PLANT COMMUNITY RESPONSES TO THE COUPLED EFFECTS OF DUST ON SNOW AND WARMING IN ALPINE ENVIRONMENTS, SOUTHWESTERN COLORADO

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ABSTRACT

Alpine plant communities in high-elevation regions of the Rocky Mountains are likely to be sensitive to environmental change, but the relative impact of different factors is not well understood. Warming air and soil temperatures (driven by global climate change) and earlier snowmelt (sometimes driven by factors such as dust deposition on the snow surface during winter) are two separate but interacting factors that can influence growing season length, plant physiology, and environmental conditions. We designed experimental treatments with shade cloth placed on snow (to mimic dust deposition) and open-topped chambers (to warm soil and air temperatures); these treatments led to significantly earlier snowmelt and to measurable changes in environmental conditions. Multivariate analyses of the plant community revealed shifts in phenological events and community composition, even in the initial growth season. These results suggest the value in considering broad regional influences (such as dust transport from distant arid locations) on specific sensitive sites such as snow-dominated alpine communities.

INTRODUCTION

Alpine plant communities are well adapted to living in cold, stressful living conditions and may be especially sensitive to environmental changes predicted from climate change (Callaway et al. 2002). Disturbed soil surfaces in arid regions of the Colorado Plateau and Great Basin are sensitive to wind erosion, especially during spring wind events (Munson et al. 2011). Westerly winds deposit airborne dust on the snowpack of Alpine regions in the Rocky Mountains (Painter et al. 2007). Dust-on-snow decreases the albedo of mountain snowpack, and this results in increased ablation rates of snow cover (Painter et al. 2010). In addition, warmer temperatures predicted as a result of global climate change can contribute to decreased snow cover and rapid melt rates (Kerr 2007; Saunders et al. 2008; Seager et al. 2007). Many studies (e.g., Painter et al. 2010) have focused on how early snowmelt and warmer temperatures will impact mountain hydrology; however, few studies have focused on how Alpine ecosystems will respond to early snowmelt and warmer temperatures.

Plants growing in Alpine systems are strong indicators for biotic responses to global warming because of their history of living in cold environments (Doak and Morris 2009). Alpine plants display a threshold response to early snowmelt where phenological events, such as greening and flowering, are initially delayed; however, under warmer conditions there is a linear relationship between day of snowmelt and plant greening and flowering (Steltzer et al. 2009; Wipf et al. 2006). Doak and Morris (2010) show that in the Northern Hemisphere, southern elevation limits and the latitudinal boundaries of plant communities have shifted north. Warming temperatures also tend to decrease plant survival rates. But plants that persist under elevated temperatures display increased above-ground biomass (Doak and Morris 2010). These confounding responses may be the result of early snowmelt exposing plants to diurnal temperature changes and frost damage, while warmer temperatures extend the growing season allowing plants with high-frost tolerance to photosynthesize over a longer period of time.

Plant communities are often the product of a balance of competitive and facilitative interactions (Wipf, Rixen, and Mulder 2006). Generally, abiotic stress and competition are inversely related; as abiotic stress decreases, competition increases (Callaway et al. 2002; Maestre and Cortina 2004; Rixen and Mulder 2009; and Wipf, Rixen, and Mulder 2006). In Alpine systems, abiotic stress is the product of cold environments and short growing seasons. Thus, warmer temperatures and early-snowmelt alleviate abiotic stress and favor a more competitive environment (Brooker et al. 2007). Plant phenology can be a powerful indicator of species responses to changing conditions (Lau and Lennon 2012). Few studies have examined how Alpine plant communities will respond to the coupled effects of early snowmelt and warming temperatures (Agrawal et al. 2007).

In this experiment, we conduct a climate manipulation study to examine how Alpine plant communities in southwestern Colorado respond to early snowmelt and warming temperatures. We used black shade fabric to decrease snow albedo and accelerate snowmelt to open top artificial warming chambers (OTCs) to simulate an increased air temperature of 2°C. We have three main objectives: 1) to determine if early snowmelt and warming temperatures extend the growing season in an Alpine environment; 2) to asses environmental factors that may contribute to plant stress under contemporary conditions, accelerated snowmelt, warming, and accelerated snowmelt coupled with warming; and 3) to determine how plant communities respond to changes in the timing of snowmelt and increased temperatures. We predict that accelerated snowmelt alone will not significantly lengthen the growing season due to exposure to cold nighttime temperatures; however, accelerated snowmelt coupled with warmer temperatures will likely expand the growing season. We also predict that warmer temperatures alone will lengthen the growing season by alleviating abiotic stress. Plant communities will likely show minimal response to early snowmelt alone. Nevertheless, warmer temperatures and especially warmer temperatures combined with early snowmelt will cause plants to change the timing of key phenological events.

METHODS

Growing Season Length

STUDY SITE SELECTION. Our study site is located at 3,688 m (12,100 ft.) on a southerly aspect adjacent to Grand Turk on Molas Pass in the San Juan Mountains, San Juan National Forest, southwestern Colorado (see plate 10). The study site is within 2 km from San Juan County Road 30 for easy summer access and winter travel. The region has an average daily temperature of 1.25°C, a maximum of 17°C in July, and a minimum of -31°C in January. The area receives an average of 45.48 cm of precipitation a year with about 26.38 falling in the form of rain during the summer and 19.1 cm falling as snow (measurements given are in water content).

EXPERIMENTAL DESIGN. Ten 8 × 12 m experimental plots were established at the study site using a random block design. Five plots had a snow manipulation treatment that used black shade fabric to increase energy absorption and mimic the effects of dust-on-snow to increase snowmelt. An additional five plots served as controls with no shade fabric. Plots were assigned as control plots or snow manipulation plots randomly within blocks. Each block had one advanced snowmelt plot and one control plot. Steltzer and others (2009) illustrated nearby Senator Beck Basin that adding black shade fabric when the snow depth is approximately 1 m will successfully advance snowmelt by nearly two weeks. Variations in microclimate created heterogeneity in the snowpack at our study site that resulted in variable snow depths. The experimental plots were located approximately 10 m apart at midslope to decrease the effects of adjacent plots and upslope areas (Steltzer et al. 2009).

Within each of the 10 experimental plots, 4 roughly 1 × 1 m subplots were established: 2 subplots with an OTC and 2 subplots with no OTC. Subplots were located randomly within the larger plots assuming they had less than 20% bare ground or rock cover. The OTCs were randomly assigned to subplots. Each OTC is a trapezoid fiberglass (Sun-Lite HP Fiberglass 2 mm from Solar Components, Manchester, NH) unit made up of 5 panels with the following dimensions: 29 1/4″ (bottom) × 20 1/2″ (top) × 18″ (height).

THE TIMING OF SNOWMELT. Site reconnaissance trips were done every 2 weeks, starting in mid-March, to monitor snow depth. Black shade fabrics were set up at the end of March when snow depth was about 1 m. At least 10 snow-depth measurements were taken, and at least 2 snow pits were dug around the study site during each reconnaissance trip. Thermochron I-button temperature data loggers (Embedded Data Systems, Lawerenceberg, KY) were installed at the soil-snow surface, 5 cm, 10 cm, and 15 cm above the soil surface to determine the exact day plots became snow free.

WARMING TEMPERATURES. The OTCs were set up on subplots the first day when plots were 80% snow free. At this time, I-button temperature loggers were installed at the soil surface and five cm above the soil surface. Temperatures were recorded at one-hour intervals until the end of the season.

STATISTICAL ANALYSIS. The I-button temperature data from each treatment was used in combination with the day of year plots became snow free to determine the number of growing-degree days for each treatment. Growing-degree days can be defined as days plots were snow free and temperatures remained above 0°C. A one-way analysis of variance (ANOVA) was used to test for significance in the timing of snowmelt. A two-way ANOVA was used to determine if treatments had a significant effect on the number of growing-degree days.

Environmental Factors

EXPERIMENTAL DESIGN. The same experimental design described above was used to assess environmental factors that may influence plant growth.

MEASUREMENTS. In addition to the I-button temperature loggers, we installed temperature loggers in each subplot five cm beneath the soil surface. We also installed HOBO Micro-station (Onset Computer Cooperation, Bourne, MA) soil moisture probes in each subplot. Soil moisture was recorded at one-hour intervals.

STATISTICAL ANALYSIS. We used two-way ANOVAs to determine if treatments had significant impacts on subsurface soil temperature, soil surface temperature, air temperature, and soil moisture.

Plant Community Responses

EXPERIMENTAL DESIGN. The same experimental design described above was used to apply treatments to plant communities.

PLANT PHENOLOGY. Plant phenology events were recorded for the entire plant community in each plot. Phenology was recorded as the Julian day of year when an individual enters a new vegetative or reproductive stage. Vegetative stages for species included first leaf emergence and first leaf fully expanded for all species, as well as first leaf color change for fall (Steltzer et al. 2009). Reproductive stages included first flower open and first fruit fully developed. Observations were made every 2–3 days or as weather permitted.

ABIOTIC MEASUREMENTS. I-button data loggers were used to quantify subnivean soil and air temperature in each subplot. Two subnivean snow temperature data loggers (one at the soil surface and one at 5 cm above the soil surface) were established from mid-March until snowmelt at one-hour intervals in each of the 10 experimental plots. These measurements along with regular field reconnaissance allowed us to determine the day of melt-out as the first day when temperatures at the soil surface reached either +5°C at day or +1°C at night and when the daily temperature exceeded 5°C, which is a temperature generally not characteristic of snow presence (Wipf, Rixen, and Mulder 2006). Following snow melt-out and subplot establishment, two I-button data loggers in each subplot were established: one at 2 cm within the soil and one 5 cm above the soil surface. Loggers recorded data every hour for the entire growing season (snowmelt-off until first snow ~mid-September). These data loggers along with information from the nearest weather station allowed us to quantify the number of potential frost events and growing-degree days that plants experienced under different experimental treatments (figure 17.1).

STATISTICAL ANALYSIS. We used PC-ORD to complete a nonmetric multidimensional scaling with a Euclidean distance measure to compare plant community responses.

RESULTS

Growing Season Length

We found a difference in snow temperature for advanced plots compared to nonadvanced

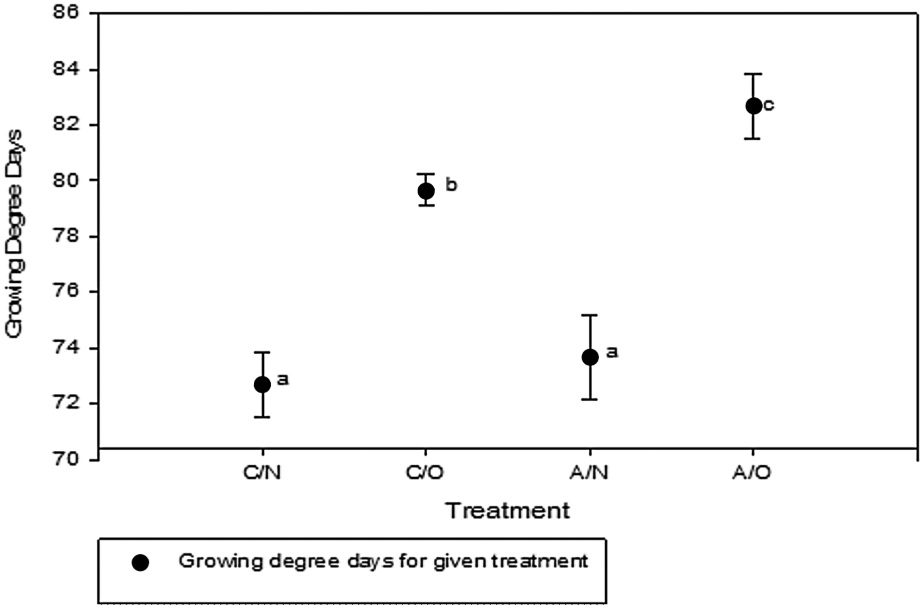

Figure 17.1. Average growing-degree days ± SE. C/N = control plot, no warming; C/O = control plot + warming; A/N = advanced snowmelt plot, no warming; and A/O = Advanced snowmelt plot + warming. Letters indicate significance (*F* = (8, 306), *P* = 0.009) and N = 5.

plots where temperature increased by about 1.4°C ± 0.02°C (*F* = (3, 895), *P* =0.007 [figure 17.2]). This change in temperature increased melt rates with advanced plots melting earlier than adjacent nonadvanced plots by up to 14 days. We also found trends in air and soil temperature related to snowmelt and warming. This created alterations in the growing season length in which early snowmelt plots with OTCs had the greatest number of growing-degree days with about 82 days, while control plots only had 72 growing-degree days (figure 17.1). Soil temperature was altered by advanced snowmelt with a 1.2°C–2.0°C ± 0.02°C decrease in overall nighttime average temperature throughout the growing season (*F* = (9, 602), *P* = 0.004 [table 17.1]).

Environmental Factors

Air temperature was altered by warming treatments throughout the growing season with an average of 2.2°C ± 1.2°C (*F* = (42, 339), *P* = 0.0001[table 17.2]). The increase in air temperature directly correlates with a decrease in soil moisture in advanced and nonadvanced plots that contain open top-warming chambers, which decreases soil moisture by about 0.2 m^3 water/m^3 soil (*F* = (29, 990), *P* = 0.0001 [table 17.3]).

Plant Community Responses

We saw strong groupings in terms of responses of the entire plant community under varying treatments in terms of first flower development and first seed development using multivariate analysis (figure 17.3a and b).

DISCUSSION

We showed that OTC warming chambers significantly increase air temperatures and lengthen the growing season supporting

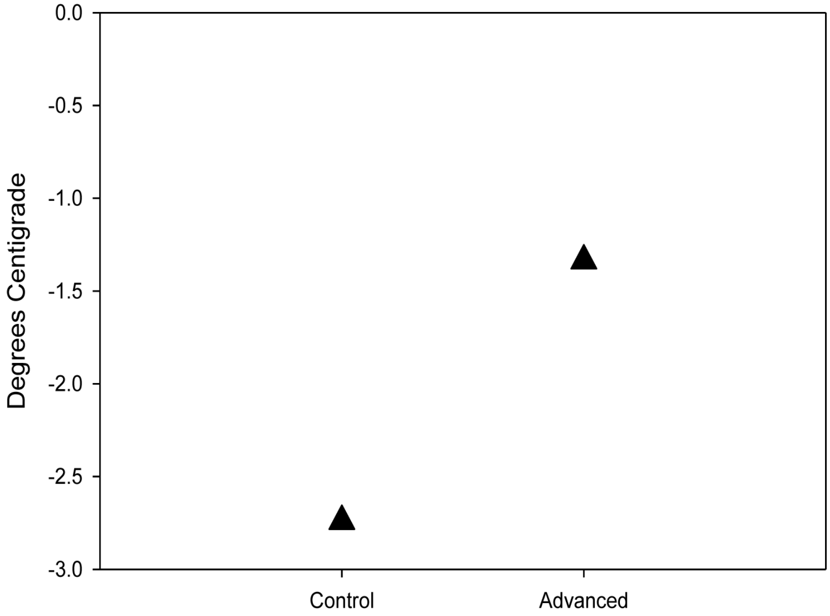

Figure 17.2. Mean temperature of snow profiles for control plots and advanced snowmelt plots near West Turkshead Peak, southwestern Colorado. Advanced plots were significantly warmer within the snowpack (*F* = (3, 895), *P* = 0.007) during the day and night than control plots (N=5).

Table 17.1. Mean and maximum day (700, 1,859 hours) and mean and minimum night (1,900, 659 hours) soil temperatures 2 cm below soil surface for advanced snowmelt/warming treatment combination plots near West Turkshead Peak, southwestern Colorado (N = 5)†

Treatment	Max Day Soil Temp (°C)	Min Night Soil Temp (°C)	Mean Day Soil Temp (°C)	Mean Night Soil Temp (°C)
Control, No Warming	14.00 a	1.75 a	9.37 a	8.49 a
Control, with Warming	19.88 a	1.75 a	9.84 a	9.28 a
Advanced Snowmelt, No Warming	12.38 a	1.13 a	8.34 b	7.26 b
Advanced Snowmelt with Warming	17.25 a	1.38 a	8.42 b	7.41 b

†Different letters indicate significance ($P \leq 0.05$) among treatments for specific temperature measurements.

Table 17.2. Mean and maximum day (700–1,859 hours) and mean and minimum night (1,900–659 hours) air temperatures (°C) 2 cm below soil surface for advanced snowmelt/warming treatment combination plots near West Turkshead Peak, southwestern Colorado (N = 5) †

Treatment	Max Day Air Temp (°C)	Min Night Air Temp (°C)	Mean Day Air Temp (°C)	Mean Night Air Temp (°C)
Control, No warming	19 a	-2 a	16.57 a	4.92 a
Control with Warming	21.5 b	-1 a	17.99 b	5.69 a
Advanced Snowmelt, no Warming	17.5 a	-4 a	16.57 a	4.56 a
Advanced Snowmelt with Warming	21 b	-3 a	19.96 b	5.19 a

†Different letters indicate significance ($P \leq 0.05$) among treatments for specific temperature measurements.

Table 17.3. Average soil moisture in different treatments near West Turkshead Peak, southwestern Colorado (N=5)†

Treatment	Soil Moisture (m^3 water/m^3 soil)
Control, No Warming	0.133075 a
Control with Warming	0.072825 b
Advanced Snowmelt, no Warming	0.162775 a
Advanced Snowmelt with Warming	0.051247 b

†In warming chambers soil moisture significantly decreased ($F = (29, 990)$, $P = 0.0001$), which is directly correlated with an increase in air temperature (DF = 15, $P = 0.007$), implying that warmer conditions significantly decrease available moisture within the soil profile.

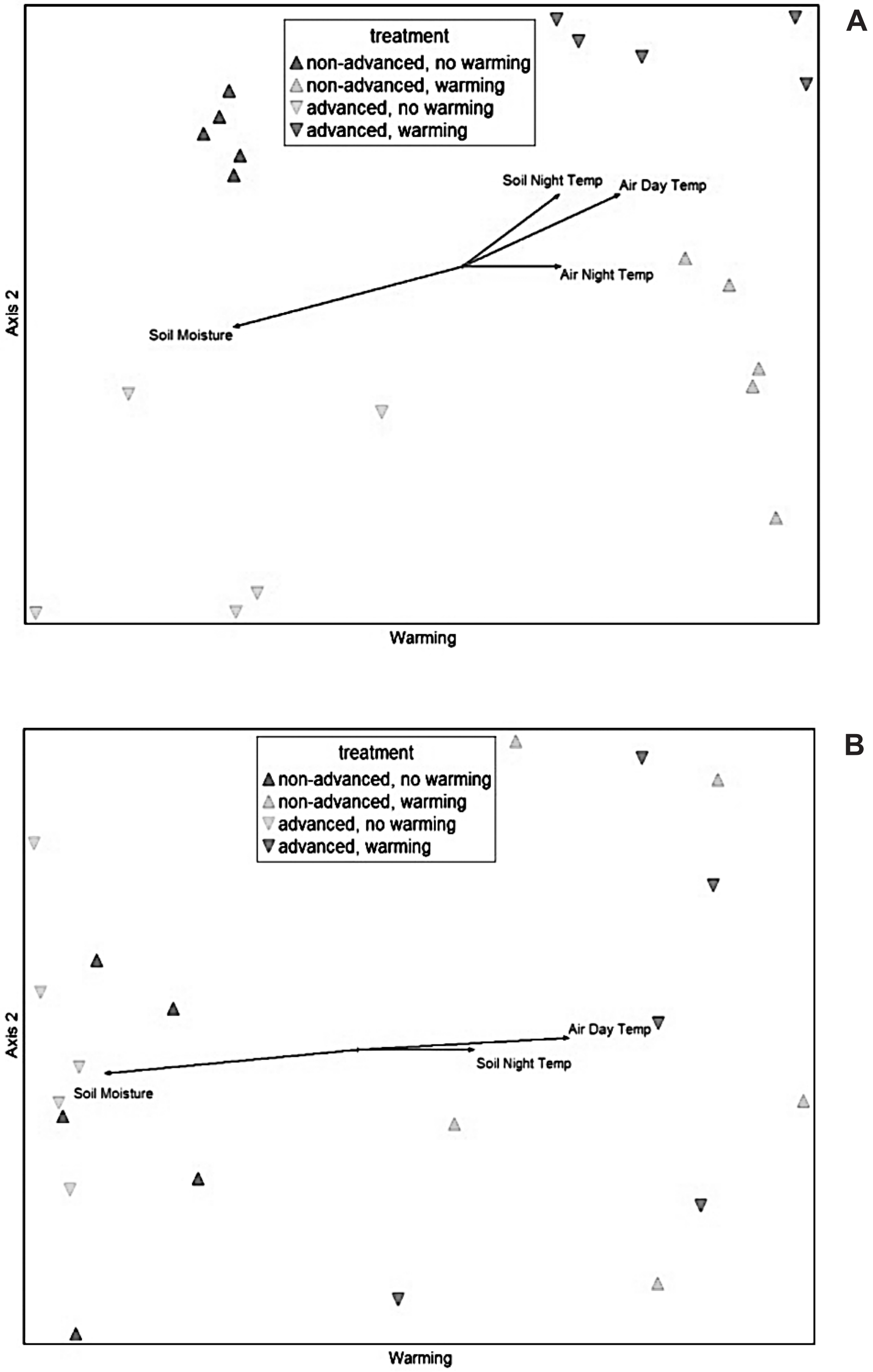

Figure 17.3. Nonmetric multidimensional scaling with Euclidean distance measure for timing of first flower (A) and first seed (B) for plant communities exposed to four different treatments. Each symbol represents one replicate for a given treatment (N = 5/treatment). Vector data represents variables driving differences in community responses.

research from multiple artificial warming experiments worldwide (Hollister, Webber, and Bay 2005; Liu et al. 2011; Takahashi 2005). The growing season was expanded more when warming treatments were combined with advanced snowmelt treatments; this supports our initial hypothesis. By extending the growing season, plants are likely to exhibit increased biomass, which may increase competition for limited nutrients (Doak and Morris 2010). Changes in the balance of competitive versus facilitative interactions due to a longer growing season may alter Alpine plant community compositions (Callaway et al. 2002).

We found that the timing of snowmelt had a direct relationship with nighttime soil temperature, and advanced snowmelt plots' lower temperatures, which may play a role in biochemical reactions in early spring, such as seed germination and root respiration. Chambers (1995) showed that in Alpine environments soil temperature, seed germination, and seedling survival rates are positively correlated. The correlation suggests that a decrease in soil temperature would decrease germination rates and seedling survivability. Following seedling maturity soil temperature still impacts survival rates of seedlings because of the temperature's effects on plant respiration rates. Higgins and Spomer (1976) found that Alpine plant species often have higher root respiration rates to accommodate for cold soil temperatures. This idea is supported by Cooper (2004) who illustrated that root respiration rates in the Alpine are directly related to the percentage of below-ground biomass for Alpine plant species. Root respiration rates in cold environments allow for Alpine plant species to rapidly develop leaves and shoots after snowmelt from large root systems that are protected from cold winter temperatures by the insulated properties of soil and snow (Bowman 2000). As air temperatures increase and the soil becomes drier, soil temperature begins to rapidly increase, which may result in a variety of species-specific alterations to growth and survival. Species that cannot adjust their sensitivity to temperature-dependent, root-respiration rates will have a poor survival rate because warmer temperatures increase respiration rates but not photosynthetic rates (Bowman 2000; Cooper 2004).

The plant community responded to the timing of snowmelt and warming temperatures individually and combined by changing the timing of key phenological events (figure 17.3). This illustrates that the Alpine plant community at our study is sensitive to changing climatic conditions and could be transformed if altered climatic conditions continue over extended periods (Zhang and Welker 1996). End-of-season phenological events, such as first seed development, show resiliency to early snowmelt but are impacted by warming; this supports findings from Steltzer et al. (2009) and Hollister, Webber, and Bay (2005). This finding also demonstrates that early-season events, such as timing of snowmelt, have little-to-no-effect on key phenological events near the end of the growing season, such as first seed development (Bowman 2000; Kudo and Hirao 2006).

Alpine plant productivity may increase, resulting in changes to biodiversity if climatic conditions favor a warmer and longer growing season (Cooper 2004; Zhang and Welker 1996). Warming in the Alpine may result in a decrease in biodiversity and a loss of species typically found only in Alpine environments (Fried, Petit, and Reboud 2010). Zhang and Welker (1996) showed that warmer conditions created a more competitive environment that favored grass species over forb species. Further research is needed to better understand the coupled effects of early snowmelt and warming on Alpine plant communities despite clear trends occurring under one event or the other. Specifically, future research should focus on species-specific responses and species interactions.

These findings suggest that management of Alpine ecosystems may be directed to prevent disturbance to Alpine environments by targeting arid system restoration. Since air-borne dust is sourced to arid landscapes that have been disturbed, a wise management objective could be to restore vegetation in arid regions and thus prevent future dust storms (Painter et al. 2010; Munson et al. 2011). Our data show the sensitivity of Alpine ecosystems to alterations of the landscape in arid regions, and this suggests that more regional-wide land management perspectives ought to be taken.

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