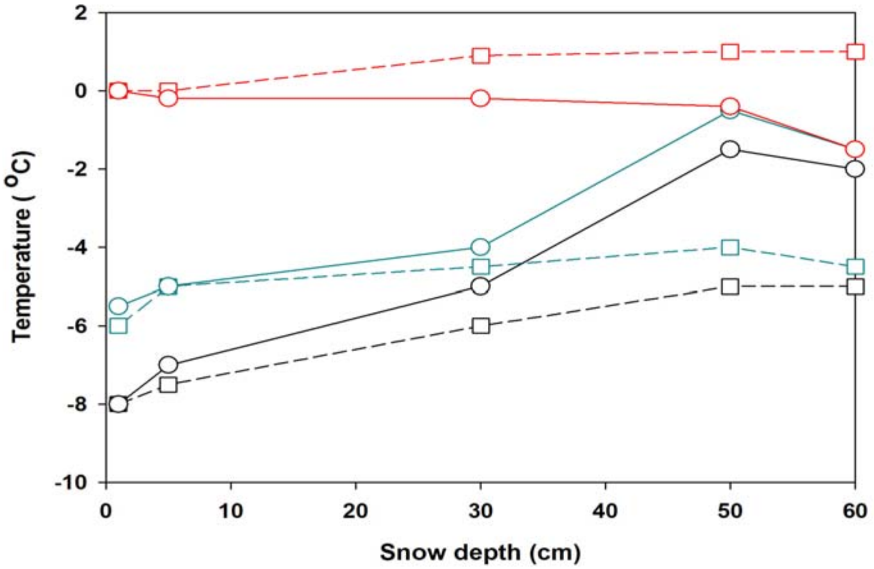

Figure 2 . Temperatures in snow profiles exposed to snowmobiling (squares, dashed lines) and controls (circles, solid lines) at three ambient air temperatures, black lines -8 °C, blue lines -6.0 °C, red lines -3.5 °C (reproduced from Neumann and Merriam 1972).

Soil temperatures in fens in southwest Colorado under alpine ski runs were different at both the soil surface and 20 cm below the soil surface, and soils under ski tracks remained significantly colder until the end of July than controls (Cooper and Chimner *Unpublished data*). Baiderin (1978) found that soil temperatures under snow on ski slopes can be 5–7 times colder and frost penetration 7–11 times higher than under non-skied snow (Baiderin 1978). Once compacted, snow is less susceptible to redistribution by wind (Fahey et al. 1999). Ski slope grooming caused a four-week delay in snow melt and soil warming (Keller et al. 2004).

Effects on soil and water chemistry

Vehicles of any sort, particularly two-stroke engines, can affect air, soil, and water chemistry. The effects of snowmobiles on air and water chemistry was investigated in Yellowstone National Park during the park's snowmobile management planning (Ingersoll et al. 1997, Olliff et al. 1999, Sive et al. 2003). Snowmobile emissions from two-stroke engines contributed large quantities of volatile organic compounds (VOCs) such as toluene and ethene, ozone (O_3), nitric oxide (NO), particulate matter (CN), carbon monoxide (CO), and methane (CH_4) into airsheds (Sive et al. 2003). Emissions can contribute to ground-level ozone formation and photochemical smog (Sive et al. 2003). High ozone can damage plants and present a health concern for humans and wildlife (Pleijel and Danielsson 1997, Trombulak and Frissell 2000, Arbaugh et al. 2003). Pollutants and dust can significantly reduce the albedo, increasing melting rates (McCarthy 2007).

The spatial pattern of pollutants varies in response to machine use and local atmospheric conditions. Mixing ratios of pollutants were found to decrease with increasing distance from the nearest road, and with still surface conditions, dilution of emissions is slow (Sive et al. 2003). Snow conditions can play an important role in influencing levels of snowmobile traffic, affecting the spatial patterns of emissions. Other meteorological effects such as boundary layer depth can influence the mixing ratios of emissions and allow the buildup of pollutants (Sive et al. 2003).

Vehicles may also lose fuel and other fluids onto the snow surface. Fluid emissions are generally lower in snowmobiles than automobiles since the introduction of wet-sump lubrication systems; however, snowmobiles may still discharge significant amounts of unburned fuel through tail pipe emissions (Bluewater Network 2002, Baker and Buthmann 2005). The pollutants contributed through fluid loss will vary depending on the number of machines, as well as machine age and condition. Site-specific impacts due to vehicle emissions may exacerbate regional increases in the deposition of pollutants

(Fenn et al. 1998, Baron et al. 2000, Fenn et al. 2003), although we found no specific research addressing the issue.

Snow and water chemistry may also be impacted as part of management for alpine skiing. For example, resorts may apply salts such as sodium chloride, calcium chloride, urea, or ammonium nitrate to alter snow physical properties and improve skiing conditions. Salting ski runs is often done for slalom races, for example, to ensure similar coarse conditions for early and late racers. While there are no specific studies examining effects on wetlands, impacts to water quality could be significant given that many wetlands receive water from affected slopes.

Effects on hydrologic processes

Compression of snow from recreation impacts reduces snow permeability, porosity, and water holding capacity, affecting the rate of runoff and soil thawing in spring (Neumann and Merriam 1972, Fahey and Wardle 1998). Compared to controls, snow tracks affected by snow grooming increased snow water content by 62% and 84% in early and late-winter snow packs, respectively (Fahey et al. 1999). Snow compaction by snowmobiles can nearly increase melting times and snowpack duration (Neumann and Merriam 1972, Kattelmann 1985). Soil in a fen under ski tracks at the Telluride Ski area in the San Juan Mountains froze and remained colder than the ambient plots for up to two months (Cooper and Chimner *Unpublished data*). As with soil temperature, snow water holding capacity, defined as the ability of snow to retain added water, is reduced throughout the snowpack due to a reduction of pore space. Neumann and Merriam (1972) reported a nearly 40% reduction in water holding capacity in snowpacks impacted by snowmobiling; however, total water content per unit volume of snow is greater because of higher snow density. The greatest increase in snow density occurs as a result of the initial vehicle pass (Keddy et al. 1979).

Net changes to hydrologic processes vary based on a number of factors. Snow compaction within wetlands is a direct impact altering basic hydrologic processes such as snowmelt-derived runnoff rates. The magnitude of hydrologic changes can be expected to increase as the extent of compaction increases. Cumulative hydrologic effects in contributing watersheds can also be important, and are also likely to increase in relation to the proportion of the watershed impacted (Winter 1988, Brinson 1988, Siegel 1988).

Wetland type may be an important variable influencing the magnitude of hydrologic response to winter recreation activities. Differences in underlying hydrologic regime among wetland types provide important context for predicting the likely effects from on-site and cumulative watershed impacts. For example, because many fens are supported by large and stable contributing aquifers, they are less likely to be affected by changes in melting rates in contributing watersheds due to compaction than wetlands with surface water regimes such as marshes. However, we found no data specifically contrasting the response of different wetland types to changes in snow properties from winter recreation.

Effects on soils

Impacts to soils from winter recreation include those related to physical structure, microbial communities, and soil chemistry (Neumann and Merriam 1972, Caissie 1999). The magnitude of the effect will vary widely depending on the nature of the activity and snow pack characteristics. Effects should be greater where use is more intense and frequent. Among common winter recreation activities, alpine skiing likely has the greatest impact on soils, although we found few studies examining soil impacts from nonmotorized activities. In general, soils are most vulnerable to direct impacts when snowpacks are thin or patchy (Felix and Raynolds 1989).

Direct soil compaction from heavy machinery can decrease soil volume, soil aeration, and porosity, damaging plant roots (Nadezhdina et al. 2006). For example, in Alaska, the passage of tracked-vehicles over partially melted Arctic tundra modified topography and vegetation with the greatest impacts in the wettest moisture regime and least in the driest (Gersper and Challinor 1975). In a European study, soils of ski runs significantly less organic carbon (-34%, -11.9 +/- 3.6 t/ha) and micropore volume and size (-33%, -0.07 +/- 0.01 cm^3/cm^{-3} and -48%, -1.62 +/- 0.28 μm) when compared to soils in control areas (Delgado et al. 2007). However, direct soil compaction from most winter recreation activities is not likely an important impact, as even moderate snow buffers the effects of soil compaction (Argow and Fitzgerald 2006). Increased soil freezing, higher snowpack density, and later melt-out could affect wetlands by compressing peat, altering microtopography in areas (Argow and Fitzgerald 2006).

Colder temperatures reduce the activity of plant roots and soil microorganisms, which can affect basic ecological processes such as soil respiration and plant productivity. Compaction of the snow cover by grooming can reduce the abundance of the whole soil fauna by approximately 70% (Meyer 1993). Effects can also include large reductions in soil bacteria and fungi under compacted snowmobile tracks, due largely to the effects of reduced soil temperatures (Neumann and Merriam 1972, Price 1985, Fahey et al. 1999) . In Europe, altered thermal characteristics and reduced micropore volume due to management for alpine skiing has been shown to dramatically reduce the density of fungal hyphae when compared to control sites (Delgado et al. 2007). We found no specific studies examining how such alterations may affect the fens or wetlands specifically, but are possible because of the importance of decomposition to the carbon balance of peatlands.

Not all studies have found lower soil temperatures under altered snowpacks. For example, although Keller et al. (2004) found greater snow density, hardness, and thermal conductivity on ski slopes versus controls, soil temperatures were not significantly different, which the authors attributed to moderate air temperatures during their study (Keller et al. 2004). It is likely that the impacts of different recreation activities on soil temperature vary as a function of the original snowpack depth and degree of compaction. Low intensity snowshoeing, for example, is less likely to affect soil temperatures then regular grooming as part of the maintenance of alpine ski runs.

Effects on vegetation

The general effects of soil compaction on soils and vegetation is well documented in the literature (Kozlowski 1999), although few studies examining the effects of snow compaction have been conducted, particularly in wetlands. Adverse effects have been demonstrated in a variety of plant communities (Greller et al. 1974, Keddy et al. 1979, Sanecki et al. 2006b). Direct mechanical injury to plants can occur, particularly where snow cover is thin. The most vulnerable plants to direct damage by vehicles are trees and shrubs (Neumann and Merriam 1972, Emers et al. 1995). Snow compaction can promote the formation of soil frost and ice layers and delay plant development (Rixen et al. 2003).

Soil compaction can alter soil structure by increasing soil bulk density, breaking down soil aggregates, reducing soil porosity, aeration, and infiltration capacity (Whitecotton et al. 2000, Kozlowski 2000, Thurston and Reader 2001, Keller et al. 2004, Nadezhdina et al. 2006). These soil effects can influence the physiological performance of plants by altering amounts and balances of growth hormones such as abscisic acid and ethylene, reducing total photosynthesis and productivity as a result of the smaller leaf area (Kozlowski 1999). Again, it is likely that the degree of impact from soil compaction is generally small where snowpacks are deep enough to buffer the weight of passing vehicles. The specific snow depth required to ensure no appreciable impacts to underlying vegetated surfaces is likely highly variable and is unknown for wetlands and fens.

Natural vegetation patterns in alpine and subalpine environments are strongly influenced by snow distribution (Billings and Bliss 1959, Kuramoto and Bliss 1970, Galen and Stanton 1995). Redistribution of snow by wind is a key natural process influencing the spatial patterning of snow depth and is strongly influenced by topography. Any activity that alters the size, thickness, or location of snow banks can affect vegetation beneath and downgradient from it. Although the effects of snowmobiling, cross-country skiing, or snowshoeing on the landscape scale patterns of snowpack distribution are likely quite small, these activities do have the potential to affect snow distribution at finer spatial scales.

Ski run grooming and use can thin and compress snow cover subjecting plants to colder temperatures. Species lacking sufficient cold hardiness may be at a competitive disadvantage, leading to shifts among plant functional groups or an increase in unvegetated ground (Fahey et al. 1999, Pickering and Hill 2003, Rixen et al. 2003, Keller et al. 2004). Where use is significant, similar impacts may be expected from snowmobile use. For example, in an analysis of data from Wanek (1974), Keddy found that early spring plants were significantly smaller and less frequent under snowmobile trails, although Keddy et al (1979) did not specifically identify the affected species.

The impact of winter recreation activities can affect plant populations (Figure 3). Ski grooming may affect vegetation by changing soil seed banks. Machine graded ski slopes in the Swiss Alps had more species-poor seed banks than non-graded sites (Urbanska et al. 1998, Urbanska and Fattorini 1998a, Urbanska and Fattorini 1998b, Urbanska et al. 1999, Urbanska and Fattorini 2000). Plant communities can also be impacted through effects on plant establishment and recruitment due to seedling and sampling mortality (Kozlowski 1999). Some species may also have their phenological patterns altered, for example later blooming of spring perennials (Baiderin 1978).

Reduced species cover and diversity occurs even on older, less heavily impacted alpine ski slopes in Washington State (Titus and Tsuyuzaki 1998). However, predicting species level responses to altered snowpack is difficult. Clonal grasses and sedges may be more resilient than plants with other life forms (Foresman et al. 1976). The tolerance of plants can be affected by plant structure, potential for recovery, and environmental conditions, as well as the disturbance intensity and frequency (Liddle 1997, Gallet et al. 2004). For example, the proportion of summer-flowering plants was reduced in ski slopes relative to control plots in Russia, with the exception of the rhizomatous *Poa pratensis,* which expanded its cover (Baiderin 1978).

Distance to gravel surface roads on ski runs, ski run width, distance to forest edge, and the amount of soil compaction were among the most important factors influencing vegetation in ski slope plant communities in southern Nevada (Titus and Landau 2003). Machine grading reduced woody plant cover and productivity between graded ski slopes and control areas (Wipf et al. 2005). Given the more severe disturbances associated with alpine skiing, these results may be more severe than impacts from cross-country skiing and possibly from snowmobiling.

The response of vascular plant species and non-vascular plants like mosses may differ. Experimental trampling in a European study found that vascular plant cover declined immediately after trampling, while bryophytes had a slower response to this treatment.

However, vascular species recovered more rapidly than bryophytes (Torn et al. 2006). Whether similar responses occur in response to winter recreation impacts is unknown.

In fens, it is important to recognize that plant growth is not just in summer. New shoots emerge from soil in winter under snow. Sedges have special winter leaves that are evergreen, while other species have pre-formed buds near ground surface and flower before leaves emerge. Much of the summer growth occurs in the 2-4 weeks after snowmelt and there may be little or no sexual reproduction. Many species are clonal and may be of great age.

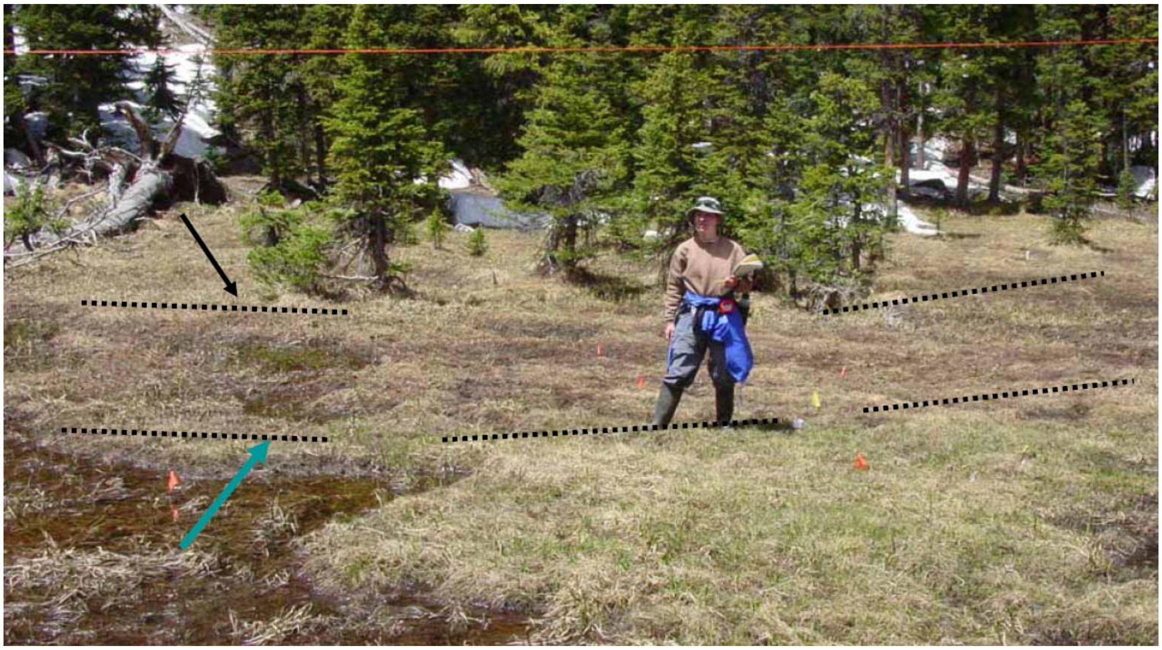

Figure 3. Altered vegetation in a groomed ski run visible by difference in vegetation color between impacted areas (areas between dashed lines) and control areas. Dashed lines and arrows indicate boundary of groomed area.

Effects on fauna

The subnivean space between the ground surface and base of the snowpack is critical for the survival of many small mammals (Sanecki et al. 2006a, Sanecki et al. 2006b). Colder temperatures in the subnivean space may reduce winter survival of small mammals and arthropods. Microtopographic features such as shrubs, saplings, and boulders are able to support the weight of the snowpack above the ground, and the loss of these features due to compaction can reduce subnivean space (Halfpenny and Ozanne 1989, Sanecki et al.

2006b). A reduction in subnivean space may deleteriously affect small mammals by reducing their ability to travel, forage, and access food caches (Benedict and Benedict 2001). Impacts to small mammals vary in relation to spatial extent and severity of snow compaction.

Richness and abundance of arthropods was significantly lower in groomed ski runs than in other plot types in one study, reducing food availability to dependent bird species (Rolando et al. 2007). As with many of the other responses discussed in this review, the severity of impacts to wetland fauna varies as a function of wetland type and the intensity, frequency, and spatial extent of use.

Additional impacts to wildlife such as deer and elk have been identified, including increased wildlife stress due to noise, and altered animal movements and competitive interactions from the creation of tracks (Olliff et al. 1999, Sive et al. 2003, Kolbe et al. 2007, McCarthy 2007). Compounds commonly found in snowmobile emissions were experimentally found to reduce the swimming stamina of brook trout (Adams 1975). Noise from snowmobiles has been associated with elevated levels of stress hormones in wildlife (Olliff et al. 1999).

Effects on ecosystem properties

In a fen within the Telluride Ski area in Colorado, the rate of photosynthesis and net ecosystem exchange (NEE) of CO_2 were lower during early summer in ski runs when compared to adjacent control areas. Average gross primary productivity and NEE rates for the entire growing season were lower in the ski track compared to controls (Cooper and Chimner *Unpublished data*). These changes were apparently caused by lower winter and early summer soil temperatures which slowed plant growth. The long-term implications of these changes are unknown, but could include species changes, and loss of peat. Increased nutrient availability to vegetation has been observed on ski runs, particularly graded ones, when compared to controls (Wipf et al. 2005).

The long-term changes in plant productivity, organic matter decomposition rates, and peat accumulation processes due to winter recreation are unknown. Peat accumulation rates in Rocky Mountain fens are exceedingly slow, approximately 20 cm (8 inches) per thousand years (Chimner et al. 2002, Chimner and Cooper 2003) and are very sensitive to changes in hydrologic regime. Altered soil temperature regimes may lower plant production in fens, lowering production and carbon gain by reducing the amount of carbon entering the wetland. Changes in basin-wide melt-out of snowpacks due to compaction may not significantly impact hydrologic function in groundwater supported fens, but snow compaction on-site may reduce the length of the growing season which is important for high-elevation plants.

Acute versus cumulative effects

The intensity, frequency, and extent of winter recreation activities differ from site to site, which influences ecological impacts. Alpine skiing operations represent the most intense and frequent impacts; however, on an aerial basis, operations are limited when compared to cross-country skiing or snowmobiling. Thus, it is important to define the area and timeframe of interest when attempting to assess impacts from different winter recreation activities.

With sufficient intensity and frequency, even nonmotorized activities within wetlands may alter snow properties, with localized effects to vegetation and soils. There are likely thresholds of impact that vary by wetland and vegetation type, and intensity and frequency of use. Unfortunately, there are insufficient data to identify potential impact thresholds for particular snow conditions.

Individual anthropogenic impacts may act synergistically on watershed processes (Siegel 1988, Winter 1988, Reid 1993, Bedford 1999). The cumulative effects of winter recreation activities in a given watershed may result in greater hydrologic and ecological changes than expected by simply summing the contributions of each individual stressor. As with acute effects, cumulative effects of winter recreation activities likely differ by wetland and vegetation type.

Conclusions

Limited information on the impacts of winter recreation on snowpack properties, vegetation, soils, and fauna has been published, and very few studies have examined impacts to the wetland types that occur in the Rocky Mountain region. Thus, the factors driving ecological response to winter recreation are poorly understood.

In general, there is insufficient information from which to identify specific management thresholds from impacts to fens and wetlands from winter recreation activities. Many of the potential impacts have only been speculated or noted anecdotally. However, there is sufficient information in the scientific literature to make general assessments of potential impacts. Alterations of the physical properties of snowpacks, generally far easier to document than changes in soil microbial communities, have been well described. A summary of some key points follows:

- Winter recreation impacts can be direct or indirect with respect to a particular resource; direct effects to soil and vegetation resources (e.g. direct mortality due to mechanical damage) are likely of less importance than indirect effects.

- Winter recreation activities vary widely in intensity and extent of impact. Intermittent or occasional impacts (e.g. off-trail snowshoeing in wilderness) will likely have a negligible effect on wetland resources. More sustained and extensive impacts, for example, as from operations associated with alpine skiing, are more likely to affect wetlands.

- Physical and chemical changes can potentially affect biota through alteration of habitat characteristics. Vulnerability of specific taxa will vary. Altered ecological conditions may lead to shifts in community composition, diversity, or structure, although studies specific to wetlands are generally lacking.

- Plant production and decomposition are elemental processes governing ecosystem structure and function in wetlands; alterations of soil thermal and hydrologic properties from winter recreation activities may change basic ecosystem function by altering decomposition rates and production.

- Fens are sensitive to changes in hydrologic regime; alteration of hydrologic flow paths may change basic ecological processes such as decomposition.

More information is needed comparing the impacts of different recreation activities on key hydrologic and ecological processes. This is particularly true if accurate models of snow depth and specific impacts are desired for management. Few such data are available for the Rocky Mountain region, with a large proportion of studies originating in other regions and continents.

An improved understanding of watershed-scale distribution, frequency, and intensity of winter recreation use is needed to evaluate potential impacts to wetland resources. Combined with wetland inventory data and occurrence records of rare species or noteworthy ecological communities, wetlands with exceptionally high conservation value, such as fens supporting rare species, can be identified and addressed in planning and management.

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