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Air quality at a snowmobile staging area and snow chemistry on and off trail in a Rocky Mountain subalpine forest, Snowy Range, Wyoming

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Abstract A study was begun in the winter of 2000–2001 and continued through the winter of 2001–2002 to examine air quality at the Green Rock snowmobile staging area at 2,985 m elevation in the Snowy Range of Wyoming. The study was designed to evaluate the effects of winter recreation snowmobile activity on air quality at this high elevation site by measuring levels of nitrogen oxides (NO_x, NO), carbon monoxide (CO), ozone (O_3) and particulate matter (PM_{10} mass). Snowmobile numbers were higher weekends than weekdays, but numbers were difficult to quantify with an infrared sensor. Nitrogen oxides and carbon monoxide were significantly higher weekends than weekdays. Ozone and particulate matter were not significantly different during the weekend compared to weekdays. Air quality data during the summer was also compared to the winter data. Carbon monoxide levels at the site were significantly higher during the winter than during the summer. Nitrogen oxides and particulates were significantly higher during the summer compared to winter. Nevertheless, air pollutants were well dispersed and diluted by strong winds common at the site, and it appears that snowmobile emissions did not have a significant impact on air quality at this high elevation ecosystem. Pollutant concentrations were generally low both winter and summer. In a separate study, water chemistry and snow density were measured from snow samples collected on and adjacent to a snowmobile trail. Snow on the trail was significantly denser and significantly more acidic with significantly higher concentrations of sodium, ammonium, calcium, magnesium, fluoride, and sulfate than in snow off the trail. Snowmobile activity had no effect on nitrate levels in snow.

Keywords Anions · Carbon monoxide · Cations · Dispersion · High elevation · Nitrogen oxides · Ozone · Particulate matter · Winter recreation

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Introduction

Air quality in high elevation ecosystems in the western US is generally considered to be relatively good with low concentrations of air pollutants. However, high-elevation environments in the western United States are sensitive to the effects of atmospheric deposition derived from anthropogenic sources (Finley 1992). Nitrogen deposition is of particular importance in these ecosystems. Emissions of nitrogen oxides are increasing in the western US (Placet 1990), as well as nitrogen (N) deposition in terrestrial ecosystems (Fenn et al. 2003; Williams et al. 1996). Research has shown that atmospheric deposition can

also cause major changes in aquatic ecosystems (Irving 1992; Schindler 1988).

The effect of emissions from snowmobile activity on air quality and deposition in high elevation ecosystems has been studied primarily at Yellowstone National Park (YNP) in NW Wyoming. Most snowmobiles currently are equipped with two-stroke engines that are more polluting than four-stroke engines (Bishop et al. 2001; USDI 2000). They emit hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and non-combusted fuel vapors (USDI 2000). Combustion engine emissions contain carcinogens, including benzene, butadiene, and polycyclic aromatic hydrocarbons (USDI 2000). Combustion engines also emit large amounts of carbon dioxide. Extensive visitor use of snowmobiles has raised concerns about air quality (especially HC, VOC and CO) and park employee health at YNP. Bishop et al. (1999), (2001) documented 'in-use' snowmobile pollutant emissions (pollutant evaluation of snowmobiles in use for recreational travel) but did not directly address associated air quality issues. Kado et al. (2001) addressed the potential health hazards to park service employees by measuring ambient air quality at YNP's West Yellowstone entrance station and at a remote site near Old Faithful geyser. They found levels of CO, PM and VOC to be elevated but not in violation of recommended exposure limits for outdoor employees. However, the National Park Service (National Park Service 1995; USDI 2000) found concentrations of CO at the West Yellowstone entrance to exceed National Ambient Air Quality Standards (NAAQS) during periods of heavy snowmobile traffic (>450 snowmobiles per hour).

Other potentially deleterious effects of recreational snowmobile use have been documented, including wildlife disturbance (e.g., Creel et al. 2002) and health hazards to park employees (Kado et al. 2001) and snowmobile riders (Eriksson et al. 2003; Snook-Fussel 1997).

Atmospheric dry deposition (CASTNET[1]) and wet deposition (NADP[2]) monitored at the Glacier Lakes Ecosystem Experiments Site (GLEES), a high elevation alpine and subalpine research area in the Snowy Range of SE Wyoming (Musselman 1994), indicate that higher amounts of N deposition occur at this high elevation (3,200 m) site than at nearby lower elevations (Korfmacher and Musselman 2004), even though the site is remote from any major source of N emissions. Higher deposition is likely due to the higher precipitation loading, about 120 cm/year at the GLEES, primarily in the form of snow. Wind blown snow and dust also contributes to higher deposition at the GLEES.

Although much of the atmospheric deposition in remote areas such as the GLEES is thought to result from long-range transport, local sources of deposition cannot be discounted. Many public lands, including the Medicine Bow National Forest in southeastern Wyoming, are experiencing increased winter recreation snowmobile use. Use is often higher on weekends and holidays. It is possible that increased snowmobile use will increase the potential for impact in the Snowy Range of Wyoming.

Contribution of snowmobiles to chemical deposition to snow in this area is unknown, and information about deposition impacts of snowmobiles is limited. Research has shown that ammonium and sulfate concentrations in snow were higher under snow machine trails than off the trails, but nitrate concentrations did not change within 100 m of the trail (Ingersoll 1999; Ingersoll et al. 1997). Nitrates are of particular concern, since wet and dry deposited nitrates accumulate in the winter snowpack and can be an important source of N for plant growth (Bowman 1992); and can cause changes in ecosystem processes, species productivity, and composition to alpine meadows (Bowman and Steltzer 1998; Bowman et al. 1993). Interlandi and Kilham (1998) suggest that high elevation aquatic ecosystems are sensitive to N deposition from automobile and snowmobile emissions.

Snowmobile trails have been shown to increase snow density resulting in longer lasting, delayed, spring melt and lower temperature under the snow (Hogan 1972; Keddy et al. 1979; Wanek 1971); factors that may be important in plant species distribution (Atkin and Collier 1992; Kudo 1991; Walker et al. 1993). Damage to ecosystems from increased density of snowpack after snowmobile activity may be caused by acceleration of heat loss and colder temperatures

[1] CASTNET – Clean Air Status and Trends Network: http://www.epa.gov/castnet/.

[2] NADP – National Atmospheric Deposition Program: http://nadp.sws.uiuc.edu/.

under the snowpack (Keddy et al. 1979; Neumann and Merriam 1972; Pesant et al. 1985; Wanek 1971).

A study was conducted to monitor air quality at a snowmobile staging area and trailhead for a major groomed snowmobile trail in the Snowy Range in southeastern Wyoming. The site has different terrain and meteorological characteristics than the Yellowstone snowmobile area. Temporal investigation of the NO_x, CO, O_3 and PM dynamics of this study area provides information on present conditions and insight towards possible snowmobile contribution to changes in air quality at the site. A separate study not related to the air quality study at the snowmobile staging area examined snow density and snow water chemistry on and off a snowmobile trail about 2 km from the trailhead.

Materials and methods

The air quality monitoring study was conducted at the Green Rock Picnic Area snowmobile trailhead and staging area (Fig. 1), Medicine Bow National Forest, about 12 km west of Centennial, Wyoming at 2,985 m elevation in the Snowy Range of Wyoming. The road parallels a stream and is widened at the Green Rock site for parking where snowmobiles are unloaded, fueled, started, and warmed before excursions are begun. Wyoming State Highway 130 through the Snowy Range is closed west of this site to automobile traffic during the winter season; and the road right-of-way is designated Snowmobile Trail U. About 2 km from the trailhead, another trail branches north (Snowmobile Trail O) following the snow-covered

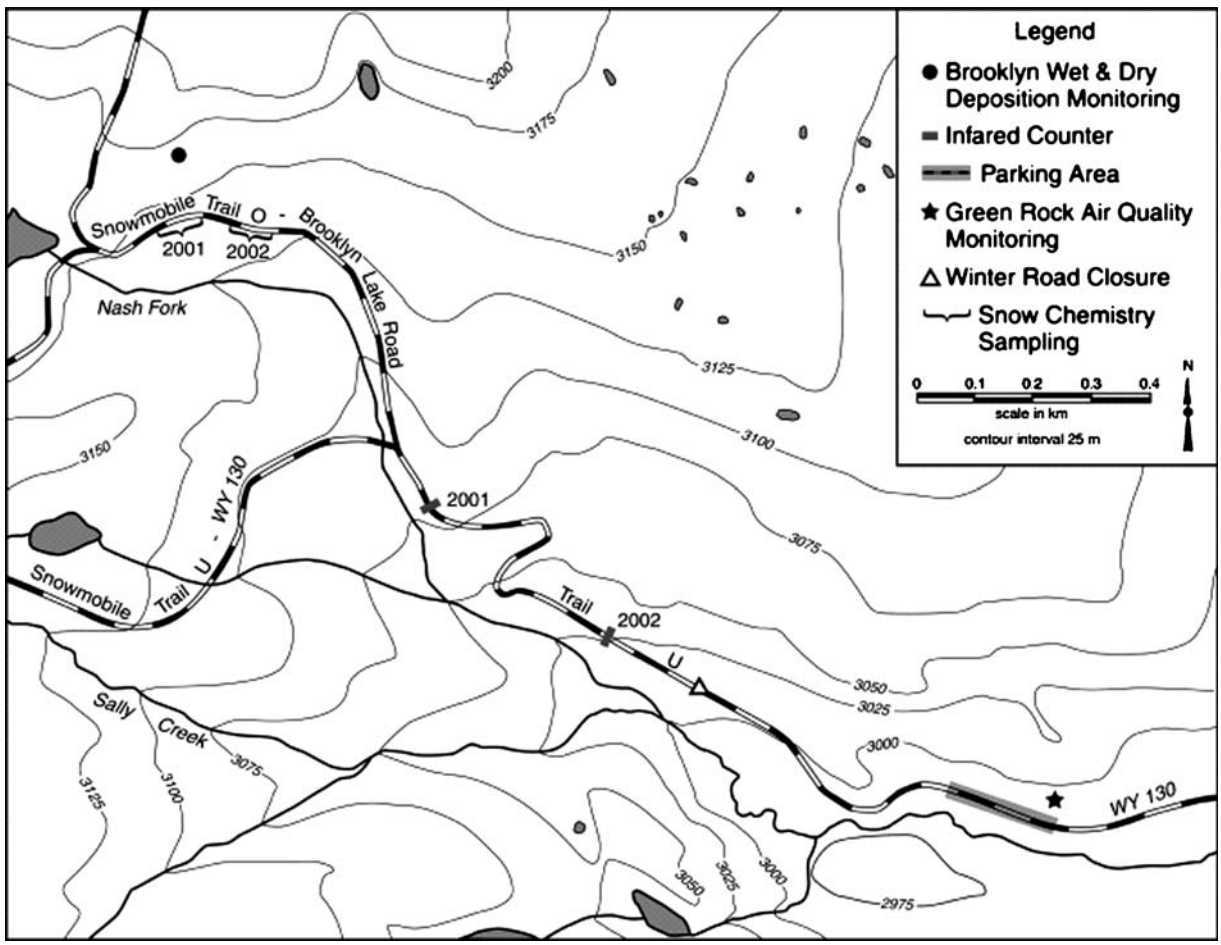

Fig. 1 Location of air quality monitoring and snow sample collection, Medicine Bow National Forest, Snowy Range, Wyoming. The CASTNet CNT169 is located at the Brooklyn Wet and Dry Deposition Monitoring site

Brooklyn Lake Road, a gravel Forest Service road. Trail O continues along the Brooklyn Lake Road except for a small off-road section just southwest of the Brooklyn Deposition Monitoring site (Fig. 1), then through the GLEES and along the summer hiking trail to Sheep Lake and beyond.

Air quality was monitored from winter 2000–2001 through the winter of 2001–2002, including the summer between the two winter seasons. A 2.5× 3 m insulated building to house meteorological and air quality instrumentation was installed near the Green Rock Picnic Area trailhead (Fig. 1). Although this site was selected for monitoring as a worse-case scenario where maximum pollution concentrations would occur, the sensors were not located directly on the roadway. The monitoring building was located about 15 m north and 5 m above the roadway to access a nearby electric power source. Air quality monitored included continuous sampling of concentrations of CO, NO_x, NO, and O_3. The sample intake was located 3.7 m above the ground, and 1.3 m above the top of the instrument building. CO was monitored using a Thermo Environmental Instruments 48C. Two monitors were used for NO_x and NO, a Monitor Labs 8840 and a Thermo Environmental Instruments 42S. The Thermo Environmental Instruments 42S monitor utilizes a low concentration range for monitoring of very low NO_x values, and thus is not a standard EPA reference or equivalent method. NO_2 was calculated from the NO_x and NO output data. O_3 was monitored using a TECO Model 49. The TECO CO and O_3 and the Monitor Labs NO_x instruments were EPA equivalency instruments. Nighttime zero and span calibration checks were conducted sequentially each day beginning at midnight for the Monitor Labs NO_x monitor, followed by the TECO NO_x monitor, then the TECO CO monitor. The zero calibration for the O_3 monitor was also checked every 24 h.

Air quality signals at the Green Rock staging area reflect all sources of pollutants, including snowmobiles and automobiles (primarily SUVs or pickup trucks) pulling snowmobile trailers. The air quality monitoring started late in the winter season of 2000–2001, Therefore, for CO, NO_x, and O_3 the 2000–2001 winter season was primarily used to test air quality monitoring equipment and calibration protocols.

Mass of 10 μm particulate matter (PM_{10}) was monitored for 24-h periods every 6 days following standard PM_{10} monitoring protocols, using a General Metal Works, Inc. particulate monitor. Air quality data were recorded on a Campbell 23X data logger every 10 s with 30-min averages calculated and saved to a data storage module.

Wyoming and national ambient air quality standards exist for particulate matter, carbon monoxide, nitrogen oxides, ozone, and other pollutants, and are listed on the Wyoming Department of Environmental Quality, Air Quality Division web site.[3] However, since the monitoring building in this study was not sited according to state or federal air quality monitoring standards (it was sited near a roadway and near trees to monitor air quality specifically at this snowmobile staging area roadway site), the data from this study cannot be directly related to ambient air quality standards. Data presented are only an indication of pollutant levels at the site for comparison with snowmobile activity. Nevertheless, the data can indicate whether air quality at this site warrant further monitoring following EPA siting protocols.

Snowmobile numbers were counted at a point on the main trail just west of the staging area using a Trail Master automatic infrared sensor. The sensor was aimed across the trail at about 60 cm height above the snow surface. The sensor height was adjusted accordingly as the snowpack depth accumulated. Data were downloaded every Tuesday for subsequent analysis.

Data were analyzed by comparing weekend (1200 Friday–2359 Sunday) with weekday (0001 Monday–1159 Friday). Seasonal differences were analyzed by comparing spring, summer, and fall (SSF, June 19–November 10, 2001, and April 21–Jun 18, 2002) with winter (WIN, November 11, 2001–April 21, 2002). These seasons were related to snowmobile season rather than meteorological season as defined in Zeller et al. (2000a, b).

Standard meteorological instrumentation was installed above the monitoring building for monitoring temperature, relative humidity, wind speed, and wind direction. Sensors were mounted 5 m above the ground. Meteorological data were recorded on a Campbell 21X data logger at 5-s intervals with 1 and 24 h averages calculated and saved to a data storage module. Data were downloaded weekly for processing.

[3] http://deq.state.wy.us/aqd.htm#Regulations.

The snow chemistry study was conducted on Trail O over Brooklyn Lake Road (Fig. 1). Snow samples were collected in February and April of 2001, to capture the early and late season snowpack, at a site along the snowmobile trail near the Saint Alban's Chapel, but over the Brooklyn Road (Fig. 1), for chemical analysis of Acid Neutralizing Capacity (ANC), pH, cations and anions and snow density (April only). Of particular interest were nitrate, sulfate, and ammonium. Snow samples were collected from three transects at least 40 m apart along the snowmobile trail, at various distances perpendicular from the trail, using a Federal snow sampler to collect from the top to the bottom of the snowpack. Snow depth was also recorded. All samples were collected in open areas and sampling near trees was avoided. It could not be verified that snowmobiles had not passed over the sampling locations even at 40 m from the trail at the sites sampled. Off-trail data were combined for comparison with on-trail data. In 2002, snow samples were collected February, March, April, and May at three points along the trail near the same location sampled in 2001 (Fig. 1). To increase replication in 2002, six samples were collected on and six off the trail at three sites rather than collecting samples along a transect perpendicular from the trail at each site as in 2001. Care was taken in 2002 to avoid areas off-trail where snowmobile activity was evident. For both years, all samples were weighed to determine snow water equivalent (SWE) and transferred to Ziploc bags, shipped to the lab frozen, and melted for chemical analysis of acid neutralizing capacity (ANC), pH, conductivity, cations (Ca^{+2}, Mg^{+2}, K^{+1}, Na^{+1}, NH_4^{+1}) and anions (NO_3^{-1}, SO_4^{-2}, Cl^{-1}, PO_4^{-2}).

Day of week (weekend vs weekday) and seasonal differences in all variables were evaluated using PROC MIXED, SAS Version 8 (SAS Institute 2000). The sampling unit was the 24-h mean of the response variable; all models used the residual maximum likelihood (REML) as the estimation method and specified a diagonal covariance structure. All models except those used for snowmobile counts incorporated two fixed effects (a first variable indicating weekday or weekend, and a second indicating season) and a term for the interaction of the two variables. The model for snowmobile counts was a one-way model using only the weekend/weekday variable. Statements of significant differences in the text indicate statistical significance at the 5% confidence level.

Results and discussion

Snowmobile counts

The counter worked reasonably well for providing rough temporal comparisons of snowmobile presence at the site; but was not accurate enough to give reliable snowmobile numbers. A one time hand count indicated that the infrared sensor counted less than half of the actual number of snowmobiles passing the sensor location. In addition, it was observed that a small number of snowmobiles passed behind the sensor, and two snowmobiles passing side by side were counted as one.

Given these numerous caveats and the high variability in the count data, the numbers recorded by the infrared sensor are not considered an accurate count of the number of snowmobile units. Nevertheless, the infrared sensor counts of approximately 200–300 daily snowmobile passes weekday and approximately 600 weekends suggest higher snowmobile activity during weekends. The number of snowmobiles also appeared to be higher weekends based on our visual observations and higher numbers of parked vehicles and snowmobile trailers weekends at the trailhead. Kado et al. (2001) have documented lower numbers midweek than weekend at the West Entrance to Yellowstone National Park. Other counting methods should be explored for counting snowmobiles, including ground mounted under snow motion or magnetic sensors.

Air quality

Because of the late winter start of this study, NO_x, CO, and O_3 air quality data were sparse for much of the 2000–2001 snowmobile season and are not reported here. Nevertheless, preliminary observations indicated that for late winter 2001 NO_x from the Monitor Labs and the TECO instruments tracked closely and no weekend/weekday differences for O_3 were evident. CO was not monitored in 2000–2001. Results of PM_{10} for 2001, and CO, NO_x, O_3, PM_{10}, and $PM_{2.5}$ for the winter of 2001–2002 are discussed.

Carbon monoxide

CO was significantly higher weekends than weekdays, and significantly higher in winter than in summer (Fig. 2). CO was low during the summer, with individual readings seldom above 1 ppm. The maximum CO concentrations recorded during this study were 9.9 ppm hourly average and 1.6 ppm 8-h average. A weekend signal was apparent in summer and winter, perhaps reflecting increased recreational weekend automobile traffic in summer, and increased snowmobile traffic in winter. Higher CO in winter than summer reflects snowmobiles starting at the staging areas and/or motor vehicles towing snowmobile trailers at the parking area. Vehicles were seldom parked along the road at the site in summer, but frequently parked here in winter to unload and start snowmobiles. The common source of pollutants during the summer was light duty motor vehicles traveling the highway, and the lower summer CO values reflect emission controls required on those vehicle.

Nitrogen oxides

There were significantly higher concentrations of NO_x, NO, and NO_2 at the site during the weekend in winter, suggesting a signal from snowmobile activity (Fig. 3). NO_x concentrations seldom exceeded 2.5 ppb. The mean NO_2 value for the entire study period (357 days) was 1.5 ppb, with the maximum 30-min value at 19.8 ppb. NO_2 and NO_x were higher in summer than in winter, reflecting general seasonal differences in nitrogen oxides at the site, but no weekend/weekday differences were evident during summer (Fig. 3). Higher mean daily maxima of NO, NO_2, and NO_x concentrations also occurred during the weekends in the winter (data not shown). The higher weekend concentrations of NO_x and CO is logical given the expected visitor use patterns, although it is the opposite of the tendency noted in a suburban setting by Blanchard and Tanenbaum (2006).

Ozone

Ozone concentrations show little diurnal change in the winter, and closely track temperature in the summer. Mean O_3 concentration appeared to be slightly (but not significantly) higher in winter (50 ppb) than in summer (45 ppb), but there were no significant weekend/weekday differences in O_3 winter or summer (data not shown). Suggested higher mean concentrations in winter might reflect the lack of NO_x scavenging of O_3 thus higher minimum O_3 concentrations in winter (Wooldridge et al. 1997). Maximum ozone concentrations appeared to be slightly (but not significantly) higher in summer than winter, perhaps reflective of higher summertime temperatures and higher solar radiation for photochemical generation of O_3; but mean daily maximum O_3 concentrations never exceeded 60 ppb. The

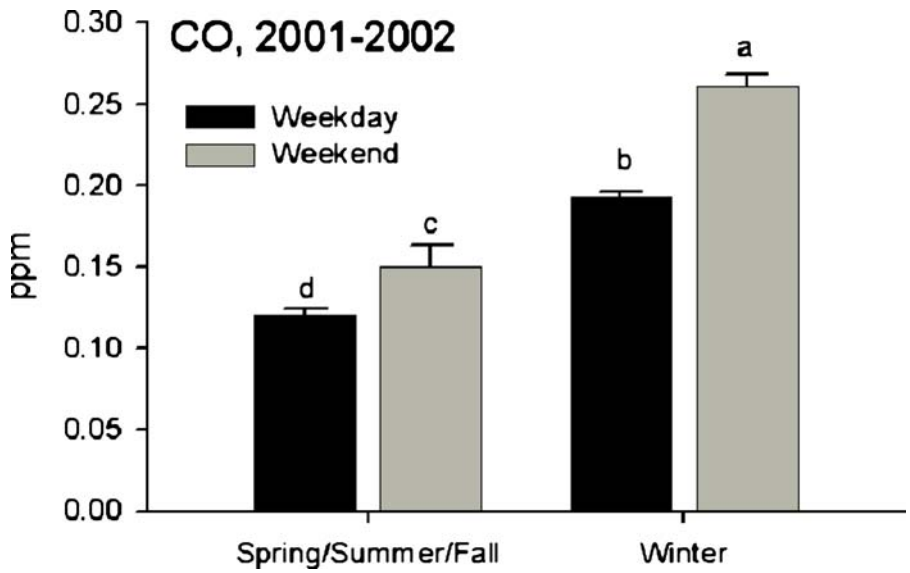

Fig. 2 Daily mean carbon monoxide at the Green Rock snowmobile staging area. *Vertical lines on each bar* indicate ± one standard error of the mean. *Different letters* indicate significant ($p<0.05$) differences in CO concentration

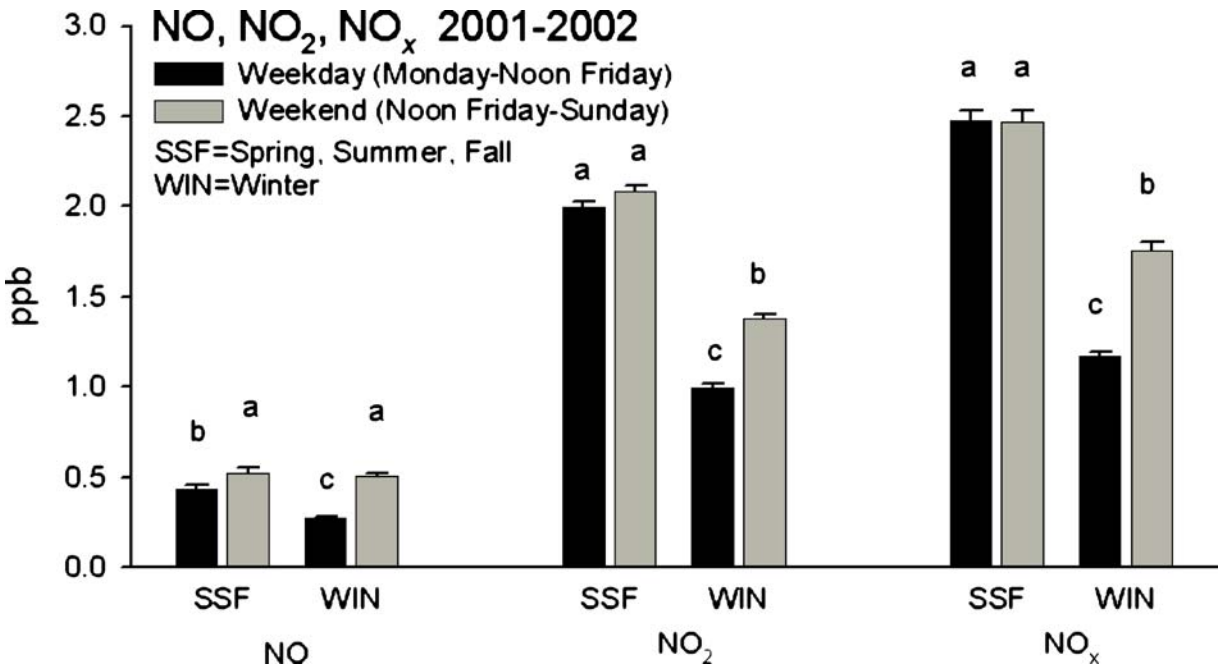

Fig. 3 Nitrogen oxides at the Green Rock snowmobile staging area. *Vertical lines on each bar* indicate ± one standard error of the mean. *Different letters* indicate significant ($p<0.05$) differences in NO, NO_2, or NO_x concentration

relationship of O_3 to NO_2 is not evident from the data, although chemically O_3 and NO react to form NO_2. O_3 values seldom reach zero at this remote site (Wooldridge et al. 1997). A comparison of the winter O_3 values at the snowmobile trailhead and at the CASTNet site (CNT169) about 2 km away (Fig. 1) found the difference between the two sites to be small, an average of 0.75 ppb less at CNT169.

Particulate matter, PM_{10} mass

PM_{10} was low, generally less than 10 μg/m^3 at the site, but appeared to be higher in the summer than winter (Fig. 4). Although differences between winter and summer were significant in 2001, the apparent winter/summer difference in 2002 was not statistically significant. PM_{10} would be expected to be higher in summer than winter, as less land surface is snow covered, and greater surface area is available for wind erosion and transport to the site during the summer. The use of unpaved rural roads and greater automobile traffic in summer would also contribute to higher airborne particulates. There apparently is little weekend/weekday differences in PM_{10} at the site, but monitoring protocols (once every 6 days) allowed considerably fewer weekend samples for comparison.

Meteorology

Temperature and relative humidity followed typical diurnal patterns for this area. Winter temperatures seldom exceeded 0°C. Wind direction is predominantly from the west. Wind speed, an important factor in pollutant dispersion, was considerably higher in winter than in summer.

Pollutants and wind

The air quality monitoring station was located north of the road on a slope facing toward the road, and the prevailing wind direction was from the west and west south west, so it is likely that some of the pollutant emissions from the roadway were not detected. Some additional dispersion of roadway pollutants occurred before reaching the intake located about 9 m above the road surface. Data analysis suggests that indeed when the winds were from the southerly direction (110.5–247.5°) where the road was located, concentrations of CO were higher than when winds were

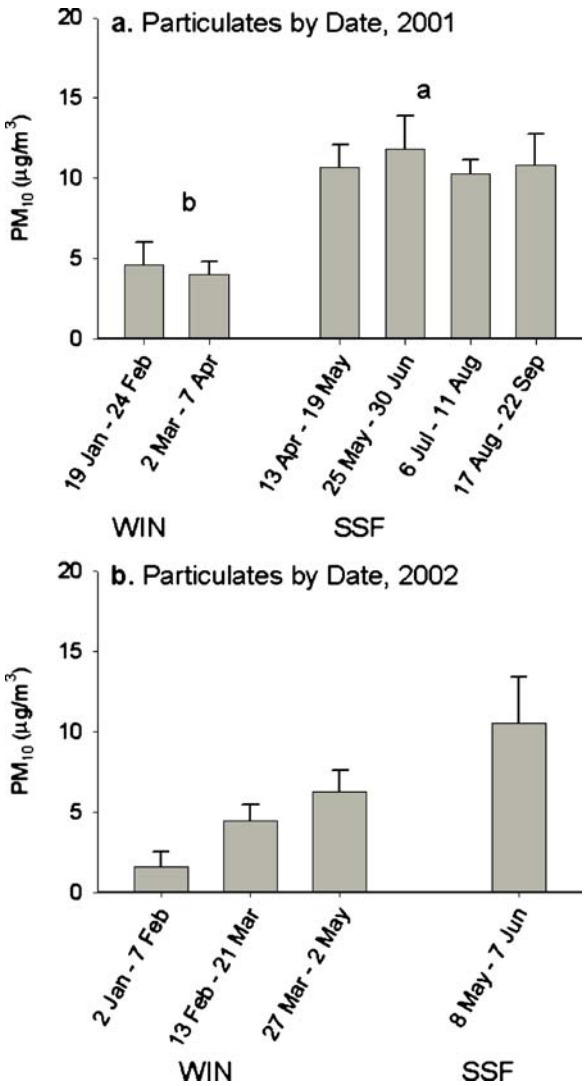

Fig. 4 Particulate matter (10 µ size) at the Green Rock snowmobile staging area. *Vertical lines on each bar* indicate ± one standard error of the mean. *Different letters* indicate significant ($p<0.05$) difference between winter (WIN) and spring/summer/fall (SSF) PM_{10} for 2001. There were insufficient data to evaluate seasonal difference in 2002. There were no significant differences between weekend/weekday for 2001 or for 2002

from the west through east direction (270–360 and 0–90°) (Fig. 5).

O_3 also was higher when the winds were from a southerly direction (Fig. 5). Wind velocities were significantly higher when winds were from the west and west south west (Fig. 6). Exposure of the monitoring building was more open in this direction than from the more northerly directions where trees and the uphill slope may absorb O_3 before it could reach the sensor. O_3 is highly reactive with plant tissue and is expected to be lower within the canopy where it can more easily be absorbed. O_3 was also lower when wind velocities were lower. Relating measured levels of ozone to local sources of pollution (i.e., snowmobiles) is somewhat problematic in any event, since ozone is a secondary pollutant not directly emitted from point sources. Assessment of local sources of this pollutant can be compounded by regional generation and transport of O_3 (e.g., Blanchard and Tanenbaum 2006), but we do not suspect that local generation of O_3 had a significant effect on measurements at the Green Rock site.

NO and NO_x concentrations were less when winds were from the west and west south west (corresponding to highest wind speeds; Fig. 6) compared to winds from the east and northerly directions (lower wind speeds). NO_2 and NO_x concentrations were lower when winds velocities were higher, suggesting greater dispersion under high winds. Data presented in Fig. 5 are for yearly means, but there was a significant seasonal effect on pollutant concentration and wind direction (data not shown). Since W and WSW winds were the strongest and most frequent (Fig. 6), it follows that pollutant dispersion (and hence lower measured levels of pollutants) would be greatest when winds were from this direction.

Exceedances of ambient air quality standards

This study was not designed to compare the air quality data to federal or state ambient air quality standards. Nevertheless, NO_2, CO, O_3, and PM_{10} concentrations monitored at this site appear to be well below the threshold levels for exceedance of National or Wyoming Air Quality Standards for these pollutants regardless of snowmobile activity. However, higher concentrations of air pollutants were detected during weekends when snowmobile activity was higher. The results of our study differ from those examining gaseous snowmobile pollution at Yellowstone National Park and elsewhere. For example, Kado et al. (2001) measured 4-h average concentrations of CO in excess of 6 ppm; another study (Ray 2005) reported CO concentrations nearly in violation of the NAAQS 8-h standard of 9.0 ppm at the West Yellowstone park entrance for the winter of 1998–1999. The highest 4-h average observed (30 Decem-

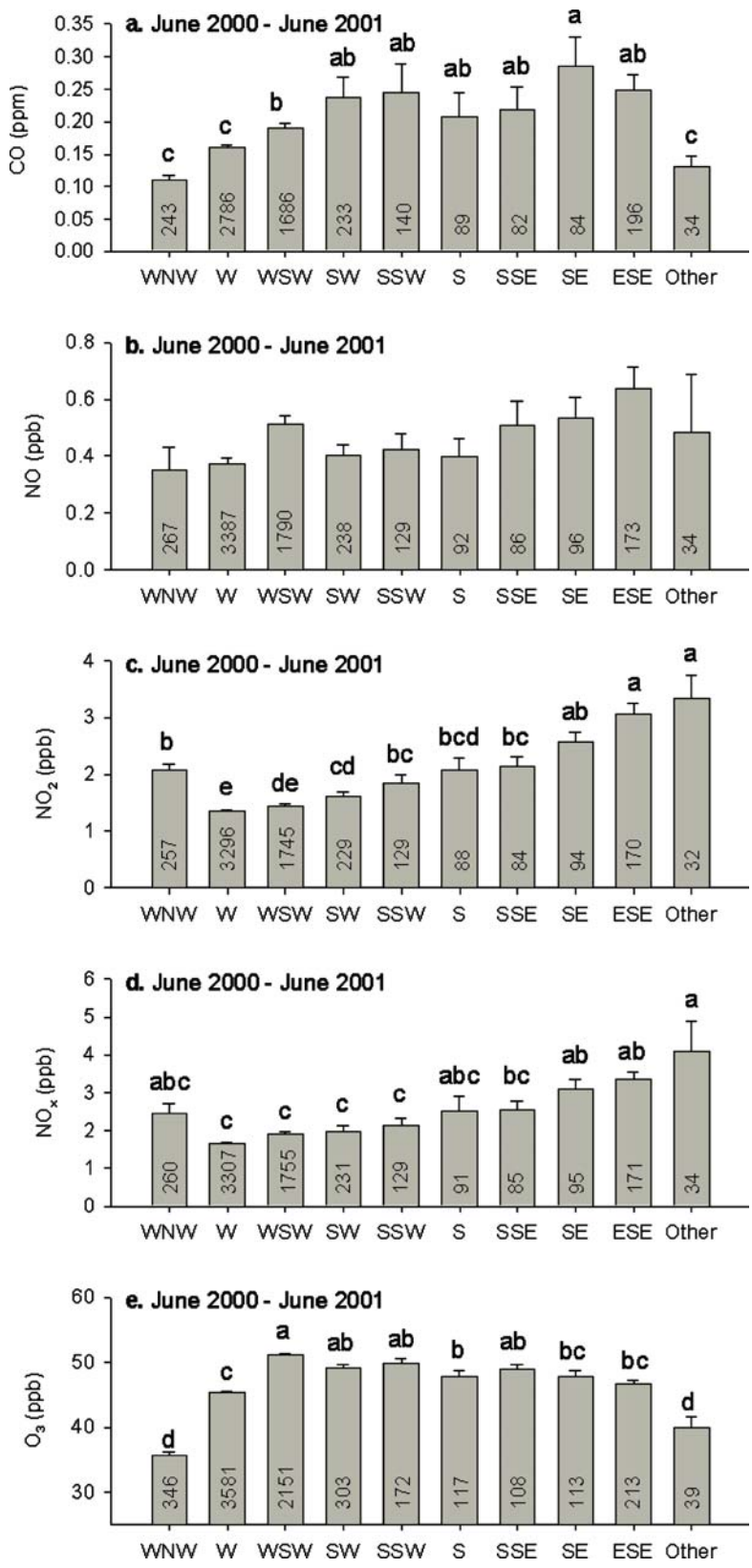

Fig. 5 Gaseous air pollutant by wind direction. *Numbers on bars* indicate number of samples available for analysis. Note there were few values for wind direction "other." These are wind directions other than those indicated on the *x*-axis. *Different letters* indicate significant ($p<0.05$) differences in gaseous pollutant by wind direction. *Vertical lines on each bar* indicate ± one standard error of the mean

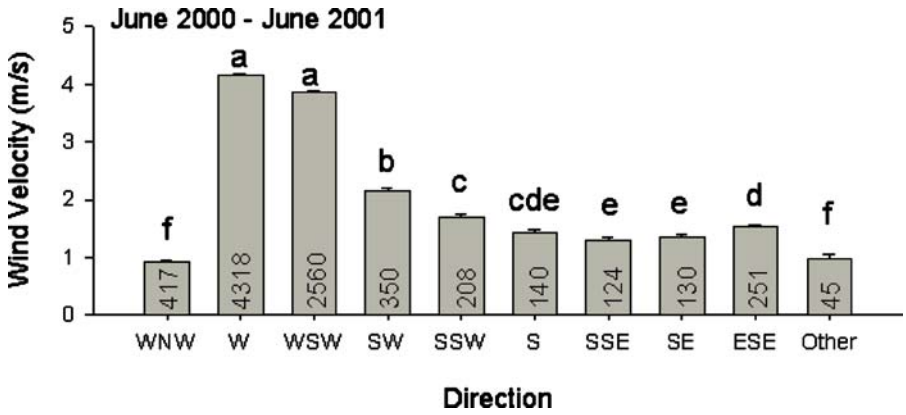

Fig. 6 Wind velocity and wind direction at the Green Rock air quality monitoring station *Vertical lines on each bar* indicate ± one standard error of the mean. *Different letters* indicate significant ($p<0.05$) differences in wind velocity; *numbers* indicate sample size

ber 2001) at Green Rock was 2.64 ppm CO. Green Rock experienced no 4-h average CO concentration greater than 1.7 ppm on any other date during the remainder of the study. The Green Rock snowmobile staging area was selected as a worst-case site, and concentrations were expected to be much lower away from the Green Rock site where snowmobile activity was significantly less.

Substantial differences exist in site characteristics and meteorology between Green Rock and the monitoring sites in West Yellowstone. The West Yellowstone site is located in a broad river valley at relatively low elevation (2,035 m) and experiences periods of light or calm winds. Kado et al. (2001) reported a maximum average wind speed of only 1.32 m/s in the course of their test. Green Rock's location (a hillslope at 2,985 m) and nearly constant winds (Fig. 6) were conducive to effective pollutant dispersion and dilution.

Snow chemistry and density

Examination of snow chemistry and snow density data indicate little difference between the trail and off-trail samples for 2001 (data not shown, concentrations similar to 2002). The trail where the snow samples were collected in 2001 is wide, and it appeared no points along the sampling transects were free of snowmobile passes. When care was taken in 2002 to sample where off trail sites had no apparent snowmobile traffic, data suggest significant on and off trail differences in snow chemistry for most cations (Fig. 7) and some anions (Fig. 8), and for snow density (significantly higher on the trail, data not shown). There was no snowmobile traffic on the trail in May. ANC on-trail/off-trail differences were significant only for April. There were no significant differences in NO_3^- concentration on or off the trail, suggesting no effect of snowmobiles on nitrate deposition at the site. These data agree with those of from Yellowstone National Park where nitrate concentrations in snow were relatively unaffected by snowmobile traffic, but ammonium and sulfate concentrations were higher in snow on the trail (Ingersoll 1999).

Seasonal changes in chemistry were evident for most analytes (Figs. 7 and 8). Early season highs in Na^+, Ca^{2+}, NO_3^-, and Cl^-concentrations, and early season low for ANC, were particularly evident. Since the snowmobile trail is routed over a gravel forest road, chemicals could have originated from the road surface even though sample collection protocols strictly avoided sampling the ground surface and bottom of the snowpack/roadway interface. Although this forest road has never been salted, vehicles travel from Highway 130 to this forest road during the summer. Highway 130 is 1 km south of the sample collection site, and is heavily salted east of the Green Rock area in the winter.

Conclusions

(1) It was evident that more snowmobiles were present at the site weekends than weekdays, but the infrared counter proved inadequate for providing accurate snowmobiles counts.
(2) There were significant differences in air quality between weekends and weekdays. Data show significantly higher concentrations on weekends

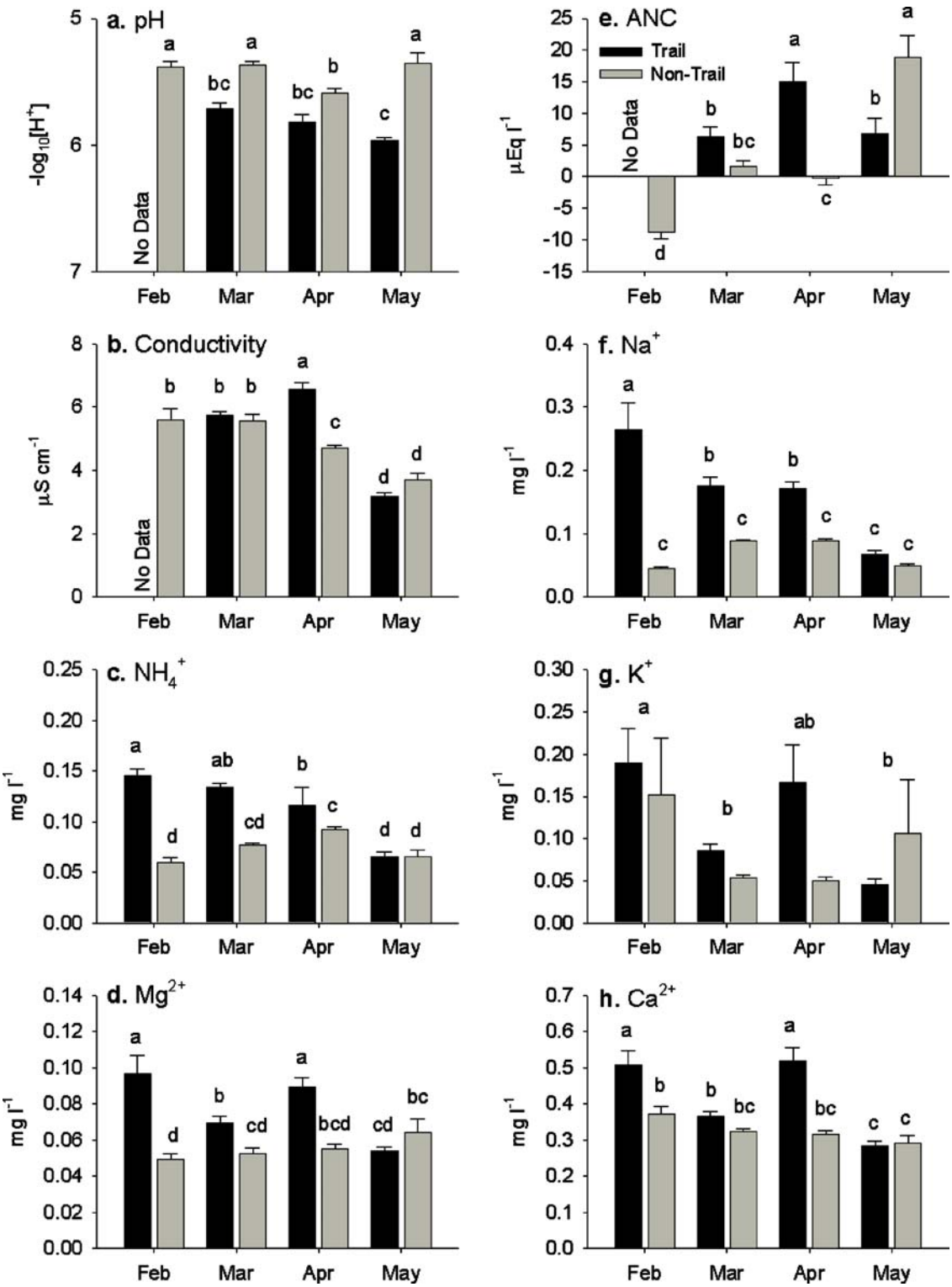

Fig. 7 pH, conductivity, and cation snow chemistry on and off the snowmobile trail, 2002. *Vertical lines on each bar* indicate ± one standard error of the mean. *Different letters* indicate significant ($p<0.05$) differences

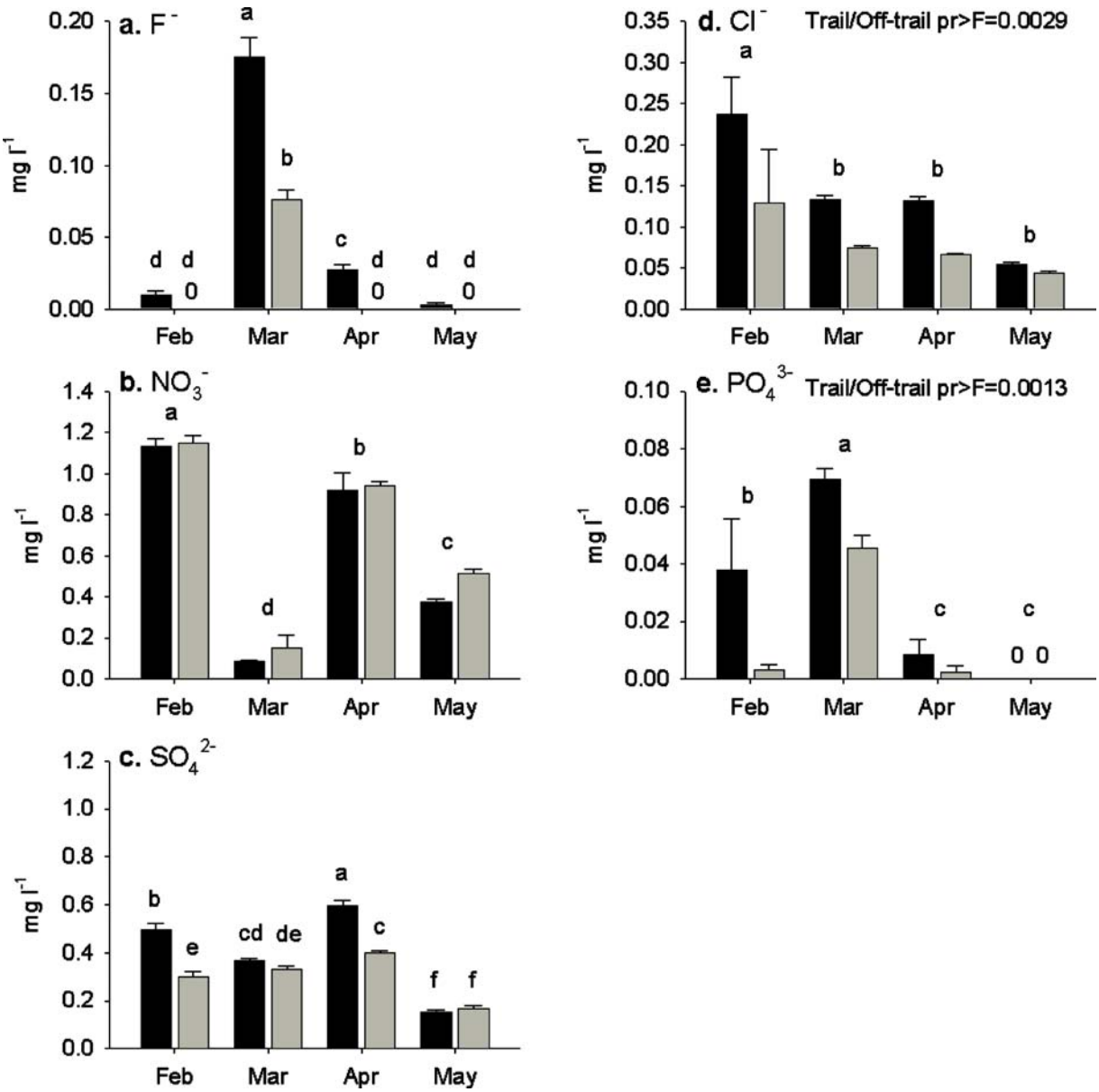

Fig. 8 Anion snow chemistry on and off the snowmobile trail, 2002. *Vertical lines on each bar* indicate ± one standard error of the mean. *Different letters* indicate significant ($p<0.05$) differences in anion chemistry

in winter when more snowmobiles were present for CO, NO_2, NO, and NO_x, but not for O_3. Concentrations of CO and NO were also higher weekends than weekdays during summer. Mean daily maxima of NO, NO_2, and NO_x occurred weekends during the winter. The data suggest that although NO_x concentrations were generally low, increased weekend concentrations resulted from snowmobile activity.

(3) Seasonal differences were evident in air chemistry, specifically for CO, NO_2, and NO_x, but not for NO or O_3. NO_2 and NO_x were higher in summer than winter, while CO concentrations were higher in winter than summer. Nevertheless, air pollutant concentrations were generally low both winter and summer, and were considerably lower than exceedence levels of NAAQS.

(4) PM_{10} was lower in winter than summer, and there were no significant weekend/weekday differences.
(5) CO and O_3 concentrations were higher, and NO_x and NO_2 were lower, when the wind was from the south. The monitoring was conducted just north of the roadway. O_3 was lower and NO_2 and NO_x were higher when wind velocities were lower. The data suggest that under prevailing wind conditions air pollutant concentrations on the roadway were likely higher than those detected by our monitoring sensors. Nevertheless, an air pollution signal was detected that could be related to snowmobile activity; but the pollutant concentrations were low and not likely to cause significant air quality impacts even at this high snowmobile activity site.
(6) Wind speed and physical site characteristics are probably the most important determinants of pollutant concentrations at the level of use described in most existing studies of snowmobile pollutants. There was greater dispersion of pollutants with high winds The open, high elevation Snowy Range site with high winds may be much less likely to experience pollutant levels at or near exceedance criteria than a (relatively) low-altitude site with somewhat restricted terrain and low wind speeds, (e.g., West Yellowstone).
(7) Snow chemistry was significantly different between on and off trail for some analytes when sampling was designed to collect from areas with or without snowmobile activity. Na^+, Ca^{2+}, Mg^{2+}, NH_4^+, $F^-$and SO_4^{2-} appeared to be higher on the trail than off, especially early in the season. The trail followed a roadway, which may have affected on-trail snow chemistry concentrations. There were no differences in NO_3^- on or off the trail. Snow density was higher on the trail than off.

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