



Projected climate change impacts on skiing and snowmobiling: A case study of the United States



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ARTICLE INFO

Keywords:

Climate change
Skiing
Snowmobiling
Snowmaking
Adaptation

ABSTRACT

We use a physically-based water and energy balance model to simulate natural snow accumulation at 247 winter recreation locations across the continental United States. We combine this model with projections of snowmaking conditions to determine downhill skiing, cross-country skiing, and snowmobiling season lengths under baseline and future climates, using data from five climate models and two emissions scenarios. Projected season lengths are combined with baseline estimates of winter recreation activity, entrance fee information, and potential changes in population to monetize impacts to the selected winter recreation activity categories for the years 2050 and 2090. Our results identify changes in winter recreation season lengths across the United States that vary by location, recreational activity type, and climate scenario. However, virtually all locations are projected to see reductions in winter recreation season lengths, exceeding 50% by 2050 and 80% in 2090 for some downhill skiing locations. We estimate these season length changes could result in millions to tens of millions of foregone recreational visits annually by 2050, with an annual monetized impact of hundreds of millions of dollars. Comparing results from the alternative emissions scenarios shows that limiting global greenhouse gas emissions could both delay and substantially reduce adverse impacts to the winter recreation industry.

1. Introduction

Projected climate change through the 21st century will generate warmer temperatures and changes in precipitation that are expected to decrease the duration and extent of natural snow cover across the northern hemisphere (e.g., Dyer and Mote, 2006; Brown and Mote, 2009; Diffenbaugh et al., 2013). A number of studies have examined how climate change could influence seasonal snowpack in the western United States (e.g., Barnett et al., 2005; Mote et al., 2005; Pierce and Cayan, 2013), with the aim of understanding impacts on water resources. However, the geographic extent and economic impacts of a changing snowpack are likely to extend well beyond the western United States (e.g., Hayhoe et al., 2007; Campbell et al., 2010). In particular, large components of the winter recreation industry will face challenges without reliable access to snow. This could threaten tens of millions of current annual recreational visits and have important repercussions in areas where winter recreation is central to economic activity.

This study follows a series of reports that quantify and monetize the potential for climate change impacts to a number of sectors in the United States (e.g., Walsh et al., 2014; U.S. EPA, 2015a,b). In particular, U.S. EPA (2015a) quantifies and monetizes impacts from climate change under a range of scenarios in terms of anticipated impacts to human health and labor, electricity, forestry and agriculture, water resources, ecosystems, and the built infrastructure. Here we model potential changes in snowpack at sites across the United States, and calculate the effects of changing season lengths on the number of recreational visits and direct revenue associated with entrance fees. Our study expands on previous impacts work related to winter recreation by combining the geographic breadth of previous studies (e.g., Burakowski and Magnusson, 2012) with the detail that has historically been applied only to site- or regionally-specific studies (e.g., Burakowski et al., 2008; Lazar and Williams, 2008, 2010; Scott et al., 2008; Dawson and Scott, 2013). We consider a range of future climate scenarios by examining outputs from five global climate models (GCMs), two representative

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<http://dx.doi.org/10.1016/j.gloenvcha.2017.04.006>

Received 30 November 2016; Received in revised form 14 April 2017; Accepted 17 April 2017

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concentration pathways (RCPs), and both mid- and late 21st century time periods. As a result, this study helps expand the type and number of sectors with national-scale estimates of quantified and monetized impacts from climate change.

The foundation of our method is a water and energy balance model that accounts for simplified, but site-specific climatic and topographic characteristics to project natural snow accumulation at 247 locations in the continental United States (CONUS). For downhill skiing and snowboarding, we combine results from this natural snow model with projections of how resorts' abilities to make artificial snow will change in the future. For Nordic (i.e., cross-country) skiing and for snowmobiling, we use the model outputs without consideration for snowmaking, since these activities are typically more reliant on natural snow. For all three winter recreation activities, we estimate season length during a baseline period, and then project the impact of climate change on season lengths through the 21st century. We summarize these impacts as anticipated changes in future season lengths, levels of recreational activity, and entry-based expenditures. Although our results are specific to the United States, our methods could be easily adapted and extended to address other international regions (e.g., the Alps, Scandinavia, New Zealand) where snow-dependent winter recreation is an important cultural or economic activity.

2. Methods

To produce nationally informative results on climate change's potential impacts on winter recreation, we considered available sources of recreational and meteorological data to select representative sites across the CONUS. We then used a well-vetted snow model to project natural snow accumulation and melt at each site. We used modeled future temperatures to project changing snowmaking conditions at each downhill skiing location. Snow modeling and snowmaking projections were repeated for baseline and future climate conditions. We then quantified and monetized the resulting changes in snow conditions by integrating available baseline recreational and population data with a series of reasonable, but simplifying, assumptions about future recreational participation and expenditures.

2.1. Recreational site selection

The first step in our work was to identify reliable recreational participation data for multiple locations, ideally with multiple observations over time, which could be paired with observed and projected climate data. To link climate projections to specific winter recreation locations, we downloaded publicly available ski area information (i.e., polylines) to create footprints for winter recreation sites in the CONUS ([OpenSnowMap, 2016](#)). We then merged this information with ski area site names and locations from the National Oceanic and Atmospheric Administration geospatial data portal ([NOAA, 2016](#)). We compared ski area polygons to aerial photography to verify ski area names, ensure a match of the area footprints, and record the type of skiing for each area (i.e., downhill, cross-country, or both) – making any edits as necessary in the review process. Our final sample included 247 ski locations, distributed across the 6 National Ski Areas Association (NSAA) regions and across private and public lands, as shown in [Fig. 1](#).

2.2. Natural snow accumulation and snowmaking model

2.2.1. Utah energy balance model

We chose the Utah Energy Balance (UEB) model ([Tarboton and Luce, 1996](#)), a physically-based model that simulates the water and energy balance of a seasonal snowpack. We used several criteria in the model selection process: (1) high computational efficiency, as the study design required over 300,000 years of model simulations; (2) minimal parameters, given the broad range of site conditions that exist across the CONUS; and (3) acceptable performance. UEB is a single-layer snow

model, and thus is more efficient and has fewer parameters than more complex, multi-layer models (e.g., [Flerchinger et al., 1996](#)). Even though the UEB model is relatively simple, its performance is on par with more complex models, as determined through snow model intercomparison efforts (e.g., [Rutter et al., 2009](#); [Förster et al., 2014](#)). As discussed below, the selection of a meteorological dataset is even more important than the model, given that uncertainty from forcing data often exceeds that from errors due to model physics or parameters ([Raleigh et al., 2015](#)). We used the current version of the model (UEBveg; [Mahat and Tarboton, 2012, 2014](#)) to simulate natural snow accumulation and snowmelt at two elevations, representing the bottom and top of a ski area, for our selected locations. The UEB model tracks three state variables: snow-water-equivalent (SWE), internal energy of the snowpack, and snow surface age, the latter which affects surface albedo.

For implementation, we set the vegetation fractional cover input to zero to simulate the open areas that predominate on wide ski area slopes. The shortwave radiation input is calculated based on date/time, latitude, and slope angle and azimuth. The diurnal cycle of the surface energy balance, and thus melt, is represented because we used hourly meteorological forcing. However, we exported only daily SWE from the UEB model.

2.2.2. Meteorological forcing and topographic adjustments

We used hourly North American Land Data Assimilation System (NLDAS-2) meteorological forcing data ([Xia et al., 2012](#)) to drive the UEB snow model. NLDAS-2 data were selected because they provide physically-consistent forcing fields for the entire United States. NLDAS-2 forcing data are provided on a 1/8th degree (~12 km) grid for the interval from January 1, 1979 through the present. No other multi-decadal, high-spatial resolution, continental-scale datasets exist, and thus NLDAS-2 data have been used in hundreds of snow and hydrology studies (e.g., [Sultana et al., 2014](#); [Fu et al., 2015](#); [Raleigh et al., 2015](#)). We used data for the following NLDAS-2 variables: air temperature, specific humidity, wind speed, downward shortwave radiation, and downward longwave radiation. The four non-precipitation variables were generated on a 32-km grid at 3 hourly intervals as a part of the National Centers for Environmental Prediction's North American Regional Reanalysis, and then interpolated to the NLDAS-2 grid ([Cosgrove et al., 2003](#)). The NLDAS-2 precipitation data are based on daily weather gauge values gridded to 1/8°, utilizing information from the Parameter-Elevation Relationships on Independent Slopes Model (PRISM; [Daly et al., 1994](#)) and disaggregated through time using radar analyses when available. The UEB snow model has previously been driven with North American Land Data Assimilation System (NLDAS)-2 meteorological forcing data (as in this study), yielding a reasonable time series of SWE as observed at individual California Department of Water Resources Snow Telemetry (SNOTEL) sites ([Sultana et al., 2014](#)).

The accuracy of the NLDAS-2 input data affects the SWE simulated by the UEB model. It is challenging to model SWE in mountain ranges: precipitation, temperature, and radiation vary dramatically on length scales from meters to kilometers, resulting in extreme spatial variability in SWE (e.g., [Clark et al., 2011](#)). Even though NLDAS-2 data are relatively high resolution (1/8th degree), it is impossible for this dataset to represent the extreme range of conditions that exist within individual grid cells. In order to represent topographic effects at scales finer than the NLDAS grid cells, we applied site-specific adjustments in temperature and precipitation as a function of elevation within each ski area boundary. To do this, we extracted monthly climate normals for 1981–2010 from PRISM, and regressed both temperature and precipitation against elevation for each cardinal direction within each ski area boundary. We used these regression results to calculate an average temperature and precipitation lapse rate for each ski area. Using these calculated lapse rates, we adjusted the baseline NLDAS forcing to estimate precipitation and temperature at the bottom and top of each ski area.

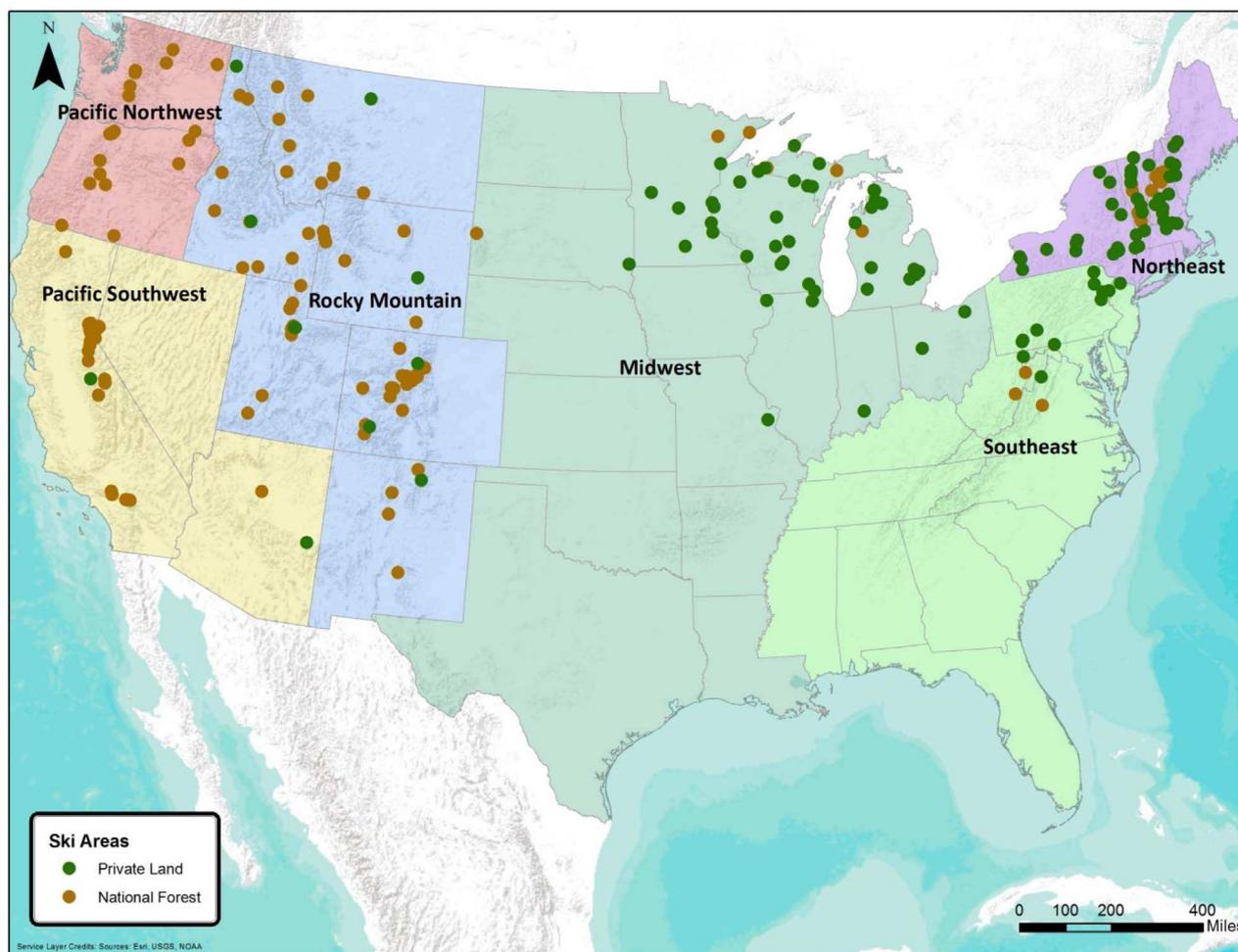


Fig. 1. Map of skiing locations, by NSA reporting region, to project climate change impacts on natural snow accumulation and potential snowmaking conditions.

The topographic adjustment accounts for differences in elevation between the ski area and the NLDAS model grid cell in which the ski area exists. However, this adjustment does not account for the low bias in NLDAS precipitation that exists in mountainous regions (e.g., Pan et al., 2003; Argus et al., 2014; Fu et al., 2015). In two similar studies that used NLDAS data as inputs for snow models, a comparison to SNOTEL data was used to adjust the input precipitation to account for this bias (Pan et al., 2003; Sultana et al., 2014). We take the same approach here. We compared both precipitation and temperature from NLDAS-2 to that measured at individual SNOTEL sites. We identified SNOTEL sites within NLDAS-2 grid cells containing one of our target skiing locations and that were within 100 m of the specified NLDAS-2 elevation. Only 27 SNOTEL stations met this criterion. Other SNOTEL sites were too different in elevation, so the comparison would have been obfuscated by topographic gradients in precipitation and temperature. NLDAS-2 precipitation is 10% lower and temperature is 0.5 °C warmer than observed at SNOTEL stations, averaged across these 27 sites. We accounted for both this 10% under-prediction relative to SNOTEL and the documented 20% undercatch of precipitation at SNOTEL gauges (e.g., Serreze et al., 2001) by multiplying the NLDAS precipitation by 1.3 prior to use in the UEB model. We also subtracted 0.5 °C from the NLDAS temperature to remove the bias relative to SNOTEL. The precipitation adjustment factor is smaller than that used by Pan et al. (2003) and similar to that from Sultana et al. (2014).

The 27 SNOTEL sites used for this meteorological forcing adjustment are all in the western United States. Homogenous monitoring networks comparable to SNOTEL do not exist in the Midwest or East, where meteorological observations are not made in environments and

at elevations similar to ski areas. Although SNOTEL stations are in the western United States, we show below that the UEB model driven by this bias-corrected NLDAS-2 forcing provides a reasonable ski season length throughout the United States (see Section 3.1). The slope and aspect of ski slopes each play an important role in controlling seasonal snow accumulation and melt, due to the change in net solar radiation per square meter depending on the incident angle of sunlight relative to the surface. To account for these topographic influences, we also calculated the mean slope and modal aspect of each ski area using a 90 m digital elevation model (USGS, 2008). Our modeling includes snow accumulation and melt at the average slope and aspect for the top and bottom of each skiing location.

2.2.3. Modeling hours suitable for snowmaking

Snowmaking is already a critical operational feature for many downhill skiing locations, and helps to ensure that an area is open for the Christmas/New Year holidays (e.g., Dawson and Scott, 2013). Typically, downhill ski areas require between 400 and 500 h of suitable snowmaking conditions before they can open (Robin Smith, TechnoAlpin, personal communication, October 13, 2016), which requires a wet bulb temperature of 28 °F or less (e.g., Scott et al., 2003; Robin Smith, TechnoAlpin, personal communication, October 13, 2016). We calculated cumulative hours of wet bulb temperature below 28 °F beginning on October 1 of each year as a proxy for snowmaking potential at each location. We calculated wet bulb temperature from NLDAS-2 humidity and air temperature (e.g., Stull, 2011) at the lowermost elevation for each location, under the assumption that most resorts need to cover their lowest slopes to open. In each simulation year, we recorded the

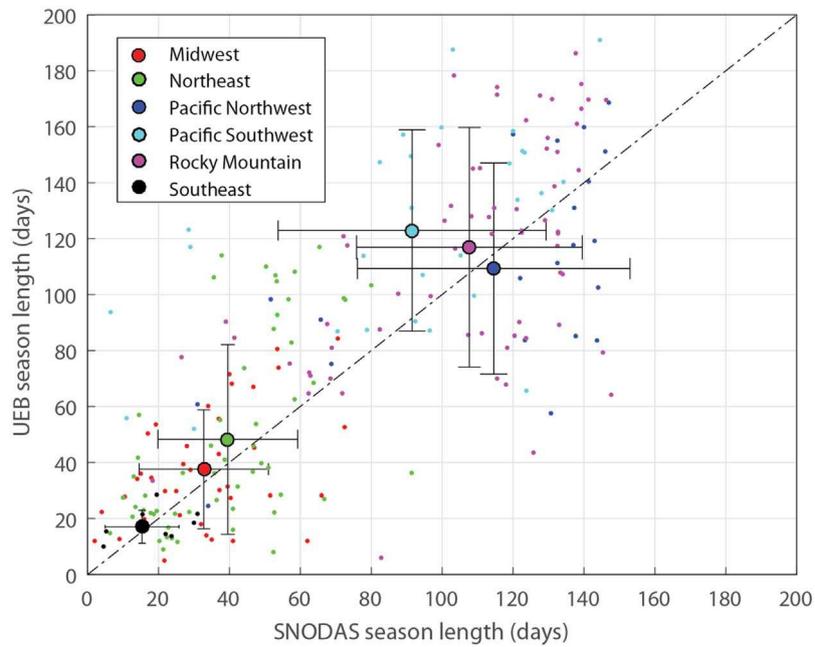


Fig. 2. Comparisons of UEB model SWE estimates with independent measures of season length from SNODAS, averaged over water years 2004–2010. Small dots represent individual sites; large dots are regional averages with 1 σ error bars.

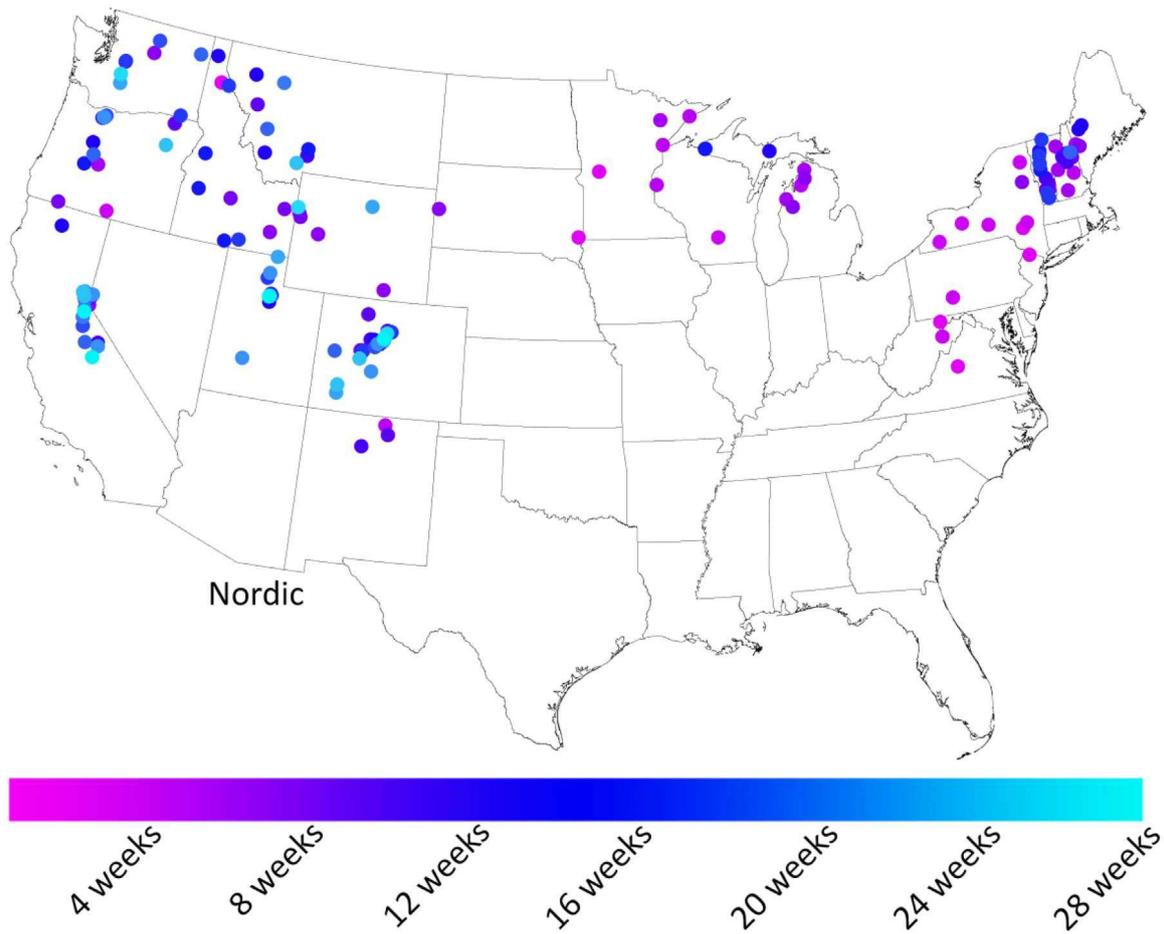


Fig. 3. Baseline season lengths for cross-country skiing and snowmobiling.

date when each location reached 450 h of cumulative snowmaking conditions. We calculated an average date to reach 450 snowmaking hours for each location from each of the individual years in the 30-year climate dataset.

2.3. Climate change scenarios

Computational and resource constraints required that we select a subset of GCMs from the full suite of the fifth Coupled Model

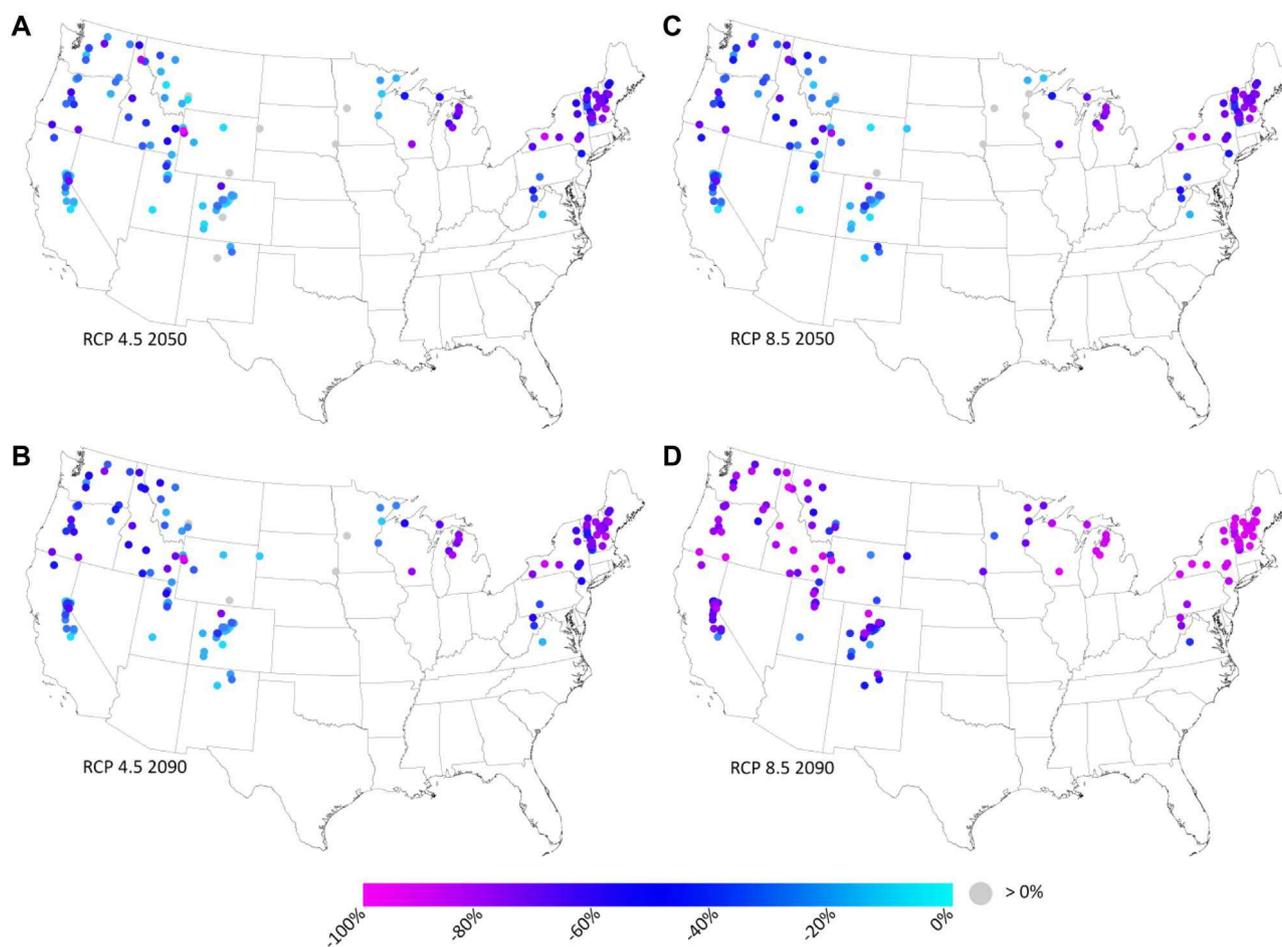


Fig. 4. Average percent change in annual cross-country skiing and snowmobiling season lengths across GCMs. A) Results for RCP4.5 in 2050. B) Results for RCP4.5 in 2090. C) Results for RCP8.5 in 2050. D) Results for RCP8.5 in 2090.

Intercomparison Project (CMIP5; Taylor et al., 2012) models. We chose five GCMs (CCSM4, GISS-E2-R, CanESM2, HadGEM2-ES, and MIROC5) with the intent of ensuring that (1) the subset captured a large range of variability in climate outcomes observed across the entire CMIP5 ensemble, and (2) the models were independent and broadly used by the scientific community. For each GCM, we chose two RCPs that captured a range of plausible emissions futures. The RCPs, originally developed for the Intergovernmental Panel on Climate Change's Fifth Assessment Report, are identified by their approximate total radiative forcing in the year 2100, relative to 1750: 8.5 W/m^2 (RCP8.5) and 4.5 W/m^2 (RCP4.5). RCP8.5 implies a future with continued high emissions growth with limited efforts to reduce greenhouse gases (GHGs), whereas RCP4.5 represents a global GHG mitigation scenario.

To provide localized climate projections and to bias correct the projections to improve consistency with the historical period, we used the LOCA dataset (Pierce et al., 2014, 2015; USBR et al., 2016). The LOCA downscaled dataset provides daily minimum and maximum temperatures (T_{\min} and T_{\max}), and daily precipitation values at $1/16^\circ$ resolution from 2006 to 2100. For each climate scenario, we calculated an average daily change factor for temperature and precipitation at each grid cell by comparing 20 years of LOCA projections centered on 2050 and 2090 to a historical $1/16^\circ$ gridded dataset from the period 1986–2005 (Livneh et al., 2015). We calculated these daily change factors as a spatial average of nine $1/16^\circ$ LOCA grid cells (3×3 window) surrounding each location.

We calculated hourly temperature change factors based on model-projected changes in T_{\min} and T_{\max} by assuming these temperatures occur at midnight and noon, respectively, and interpolating between T_{\min} and T_{\max} values over the course of each day. These hourly changes

were then added to the baseline NLDAS-2 temperature time series. For precipitation, we used the GCM outputs to calculate a multiplier to apply to the hourly NLDAS-2 precipitation time series. In some cases, the LOCA-modeled precipitation led to unrealistically high change factors. To eliminate these outliers, we first discarded values that exceeded the 90th percentile of all change factors for each station. We then calculated daily change factors as a 31-day moving average ratio of this filtered time series, and applied them to the NLDAS baseline. Additional details regarding our GCM selection process, an overview of the selected models, and processes for producing the relevant temperature and precipitation measures are provided in Supplementary information file #1.

2.4. Winter recreation activity, season length, and monetization approach

We combined the physical modeling, described above, with available recreational visit and entrance fee data to advance the understanding of how climate change affects winter recreation. First, we created baseline recreational activity levels for downhill skiing, cross-country skiing, and snowmobiling using NSAA and National Visitor Use Monitoring (NVUM) program data (NSAA and RRC, 2016; USFS, 2016). NSAA provides a comprehensive, annual dataset that uses survey data from approximately 195 ski resorts to report downhill ski visits by state (consistent with the NSAA survey, we use the term “visit” throughout to represent one person’s activity for a single day of a given type of recreation). To produce the downhill skiing baseline, we constructed a decadal average of skier visits by state using visit data from the 2006–2007 season through the 2015–2016 season (NSAA and RRC, 2016). The United States Forest Service (USFS) uses onsite surveys to

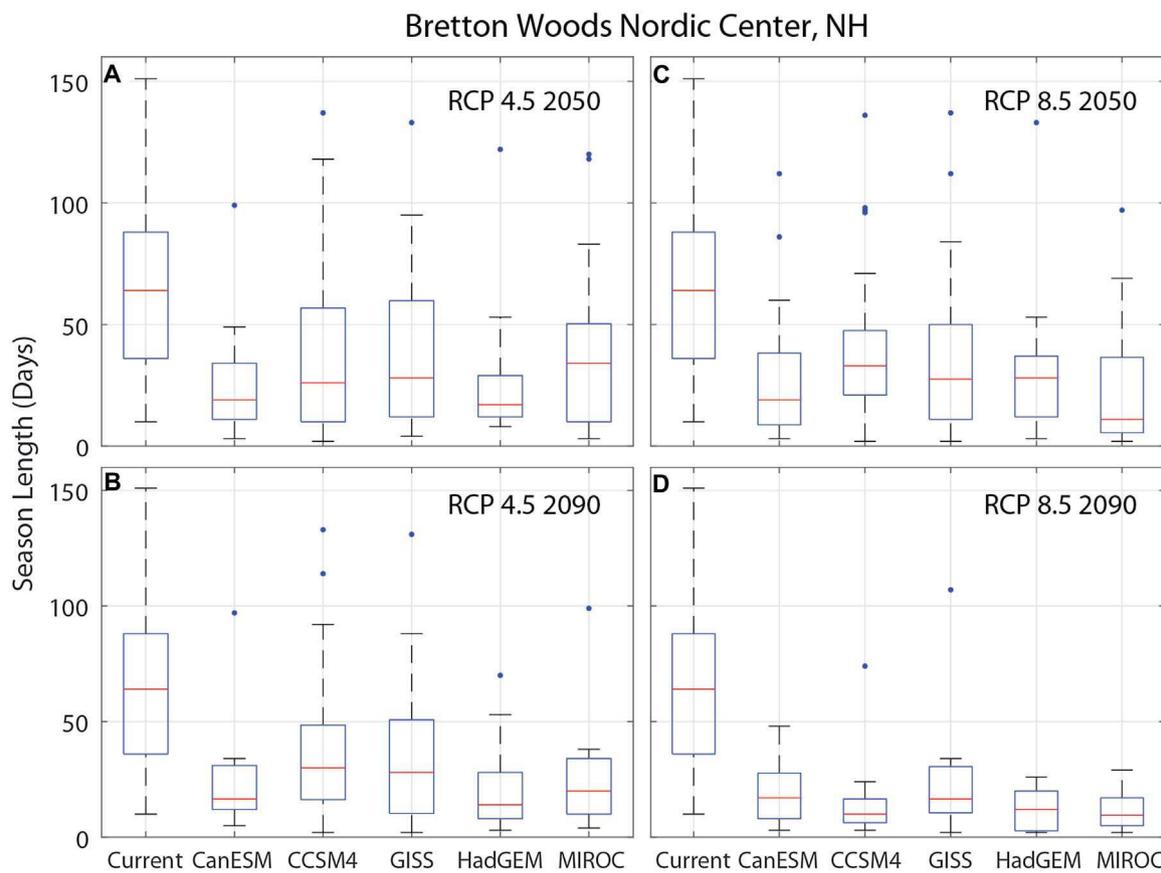


Fig. 5. Baseline and future cross-country skiing and snowmobile season length for Bretton Woods resort in New Hampshire. Boxplots represent the distribution of 30 annual UEB model simulations for baseline conditions and each of the future scenarios specified. A) Results for RCP4.5 in 2050. B) Results for RCP4.5 in 2090. C) Results for RCP8.5 in 2050. D) Results for RCP8.5 in 2090.

estimate the level of recreation use on national forests through the NVUM program. NVUM has a time-series of recreation visits and expenditure data for cross-country skiing and snowmobiling, as well as downhill skiing and other recreational activities (USFS, 2016). To produce the cross-country and snowmobiling baseline, we used the average of visits from two rounds of survey data (Round 1 from 2005 to 2009 and Round 2 from 2010 to 2014). For national forests that span multiple states, we allocated baseline visits according to the distribution of the forest area in the respective states. The NSAA data are representative of visits in 2011 and the NVUM data are representative of visits in 2010.

We applied changes in season length, as modeled at each of the 247 locations in the CONUS, to estimate changes in winter recreation visits. For downhill skiing season lengths, we incorporated snowmaking, which is consistent with Scott et al. (2003, 2008). We defined the start of each season as the earlier of 10-cm SWE or 450 h of snowmaking at the base of each location, and the end of each season as the last date with 10 cm SWE at the upper elevation of each location. For Nordic skiing and snowmobiling, the use of snowmaking is relatively uncommon (Reese Brown, Cross Country Ski Areas Association, personal communication, July 7, 2016) and, therefore, we did not incorporate snowmaking into our analysis. We used the direct outputs from the UEB model to simulate snowpack, and determined season length as the difference between the first and last dates with 10 cm SWE at the base elevation of each location.

Winter recreation use is strongly correlated to season length; this correlation is particularly strong at the regional level for downhill skiing (correlation coefficients for season length versus total annual visits range from 0.60 in the Rocky Mountains to 0.99 in the Southeast NSAA regions). To project potential impacts of climate change on winter recreation activities, we assumed recreational visits will change

in direct proportion to the length of the associated recreational season. This assumption is consistent with NSAA data that show the percent visitation by month is approximately even throughout the ski season, particularly in the Rocky Mountain region (NSAA and RRC, 2016).

Finally, we monetized the impacts of climate change on winter recreation using ticket prices for downhill skiing and entry fees at national forests for cross-country skiing and snowmobiling to reflect the price of access to each recreational opportunity. For downhill skiing, we used the average of reported adult ticket prices, by region, for the 2014–2015 through 2015–2016 seasons (NSAA and RRC, 2016). Regional ticket prices ranged from approximately \$59 in the Midwest region to \$127 in the Rocky Mountain region (NSAA and RRC, 2016; all prices in year 2015 dollars). For comparability, we used entry fees from the NVUM data to monetize projected changes in cross-country skiing and snowmobiling visits in national forests. Entry fees are one component of USFS's NVUM trip spending profiles and include site admission, parking, and recreation use fees (Stynes and White, 2005; Dan McCollum, U.S. Forest Service, personal communication, October 12, 2016). The NVUM data ask visitors surveyed about trip-related spending. We converted trip spending to visitor spending by dividing the trip entry fees by the average number of people per trip. We use these entry fee measures to monetize recreational impact given the scale and goals of the analysis, and to avoid a number of more complex economic issues discussed in greater detail in the Conclusions section.

For all three winter recreational activities, we first evaluated impacts holding population constant over time to isolate the impact of climate change. A second set of impact estimates were then calculated to account for projected population growth. We used the Integrated Climate and Land Use Scenarios (ICLUS) v2.0 (U.S. EPA, 2016) county-level, all-age population projections, to project 2050 and 2090 populations by state. To estimate future visitation, we multiplied

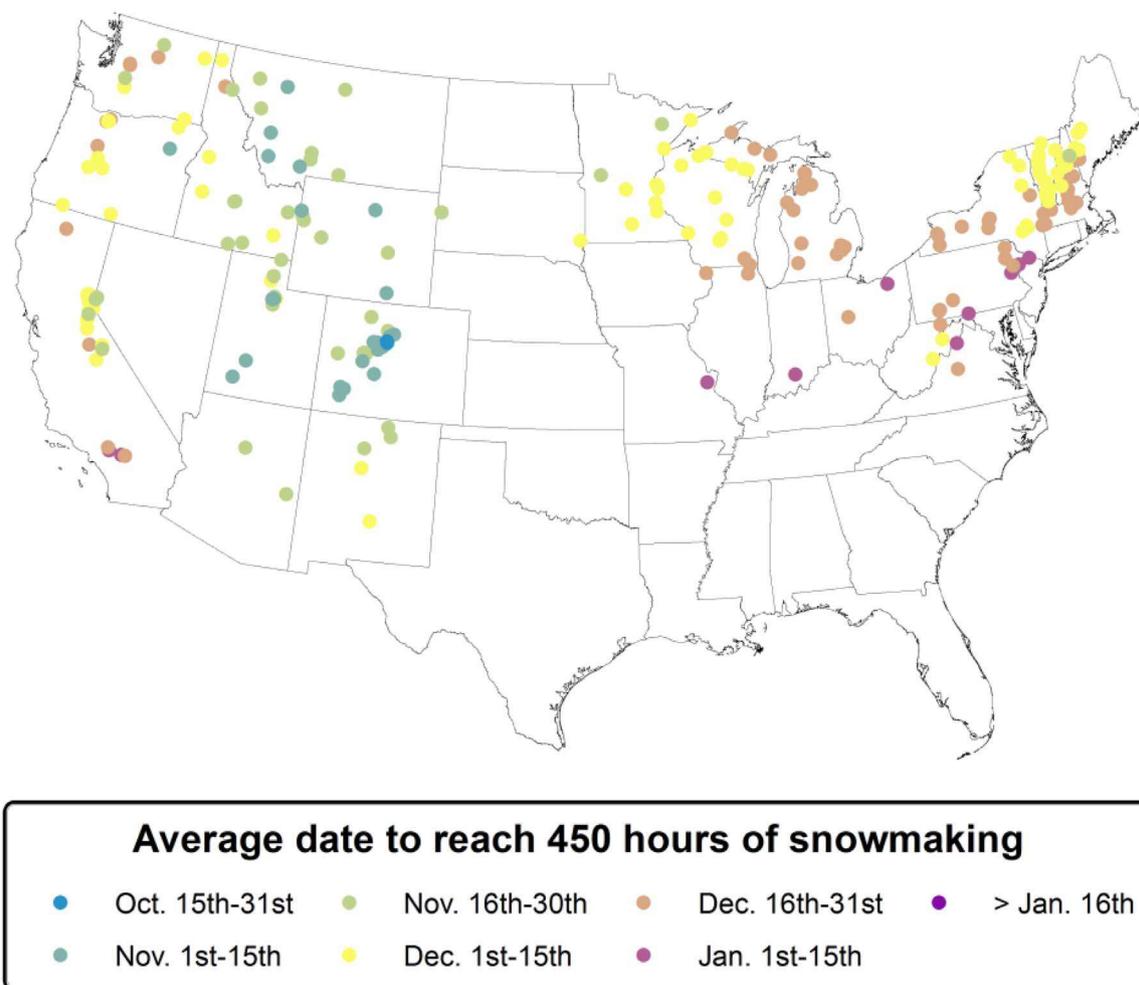


Fig. 6. Average date to reach 450 cumulative hours with conditions suitable for snowmaking ($T_{wb} < 28^{\circ}\text{F}$), based on 30 years of baseline NLDAS-2 forcing data.

the ICLUS state population projections by the average annual number of visits in each state per resident calculated for the baseline period, and then scaled the resulting product by the estimated proportional change in season length for the activity in that state. The change in season length used in this calculation represents an average of change for all sites in each state, by activity type.

3. Results

Below, we summarize results for each NSAA region by RCP and time period and provide detailed baseline and future snow modeling results for representative sites across the United States. Detailed annual season length results for all locations for the 21 simulations (one baseline and 20 future projections) are included in Supplementary information file #2. We also provide detailed baseline and future winter recreational activity levels under climate change scenarios. Detailed state-level changes in winter recreation visits and dollars are included in Supplementary information file #3.

3.1. UEB model validation

We used season length derived from the Snow Data Assimilation System (SNODAS; Barrett, 2003) to validate our baseline simulations, by examining how UEB-simulated season length varies from region to region across the United States. SNODAS provides daily SWE at ~ 1 km resolution nationwide, based on a multi-layer snow model that is forced to be consistent with remotely-sensed observations of snow extent. SNODAS data are available beginning in 2003, so we compared season

length (duration of $\text{SWE} > 10$ cm) at each of the 247 sites averaged over the 7 overlapping seasons between SNODAS and our baseline simulations (water years 2004–2010). The correspondence between UEB and SNODAS season length estimates at the ski area scale is reasonable given the coarseness of the NLDAS-2 forcing: including all outliers, the r^2 is approximately 0.6 and there is little bias (Fig. 2). The only clear difference between UEB and SNODAS is in the Pacific Southwest, where the UEB season length is longer than SNODAS by ~ 30 days.

We also compared UEB SWE with SNOTEL data at the 27 sites that are within 1 km of ski areas. Although differences at individual SNOTEL sites are in some cases substantial, the average season length from UEB at these 27 sites is nearly the same as from SNOTEL (UEB season length for these 27 sites is 112 ± 30 days; SNOTEL is 125 ± 40 days).

3.2. Baseline and projected season lengths

3.2.1. Cross-country skiing and snowmobiling

For cross-country skiing and snowmobiling, season lengths vary from less than 1 week for some sites in the Northeast and upper Midwest to more than 24 weeks for many sites in the western United States (Fig. 3). These season length projections assume no adaptation from snowmaking.

Average annual changes in cross-country skiing and snowmobiling season lengths across the GCMs range from small increases in some locations, to declines of more than 80% under the RCP4.5 scenarios in 2050 (Fig. 4A). In general, the most significant reductions in season length occur in the upper Midwest and the Northeast, and the smallest

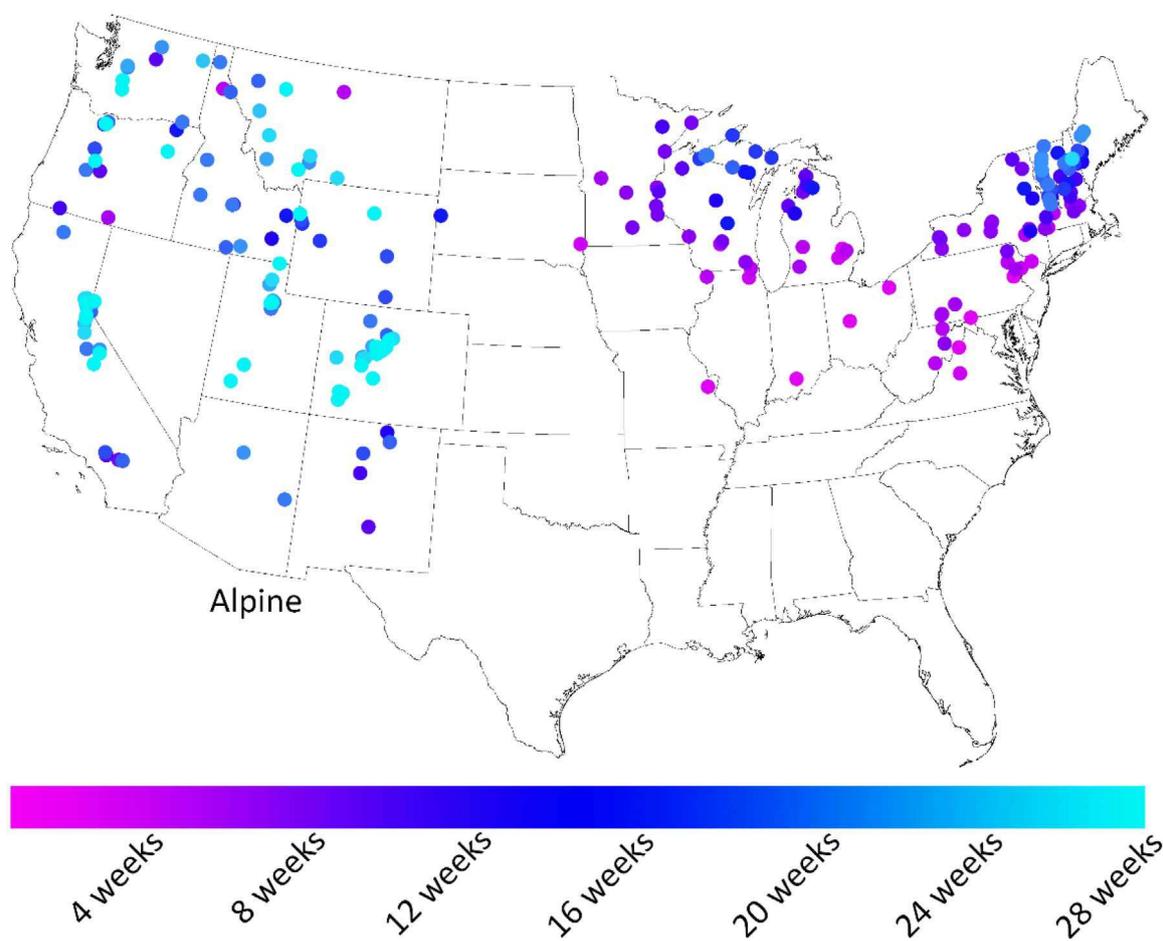


Fig. 7. Modeled baseline season lengths for downhill skiing, including snowmaking.

reductions occur at locations in the central Rockies and Sierras. The few locations with increases in season length are generally in arid regions of the Southwest and parts of the upper Midwest. These increases in season length are driven by projected increases in precipitation, which offset projected increases in temperature by mid-century.

The general regional pattern of changes in cross-country skiing and snowmobiling season length persists across GCMs into the late century under the higher emissions scenario (i.e., RCP8.5 in 2090; Fig. 4D). However, under this scenario a much larger fraction of the modeled locations are projected to see average annual reductions from their baseline season length of > 80% compared to the RCP4.5 estimates in 2090 (Fig. 4B).

Beneath these regional trends, there is substantial variability across the GCMs. Fig. 5 illustrates projected changes in cross-country skiing and snowmobiling season length at the Bretton Woods resort in New Hampshire for each climate model/RCP combination. For this resort, the average projected decrease in season length ranges from approximately 65% by 2050 under RCP4.5, to more than 90% by 2090 under RCP8.5. While inter-annual variability remains high in 2050 under some of the models (e.g., CCSM4, GISS), this variability effectively collapses in the relatively unconstrained RCP 8.5 emissions scenarios, particularly late in the century.

3.2.2. Downhill skiing and snowboarding

The length of the winter season for downhill skiing reflects the combined influence of early season temperatures, which modulate resorts' ability to make snow; and natural precipitation and temperature throughout the ski season, which control the water and energy balance that drive the natural snowpack. Under baseline conditions, locations with the highest base elevations (e.g., those in the central

Rocky Mountains) typically reach the 450 cumulative hours of snowmaking threshold by late October, whereas this snowmaking threshold is not reached until late January or later in some locations in the Southeast (Fig. 6). Including snowmaking, baseline season lengths for alpine skiing range from just 1–2 weeks in some resorts in the Southeast, to more than 28 weeks in the highest elevations of the Rocky Mountains and Sierras (Fig. 7; Supplementary information File #2).

Under climate change scenarios, the average date to reach the cumulative 450 h snowmaking threshold increases by approximately 10–20 days by mid-century under RCP4.5, and by 30–70 days by late century under RCP8.5 (Fig. 8). Winter recreation impacts are regionally variable, with the largest delays in reaching this snowmaking threshold occurring in the Pacific Northwest and smaller delays in the Rocky Mountain region.

For most downhill skiing locations, opening prior to the Christmas and New Year's holidays is critical to remaining profitable and staying in business (e.g., Dawson and Scott, 2013; Robin Smith, TechnoAlpin, personal communication, October 13, 2016). While approximately 70% of modeled downhill skiing sites can reach 450 h of snowmaking by December 15 under baseline climate conditions, this percentage declines markedly under each of the future scenarios (Fig. 9). By 2050 this percentage is reduced by nearly half under both RCPs. In 2090 the contrast is sharper, as only 23% of locations would meet the December 15 date under the RCP4.5 scenarios and only 11% of locations under the RCP8.5 scenarios.

Nationally, changes in projected downhill skiing season lengths range from slight increases at a few areas (10 areas and 6 areas, respectively, for RCP4.5 and RCP8.5 in 2050; and 4 areas for RCP4.5 in 2090) to declines of more than 80% under RCP8.5 in 2050 for some

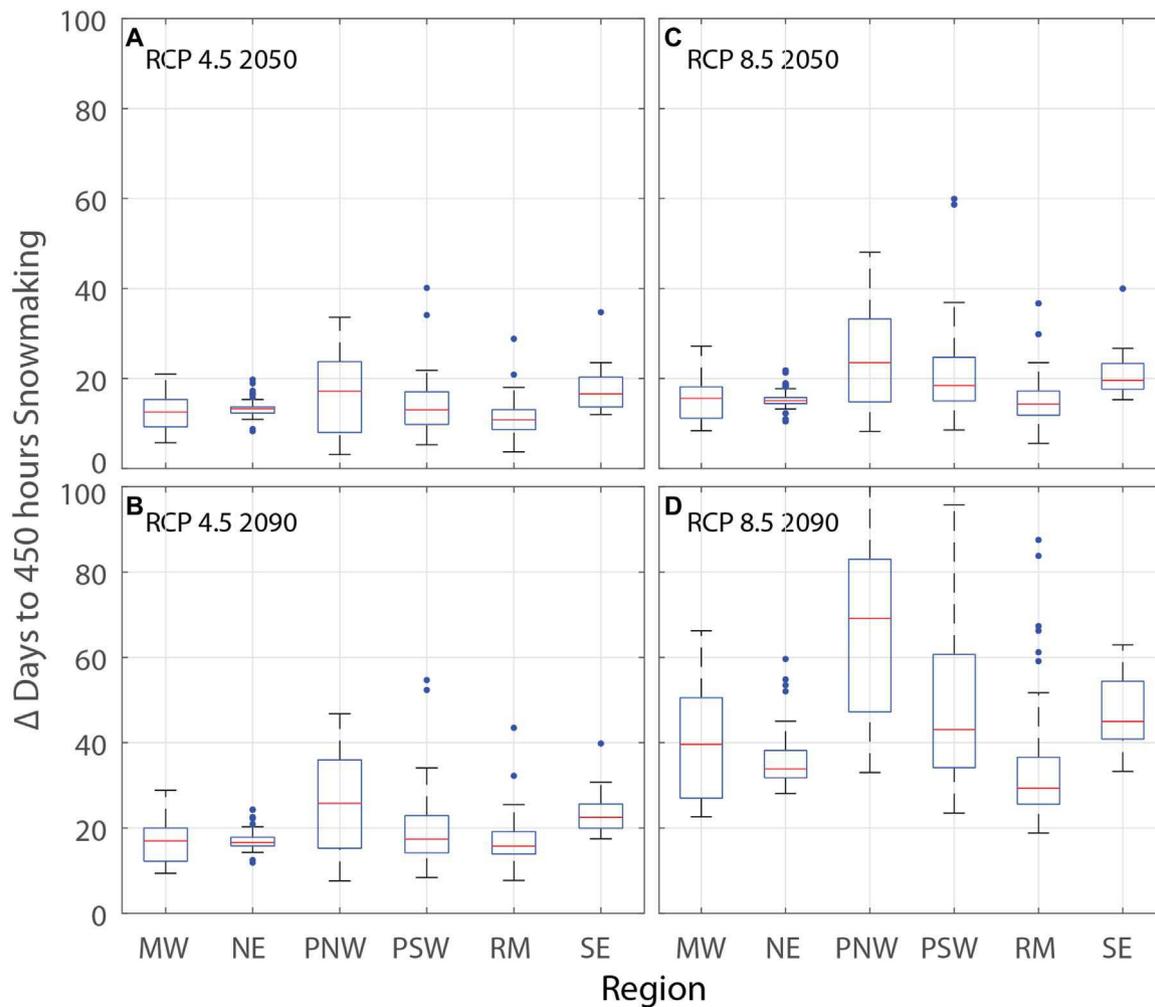


Fig. 8. Lost season days due to additional time required to reach 450 h of potential snowmaking time, by region. A) Results for RCP4.5 in 2050. B) Results for RCP4.5 in 2090. C) Results for RCP8.5 in 2050. D) Results for RCP8.5 in 2090. (MW = Midwest, NE = Northeast, PNW = Pacific Northwest, PSW = Pacific Southwest, RM = Rocky Mountain, SE = Southeast; see Fig. 1 for regions).



Fig. 9. Percentage of modeled areas able to reach 450 h of snowmaking before December 15.

locations (Fig. 10). As with the cross-country skiing and snowmobiling season length results, the general spatial patterns of changes in season length are largely preserved under RCP8.5 in 2090, but are amplified relative to the 2050 results. Specifically, the projected changes in season length are most dramatic in the Northeast and upper Midwest, and are less dramatic in the higher elevations in the Rockies and Sierras. Further, in 2090 under RCP8.5, no areas are projected to have an increased season and the smallest projected reduction in season length is 15%.

As with the cross-country skiing and snowmobiling season results, there is also considerable inter-model variability in climate change

results for downhill skiing season lengths. At Aspen Mountain, for example, average season lengths decrease by 10–20 days under RCP4.5 in 2050 and by 25–75 days under RCP8.5 in 2090 (Fig. 11).

While Figs. 8 and 9 highlighted potential delays in opening dates relative to the critical Christmas and New Year’s holidays, climate change generally has a larger impact on closing dates than opening dates across the combinations of RCPs and future years (Fig. 12). In the most extreme reductions (RCP8.5 projections for 2090), the median closing date is more than a month earlier than the baseline, moving from early April to the end of February. In contrast, the largest shift in the start date from the baseline involves several weeks from the beginning to the end of December. Although we did not incorporate detailed data on user visits by month, we do know that revenue from spring break is important for some resorts, particularly in the Rockies. Thus, scaling user visits and entry fee revenue linearly with changes in season length (see Section 3.3) is likely to be conservative.

3.3. Quantifying and monetizing potential changes in future winter recreation

3.3.1. Baseline winter recreation activity levels

Nationally, we estimated a baseline winter recreational activity level of approximately 56.0 million downhill skiing visits from the available NSAA data, with an additional 3.6 million cross-country ski visits and 2.8 million snowmobile visits from the available NVUM data (Table 1). Using calculated regional average adult weekend ticket

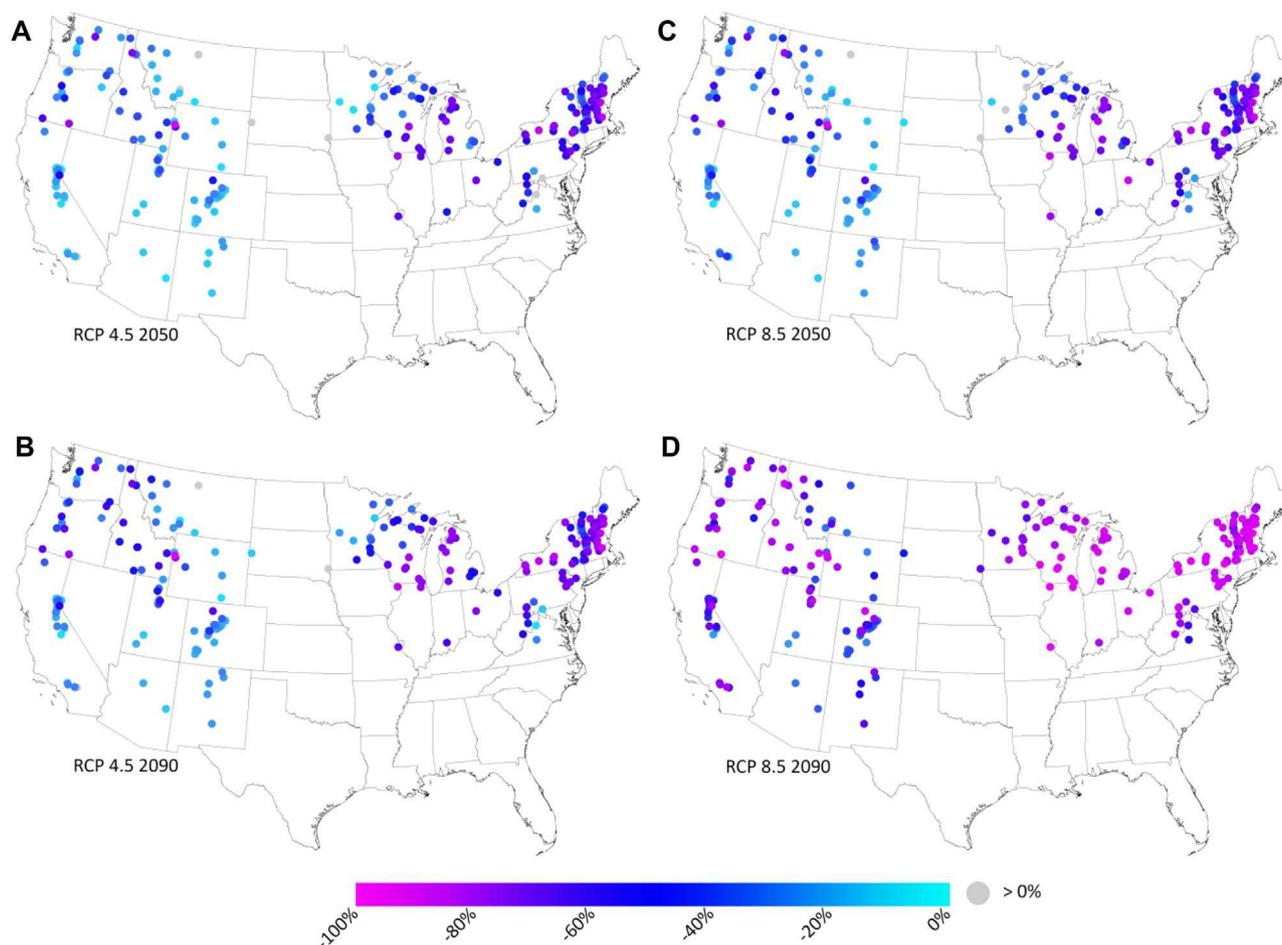


Fig. 10. Average percent change in downhill skiing season length based on a combination of UEB model and snowmaking results. A) Results for RCP4.5 in 2050. B) Results for RCP4.5 in 2090. C) Results for RCP8.5 in 2050. D) Results for RCP8.5 in 2090.

prices from the NSAA data, we monetized baseline downhill skiing at \$5.4 billion; using the conceptually-equivalent entry fees results in \$32.4 million for cross-country skiing and \$12.6 million for snowmobiling.

3.3.2. Monetized impact holding populations constant

Holding population constant at baseline levels, we project climate change would reduce national downhill skiing visits to 35.4 million visits under RCP4.5 and 19.8 million under RCP8.5 by 2090; this is a decrease of 20.6 million and 36.3 million visits from the baseline, respectively (Table 1). Holding population constant, national cross-country skiing visits would be projected to decrease to 2.7 million under RCP4.5 and 1.5 million under RCP8.5 by 2090, and national snowmobiling visits would decrease from approximately 2.8 million in 2010 to 1.9 million under RCP4.5 and 1.0 million under RCP8.5 by 2090.

3.3.3. Monetized impact including population growth

In our approach, population growth increases projected winter recreation visits. As a result, population growth dampens the projected adverse impacts of climate change on the winter recreation industry. Nationally, downhill skiing visits decrease slightly after adjusting for changes in climate and population to 52.8 million under RCP4.5 and 30.6 million under RCP8.5 by 2090; a decrease in 3.2 million and 25.4 million visits from baseline, respectively (Table 1). Under RCP4.5, cross-country skiing visits increase slightly in 2050 and 2090, and snowmobiling visits increase slightly in 2090 (Table 1). However, for RCP8.5, which reflects a higher emissions scenario, the shortened seasons overwhelm the increase in visits driven by population growth,

resulting in an overall decrease in recreational visits in both 2050 and 2090 (Table 1).

To clearly demonstrate the offsetting impact of population growth on these recreational visit results, we aggregated state-level results for downhill skiing to the NSAA regions and compared projected regional visits with and without population growth for 2050 and 2090 (Fig. 13). The effect of population growth on winter recreation visits is most clearly seen in the results for the Rocky Mountain and Pacific Southwest regions. Under the RCP4.5 scenarios, downhill skiing visits in these regions increase in 2050 and 2090 when we account for the combined impacts of climate change and population growth. However, when we hold population growth constant and account for only the impacts of climate change, downhill skiing visits decline in both regions in the RCP4.5 scenario. In the RCP8.5 scenario, this impact is still observable in these regions. In all cases, projected visitation at each time period is larger when population change is included.

As shown in Table 1, holding the population constant at baseline values, the projected impacts of climate change alone could result in the loss of tens of millions of winter recreation visits with an undiscounted annual impact measured in the billions of dollars. Integrating the impacts of projected climate change and population growth complicates these results, as seen in Fig. 13. In general, our assumption that winter recreation visits will increase with population, all else equal, mitigates but does not fully offset the projected adverse impacts of climate change at a national level. Regional trends in projected population growth are also critical. Specifically, the combination of relatively large population increases in the Rocky Mountain and Pacific Southwest regions, which have the highest average ticket prices, mitigate projected national-scale losses in visits and ticket revenue, especially under

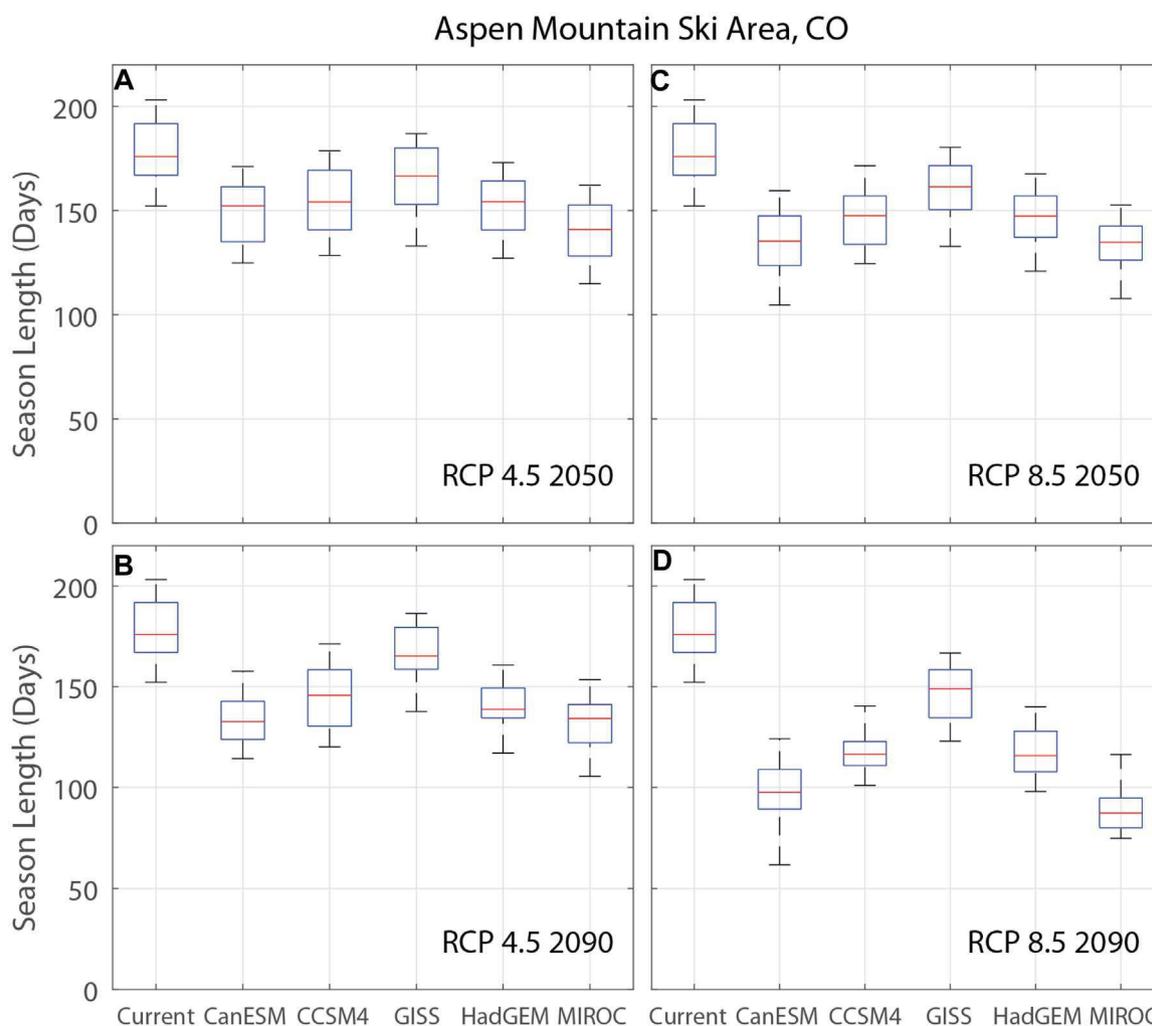


Fig. 11. Example output for Aspen Mountain showing change in season length for downhill skiing across all GCMs under A) RCP4.5 in 2050, B) RCP4.5 in 2090, C) RCP8.5 in 2050, and D) RCP8.5 in 2090.

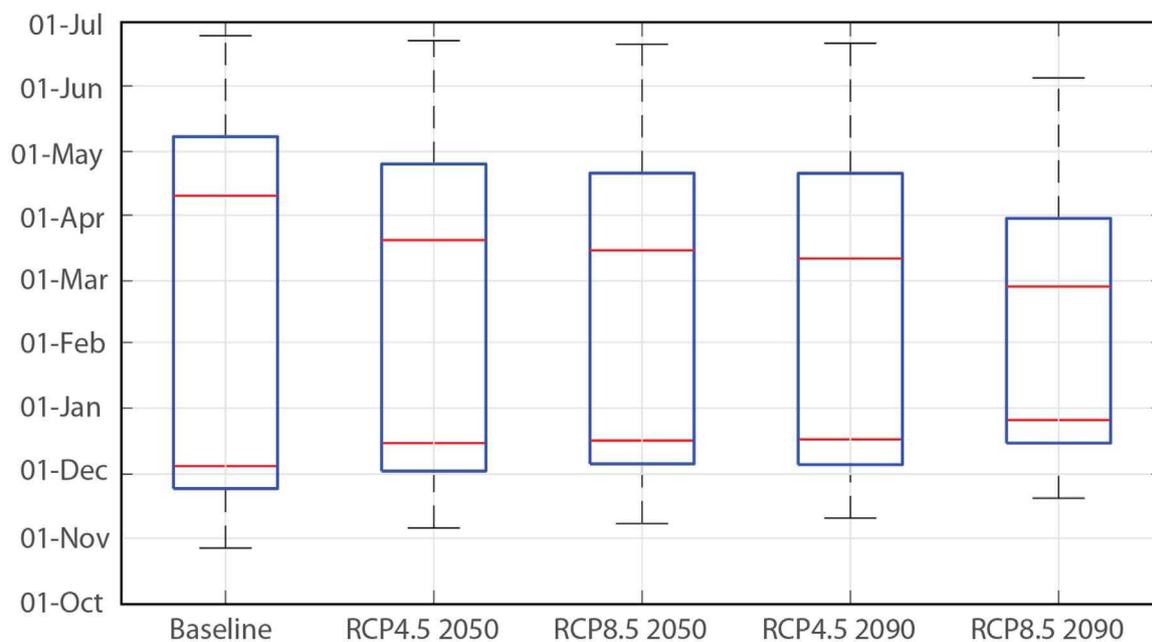


Fig. 12. Average baseline and projected season start and end dates for the downhill ski season, across all modeled resorts. Median opening date is represented by the red line at the bottom of the box and whiskers plot, and median closing date is represented by the red line at the top of the box. Boxes enclose the middle 50% of the season length distribution, and whiskers extend to the 5th and 95th percentiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
National projected impacts in terms of visits by recreational activity averaged across models for different time periods and RCPs.

	Baseline		Impacts in 2050			Impacts in 2090			Equivalent monetized impact (RCP8.5)	Equivalent monetized impact (RCP4.5)	Equivalent monetized impact (RCP8.5)
	Visits	Dollars	Change in visits (RCP4.5)	Change in visits (RCP8.5)	Equivalent monetized impact (RCP4.5)	Equivalent monetized impact (RCP8.5)	Change in visits (RCP4.5)	Change in visits (RCP8.5)			
National impacts of climate change holding population constant											
Downhill skiing	56,028,000	\$5,400,134,000	(16,131,000)	(19,772,000)	(\$1,367,232,000)	(\$1,716,806,000)	(20,608,000)	(36,259,000)	(\$1,783,996,000)	(\$3,255,810,000)	
Cross-country skiing	3,590,000	\$32,368,000	(636,000)	(873,000)	(\$5,949,000)	(\$8,037,000)	(935,000)	(2,055,000)	(\$8,623,000)	(\$18,711,000)	
Snowmobiling	2,821,000	\$12,641,000	(681,000)	(844,000)	(\$3,072,000)	(\$3,798,000)	(912,000)	(1,802,000)	(\$4,106,000)	(\$8,102,000)	
Total	62,439,000	\$5,445,143,000	(17,448,000)	(21,489,000)	(\$1,376,251,000)	(\$1,728,641,000)	(22,455,000)	(40,116,000)	(\$1,796,725,000)	(\$3,282,623,000)	
National impacts of climate change with anticipated population growth											
Downhill skiing	56,028,000	\$5,400,134,000	(6,845,000)	(11,270,000)	(\$345,580,000)	(\$778,142,000)	(3,228,000)	(25,448,000)	\$125,888,000	(\$2,029,791,000)	
Cross-country skiing	3,590,000	\$32,368,000	220,000	(87,000)	\$1,635,000	(\$1,060,000)	628,000	(1,106,000)	\$5,226,000	(\$10,299,000)	
Snowmobiling	2,821,000	\$12,641,000	(113,000)	(318,000)	(\$525,000)	(\$1,442,000)	83,000	(1,212,000)	\$352,000	(\$5,469,000)	
Total	62,439,000	\$5,445,143,000	(6,738,000)	(11,675,000)	(\$344,470,000)	(\$780,644,000)	(2,517,000)	(27,766,000)	\$131,466,000	(\$2,045,559,000)	

RCP 4.5 (Table 1).

4. Conclusions

Physical models that account for changes in natural snow and ski resorts' ability to make snow demonstrate that season lengths for winter recreation activities will decline at nearly all sites in the CONUS under the considered future climate scenarios. In each region of the United States, these impacts increase in severity over time for a given emissions scenario, and also increase in severity with GHG emissions for a given time period: impacts are more severe under RCP8.5 vs RCP4.5 at any point in time and more severe in 2090 compared to 2050 for a given RCP.

Underlying these national results, we found considerable variability at all levels of the analysis, particularly with respect to the spatial distribution of impacts. In general, sites at higher elevations (such as the Rocky Mountains and Sierras) tend to be more resilient to projected changes in temperature and precipitation, whereas sites at lower elevations (generally in the upper Midwest and New England) are more sensitive to climate change. Based on our modeling, the difference between RCP4.5 and RCP8.5 could represent the difference between preserving skiing and snowmobiling in the eastern half of the country and losing these activities almost completely by 2090 (Fig. 10). When these physical modeling results are monetized using current prices for recreational entry while accounting for population change, we find that the changes in winter recreation season lengths under RCP8.5 could result in a loss of more than \$2 billion annually for downhill skiing, and an additional \$5 million and \$10 million for snowmobiling and cross-country skiing, respectively (Table 1).

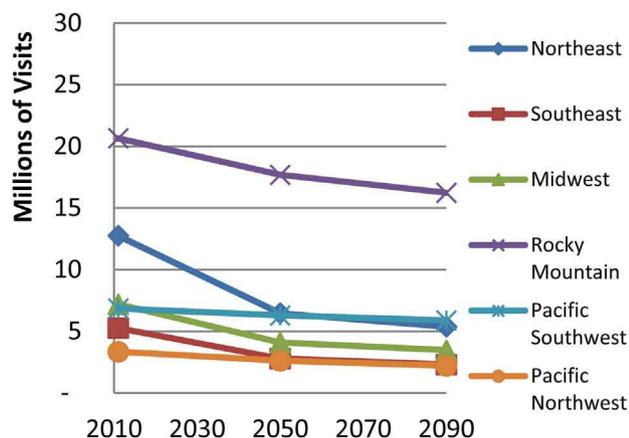
These results include a number of important caveats. On the physical modeling side, our snow model was simplified to simulate average conditions at the top and bottom of 247 areas across the CONUS, and was driven by a relatively coarse-scale representation of climate. The UEB model framework is flexible enough that it could be refined on a site basis to generate an improved calibration for each individual site. However, this added level of specificity would have made both the data requirements and the computational burden too high for this national study.

Our monetization approach also required a number of simplifying assumptions. For example, not all downhill ski areas participate in the NSAA data collection or are located on national forest lands, so our impacts on estimated visits may be understated. Similarly, considerable cross-country skiing and snowmobiling activity occurs outside of national forests, so those impacted visit estimates are likely also understated. Our entry fee also does not measure the implicit value of winter recreation or the full monetary impact of these activities in a specific region or collection of regions. While alternative economic approaches could be incorporated to try to fully monetize the projected impacts of climate change on winter recreation, we did not attempt to do that here.

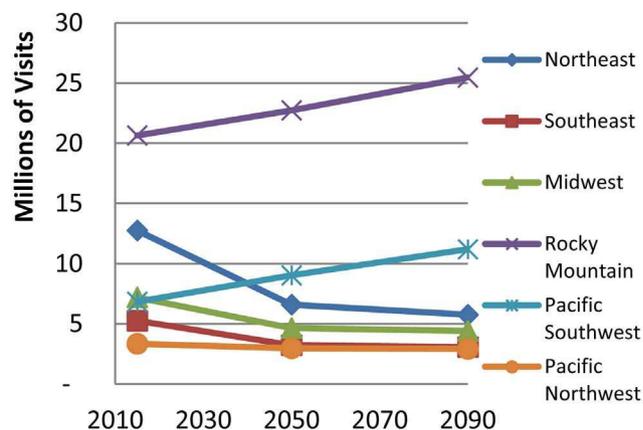
We also have not attempted to account for the complete loss of recreational activity with the closure of facilities, as this would require consideration and development of business models or general operating rules that are beyond the scope of this study. However, our modeling does suggest increased pressure on downhill ski facility operators in general as sequences of what would currently be considered marginal snow seasons increase over time. This is particularly relevant when recognizing that revenue and profit for downhill ski operators is often concentrated into the start and end of the current winter season (e.g., Christmas/New Year's holiday and spring break). Over time, pressure on these important revenue periods could result in a facility's closure. Since we have not attempted to project potential closures, our projected estimates of downhill skiing visits could be conservative if visits to a closed area are not transferred to those that remain open.

Finally, we have not accounted for the different types of substitution that could arise with climate change. The impacts of climate change on

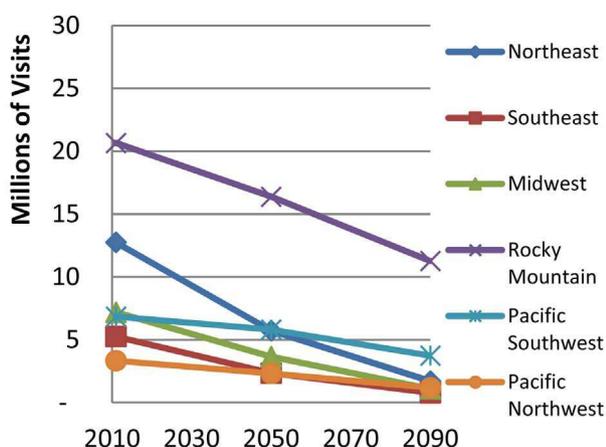
A. RCP4.5 holding population constant



B. RCP4.5 with population change



C. RCP8.5 holding population constant



D. RCP8.5 with population change

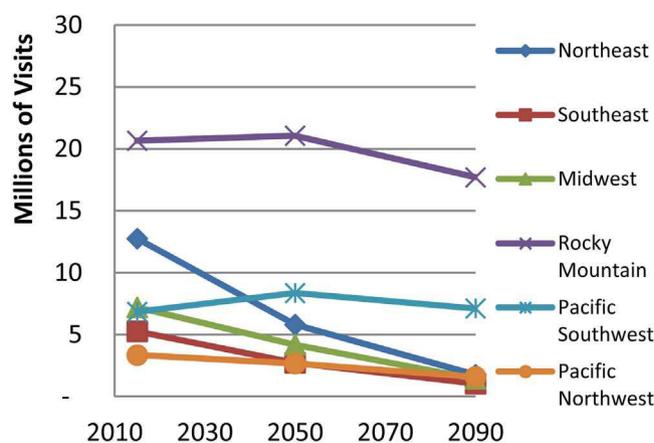


Fig. 13. Comparison of projected impact of climate change on downhill skiing visits holding population constant and allowing for population changes over time.

future winter recreation season lengths and associated conditions raise the potential for three general types of substitution, including (1) temporal, where the timing of future recreation will change, generally shifting to later in the season; (2) spatial, where recreators will change travel patterns to access different areas; and (3) activity, where some recreators may switch to different recreational activities altogether. By adjusting future recreation for projected season length, we are imposing a strong assumption that captures some, but not all of these substitution elements.

All of these caveats represent simplifications that were required to complete this national-scale analysis. Despite these simplifications, however, our approach represents an important step forward in that it combines detailed physical modeling with a nationally consistent monetization approach to evaluate how climate change might affect this important industry in the United States. The methodology we have employed in this study is also easily transferable, and could be refined and adapted for further insight within the United States or for applications elsewhere. For example, we could gather more detailed meteorological, topographic and spending data from a single resort to develop a site-specific model to dive deeper into the potential impacts for a specific location. Alternatively, we could synthesize national-scale meteorological and topographic data from other parts of the world to develop scoping analyses of climate change impacts on winter recreation for other countries or regions. In any case, it is clear from this study that climate change will have profound impacts on users' ability to enjoy skiing and snowmobiling over the 21st century in the United States. These impacts will ripple through the economies of regions that depend strongly on these activities, and indicate significant challenges

for snow-dependent communities under these, and similar, climate change scenarios.

Funding sources

This work was funded by the U.S. Environmental Protection Agency's Office of Atmospheric Programs through contract No. EP-BPA-12-H-0024.

Acknowledgements

This work greatly benefited from information provided by Robin Smith of TechnoAlpin and Harry Lynk of the Aspen Skiing Company with respect to snowmaking and downhill ski area operations. The work also benefited from discussions with U.S. Forest Service (USFS) staff including Dan McCollum, Don English, David Chapman, and Eric White over the use and interpretation of different USFS recreational survey data and reports. The views expressed in this article are solely those of the authors, and do not necessarily represent the views of their employers.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.gloenvcha.2017.04.006>.

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