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Climate change impacts on natural icons: Do phenological shifts threaten the relationship between peak wildflowers and visitor satisfaction? ☆

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ABSTRACT

Climate change will affect the timing of natural features of recreational interest, like fall colors, salmon migration, and wildflower blooms; and may therefore alter social-ecological relationships. For example, if fewer recreational visits are aligned with seasonal events of interest, visitor satisfaction could be affected. To explore this possibility at Mount Rainier National Park, we combined data from a community science program (MeadoWatch – MW) with hiking trip reports posted to a hiking organization (Washington Trails Association – WTA). We first explored how peak flowering, WTA trip reports, and visitation varied across years that differed in snow disappearance, a climatic factor that correlates with flowering phenology. We found that wildflower blooms tracked snow disappearance more closely than did trip reports and park visitation, implying a decreasing proportion of future visitors will experience peak wildflower blooms. We next extracted sentiment related to specific trail-experiences (e.g., wildflowers, views) and overall hike satisfaction from WTA trip reports. While wildflowers were a positive component in overall hiker satisfaction, other non-seasonal trail experiences also had positive effects. In all, a shifting wildflower season that is less accessible to visitors could alter perceptions of natural areas like Mount Rainier National Park. Countering negative social-ecological impacts could be achieved by highlighting non-seasonal aspects of the visitor experience, or alternatively, communicating the altered timing of the peak wildflower season while also increasing accessibility during this time. Such actions likely require partnerships between managers of natural areas, interpretive staff, and scientists that study seasonal phenomena of recreational interest.

1. Introduction

Some of the most ubiquitous ecological responses to climate change are phenological shifts: changes in the timing of important life events as environmental cues for these activities shift earlier or later in time [1]. For example, many studies in temperate climates have shown that spring events such as leafout, flowering and egg laying by birds are occurring earlier in time, while late summer and fall events such as leaf fall and the onset of fall hibernation are occurring later in time [2–6]. Responses to ongoing climate change do vary among species, but the magnitude of climate change means that most spring and early summer phenological events are occurring earlier [1]. Such shifts are especially large and consistent in ecosystems where the growing season is particularly constrained, such as high mountain meadows, which are generally under snow for 7–9 months of the year [7].

The possible ecological consequences of such phenological shifts, whether negative or positive, are relatively well understood. For example, alpine wildflowers that shift their flowering too early may be exposed to damaging frosts or be mismatched in timing with important pollinator mutualists [8–10]. Alternatively, such shifts may allow plants to experience a longer growing season or reproduce before damaging insect floral or seed predators emerge [11]. However, the effects of such phenological shifts on the relationship between humans and their natural environment are less well understood ([12] but see [13,14]). On the one hand, timing-sensitive events such as flowering, fall colors, and / or animal migrations (and others) are often a major seasonal draw for visitors to natural areas (Fig. 1) - suggesting that unless people change their behavior, social-ecological mismatches in these natural areas may occur as a result of climate change. On the other hand, humans are adaptable and visit natural areas for diverse reasons, suggesting that changes in

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Fig. 1. Visitors to mountain meadows in Mount Rainier National Park during the peak flowering season enjoy colorful displays of wildflowers like the Magenta paintbrush (*Castilleja parviflora* - magenta), Broadleaf arnica (*Arnica latifolia* - yellow) and Subalpine lupine (*Lupinus articus* - purple). Picture by Janneke Hille Ris Lambers.

visitor timing or expectations can buffer any negative consequences of these social-ecological mismatches.

Here, we explore the relationship between the peak wildflower season and the experience of visitors to Mount Rainier National Park. We do so by combining several sources of data: Visit timing data collected by the National Park Service, observations from a wildflower phenology community science program (MeadoWatch), and trail reports posted by hikers to the Washington Trails Association (WTA) website. We ask the following questions:

1. What is the relationship between the timing of snow disappearance and peak flowering, social media posts, and recreational visitor numbers to Mount Rainier National Park? *We hypothesize that peak flowering, the peak timing of social media posts and recreational visitor numbers vary with snow disappearance (a key driver of access to Park features which additionally correlates with wildflower phenology - [7]). We also hypothesize that social media posts and recreational visits are less responsive to earlier snow disappearance than is peak flowering [13].*

2. How are specific trail experiences commented on by hikers, including views, wildlife, wildflowers, and insects, related to their overall satisfaction with their hiking experience? *We hypothesize that the more positively hikers perceive individual components of their trail experiences, the higher their overall satisfaction with their hike.*

3. How does the overall satisfaction of hikers on trails vary with the timing and richness of the peak wildflower season? *We hypothesize that hikers have a higher satisfaction with their hike during the peak wildflower season. We also hypothesize that hiker satisfaction is positively related to the number of wildflower species in peak flowering encountered during their hike.*

Additionally, we use our findings to discuss how phenological studies that focus on seasonal phenomena of recreational interest can inform the management of natural areas and communication to visitors to these natural areas.

2. Materials & methods

2.1. Study system

This study takes place in subalpine meadows at Mount Rainier National Park, a 4392 m volcano in the Cascade mountain range in Western Washington State (46.8529° N, 121.7604° W). Subalpine meadows on the mountain range in elevation from approximately 1450–2100 m, below which coniferous forests dominate and above which bare ground, rock, and ice are ubiquitous. With dry summers and wet winters [15], the onset of spring/summer flowering is largely controlled by winter snowfall [7]. About two million visitors come to Mount Rainier National Park annually [16], with the majority of those visitors coming in the summer. Many summer visitors are likely drawn by the wildflower displays that typically occur in high mountain meadows between July and August (Fig. 1).

2.2. MeadoWatch program

MeadoWatch (MW) is a community science program that monitors subalpine wildflower phenology, run collaboratively by University of Washington and the National Park Service at Mount Rainier National Park. Volunteers collect phenological data (flowering - yes / no) for thirteen focal species along two trails - the Glacier Basin (GB) trail and the Reflection Lakes (RL) trail, occurring on the northeast and south sides of the mountain (respectively). Data collection occurred at 15 (2015–2016) or 17 (2017–2019) plots on the GB Trail; and 9 (2013–2015) or 11 (2016–2019) plots on the RL trail. Data were collected from 2015 to 2019 on the GB trail, and 2013–2019 on the RL trail. Plots are approximately 1.25 m^2. Temperature sensors (HOBO pendant loggers) were deployed at each plot to estimate snow disappearance dates at each plot in each year of sampling. The thirteen focal wildflower species monitored by MW volunteers are all herbaceous long-lived perennials and vary in their flowering phenology and the color and showiness of their flowers (Appendix A).

Each summer, MW volunteers collected flowering phenology data over the course of 2.5–3.5 summer months, with ∼3–9 volunteers collecting data per week (depending on the trail and year). In total, the MW data used for analyses contained between 57 and 114 observations per year-, plot-, and species-combination, with 41,339 total observations of flowering collected between 2013 and 2019. See our program website (www.meadowatch.org) for more details about the MW program. Additionally, appendices provide information on the focal wildflower species monitored (Appendix A), plot locations (Appendix B), how temperature data is used to quantify snow disappearance (Appendix C), how sampling effort and temporal grain varied each year (Appendix D), and quality assurance and quality control of community science derived phenology data (Appendix E, [17]).

2.3. Using MeadoWatch data to characterize the wildflower season

We first used MW data to quantify year-, species- and plot-specific flowering phenology curves [7,17]. We assumed that individual observations by volunteers, documenting whether or not wildflower species i was flowering within the j^{th} plot and in the k^{th} year (f_{ijk} - recorded as yes / 1 or no / 0) in which volunteers made observations follow a Bernoulli distribution with mean φ_{ijk}:

$$f_{ijk} \sim Bernoulli(\varphi_{ijk}) \tag{1}$$

The probability of flowering (φ_{ijk}) was defined as a unimodal function of when within the growing season the observation was made (DOY, days since January 1) on a logit scale (to assure predictions <1 and >0) determined by the timing of peak flowering for that species in that plot and year (ρ_{ijk}, in days), the species-, plot- and year-specific duration of flowering in that plot and year (δ_{ijk}), and the maximum probability of flowering observed (μ_{ijk}, also species-, plot- and year- specific):

$$\mathrm{logit}\left(\varphi_{ijk}\right) = \delta_{ijk} * \left(DOY_k - \rho_{ijk}\right)^2 + \mu_{ijk} \quad (2)$$

These year-, species- and plot-specific parameters allowed us to understand the flowering phenology our volunteers observed for each species within each MW plot in each year. We used maximum likelihood approaches to estimate parameters describing flowering phenology for each year-, species- and plot combination (δ_{ijk}'s, μ_{ijk}'s, and ρ_{ijk}'s from Eq. (2)) from MeadoWatch data. We checked for model convergence and used multiple fitting algorithms (e.g. Nelder-Mead, BFGS) to increase the likelihood that model fitting achieved global, and not local maximum likelihood estimates. We used ρ_{ijk}'s to estimate the timing of the overall peak wildflower season (see Section 2.5) and to validate phenological models fit at the species level (see Eqs. (3 & 4) below).

We conducted additional model fitting, because we felt that parameters from Eq. (2) did not adequately describe the duration of flowering or richness of wildflowers hikers experience along the entirety of each trail. For one, the relatively small MW plots do not contain all focal species, even when those species occur in abundance in meadows nearby (and are enjoyed by hikers on the trail). Moreover, many of our lower elevation plots occur in small gaps within forested areas, where meadows and dense displays of wildflowers do not occur. We therefore fit additional statistical models to determine the relationship between peak flowering and snow disappearance for each focal species. These statistical models allow us to predict when focal species are at peak flower for any range of snow disappearance dates (e.g. within meadows).

For models relating snow disappearance to peak phenology, we again assumed the probability of flowering (φ_{ijk}) for the i^{th} species in the j^{th} plot and k^{th} year was a unimodal function of when within the growing season the observation was made (DOY, days since January 1) on a logit scale (to assure predictions <1 and >0). This time, parameters describing the duration of flowering (δ_i) and the maximum probability of flowering observed (μ_i, on a logit scale) were fit at the species, rather than species, plot and year level. We assumed the timing of peak flowering varied by year, plot and species ($\hat{\rho}_{ijk}$, in days):

$$\mathrm{logit}\left(\varphi_{ijk}\right) = \delta_i * \left(DOY_k - \hat{\rho}_{ijk}\right)^2 + \mu_i \quad (3)$$

In this model, the species-, plot- and year-specific timing of peak flowering ($\hat{\rho}_{ijk}$) is not a fitted parameter, but rather depends on the year and plot-specific date of snow disappearance ($SDDDOY_{jk}$) via two species-specific parameters (the intercept α_i and the slope β_i):

$$\hat{\rho}_{ijk} = \alpha_i + \beta_i SDDDOY_{jk} \quad (4)$$

To test our assumption that the relationship between peak flowering and snow disappearance is linear (with earlier snowmelt corresponding to earlier flowering), as has been found in previous studies in the same system [7], we compared the slope and intercept parameters from Eq. (4) (α_i and β_i) to those generated by regressing peak flowering estimates fit separately to species-year-plot specific data (ρ_{ijk} from Eq. (2)) to plot-specific date of snow disappearance (SDDDOY_{jk}), and found strong concurrence Appendix F). We used maximum likelihood approaches to estimate the four parameters describing flowering phenology (δ_i, μ_i, α_i and β_i in Eqs. (3 and 4)) from MeadoWatch data for each species. We checked for model convergence and used multiple fitting algorithms (e.g. Nelder-Mead, BFGS) to increase the likelihood that model fitting achieved global, and not local maximum likelihood estimates.

Finally, we used phenological models fit at the species level (Eq. (3 & 4)) to estimate two wildflower metrics that we thought would be relevant to hikers' wildflower experiences on the day, in the year and on the trail that they hiked: an estimate of the number of wildflowers they encountered in peak flowering (peak flowering richness) and whether they were hiking during the peak flowering season (defined as 50% of focal species in peak flower). We did this as follows. We first applied parameters δ_i, μ_i, α_i and β_i to the earliest and latest observed snow disappearance dates (for that year) in meadows to identify the first and last day at which the probability of flowering for each focal species was greater than 50% of the max flowering probability (parameter μ_i). We then assumed that anyone hiking between those two dates would have encountered the focal species in question in peak flowering in meadows. From this information, we could calculate peak flowering richness in meadows for any day that a hiker hiked, which depended on how many focal species were encountered at peak flowering on the trail. We defined the trail and year specific start and end of the wildflower season as the first and last day in which at least half of our focal wildflower species were estimated to be in peak flower. Of course, there are many other plant species flowering in meadows than just MW focal species, but we assume that flowering richness of MW species is a good proxy for total flowering richness. We believe this a reasonable assumption because MW focal species include many of the most abundant and photographed species at Mount Rainier National Park (per. obs). Appendix H is flowchart describing how MW data allowed us to address our objectives.

2.4. Washington trail association trip reports

To understand hikers overall satisfaction with their hikes, and how this related to specific trail experiences, we examined publicly available hiking records, crowdsourced from a popular hiking social network in Washington state (Washington Trail Association, WTA, https://www.wta.org/). In total, we scored 193 trip reports describing experiences on the Glacier Basin Trail and 372 trip reports describing experiences on the Skyline Trail Loop (which overlaps with the MW Reflection Lakes hike). Trip reports were collected within the time period in which MW data were collected (2015–2019 for Glacier Basin: 2013–2019 for Reflection Lakes / Skyline Loop). Appendix H is flowchart describing how WTA data was combined with MW data to address our objectives.

Our goals in scoring trip reports were to understand A) Overall hiker satisfaction with their hike, and B) Their sentiment about specific trail experiences they encountered and chose to write about. Thus, we qualitatively coded the text hikers submitted for their trip report on seven specific sentiments: wildflowers, bugs (biting insects), weather, views, wildlife, trail conditions and crowding. Each of these sentiments were coded by independent, previously trained coders on a five-point Likert-like scale, from extremely negative, negative, neutral, positive, extremely positive. We also coded each trip report for a hikers' overall satisfaction with their hike, using the same scale. This is identical to a sentiment score for the entire hike, although we refer to this sentiment score as 'satisfaction' to clearly distinguish this measure from the individual sentiment scores representing individual experiences. See Appendix G for more details on sentiment and satisfaction scoring. Note that because trip reports are free-form and hikers could choose what aspect to write about, a trip report could receive an NA instead of a sentiment score if there was no mention of this aspect in the report (e.g. if the text did not mention biting insects, sentiment for bugs was 'NA').

We used the following process to ensure data quality for sentiment and satisfaction scoring. Each trip report was randomly assigned to 2 reviewers and was independently scored - after which scores were averaged. A third coder provided an additional score for a subset of trip reports to resolve large discrepancies in the two sentiment scores. For trip reports with three scores, we dropped the most disparate score or averaged the three scores (if there was not one most disparate score). Finally, we conducted an inter-rater reliability (IRR) analysis with the 'icc' package to measure reliability in sentiment coding between coders [18,19]. We excluded two of the seven individual sentiments (crowding and wildlife) from further analyses, because their IRR scores were below 0.7 [20,21]. See Appendix G for more details.

2.5. The relationship between snow disappearance, flowering, trip reports, and NPS visits

We used linear models to explore the relationship between the average timing of snow disappearance in each year and A) the mean timing of peak flowering (across all MW species monitored on each trail), B) the mean date of WTA trip reports (a measure of trail activity), and C) the mean timing of recreational visits to the entire park (data available via the NPS). For flowering, we averaged year-, species- and trail-specific peak flowering estimates for all focal species (i.e. ρ_{ijk}'s from Eq. (2)), to approximate the timing of the peak wildflower season in each year. For WTA trip reports, we averaged the day of year of trip reports for each trail-year combination. The timing of park visitation was estimated from seven years of recreational visitation data that overlapped with MW and WTA data, available in the Integrated Resource Management Applications portal of the National Park Service website [16]. These values were reported by month, not day, so we averaged monthly values and transformed them into day of year values. We calculated yearly snow disappearance dates by averaging trail and plot-specific snow disappearance dates ($SDDDOY_{jk}$'s). We related yearly park visitation to yearly snow disappearance dates along the RL trail, as these observations spanned the entire time frame over which our study occurred (2013–2019). We then conducted individual linear regressions relating annual snow disappearance date to the average day of year for each event of interest (peak flowering, WTA trip report, NPS visitors). We also conducted a multiple regression with all data, with snow disappearance date, event type (MW, WTA, NPS) and their interaction as explanatory variables for the yearly timing of events (day of year of peak flowering, WTA trip reports, or recreational visits).

2.6. How do individual experiences influence hiking satisfaction?

We wished to relate sentiment scores describing individual experiences (e.g. wildflowers, views, biting insects) to overall hiker satisfaction, but encountered challenges. A high proportion of scores for sentiments associated with individual experiences were “NA’s” (between 20% and 83%, depending on the experience), as many hikers did not mention all specific experiences in their trip reports (either because they did not experience them or did not feel compelled to describe them). The abundance of missing values is a common challenge to self-reported or questionnaire analyses [22]. Additionally, several individual sentiment score distributions had a very low representation of 1 and 2 scores. This pattern of a strong ceiling effect is also a common challenge in Likert-scale like surveys [23]. To accommodate both these challenges, we transformed individual sentiment scores into categorical variables with the categories “No mention” (for NAs), “Negative” (sentiment less than 2.5), “Neutral” (sentiment between 2.5 and 3.5) and “Positive” (sentiment greater than 3.5). We then conducted several one-way analyses of variance with these individual sentiment scores as categorical explanatory variables and overall satisfaction with the hike as a continuous response variable.

Since we also wished to understand the relative importance of wildflowers vs. other hiking related experiences to overall hiker satisfaction, we used a Random Forest classifier (RF, [24]) to simultaneously relate all sentiments associated with individual experiences (e.g. views, wildflowers) to our measure of overall trail satisfaction. RF classifiers are a model-averaging or ensemble-based approach in which multiple classification tree models are built using random subsets of the data and predictor variables. RF classifiers use a recursive partitioning algorithm to repeatedly partition the dataset, according to predictor variables, into a nested series of mutually exclusive groups, each as homogeneous as possible with respect to the response variable. It requires fewer parameters to fit and has been shown to be less biased than other machine learning methods [25]. RF models were fit using the ‘randomForest’ package in R [19,26].

2.7. How is overall hiker satisfaction affected by the wildflower season?

Finally, we asked whether overall satisfaction of hikers differed based on whether summer hikes occurred during peak flowering or not, in addition to whether overall satisfaction was related to peak flowering richness on the day of the hike. This allows us to determine whether hiker satisfaction is related to the peak wildflower season, regardless of whether wildflower blooms were explicitly commented on in trip reports. We used ordinal regression for this analysis, with overall satisfaction as the response variable. As with individual sentiment scores, lower overall satisfaction scores were poorly represented (e.g. fewer than 17 out of 508 scores were less than 3 and 212 were greater than 4). An additional challenge is that satisfaction scores were not categorical, as they were averages of multiple scores and we allowed for half-point scores. We therefore recoded overall satisfaction to have 3 more balanced categories, as follows: 1 = neutral and negative (3 and under); 2 = positive (greater than 3 and less than or equal to 4) and 3 = highly positive (greater than 4). There were only 2 NA’s (trip reports with no text) in our data set, so we excluded these two data points from further analysis.

We included one of two flowering metrics, richness or peak wildflower (y/n), as explanatory variables in these ordinal regression models. We quantified flowering richness as a continuous variable (the projected number of MW focal species encountered in peak flowering in meadows, which ranged from 0 to 12), to test the hypothesis that each additional species in peak flowering increases hiker satisfaction. The second flowering metric is the categorical variable “peak flowering season” (“yes” or “no” - when 50% of MW species are in peak flowering). This metric would best describe a threshold effect, where hiker satisfaction increases when hiking during the peak wildflower season but does not continue to linearly increase with each additional wildflower encountered in peak flowering. For each flowering metric, we used model selection to determine what combination of year (categorical), trail (categorical), and 2-way interactions between the flowering metric, year, and trail best described variation in overall satisfaction in ordinal regressions. We also used a brant test (package and function brant) to test the proportional odds assumption in our final model [19,27].

We ran all analyses described in this and previous sections, as well as in appendices, in R version 4.0.3 [19].

3. Results

3.1. How do peak flowering, WTA posts, and NPS visitation vary in years that differ in climate?

Consistent with previous work in this system [13], we found that shifts in peak flowering with earlier snowmelt was greater than shifts in the timing of social media posts (Fig. 2a vs. 2c; Fig. 2b vs. 2d), and much greater than those in overall visitation to Mount Rainier National Park (Fig. 2a & 2b vs. Fig. 2e). Specifically, the coefficient describing the average date of snowmelt observed on MW trails and the average date of peak flowering was positive (slope = 0.562, $p < 0.001$), and greater than the coefficient describing the relationship between snow disappearance and the average date WTA trip reports were posted on the same trail (slope = 0.374, $p = 0.012$). The coefficient describing the relationship between snow disappearance and recreational visitors to all of Mount Rainier National Park, by contrast, was not significantly different from 0 (slope = 0.039, $p = 0.299$). We also found that the interaction between snow disappearance and event type (MW, WTA, NPS visitor) significantly explained variation in the timing of these events (Table 1).

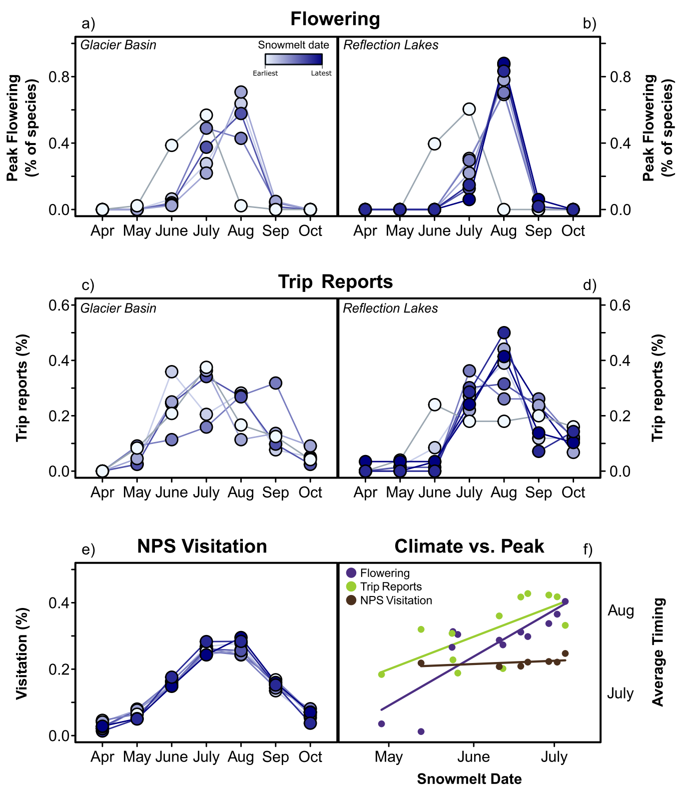


Fig. 2. Comparison of the mean yearly timing of peak flowering (a, b), WTA trip reports (c, d), visitation to Mt. Rainier National Park (e) between 2013 and 2019; and the relationship between snow, flowering, WTA reports and visitation (f). Peak flowering, trip reports and visitation (in a-e) are shown as proportions (e.g. proportion of total wildflowers observed at peak flowering, trip reports posted, and visitors in that year). Points in a-e are color-coded depending based on the ranked snowmelt year (lighter blue = earlier snowmelt). Best fit lines from linear models describing the relationship between snow disappearance date and the average timing of flowers, WTA trip reports, and NPS visitors are shown in f. A linear model including snow disappearance, event type, and their interaction indicates that the slopes of the three lines in f are significantly different ($p = 0.0496$).

Table 1
Results of a linear model testing whether the relationship between yearly snow disappearance date and the timing of peak flowering, WTA trip report posts, and NPS visitation differs. Snow disappearance date, event type (MW, WTA, or NPS) and their interaction were included as explanatory variables, with annual timing (day of year) as the response variable.

Explanatory variable	Df	Sum Sq	Mean Sq	F-value	P(>*F*)
Snowmelt date	1	1450.34	1450.34	24.79	<0.0001
Event type	2	1069.21	534.61	9.14	0.0010
Snowmelt*Event type	2	397.29	198.64	3.40	0.0496
Residuals	25	1462.45	58.50		

3.2. *Which trail experiences contribute to overall hiker satisfaction?*

Overall, we found that hiker experiences with biting insects (bugs), trail conditions, weather, views, and wildflowers correlated with overall hiking satisfaction in the expected direction. Specifically, hikers that described more positive experiences (or, in the case of biting insects, a lack of negative experiences) with each of these trail features expressed greater overall satisfaction with their hike (Fig. 3a-e), although the effects of bug sentiment on overall satisfaction were not significant (Table 2). Posthoc Tukeys tests indicated that hikers describing negative, neutral, and positive sentiments for crowding, trail conditions, wildflowers, or views predictably differed in their overall satisfaction

Table 2
The relationship between individual trail experiences and hiker satisfaction. Results from 1-way analysis of variance between individual sentiments and overall hike satisfaction are shown in the first section of the table (sample size 547 for all five tests). In the second section of the table, results from Posthoc Tukeys tests for differences in total satisfaction between sentiment categories (positive, neutral, negative, NA) of individual trail experiences are shown. The differences are bolded if p-values from Tukey tests of this difference are less than 0.05.

	Total Hike Satisfaction ~f(Individual Trail Experiences)				
	Bugs	Trails	Weather	Views	Wildflowers
Analysis of Variance					
F-statistic	1.849	18.66	22.89	42.82	17.26
P-value	0.137	<0.001	<0.001	<0.001	<0.001
R^2 (adjusted)	0.005	0.088	0.107	0.187	0.082
Df (sent, residuals)	3, 543	3, 543	3, 543	3, 543	3, 543
HSD Tukey Tests					
Pos-Neut	0.375	**0.273**	**0.371**	**0.458**	**0.336**
Pos-Neg	0.310	**0.693**	**0.729**	**1.027**	**1.178**
Pos-NA	0.312	0.147	**0.328**	**0.532**	**0.318**
Neut-Neg	−0.065	**0.420**	**0.358**	**0.569**	**0.842**
Neut-NA	−0.064	−0.126	−0.043	0.074	−0.018
Neg-NA	0.001	**−0.546**	**−0.401**	**−0.495**	**−0.860**

with their hiking experience (pos>neut, neut>neg, pos>neg – Table 2). Tukeys tests also indicated that those not writing about individual experiences (i.e. the ‘NA’ category) expressed similar overall satisfaction as those describing neutral experiences, and generally differed significantly from those expressing positive and negative sentiments (Table 2). Note that the proportion of hikers writing about these different experiences varied greatly, from less than 20% commenting on biting insects and greater than 80% commenting on views - which likely contributed to the power of these tests (Fig. 3). Overall, the proportion of variance explained by linear models including single explanatory variables was relatively low (ranging between 8.2% for wildflowers to 18.7% for views – Table 2).

Random Forest regression models, which included all individual sentiments as explanatory variables, provided results that were largely consistent with results from one-way analysis of variance results (Fig. 3f). Views provided the greatest ability to distinguish sentiment scores (32.8% importance), followed roughly equally by wildflowers (24.0%), trail conditions (23.6%) and weather conditions (23.5%), and finally by biting insects (i.e. bugs - 6.3%). Overall, we found that the individual sentiments together explained 31.24% of the variance in total hiker satisfaction, implying that multiple individual trail experiences contribute to the overall experience of hikers on hiking trails.

3.3. *Is overall hiker satisfaction with a trip influenced by the peak wildflower season?*

We found that overall hiker satisfaction differed depending on the nature of peak flowering encountered during the hike. Models including trail and one of the two flowering metrics (richness - continuous; or peak - categorical) had the lowest AIC values (Table 3). AIC values did not distinguish between equivalent models including the two different flowering metrics, with nearly identical AIC values for best fitting models including trail and richness vs. trail and flowering season (Table 3). Coefficients and odds ratios suggest that flowering richness and / or peak flowering increased hiker satisfaction, with higher satisfaction overall on the RL than GB trail (Table 4, Fig 4).

4. Discussion

Overall, we show that the peak of visitor (human) activity in Mount Rainier National Park is likely to become increasingly mismatched with the peak wildflower season as temperatures warm, causing a lower proportion of park visitors to experience this seasonal phenomenon (Fig. 2,

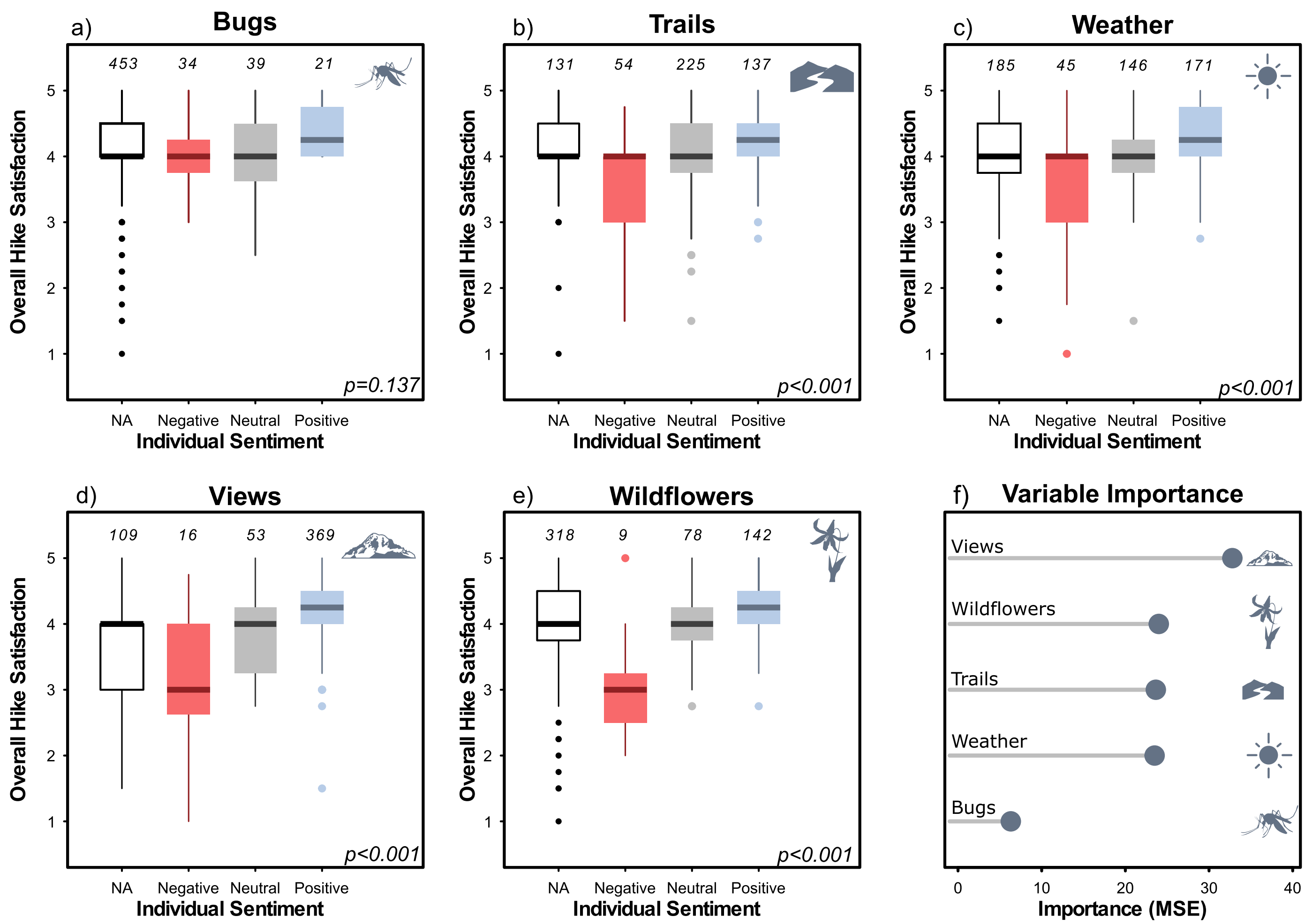


Fig. 3. The effect of individual trail experiences on the overall satisfaction expressed by hikers in trip reports. In a-e, white bars represent trip reports that did not contain text describing the experience in question, red bars represent text with negative sentiment, gray with neutral sentiment, and blue with positive sentiment. Numbers above each bar in a-e represent the number of trip reports falling into each category for the sentiment in question. P-values reported on the bottom right of panels a-e are from a one-way analysis of variance. In f, importance values (the increase in mean squared error) from a random forest model relating overall hiker satisfaction to individual trail experience sentiments is shown. Higher values indicate the individual sentiment was more likely to be retained in decision trees, indicating a greater effect on overall trail satisfaction.

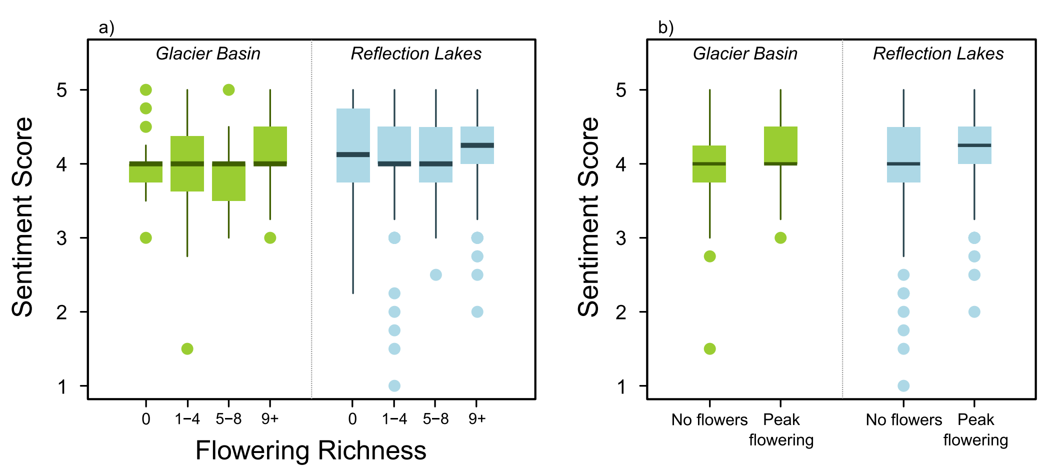


Fig. 4. The relationship between the richness (a) or the peak wildflower season (b) experienced by hikers on two trails (Glacier Basin and Reflection Lakes / Skyline Loop) and their overall satisfaction. Fig. 4a shows how satisfaction changes in binned categories of species richness (note that in the analysis, richness was treated as continuous, not as binned); while Fig. 4b shows how satisfaction varies between trips taken during peak wildflower season (Peak) and outside of peak wildflower season (No flowers).

Table 3
Delta AICs from model selection of two sets of ordinal regression models relating hiker satisfaction to year, trail and the richness of wildflowers in peak flowering (column 2) or the presence of the wildflower season (column 3) encountered on the trail. AICs of lowest AIC models for each metric are included in parentheses.

Model parameters	*Fl* = Flowering richness	*Fl* = Flowering peak (y / n)
Null	10.10	9.99
Year	8.41	8.31
Trail	2.78	2.68
Fl	7.15	6.17
Year + Trail	2.93	2.83
Year + Fl	5.99	5.24
Trail + Fl	**0.00** (965.42)	**0.00** (965.52)
Year*Trail	6.40	6.30
Year*Fl	9.94	10.12
Trail*Fl	1.98	2.00

Table 4
Coefficients, p-values (from t-tests), Odds ratios (and 95% confidence intervals) from ordinal regression models relating flowering metrics (richness and yes / no peak flowering) to the overall satisfaction of hikers on each trail. All statistical tests are based on 506 observations of hikers overall satisfaction on trails (on hikes taken between April 15 and October 15).

Model Parameter	Value (std.err)	p-value	Odds (2.5%–97.5%)
Satisfaction~f(rich, trail)			
richness	0.050 (0.023)	0.029	1.051 (1.005, 1.010)
trail (RL)	0.537 (0.178)	0.003	
1|2 (intercept)	−1.54 (0.207)	<0.001	1.710 (1.208, 2.432)
2|3 (intercept)	0.941 (0.192)	<0.001	
Satisfaction~(peak, trail)			
peak	0.376 (0.174)	0.031	1.457 (1.036, 2.051)
trail (RL)	0.510 (0.179)	0.004	
1|2 (intercept)	−1.660 (0.184)	<0.001	1.665 (1.173, 2.368)
2|3 (intercept)	0.820 (0.163)	<0.001	

[13,28]). Because our analysis suggests that a positive experience with wildflowers affects hikers' overall enthusiasm for their hiking experience (Fig. 3,4), it is possible that this social-ecological mismatch could decrease the satisfaction of visitors to this National Park. However, results also show that hikers are positively affected by less seasonal trail experiences, including views, well maintained trails, and good weather (Fig. 3). Moreover, the majority of hikers felt positively about their hiking experience [29], although those who felt less positively about their hiking experiences may have been less likely to post about their experiences [30]. In all, we believe that the likely loss in visitor satisfaction due to a social-ecological mismatch with peak wildflowers can be mitigated through management of access and communication with future visitors. We discuss these findings in more detail below.

4.1. An increasing mismatch between wildflowers and visitation with climate change

Our results suggest that future visitors to Mount Rainier National Park are less likely to experience the peak wildflower season in mountain meadows for which the park is renowned (Fig. 1). This is because wildflower phenology appears much more sensitive to shifts in snowmelt than recreational visitation (Fig. 2a & b vs. 2e & f, but see [31]). In all, this suggests an increasing social-ecological mismatch between peak visitation and the timing of the peak wildflower season [13]. It is possible that visitor behavior could offset this mismatch, if hikers choose which trails to visit based on knowledge of current flowering. Indeed, our results suggest that WTA hikers who visit our two focal trails (a small subset of total visitors to the park) shift their hiking activity in years with earlier snowmelt (Fig. 2c, d). Additionally, Mount Rainier National Park could provide earlier seasonal access to high mountain meadows, as current access is limited by road maintenance and campsite opening dates, which are less variable timing-wise as compared to snowmelt and wildflower phenology [13]. However, given the accelerated pace of climate change forecasted for the region, we believe the wildflower season at Mount Rainier National Park will eventually shift to before the summer vacation, which would greatly limit behavioral changes by visitors, even if changes to park management would allow visitors to shift their visits earlier.

The extent to which the biological impacts of climate change will result in an increasing social-ecological mismatch between visitors and ecological phenomena of interest in other natural areas, as we believe it will in Mount Rainier National Park, will depend on several factors. Most obviously, a social-ecological mismatch won't occur in natural areas where visitors are primarily drawn by non-seasonal phenomena (e.g., volcanic activity in Yellowstone National Park). This is not to say that there won't be effects of climate change on visitor experiences in these natural areas, just that these impacts will not be related to the altered timing of biological phenomena. For example, range contractions and local extinctions may threaten the iconic Joshua Trees in Joshua Tree National Park within the next century [32], providing future visitors with fewer opportunities to see this charismatic species. It is also possible that some natural areas primarily draw visitors who can more easily respond to shifts in seasonally attractive phenomena, as might be the case when visitors are local or primarily from an older demographic without school-aged children and are thus less tied to an academic calendar. Finally, there are some cases where climate change could *increase* the likelihood that visitors experience a seasonal phenomenon of interest, as might occur in two Japanese cities, where climate change could shift cherry flowering to more often coincide with flower festivals that occur at a fixed time [33].

4.2. Hikers enjoy wildflowers, but not only wildflowers

Of course, whether or not a social-ecological mismatch between flowering and peak visitation in Mount Rainier National Park results in declining visitor enjoyment with climate change depends on how much wildflowers contribute to that enjoyment in the first place. Hikers with a higher wildflower sentiment (i.e., wrote more enthusiastically about wildflowers in their trip report) also expressed a higher overall satisfaction with their hike (Fig. 3), implying that wildflowers do increase visitor satisfaction, as we expected. Of course, as a majority of hikers did not explicitly mention wildflowers in their trip report (58%), it is possible that these results are primarily driven by the subset of hikers seeking out wildflowers and expressing their excitement or disappointment depending on their experience. We do not believe this is the sole explanation for these results, as hikers visiting during the peak wildflower season and experiencing a greater richness of wildflowers on their hike also reported a higher overall satisfaction with their hike, regardless of whether they described wildflowers in their trip report (Fig. 4).

However, our results also suggest that although wildflowers increase hiker satisfaction, the effects are probably not large enough to substantially shift visitor satisfaction in a future, warmer Mount Rainier National Park where visitors are less likely to experience wildflowers (Fig. 2). For one, given that a large fraction of visitors to Mount Rainier National Park already do not experience peak flowering, a further decline in this number may only have marginal effects on the average satisfaction across all visitors. Moreover, while significant, wildflower metrics had relatively small effects on overall satisfaction (Table 4, Fig. 4), which was generally high to start with [29]. Finally, non-seasonal trail experiences that are less likely to be influenced by climate change also influenced overall hiker satisfaction, and in some cases, the effects of these experiences on overall trail satisfaction were equal to if not greater than the effects of wildflowers (e.g. views, weather, trail conditions - Fig. 3). This likely explains why hikers largely expressed positive satisfaction with their hikes on our two focal trails, regardless of their stated or likely experience with wildflowers in peak bloom (Fig. 3, 4).

4.3. Altered visitor experiences under future climate change

Clearly, climate change will bring changes to the biological features visitors come to visit in natural areas [34], and these effects could have negative impacts on their experiences. For example, as the peak wildflower season at Mount Rainier National Park shifts earlier, visitors that cannot also shift their visitation may be disappointed at missing this iconic feature. Fortunately, there are ways to help visitors manage their expectations. One option is to ensure visitors are also aware of non-seasonal features of recreational interest (e.g. views) that could help maintain their satisfaction even as seasonal features of interest might shift in a way that makes them inaccessible to many (as the peak wildflower season at Mount Rainier National Park might). Another option is to create alternative experiences that do not require in-person visits, for example, virtual tours of mountain meadows during peak flowering. Finally, relieving seasonal constraints on visitor access could allow visitors to better match their activities to phenological features of interest [14,28,34]. For example, access to high mountain meadows at Mount Rainier National Park is often constrained by road clearing and campground opening schedules in the early part of the summer that could be eased to allow for earlier visitation that matches the peak wildflower season [13]. However, this latter strategy requires that visitors have up-to-date information on the timing of the seasonal features of interest as they shift in response to climate change, so visitors can better time their visits. In all, we believe that partnerships between managers of natural areas, interpretive staff (who communicate regularly with visitors) and scientists who study seasonal phenomena of recreational interest are best equipped to prepare visitors for altered experiences under a changing climate.

4.4. Caveats and limitations of these analyses

Our conclusions about visitor satisfaction rely on our assumption that trip reports posted to the Washington Trail Association are representative of the broader visitor experience, but there are several aspects we should be aware of when interpreting our results. For one, WTA trip report posters are unlikely to be representative of all visitors to Mount Rainier National Park. For example, the regional focus of the Washington Trail Association means that WTA trip reporters likely represent hikers from Washington state rather than out of town visitors to Mount Rainier National Park. It is also likely that WTA trip reporters represent a small but enthusiastic subset of all Washington State residents who are users of this platform, as is generally the case for social media posts [30]. Finally, WTA account holders may be more or less likely to post a trip report depending on the very trail-wide experiences whose sentiments we explored, potentially biasing trip report sentiments of these features. Whether or not any of these factors strongly influence our estimates of the timing of hiker visits to focal trails (e.g. Fig. 2c, d) or the sentiment expressed by these hikers about these experiences (e.g. Fig. 3, 4) is still unknown. We hope that the large number of WTA trip reports we analyzed will aid in producing more general results, but these biases are currently impossible to quantify without a long-term in-situ assessment of visitor sentiments and their overall satisfaction with their hike.

4.5. Conclusions

There is no doubt that the effects of climate change on natural features of interest will also alter the experience of visitors to National and Regional State Parks, and other natural areas drawing recreational visits [34]. Given the large and complex challenges faced by resource managers, interpretive staff, and scientists in natural areas experiencing a warming climate [34,35], prioritizing strategies to allow visitors to adapt to climate-change induced shifts in the timing of key biological features of interest (e.g. peak flowering) may not seem like a top priority. However, developing strategies to address a potential future mismatch between visitors and a seasonal feature of interest may offer additional benefits. For example, providing visitors with information on how seasonal phenomena of recreational interest have shifted over time would complement existing efforts within natural areas to highlight climate change impacts on the abundance of threatened plants and animals, while potentially increasing public support for action [36,37]. Interpretive materials that focus on shifts in phenological features of interest (e.g. wildflowers), rather than the outright disappearance of natural features (e.g. glaciers - [38]) may also minimize the ecological grief associated with climate change related loss [39] while helping the public understand the nuanced and complex effects of climate change. Developing virtual tours of high mountain meadows during peak flowering, while not a substitute for an in-person hiking experience, could allow those who are unlikely to ever visit National Parks to also experience this iconic feature [40]. In all, we believe combining an ecological and sociological understanding of how climate change will alter seasonal features of recreational interest can contribute to efforts to help visitors to natural areas understand and adapt to these changes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank the over 500+ MeadoWatch volunteers who helped collect wildflower phenology data between 2103 and 2019, as well as the hikers who posted about their experiences to the WTA website. Vicente Velasco and Floris Schenk helped score WTA trip reports, we thank them for their efforts. We also thank Mount Rainier National Park (especially Kevin Bacher, Yonit Yogev and Tara Chestnut) for providing support to the MeadoWatch program and volunteers. We thank Elia Pirtle for providing the illustrations shown in the graphical abstract and the methods flowchart. Funding was provided to MeadoWatch / JHRL from NSF (Career DEB-1054012), NASA (NNX 14AC34G), Washington's National Park Fund, and many generous donors. Hiking and data collection activities took place on Mt. Tahoma (encompassed by Mount Rainier National Park), which was historically utilized and continues to be stewarded by the people osf the Nisqually, Puyallup, Squaxin Island, Muckleshoot, Yakama, and Cowlitz Nations.

Appendix A

Table A1

Table A1
Thirteen focal species monitored by MeadoWatch volunteers. Four additional MW species were not included in this study because they are not abundant in mountain meadows.

Species (code)	Flower Color	Flowering lag after snow*	Trail(s) monitored	Total year / plot locations
Anemone occidentalis (ANOC)	White	11	Reflection Lakes	25
Arnica latifolia (ARLA)	Yellow	66	Glacier Basin	23
Aster ledophyllus (ASLE)	Pink	69	Glacier Basin	29
Castilleja miniata (CAMI)	Orange / red	66	Glacier Basin	20
Castilleja parviflora (CAPA)	Pink / Magenta	35	Reflection Lakes	49
Erigeron peregrinus (ERPE)	Pink	39	Reflection Lakes	19
Erythronium grandiflorum (ERGR)	Yellow	12	Glacier Basin	10
Erythronium montanum (ERMO)	White with yellow center	14	Reflection Lakes	37
Ligusticum grayii (LIGR)	White	41	Reflection Lakes	35
Lupinus arcticus (LUAR)	Purple	45	Glacier Basin, Reflection Lakes	111
Pedicularis bracteosa (PEBR)	Yellow / green	36	Glacier Basin, Reflection Lakes	43
Polygonum bistortoides (POBI)	White	41	Glacier Basin, Reflection Lakes	58
Valeriana sitchensis s(VASI)	White	38	Glacier Basin, Reflection Lakes	76

* Average days between snowmelt and peak flowering. On average, snowmelt occurs in early June on the Glacier Basin trail and early July on the Reflection Lakes trail.

Appendix B. MeadoWatch plot locations

Trail	Plot name(s)	Years monitored	Type	Latitude	Longitude	Elevation
RL	RL1	2013–2016	Forest	46.77058	−121.723	1490
RL	RL1	2017-present	Forest	46.77058	−121.72337	1496
RL	RL2	2013-present	Forest	46.77334	−121.72337	1540
RL	RL3, RL3a	2013–2016	Forest	46.7748	−121.7198	1600
RL	RL3	2017-present	Forest	46.7748	−121.7198	1605
RL	RL4, RL3b, RL4	2013, 2016-present	Forest	46.77567	−121.72017	1615
RL	RL4	2014-present	Forest	46.77567	−121.72017	1650
RL	RL5, RL5a, RL6	2013-present	Meadow (low)	46.7817	−121.71968	1680
RL	RL5b, RL7	2016-present	Meadow (low)	46.78403	−121.72019	1711
RL	RL6	2013–2016	Meadow (low)	46.78736	−121.71936	1745
RL	RL7, RL9	2013–present	Meadow (low)	46.7919	−121.71693	1805
RL	RL8	2017–present	Meadow (low)	46.78736	−121.71936	1745
RL	RL8, RL10	2013–present	Meadow (high)	46.79403	−121.71604	1840
RL	RL9, R11	2013–present	Meadow (high)	46.79654	−121.71194	1889
GB	GB1	2015–2016	Forest	46.90013	−121.665671	1460
GB	GB1	2017–present	Forest	46.90013	−121.665671	1483
GB	GB2	2015–present	Forest	46.89985	−121.667978	1469
GB	GB3	2015–present	Forest	46.89945	−121.671581	1500
GB	GB4	2015–2016	Forest	46.89918	−121.672367	1512
GB	GB5, GB4	2015–present	Forest	46.89704	−121.678036	1547
GB	GB6, GB5	2015–present	Forest	46.89661	−121.681483	1613
GB	GB6	2017–present	Forest	46.89661	−121.681483	1582
GB	GB7	2015–present	Forest	46.89693	−121.683676	1600
GB	GB8	2015–present	Forest	46.89612	−121.687292	1647
GB	GB9	2015–present	Forest	46.89422	−121.692884	1713
GB	GB10	2015–present	Meadow (low)	46.89297	−121.696405	1748
GB	GB11	2015–present	Meadow (low)	46.89089	−121.698386	1766
GB	GB12	2015–present	Meadow (low)	46.89052	−121.698728	1776
GB	GB13	2015–present	Meadow (low)	46.89004	−121.699324	1775
GB	GB14	2015–present	Meadow (low)	46.88932	−121.700194	1804
GB	GB15, GB17	2015–present	Meadow (high)	46.8885	−121.704328	1831
GB	GB15	2017–present	Meadow (high)	46.8885	−121.704328	1823
GB	GB16	2017–present	Meadow (high)	46.88932	−121.700194	1810

Appendix C. Estimating snow disappearance from temperature loggers

To quantify snow duration, we buried temperature sensors (Hobo pendant loggers) just beneath the soil surface in each plot and year to record temperature from late summer until early summer the following year. Loggers were set to record temperature every 2 or 3 h. When plots are covered in snow, temperature sensors measure temperatures close to 0 °C without diurnal variation (Raleigh et al. Ford et al.). Thus, these temperature records can be used to identify the date when snow first covers the ground as well as the date when snow disappears. Temperature data was missing in some plots due to sensor failure and / or lost sensors (approximately 20% of the data). However, we replaced these missing values with estimates from models fit to snowmelt disappearance dates from MeadoWatch and three other datasets collected in the same years in nearby locations (890 total observations). Models included a year and location specific coefficient. This was possible because spatial and annual differences in snow duration were highly consistent between plots and trails. Model predictions vs. observed values of snow disappearance dates were high with an $R^2 = 0.931$ (Fig. C1), similar to models fit for previous studies (Kroiss et al.).

References cited in Appendix C

KR Ford, AK Ettinger, JD Lundquist, MS Raleigh, J HilleRisLambers.,Spatial heterogeneity in ecologically important climate variables at coarse and fine spatial scales, Plos One. 8 (6) (2013) e65008.

S.J. Kroiss, J. HilleRisLambers, The importance of recruitment and microsite limitation for conifer regeneration in a warming world, Ecology. 96 (5) (2015) 1286–1297.

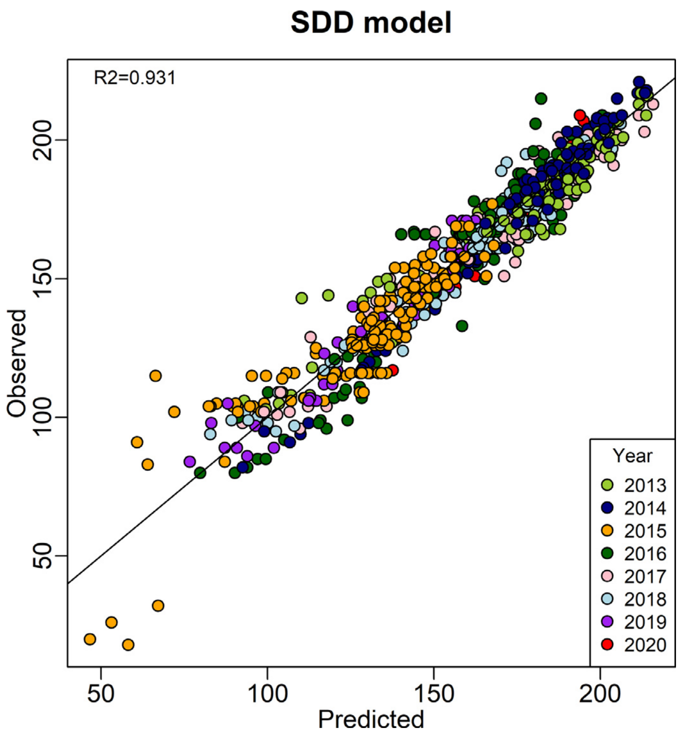


Fig. C1. Relationship between predicted snow disappearance date (in days after January 1) and observed snow disappearance date, from 890 observations of snow disappearance measured between 2013 and 2020.

M.S. Raleigh, C.C. Landry, M. Hayashi, W.L. Quinton, J.D. Lundquist, Approximating snow surface temperature from standard temperature and humidity data: New possibilities for snow model and remote sensing evaluation, Water Resources Research 49 (2013) 8053–8069.

Table D1
Sampling effort on both trails – specifically, the number of total hikes volunteers conducted each year on each trail (corresponding to the number of observations per species in each plot in which it occurred in that year); the average number of observations per week, and the time span over which observations occurred (DOY latest – DOY earliest hike).

Metric (in days)	Glacier Basin Trail	Reflection Lakes Trail
Years sampled	2015-present	2013-present
Sampling effort (total)		
2013	NA	93
2014	NA	114
2015	57	101
2016	73	82
2017	87	105
2018	70	90
2019	81	99
Observations per week (avg)		
2013	NA	8.27
2014	NA	8.58
2015	3.14	5.72
2016	4.14	5.46
2017	6.55	7.12
2018	4.84	7.31
2019	5.95	7.43
Sampling range (last-first)		
2013	NA	77
2014	NA	90
2015	124	121
2016	121	103
2017	91	101
2018	99	84
2019	93	91

Appendix D. Sampling Effort

Table D1 and Fig. D1, Fig. D2

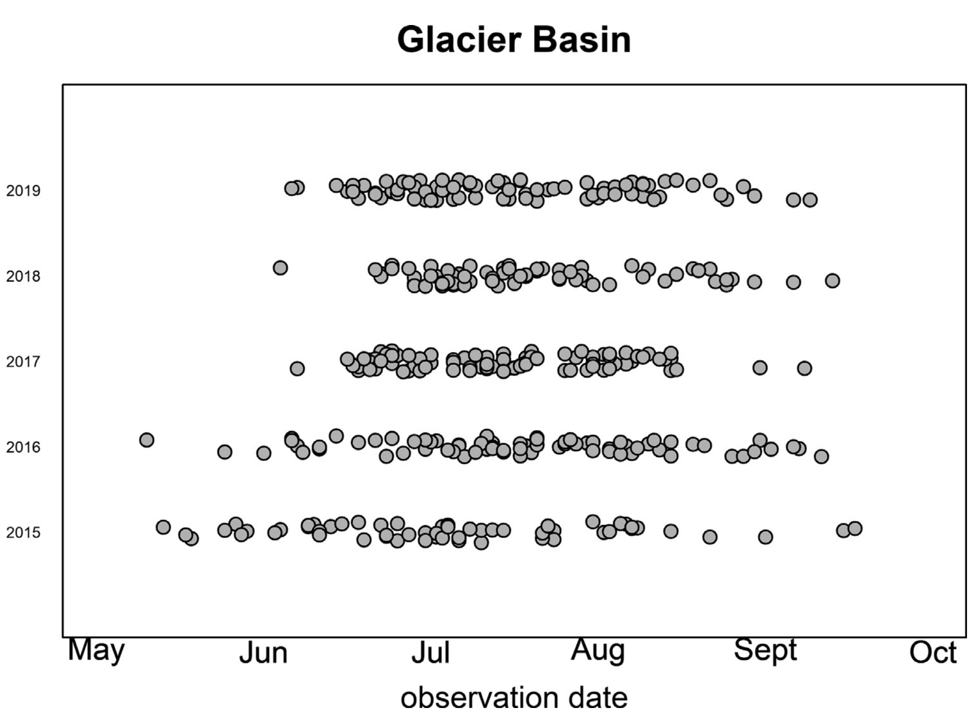


Fig. D1. Distribution of sampling effort each year of sampling in the Glacier Basin Trail. The start of each sampling season was determined by trail access after snow disappearance.

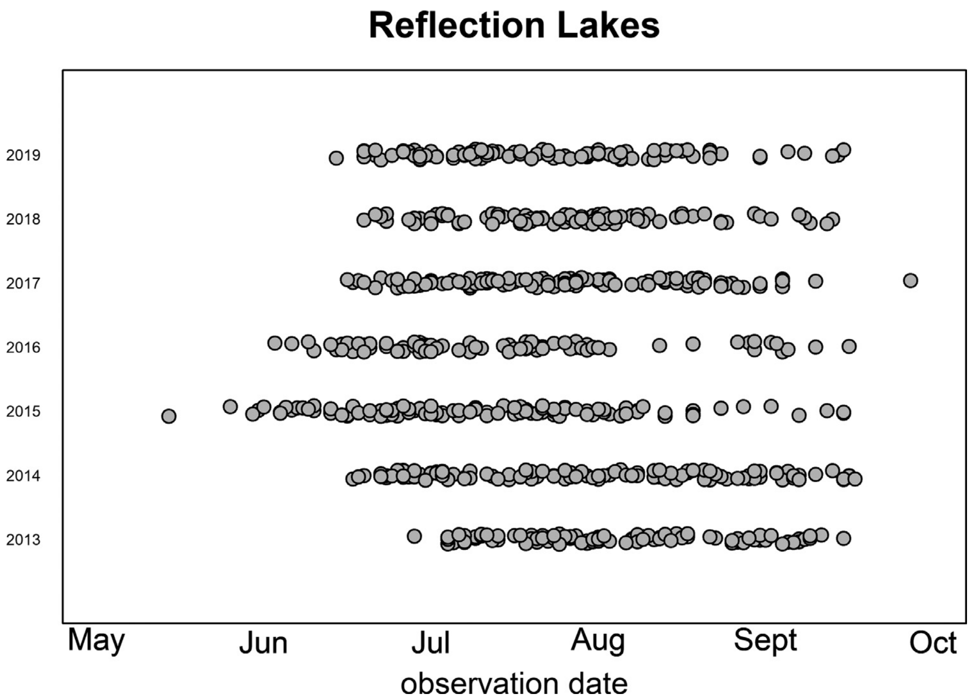


Fig. D2. Distribution of sampling effort each year of sampling on the Reflection Lakes trail. The start of each sampling season was determined by trail access after snow disappearance.

Appendix E. QA / QC of MeadoWatch data

One question frequently asked about data collected by community scientists, who generally do not have the same level of scientific training as professional scientists, is whether the quality of the data is sufficient for scientific insight. High quality data depends greatly on program structure. In the case of MeadoWatch, we ensured high data quality in several ways. First, we required all volunteers to attend a three-hour training session, in which volunteers were trained in sampling methods and species identification. Returning volunteers were strongly encouraged to attend training sessions each year, or view materials and orientation videos posted online. Second, we provided volunteers with a pamphlet including information on plot locations (including latitude / longitude, descriptions of sampling sites, and pictures of landmarks) and species / phenophase identification (including text and pictures). Third, our MeadoWatch volunteer coordinator and / or members of the HilleRisLambers lab (including the PI, graduate students, and trained interns) collected flowering phenology data from 2013 to 2018 (6 of the 7 years) approximately once weekly so we could compare phenological parameters derived from volunteer data to those derived from data collected by trained scientists. Finally, we identified likely false positives (likely due to misidentifications) by examining the pairwise distances (in days) between all observations of flowering in a year (yes – flowering). We assumed that any observation of flowering 3 or more weeks away from the nearest flowering observation of that species in that same plot and year reflects an identification mistake and excluded these observations from model fitting (Fig. E1). A comparison of species-specific estimates of peak flowering at each MeadoWatch plot location for which both volunteer and 'expert' data exists suggests that MeadoWatch volunteers provide data that is consistent with that collected by trained scientists (Fig. E2).

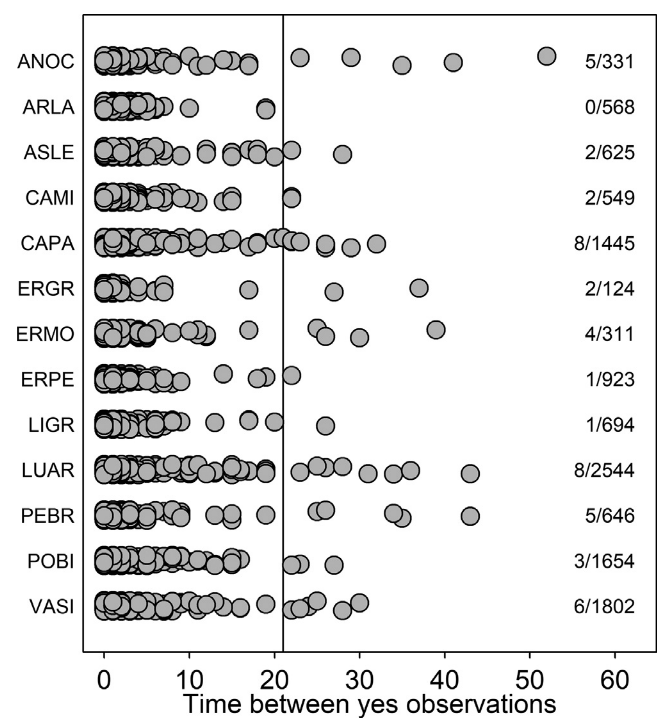


Fig. E1. The distribution of the pairwise distance (in days) between all yes observations of flowering for each of the fourteen focal species (one per row). Observations are jittered. The vertical line represents the threshold for inclusion - any flowering observation of yes that was more than 21 days (3 weeks) separated from the nearest yes observation was assumed to be an error. Numbers on the right-hand side of the graph indicate the number of such outlier observations (number on the left) discarded out of all 'yes' observations for each species (number after the / on the right).

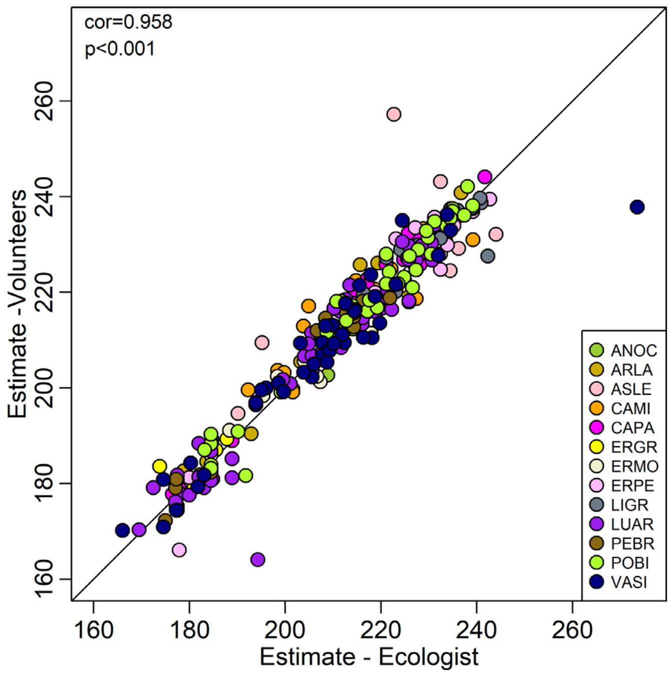


Fig. E2. The relationship between peak flowering (in days since January 1 of the year in question) as estimated per year, plot and species collected by 'trained' scientists (graduate students, postdocs, the PI, and trained interns) on the x-axis as compared to estimates of peak flowering from data collected by volunteers (y-axis).

Appendix F. Wildflower phenology models

We relied on our previous work (Theobald et al. 2017, Sethi et al. 2019) to develop models relating phenology to snow disappearance (Fig. G1), but simplified functions describing these relationships. For example, we know that climate variables besides snow disappearance (e.g. warmth, soil moisture) can influence the timing of peak flowering for wildflower species occurring within Mount Rainier National Park. Additionally, previous work indicates that climate not only influences the timing of peak flowering (ρ_{ijk}) but can also influence the duration of flowering and max flowering (δ_{ijk}, μ_{ijk},). Unfortunately, location-specific information on climatic parameters besides snow disappearance do not exist for MeadoWatch plots, and preliminary model fitting suggests allowing duration and max parameters to vary with snow disappearance rendered maximum likelihood models unstable during model fitting. However, we believe the simpler phenological models we fit (Eqs. (3) & 4 in the main text) are still reasonable for our purposes, for two reasons. First, our previous work demonstrates that snow disappearance has its largest and most consistent effects on wildflower species through its impacts on peak flowering (Theobald et al.), while effects on duration and maximum flowering parameters are smaller and less consistent. Second, snow disappearance has much larger and more consistent effects on flowering phenology than do other microclimate variables (Theobald et al.). Since our estimates of the timing and richness of the wildflower season largely rely on estimates of the date of peak flowering, we therefore feel comfortable with the simplified models we fit.

References cited in Appendix F

M.L. Sethi, E.J. Theobald, I. Breckheimer, J. HilleRisLambers, Early snowmelt and warmer, drier summers shrink postflowering transition times in subalpine wildflowers, Ecology. 101 (2020) e03171. https://doi.org/10.1002/ecy.3171.

E.J. Theobald, I. Breckheimer, J. HilleRisLambers, Climate drives phenological reassembly of a mountain wildflower meadow community, Ecology. 98 (2017) 2799–2812. https://doi.org/10.1002/ecy.1996.

Fig. F1

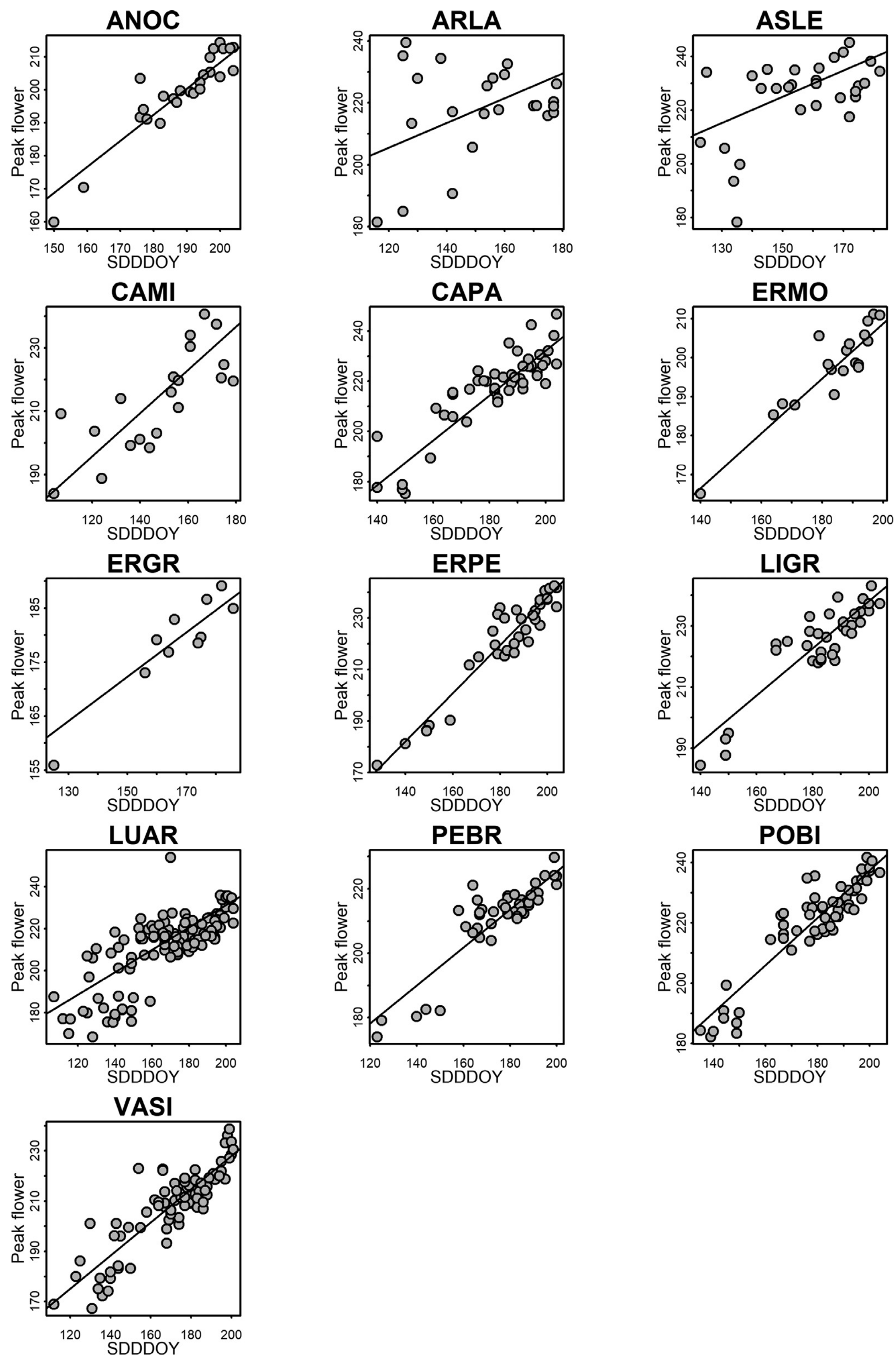


Fig. F1. The relationship between snow disappearance date (in days since January 1) and peak flowering as estimated from phenological curves fit to individual species-year-plot data. Lines show the fitted relationship from a maximum likelihood model fit to all species-level data (see Eqs. (3) & 4 in the main text). See Table A1 for Latin names corresponding to 4-letter codes.

Appendix G. WTA trip report protocol

We used trip reports posted online on the Washington Trails Association (http://www.wta.org) to explore hiker experiences and sentiments along two hikes: Glacier Basin (GB) and Skyline Loop (SL – which overlaps with our Reflection Lakes MeadoWatch trail). MeadoWatch volunteers have collected in-situ flowering presence and timing data along all or parts of these trails for seven years.

Categorical information

For each trip report, we collected information that would allow us to identify when the hiker in question hiked the trail and some categorical (non-text) aspects of the hikers' experience:

- reviewer.uw: trip report reviewer's name
- hike: either 'glacier basin' or 'skyline loop'.
- year: numeric, YYYY, year the hike was completed.
- month: character, month name, month the hike was completed.
- day: numeric, DD, day of the month the hike was completed.
- author: character, name of the author of the report (this was not used for analysis, but used together with year / month / day to identify unique reports).
- flowerbadge: 'yes' / 'no'. When posting a trip report, hikers can select a flower badge to indicate 'wildflowers blooming'. These data were not used for analysis.
- bugs.summary: When posting a trip report, hikers can select among 4 options to indicate their experience with bugs: 'No Bugs', 'Bugs were not too bad', 'Bugs were an annoyance', and 'Bugs were terrible'. This was coded as an NA if none of these four options were included. These data were not used for analysis.
- snow.summary: When posting a trip report, hikers can select among 5 options to indicate their experience with snow on the trail: 'Snow free', 'Intermittent snow – not hard to cross', 'Trail snow-covered at times – gear and expertise recommended', 'Snowfields to cross – could be difficult' and 'Avalanche danger'. This was coded as an NA if none of these five options were selected. These data were not used for analysis.

In addition to the information above, we also noted whether hikers visited additional trails on their hike (both hikes have the possibility of linking up to additional trails for much longer hikes), whether hikers posted pictures (and how many pictures), whether those pictures included flowers, and (for a subset of pictures) what species of wildflower was pictured. These variables were not included in analyses.

Sentiments

Report reviewers also read and examined the text associated with the trip report to code, on a numeric scale, the 'sentiment' associated with different experiences hikers might have encountered on the trail. Prior to collecting sentiment data, report reviewers discussed which individual experience categories to include in sentiment coding. Eventual categories (e.g. bugs, wildflowers, etc.) chosen was based on a combination of own personal experience on the trails, and what was most frequently mentioned in an initial scan of a subset of trip reports. Report reviewers also discussed how to score sentiments (after each reading a handful of trip reports) prior to sentiment scoring. Additionally, examples of phrases that would be coded in the different categories were discussed and included in the protocol (see below). Final sentiments scored included: bugs, wildlife, crowding, trail conditions, weather, view, and an overall hike experience (name satisfaction in the main text). If the trip reporter in question did not describe the experience in question, the sentiment was coded as an "NA" (i.e. experience not mentioned).

Sentiments were coded on a 5-point likert scale, including 1 (strongly negative), 2 (negative), 3 (neutral - neither positive or negative), 4 (positive) and 5 (strongly positive). Half point scales (e.g. 3.5) were allowed. Eight reviewers were involved in trip report assessments, with each trip report receiving at least 2 assessments from different reviewers. An additional third assessment was provided for a subset of trip reports (from a different reviewer than the first two reviewers).

Example phrases for sentiment scoring

bugs.sentiment

- Example: "The bugs were very annoying" (strongly negative) or "No bugs, it was awesome!" (strongly positive) or "No bugs." (neutral)

wildlife.sentiment

- Example: "We were disappointed by the lack of wildlife!" (strongly negative). "Wildlife was fantastically plentiful" (strongly positive). "There were squirrels near the trail" (neutral).

crowding.sentiment

- Example: "The trail was so crowded; I won't be returning here." (strongly negative). "The trail had no other people on it, it really improved the day!" (strongly positive), "Saw a few people" (neutral).

trail.condition.sentiment

- Example: "Trail was very hard to follow and in terrible condition" (strongly negative). "The trail was very well maintained, a pleasure!" (strongly positive). "The trail was easy to follow in some places but not others" (neutral).

view.sentiment: We include in 'view' all the visual non-flower elements of the trail. Therefore, descriptions of mountain view, glacier sighting, rivers, fall leaf colors, etc. were included in this category.

- Example: "The vista at the end of the trail was stunning and totally worth it!" (strongly positive) "Way too long of a hike for a pretty boring view!" (strongly negative). "OK views" (neutral).

weather.sentiment

- Example: "The rain really put a damper on our day" (strongly negative). "The blue sky and sunshine were wonderful!" (strongly positive). "It was partially cloudy" (neutral)

wildflower.sentiment

- Example: "There were very few wildflowers blooming this year, such a disappointment" (strongly negative). "Amazing flowers in full bloom" (strongly positive). "There were some flowers along the trail" (neutral)

Overall.report.sentiment: Note this was scored based on text that independently described the experience of hikers on trail, and was not related to text describing the individual experiences (e.g. bugs, wildflowers).

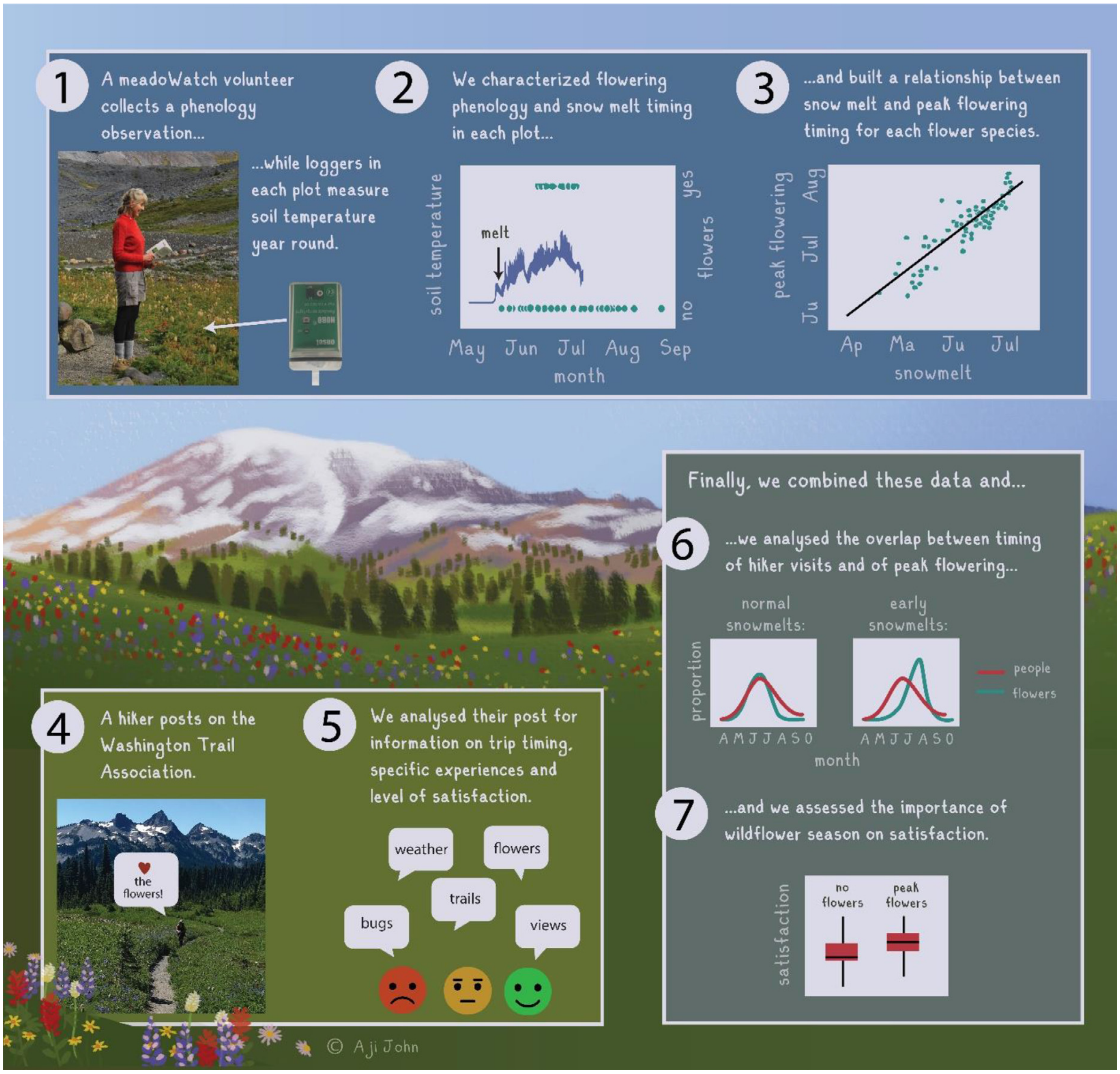
- Example: "What a perfect day we had!" (strongly positive). "Waste of time, would not recommend" (strongly negative). "Alright hike" (neutral).

Table G1: Interrater Reliability (IRR)

Cohen's Kappa (IRR) describing interrater reliability between coders for all sentiment scores, calculated using the 'icc' function in the *irr* package in R (R Core Team, 2018). Scores above 0.7 indicate high agreement; those < 0.7 were excluded from analysis (wildlife, crowding).

Sentiment	IRR
bugs	0.768
wildlife	0.611
crowding	0.661
trail	0.786
weather	0.814
view	0.734
wildflowers	0.727
overall	0.775

Appendix H. Methods flowchart illustrating how MW and WTA data are combined to address our objectives. Illustration by Elia Pirtle



References

[1] C. Parmesan, Ecological and evolutionary responses to recent climate change, Ann. Rev. Ecol. Evol. Syst. 37 (2006) 637–669, doi:10.1146/annurev.ecolsys.37.091305.110100.

[2] P.J. CaraDonna, A.M. Iler, D.W. Inouye, Shifts in flowering phenology reshape a subalpine plant community, Proc. Natl. Acad. Sci. USA 111 (2014) 4916–4921, doi:10.1073/pnas.1323073111.

[3] L. Halupka, K. Halupka, The effect of climate change on the duration of avian breeding seasons: a meta-analysis, Proc. Royal Soc. B-Biol. Sci. 284 (2017) 1–10, doi:10.1098/rspb.2017.1710.

[4] S. Han, H. Chung, N.J. Noh, S.J. Lee, W. Jo, T.K. Yoon, et al., Effect of open-field experimental warming on the leaf phenology of oriental oak (Quercus variabilis) seedlings, Journal of Plant Ecology 7 (2014) 559–566, doi:10.1093/jpe/rtt067.

[5] J.E. Lane, L.E.B. Kruuk, A. Charmantier, J.O. Murie, F.S. Dobson, Delayed phenology and reduced fitness associated with climate change in a wild hibernator, Nature 489 (2012) 554–557 554-+https://doi.org/, doi:10.1038/nature11335.

[6] C.A. Polgar, R.B. Primack, Leaf-out phenology of temperate woody plants: from trees to ecosystems, New Phytol. 191 (2011) 926–941, doi:10.1111/j.1469-8137.2011.03803.x.

[7] E.J. Theobald, I. Breckheimer, J. HilleRisLambers, Climate drives phenological reassembly of a mountain wildflower meadow community, Ecology 98 (2017) 2799–2812, doi:10.1002/ecy.1996.

[8] D.W. Inouye, Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers, Ecology 89 (2008) 353–362, doi:10.1890/06-2128.1.

[9] Z.J. Gezon, D.W. Inouye, R.E. Irwin, Phenological change in a spring ephemeral: implications for pollination and plant reproduction, Glob. Chang Biol. 22 (2016) 1779–1793 10.1111/gcb.13209, doi:10.1111/gcb.13209.

[10] J.D. Thomson, Flowering phenology, fruiting success and progressive deterioration of pollination in an early-flowering geophyte, Philos. Trans. Royal Soc. B-Biol. Sci. 365 (2010) 3187–3199, doi:10.1098/rstb.2010.0115.

[11] G. Kudo, E.J. Cooper, When spring ephemerals fail to meet pollinators: mechanism of phenological mismatch and its impact on plant reproduction, Proc. Royal Soc. B-Biol. Sci. 286 (2019), doi:10.1098/rspb.2019.0573.

[12] M. Soga, K.J. Gaston, The ecology of human-nature interactions, Proc. Royal Soc. B-Biol. Sci. 287 (2020), doi:10.1098/rspb.2019.1882.

[13] I.K. Breckheimer, E.J. Theobald, N.C. Cristea, A.K. Wilson, J.D. Lundquist, R.M. Rochefort, et al., Crowd-sourced data reveal social-ecological mismatches in phenology driven by climate, Front. Ecol. Environ. 18 (2020) 76–81, doi:10.1002/fee.2142.

[14] R.A. Graves, S.M. Pearson, M.G. Turner, Landscape dynamics of floral resources affect the supply of a biodiversity-dependent cultural ecosystem service, Landsc. Ecol. 32 (2017) 415–428, doi:10.1007/s10980-016-0452-0.

[15] J.F. Franklin, W.H. Moir, M.A. Hemstrom, S.E. Greene, B.G. Smith., The forest communities of Mount Rainier National Park, (1988).

[16] National Park Service. https://irma.nps.gov/STATS/Reports/Park, December 21, 2020.
[17] A.K. Wilson, K. Bacher, I. Breckheimer, J. Lundquist, R. Rochefort, E.J. Theobald, et al., Monitoring wildflower phenology using traditional science, citizen science, and crowd sourcing, Park Sci. 33 (1) (2017) 17–26.
[18] M.E. Wolak, D.J. Fairbairn, Y.R. Paulsen, Guidelines for estimating repeatability, Methods Ecol. Evol. 3 (2012) 129–137, doi:10.1111/j.2041-210X.2011.00125.x.
[19] R core teamR: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2020.
[20] K.A. Hallgren, Computing inter-rater reliability for observational data: an overview and tutorial, Tutor Quant. Methods Psychol. 8 (2012) 23–34, doi:10.20982/tqmp.09.2.p095.
[21] A. Oleinik, I. Popova, S. Kirdina, T. Shatalova, On the choice of measures of reliability and validity in the content-analysis of texts, Qual. Quant. 48 (2014) 2703–2718, doi:10.1007/s11135-013-9919-0.
[22] M.R. Stavseth, T. Clausen, J. Røislien, How handling missing data may impact conclusions: a comparison of six different imputation methods for categorical questionnaire data, SAGE Open Med. 7 (2019) 1–12 https://journals.sagepub.com/doi/10.1177/2050312118822912, doi:10.1177/2050312118822912.
[23] S.Y. Chyung, K. Roberts, I. Swanson, A. Hankinson, Evidence-based survey design: the use of a midpoint on the likert scale, Perform. Improv. 56 (10) (2017) 15–23, doi:10.1002/pfi.21727.
[24] L. Breiman, Random forests, Mach Learn 45 (2001) 5–32, doi:10.1023/A:1010933404324.
[25] D.R. Cutler, J. Edwards Thomas C., K.H. Beard, A. Cutler, K.T. Hess, Random forests for classification in ecology, Ecology 88 (2007) 2783–2792, doi:10.1890/07-0539.1.
[26] A. Liaw, M. Wiener, Classification and regression by randomForest, R News 2/3 (2002) 18–22.
[27] R. Brant, Assessing proportionality in the propotional odds model for ordinal logistic-regression, Biometrics 46 (1990) 1171–1178, doi:10.2307/2532457.
[28] A. Marshall, V. Butsic, J. Harte, The phenology of wilderness use: backcountry recreation in a changing climate, weather, Clim. Soc. 10 (2018) 209–223, doi:10.1175/WCAS-D-17-0087.1.
[29] A. Hausmann, T. Toivonen, C. Fink, V. Heikinheimo, R. Kulkarni, H. Tenkanen, et al., Understanding sentiment of national park visitors from social media data, People Nat. 2 (2020) 750–760, doi:10.1002/pan3.10130.
[30] S.F. Waterloo, S.E. Baumgartner, J. Peter, P.M. Valkenburg, Norms of online expressions of emotion: comparing Facebook, Twitter, Instagram, and WhatsApp, New Media Soc. 20 (2018) 1813–1831, doi:10.1177/1461444817707349.
[31] L.B. Buckley, M.S. Foushee, Footprints of climate change in US national park visitation, Int. J. Biometeorol. 56 (2012) 1173–1177, doi:10.1007/s00484-011-0508-4.
[32] K.L. Cole, K. Ironside, J. Eischeid, G. Garfin, P.B. Duffy, C. Toney, Past and ongoing shifts in Joshua tree distribution support future modeled range contraction, Ecol. Appl. 21 (2011) 137–149, doi:10.1890/09-1800.1.
[33] S. Nagai, T.M. Saitoh, S. Yoshitake, Cultural ecosystem services provided by flowering of cherry trees under climate change: a case study of the relationship between the periods of flowering and festivals, Int. J. Biometeorol. 63 (2019) 1051–1058, doi:10.1007/s00484-019-01719-9.
[34] W.B. Monahan, A. Rosemartin, K.L. Gerst, N.A. Fisichelli, T. Ault, M.D. Schwartz, et al., Climate change is advancing spring onset across the US national park system, Ecosphere 7 (2016) 1–17, doi:10.1002/ecs2.1465.
[35] J.S. Baron, L. Gunderson, C.D. Allen, E. Fleishman, D. McKenzie, L.A. Meyerson, et al., Options for national parks and reserves for adapting to climate change, Environ. Manage. 44 (2009) 1033–1042, doi:10.1007/s00267-009-9296-6.
[36] I. Curnock Matthew, N.A. Marshall, L. Thiault, S.F. Heron, J. Hoey, G. Williams, et al., Shifts in tourists' sentiments and climate risk perceptions following mass coral bleaching of the Great Barrier Reef, Nat. Clim. Chang. 9 (2019) 535, doi:10.1038/s41558-019-0504-y.
[37] S.M. De Urioste-Stone, M.D. Scaccia, D. Howe-Poteet, Exploring visitor perceptions of the influence of climate change on tourism at Acadia National Park, Maine, J. Outdoor Recreat. Tourism-Res. Plann. Manage. 11 (2015) 34–43, doi:10.1016/j.jort.2015.07.001.
[38] J. Bosson, M. Huss, E. Osipova, Disappearing world heritage glaciers as a keystone of nature conservation in a changing climate, Earths Future 7 (2019) 469–479, doi:10.1029/2018EF001139.
[39] A. Cunsolo, N.R. Ellis, Ecological grief as a mental health response to climate change-related loss, Nat. Clim. Chang. 8 (2018) 275–281, doi:10.1038/s41558-018-0092-2.
[40] T. Larsen, L. Tabor, P. Smith, End of the field? hacking online and hybrid environments for field-based learning in geography education, J. Geogr. 120 (2020) 3–11, doi:10.1080/00221341.2020.1858325.