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Brief Communication: Early season snowpack loss and implications for over-snow vehicle recreation travel planning

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Abstract. Over-snow vehicle recreation contributes to rural economies but requires a minimum snow depth to mitigate negative impacts. Daily snow water equivalent (SWE) observations from weather stations in the Lake Tahoe region (western USA) and a SWE reanalysis product are used to estimate the onset dates of SWE corresponding to ~30 cm snow depth (SWE_{min}). Since 1985, median timing of SWE_{min} has increased by approximately two weeks. Potential proximal causes of this delay are investigated; rainfall is increasing during October-December with dry days also becoming more frequent. Adaptation strategies to address over-snow vehicle management challenges in recreation travel planning are explored.

1 Introduction

Ongoing and projected climate change is accelerating the decline of the cryosphere throughout Earth's mountain regions (Huss et al., 2017). Reductions in winter season snow, ice, and permafrost cover and volume primarily result from rising air temperatures (Brown and Mote, 2009) and shifts in precipitation from snow to rain (McCabe et al., 2018). These changes have cascading effects from mountains to lowlands with wide-ranging socioeconomic and ecologic impacts (Huss et al., 2017). In mountain regions of the United States, Europe, and Canada, winter recreation and tourism are central to economic activity. The economic benefits from winter recreation are projected to decline as a result of continued climate change that reduces season length and makes access to reliable snow more difficult (Wobus et al., 2017; Steiger et al., 2017).

Most winter tourism-based climate change impact studies have focused on ski resort-related activity (Steiger et al., 2017), although research has begun to address how other recreation-based components of the winter economy may be affected (e.g., Tercek and Rodman, 2016; Wobus et al., 2017). In the Lake Tahoe region of California (Figure 1a), and many other rural mountain areas of the western United States, over-snow vehicle (OSV) use is a regionally significant component of winter season recreation. Estimates of economic revenue from OSV recreation in the United States range between 7 and 26 billion USD (Fassnacht et al., 2018). As a result, OSV recreation has an appreciable economic impact on rural counties within the northern Sierra Nevada, many of which have a greater dependence on tourism-related employment than elsewhere in California (United States Census, 2013).

The proximity of the Lake Tahoe region to large population centres creates demand for OSV recreation over a limited and ecologically sensitive area. In order to limit potential negative impacts on natural resources (e.g., Keddy et al., 1979) during OSV operation, a minimum snow depth must be present. Minimum snow depth restrictions have been proposed by several forests undergoing winter travel management planning across the Sierra Nevada with a 30 cm recommended depth (United States Forest Service (USFS), 2013). Few forests have such a requirement at this time, but several are currently engaging in the process of winter travel management planning in response to a 2015 U.S. Federal Court ruling (Federal Register, 2015). The Eldorado National Forest in northern California (located in the southwestern quadrant of the study area) currently requires a minimum snow depth of approximately 30 cm for off-trail OSV use.

To our knowledge, no precise value of this minimum depth has been established through comprehensive studies quantifying OSV use and impacts or disturbance. Nonetheless, evidence indicates that OSV can alter the landscape when a shallow snowpack is present. Keddy et al. (1979) observed that OSV use on very shallow snow (10-20 cm deep) doubled snow density and compressed underlying vegetation. When OSV use began under a deeper snowpack, less difference in snow density and hardness was observed compared to a control (no-OSV use) snowpack (Fassnacht et al., 2018). Further complicating the minimum depth requirement is the dependence of snow depth on the density of the snow, which varies seasonally and as a function of weather conditions that drive snowpack metamorphism processes (Sturm et al., 2010).

Resource managers tasked with day-to-day operations such as opening and closing OSV trailheads over large, diverse areas may not have the resources to visit trailheads to obtain snow depth and density measurements. Instead, they often rely on subjectively-based qualitative assessments of what is deemed sufficient snow. Managers often do not set a specific OSV season, leaving it to user discretion to determine when OSV use is appropriate. This can potentially cause conflict with other uses during the start and end to the winter season and can allow opportunities for inadvertent damage to natural resources due to insufficient snow depth. Here, we estimate the median timing of achieving sufficient snow depths for OSV operation and their trends during the past 34 years using observations of snow water equivalent (SWE) and a reasonable assumption of snow density. The proximal causes of the identified increasingly later onset of achieving a minimum SWE value are further investigated. Because this trend towards later onset is not expected to reverse under continued regional warming, we provide adaptation strategies to cope with diminishing early season snowpack resources that can be included in forest travel management plans. The techniques can be extended to other regions where OSV recreation is an important component of economic activity and where early winter snowpack losses may be impacting winter recreation.

2 Data and Methods

The study area is the Lake Tahoe region of the western United States, a coastal, moderate elevation snow-dominated mountain range (Figure 1a). Daily maximum and minimum temperature, SWE, and precipitation were acquired for 16

SNOTEL stations from the Natural Resource Conservation Service (http://www.nrcs.gov/snotel). Daily, gridded estimates of SWE at 100 m horizontal resolution were provided by a satellite-era SWE reanalysis product (Margulis et al., 2016). The period studied encompasses October 1 1984 to March 31 2018 (2016 for the SWE reanalysis), which corresponds to the winter seasons of 1985-2018.

No accepted value of a minimum snow depth exists for OSV operation. Anecdotal values used by managers vary between 150-450 mm depending on compaction (USFS, 2013), but these do not take into account variability in snow density. To provide a conservative and reasonable estimate of sufficient snow depth for what is assumed to be required for non-intrusive OSV operation, we specified 90 mm SWE (hereafter SWE_{min}) as the required depth for approval of OSV use. This value was obtained by equation (1):

$$SWE\ [mm] = d\ [mm] * {}^{\rho_s}/_{\rho_w}, \quad (1)$$

where d is depth, ρ_s is the density of the snow and ρ_w is the density of water. We assume that in a coastal snowpack with marginal compaction, ρ_s is typically 0.3 g/cm^3 (Sturm et al., 2010). This value appears reasonable to approximate a depth of 300 mm for early season conditions and is consistent with values used by the USFS (2013). Our SWE_{min} value is close to Patterson (2016) and Tercek and Rodman (2017), who both chose 100 mm SWE as a threshold value for winter recreation in the Rocky Mountain National Park and Yellowstone National Park, respectively. We report the median timing of when each SNOTEL station and reanalysis gridpoint achieves SWE_{min} and the annual timing as the median of the 16 SNOTEL stations.

To explore possible processes controlling the onset date of SWE_{min}, snow fractions (S_f) between October 1 and December 31 were calculated using the empirical hyperbolic tangent function formula developed by Dai (2008) with Sierra Nevada ecoregion parameter values estimated by Rajagopal and Harpold (2016). In contrast to Rajagopal and Harpold (2016), who used maximum temperature to estimate snow fraction, we selected average temperature because it gave a closer approximation to the mean snow level (~1,750 m) based upon independent estimates from observations (Hatchett et al., 2017). Dry days were days that zero precipitation was measured at the SNOTEL stations.

For all data, linear fits were estimated using a Theil-Sen slope and we report Spearman rank correlations. Statistical significance was tested using a modified Mann-Kendall test that accounts for serial correlation (see Hatchett et al., 2017 and references therein).

3 Results and Discussion

3.1 Timing of SWE_{min}

Median timing of achieving SWE_{min} ranged from early November to early January and was positively correlated with elevation (R^2=0.41, p<0.01; Figures 1a and 1b). For the selected SWE_{min}, nine of the 16 stations have significant (p<0.1) trends in towards later onset of SWE_{min} (Figure 1b). 13 of the 16 stations demonstrated a significant ($p<0.1$) trend when a value of SWE_{min} between 80 and 100 mm was chosen (Figure 1b). There was no relationship between trend in onset date and elevation, which suggests that regional weather variability is a first-order control on snowpack conditions. At the regional level, the median trend across all stations was 0.55 day $year^{-1}$ ($p<0.001$; Figure 2a). This equates to SWE_{min} being achieved approximately 19 days later between the present day and the beginning of the record, although interannual variability still exists (Figure 2a). Results from the SWE reanalysis product are broadly consistent with the station-based analysis, indicating that timing of SWE_{min} is largely a function of elevation (Figure 1a). The median trend of the domain (approximately 15 days over the study period or 0.48 day $year^{-1}$) is close to the SNOTEL-based trend with the largest trends occurring above 2000 m (Figure 1c). The median trend of the domain when only considering statistically significant gridpoints ($p<0.05$) is approximately 21 days over the study period or 0.67 day $year^{-1}$ (Figure 1d). The consistency of the results between the independent SNOTEL data and the SWE reanalysis product support the hypothesis that a delayed onset of SWE_{min} is occurring in the Lake Tahoe region. During years with later onset of SWE_{min} (such as 1991, 2012, or 2014; Figure 2a) most OSV users would likely opt out of recreating due to potential mechanical damage to OSVs. However, if sufficient snow existed above a certain elevation, inadvertent damage to the landscape could result when OSVs travel over shallow snowpacks in order to reach destinations with deeper snow. To ensure access to higher elevation areas for OSV use during poor lower elevation snowpack conditions, management plans could identify and implement corridors or rights-of-way that minimize landscape impacts while allowing access (Table 1).

3.2 Possible drivers of timing changes of SWE_{min}

The increasingly later onset of SWE_{min} (Figures 1c, 1d and 2a) is consistent with an observed increase (0.6 days yr^{-1}, $p<0.0001$) in the number of dry days during early winter (October-December; Figure 2b). The observed decreasing trend towards reduced early season snow fraction (S_f; 0.6% $year^{-1}$, $p<0.0001$; Figure 2c), implies that both increasing numbers of dry days and a shift towards increased rainfall are likely contributing to later onset of SWE_{min}. The reduction in precipitation falling as snow is primarily driven by warming temperatures (McCabe et al., 2018), which may be controlled by regional atmospheric and oceanic circulations that favour higher snow level storms (Hatchett et al., 2017). The higher snow levels (and hence lower S_f; Figures 2a-b) reduce snowpack accumulation during precipitation events and can allow for snowpack loss due to turbulent heat fluxes and heat input by rain. The more frequent dry conditions create more opportunities during which snowpack loss can occur via radiative and turbulent fluxes.

3.3 Implications for regional winter travel management planning

Due to its moderate elevation, the Lake Tahoe region is susceptible to climate change-induced warming (Walton et al., 2017). Our results provide another metric (later onset date of SWE_{min}) that is consistent with observations of ongoing changes in the Sierra Nevada cryosphere, including rising winter snow levels (Hatchett et al., 2017) and snowpack declines (Mote et al., 2018). Climate model projections for California support the continuation of these trends, with a drying and

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warming of the fall season (Swain et al., 2018) and an increased frequency of dry days (Polade et al., 2015). Projected snow-covered area declines are estimated to be the greatest during the beginning and end of the snow season (Walton et al., 2017). As a result, forest travel management plans should include adaptation strategies (Table 1) that can help managers and recreators cope with the increasing chances of a later opening date for OSV use but also provide flexibility in the event of an early, snowier-than-normal start to the winter. Flexible strategies developed by diverse stakeholder groups through public discourse are encouraged, as the continued reduction of area available for motorized and non-motorized users will lead to increasingly frequent use conflicts if not addressed.

Developing a suite of adaptive management strategies is essential if land managers are to meet legal obligations to manage OSV recreation in a manner that minimizes impacts to natural resources, wildlife, and conflict between uses (Federal Register, 2015). As snow seasons become more variable and less dependable overall, it will be necessary to utilize several complementary management strategies if land managers want to continue to provide high quality opportunities for all forms of winter recreation. For example, setting season dates that encompass the general times of the year when OSV use is appropriate, paired with a minimum SWE (or snow depth, depending on data availability), and allowing for OSV use on certain routes with a lower snowpack to provide access to higher-elevation areas may help to extend the OSV season. Likewise, it may be necessary to relocate winter trailheads to higher elevations as areas with consistent snowpack become shifted upwards in elevation. As the strategies in Table 1 show, however, there are tradeoffs with any strategy and OSV recreation is not the sole use of public lands in winter. Managing OSV recreation must occur in concert with managing other forms of winter recreation and protecting wildlife and natural resources (Federal Register, 2015). There is no one-size-fits-all strategy that will work for every national forest. It is essential that land managers work with public and agency stakeholders to craft locally-appropriate and equitable adaptation measures, taking into account potential impacts to and conflicts with other recreation uses, wildlife, natural resources, and other land management goals. It may also be necessary to accept that in the future, OSV and other forms of winter recreation (e.g., backcountry skiing and snowshoeing) will not be supported across all of the areas where it historically occurred. Winter travel planning is thus an excellent opportunity for land managers, particularly the United States Forest Service, to proactively address OSV management and consider how climate change is affecting OSV activities on national forests in order to maintain the opportunity for this form of winter recreation and its positive economic impact.

4 Concluding Remarks

Using snow water equivalent and a density assumption as a proxy for depth, we have presented a pilot study aimed at a better understanding of when the Lake Tahoe region attains sufficient snowpack depth to allow safe over-snow vehicle (OSV) usage. A station-based analysis of 16 remote weather stations in the region and a spatially distributed SWE reanalysis product indicated that the median timing of achieving sufficient depth varies with elevation from early November to late December. The median timing of sufficient depth has increased by approximately two weeks during the past three decades with significant changes on the order of three weeks. The proximal causes for this shift towards later onset appear to be due to both a shift from snowfall to rainfall and increases in dry day frequency during the early winter season. However, further research is needed to estimate specific contributions from each cause and constrain the role of surface-albedo (or other) feedbacks (Walton et al., 2017).

A primary limitation of our study is the lack of an established snow depth to avoid negative impacts of OSV operation as a function of land cover type and snow density. The work of Fassnacht et al. (2018) represents an important advance towards achieving this value, which can be used to guide winter travel management planning, although the United States Forest Service has begun to recommend a depth (USFS, 2013). Additional studies on achieving regionally-relevant minimum snow depths and better quantification of economic impacts from reduced snow cover area and duration will guide more robust travel management plans in national forests. They also can help prioritize pragmatic adaptation strategies for specific regions. Given the economic impact of OSV recreation and the likely reduction in land available for OSV or other human-powered recreation uses (Tercek and Rodman, 2016), combined with increasing numbers of winter recreation participants (Fassnacht et al., 2018), achieving winter travel management plans that are adaptive to varying snowpack conditions while minimizing user conflicts will be a key step towards sustainable mountain recreation.

Code Availability

The MATLAB code used for analysis is available upon request.

Data Availability

All data is publically available and has been properly cited in the text.

Competing Interests

HGE is employed by the Winter Wildlands Alliance (WWA). BJH has consulted for the WWA.

Author Contributions

BJH and HGE conceived and designed the study, interpreted the results, and wrote the paper. B.J.H. acquired data and performed the analysis.

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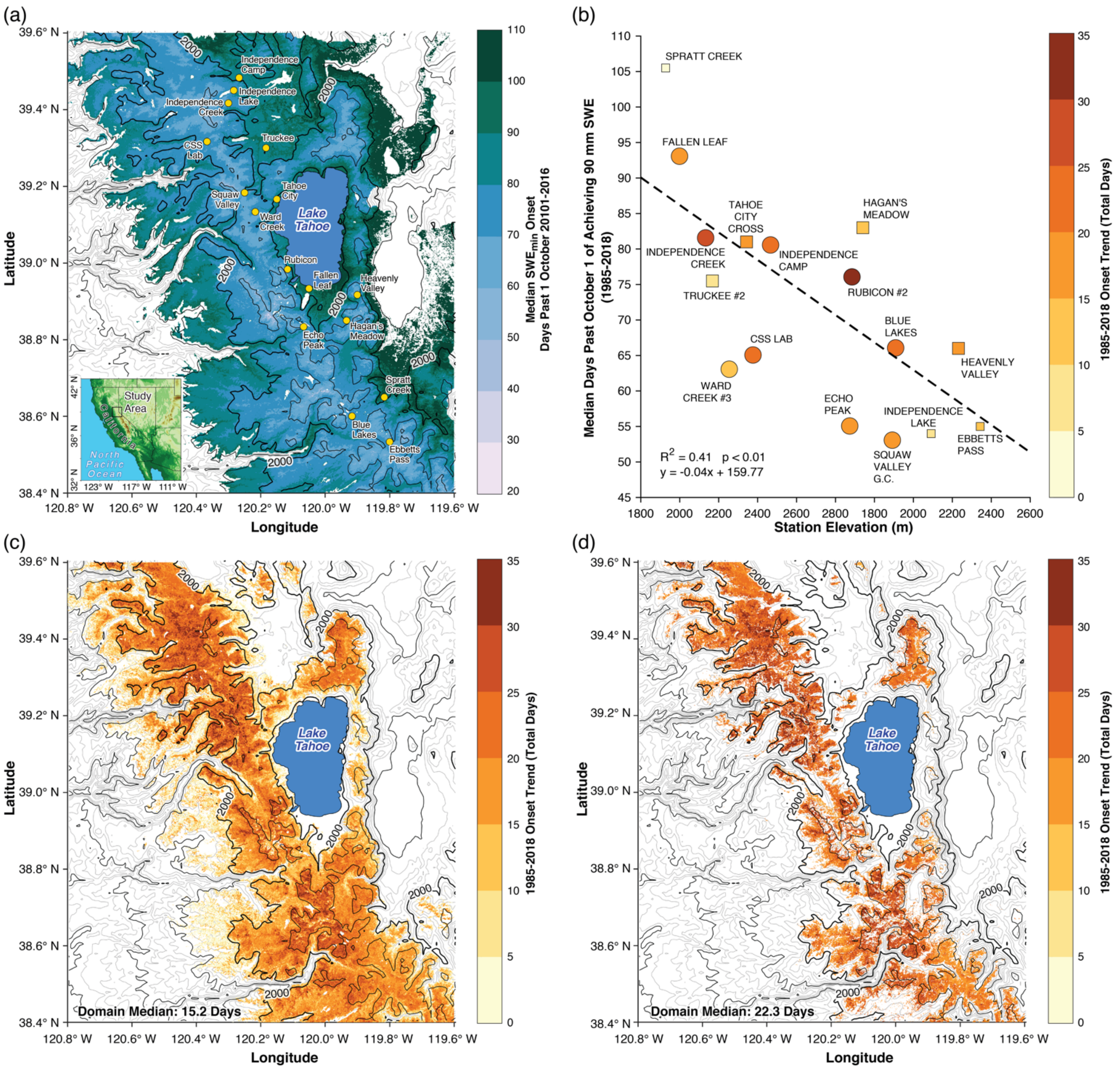

Figure 1: (a) Median 2001-2016 SWE_{min} (days past October 1) based on the SWE reanalysis product (Margulis et al., 2016) with SNOTEL stations shown as gold dots. The inset map shows the study area. (b) Timing of median SWE_{min} (days past October 1) by SNOTEL station elevation. Dots are colored by the trend (annual rate of snow depth timing change times 34 years). Dashed black line denotes the Theil-Sen linear fit. Large circles indicate significant trends ($p<0.1$) for SWE_{min}, while large squares indicate a significant ($p<0.1$) trend in SWE_{min} was identified for a value of SWE_{min} between 80 and 100 mm. Small squares indicate no significant trend. (c) Spatially distributed Theil-Sen linear trends in SWE_{min} over the period 1985-2016, calculated as the annual rate times the 32-year period. (d) As in (c) but showing only gridpoints with a statistically significant ($p<0.05$) trend in onset date. In panels a, c, and d, the thin (thick) grey contour lines indicate elevations every 125 m (500 m) while the thick black line indicates the 2000 m elevation contour (labeled). Gridpoints with more than three missing years were excluded from the analysis.

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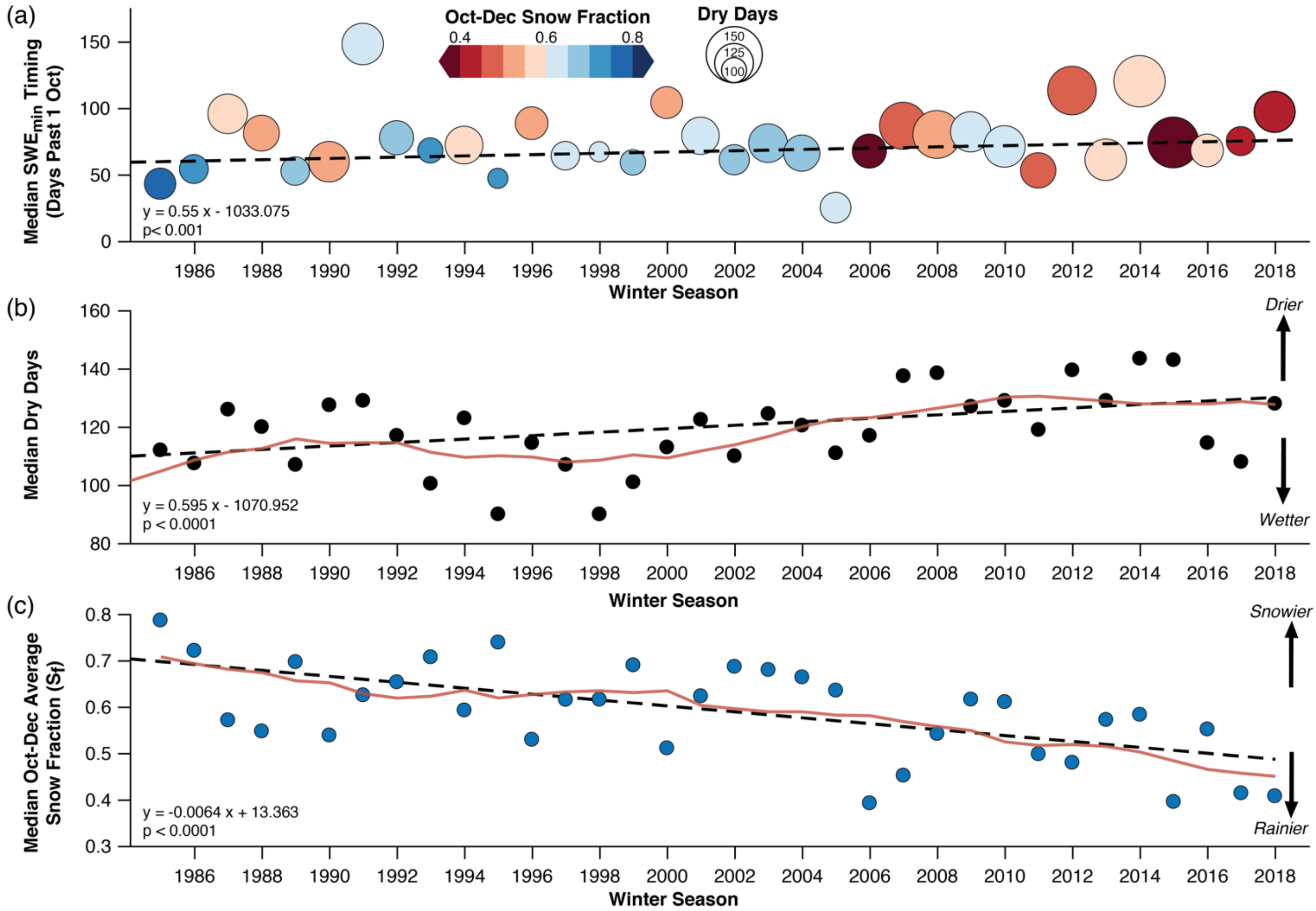

Figure 2: (a) Annual median timing of SWE$_{min}$ (days past October 1) with dots colored by median Oct-Dec average snow fraction and sized according to the median number of Oct-Dec dry days. (b) Median early season (1 October-31 December) dry days. (c) As in (b) but for median snow fraction averaged over the 16 stations. In all figures, the dashed lines demonstrate Theil-Sen linear fits and red lines (b and c) show the five-year running mean.

Adaptation Measure	**Benefit(s)**	**Challenge(s)**
Requirement of minimum snow depth off trail, but not on roads, or a lower minimum snow depth on roads	Allow OSV use even under extremely low snow conditions; grooming could be utilized to maximize snow depth on road	Preventing users from going off trail under low snow conditions; enforcement
Ensure high elevation access via a right-of-way	During warmer/drier years, snow conditions are likely to be better (deeper snowpack) at higher elevation	User group conflicts; presence of Wilderness at high elevation; impacts to snow-dependent wildlife species; demand; parking
Removal of blanket opening dates	Prevents opening before SWE_{min} achieved and will limit damage to landscape	Resources required to obtain snow condition information
Identify corridors that collect/retain more snow	During otherwise poor snow conditions, these areas may allow OSV recreation to occur, particularly at lower elevation areas	Need for data on these corridors
Trade-off: closure of low elevation/sensitive habitat for improved high elevation access	Eliminate chance of damaging landscapes in low elevation regions, increase in the number of days/year that OSV recreation can occur by enhanced high elevation access	Need for collaboration between stakeholders/user groups to identify areas where compromise could occur. May be opposed by those who must travel much further for OSV use.
Fee increases to enhance access and offset impacts from higher demand (i.e., restoration projects)	Would provide for additional resources to monitor trailhead conditions, improve parking/bathrooms at trailheads, fund restoration projects and creation of low-snow OSV trails	Fees are generally opposed by members of the public.

Table 1: Adaptation strategies to address loss of early winter snowpack for OSV recreation.