Crowd-sourced data reveal social–ecological mismatches in phenology driven by climate

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Shifts in phenology that are driven by climate change have substantial impacts on ecosystems, but the effects of these ecological shifts on coupled social–ecological systems remain largely unexplored. Using a large database of crowd-sourced photographs from the image-hosting website Flickr, we show that early snow disappearance conditions similar to those expected by the late 21st century cause the seasonal peak of human visitation at Mount Rainier National Park (NP) to become mismatched from the seasonal peak of wildflower displays, a key visitor draw. Our work indicates that these mismatches between social and ecological systems were a product of both visitor behavior and management constraints, and could fundamentally alter visitor experiences in iconic natural areas like Mount Rainier NP. Recent dramatic growth in the volume of georeferenced citizen-based observations and the increased availability of high-resolution climate data will soon make it feasible to examine how climate affects social–ecological mismatches at very large spatial scales.

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When John Muir wrote of his preparations to summit the south side of Mount Rainier in August of 1888, he unwittingly recorded an important piece of ecological information: "Here we lay all the afternoon, considering the lilies and the lines of the mountain" (Muir 1918). The lilies, almost certainly avalanche lily (*Erythronium montanum*; Figure 1) and glacier lily (*Erythronium grandiflorum*), are among the earliest and most ephemeral wildflowers to emerge after snow disappears in the subalpine ecological zone of the Cascade Mountains (Theobald *et al*. 2016). Although Mount Rainier's meadows have been used by humans for millennia, Muir was one of the first visitors of European descent to record the state of plant phenology in an ecosystem he described as "the most luxuriant and the most extravagantly beautiful of all the alpine gardens I ever beheld in all my mountain-top wanderings" (Muir 1918).

Today, the subalpine ecosystem in Mount Rainier National Park (NP) attracts more than a million visitors annually (NPS 2019), and many come to see these spectacular wildflower displays (Figure 1). Like other seasonal events drawing high visitation in natural areas (eg fall migration of birds, fall colors in deciduous forests, spawning salmon), climate plays an important role in driving the timing of peak wildflower season at Mount Rainier NP, particularly the timing of snow disappearance, as snowpack typically persists into June or July in Rainier's subalpine zone. The links between climate and wildflower phenology are strong but less clear is how climate and the timing of the wildflower season influence visitor use of Mount Rainier NP for recreation, and, more generally, how coupled social–ecological systems like this respond to seasonal and annual variations in climate. This knowledge gap may seem surprising, given the rapid climate change affecting many US national parks (Monahan *et al*. 2016) and the increasing emphasis on understanding the interactions in coupled social–ecological systems (McGinnis and Ostrom 2014; Cumming *et al*. 2015). This contrasts with the large body of scholarly literature exploring how climate affects the timing and intensity of interactions between non-human components of ecosystems ("phenological mismatch"; Edwards and Richardson 2004; Renner and Zohner 2018).

Phenological mismatch refers to differences in the timing of life-history events between interacting species that affect their performance (Chmura *et al*. 2019). Changes to the environment, including climate change, can shift the seasonal timing and temporal overlap of these interactions (Kharouba *et al*. 2018). Similar shifts might affect interactions in social–ecological systems but evidence is lacking. Although some recent work has examined the spatial relationships between environmental conditions and human use of landscapes (Graves *et al*. 2019), few studies have examined the effects of climate on the temporal match or mismatch between people and cultural ecosystem services. Those that have done so relied on ethnographic or survey methods with limited spatial and temporal resolution (eg Tyler *et al*. 2007). These limitations might be overcome through the use of georeferenced social media, which tracks the locations and activities of people over time. These data have been used to map cultural landscape values (Tenerelli *et al*. 2016; van Zanten *et al*. 2016), visitation rates to natural areas (Wood *et al*. 2013; Sessions *et al*. 2016; Mancini *et al*. 2018), and the economic value of ecosystem services (Keeler *et al*. 2015), but we are unaware of any pre-existing work that relies on crowd-sourced data to simultaneously track the phenology of coupled social–ecological systems or estimate how the spatial and temporal matches between them are affected by changes in climate.

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Figure 1. John Muir's "the lilies and the lines of the mountain" (Muir 1918).

To address this issue, we applied high spatial- and temporal-resolution data derived from social media to ascertain whether changes in climate can cause mismatches in space and time between people and the services provided by ecosystems. We focused on the effects of changing patterns of snow disappearance on the match between mountain visitors like Muir and the wildflower displays that captivated him and popularized Mount Rainier NP as a tourist destination. First, we quantified how wildflower and visitor phenology is affected by the timing of snow disappearance at Mount Rainier NP. Second, we examined how snowpack conditions similar to those expected by the end of the 21st century affect the spatial and temporal match between people and wildflower displays. Finally, we investigated the possible drivers of mismatches between people and wildflower displays by comparing mismatches in parts of Mount Rainier NP with different environmental conditions and visitor-use constraints. Although we focused here on the relationship between wildflowers and visitors to a specific national park, we believe that our approach and findings are likely relevant to any seasonal biological event of recreational value.

Methods

Overview

To measure the relationships between snow, visitors, and wildflowers, we manually searched for wildflowers in 17,403 geotagged photographs taken from the subalpine and alpine vegetation zones (1400–2400 m) at Mount Rainier NP from 2009 to 2015 (Figure 1). Of these, approximately 11% contain recognizable flowers of ten common wildflower species (WebTable 1), which we selected beforehand because they were also tracked by a citizen-science program MeadoWatch (www.meadowatch.org), as well as by traditional plot-based field observations by scientists. We used the latter observations to extensively validate photo-based measurements of wildflower phenology (details can be found in Wilson *et al.* [2017]; WebFigure 1). We also compared two independent metrics of visitor phenology: Flickr unique users per day and National Park Service (NPS) visitor records (WebFigure 2). The study interval also contained extreme annual climate variation, including years among the earliest (2015; Figure 2a) and latest (2011; Figure 2b) seasonal snow disappearances in the century-long climate record at Mount Rainier NP (Figure 2c).

Retrieving photos

We used the Flickr Application Programming Interface (www.flickr.com/services/api) to retrieve metadata on all publicly accessible and accurately geotagged photos (accuracy codes 15 and 16, generally accurate to within 100 m) taken in the subalpine elevation zone (1200–2400 m elevation) at Mount Rainier NP between 1 Jan 2009 and 31 Dec 2015. Records were downloaded on 26 Oct 2015, and additional records covering the 2015 season were downloaded on 24 Jan 2016. The resulting database of photos (17,403 records) was used to track human visitation and wildflower blooms.

Measuring park visitation

We verified that the number of unique Flickr users per day is strongly correlated with park visitation for the time that our photo database covers. We used the number of unique users instead of the number of photos because the former was in closer agreement with NPS visitor records (WebFigure 2) and has previously been demonstrated as a reliable indicator of visitor use across a large network of US national parks (Sessions *et al.* 2016). For the analysis of visitation in different areas of the park, we grouped the photos by which center of park access (Paradise, Sunrise, Chinook Pass, Mowich Lake) was closest by geographic distance (groups shown as contrasting colors in Figure 2a).

Classifying photos

In each photo downloaded from Flickr, we manually identified flowers of ten focal wildflower species with conspicuous and distinctive flowers (WebTable 1). If a photo contained flowers that were definitively identified as belonging to any of the ten focal species, then it was coded as "focal flowers present";

conversely, if a photo contained none of the focal species, or if a focal species could not be definitively identified in the photo, then it was coded as "focal flowers absent".

Estimating microclimate for photo locations

We estimated the most important aspect of local microclimate relevant to phenology at Mount Rainier NP – day of snow disappearance (Ford *et al.* 2013) – for each photo location using a linear mixed-effects model fit to data from an existing network of snow duration sensors (Maxim iButton and Onset HOBO Pendant temperature loggers; Ford *et al.* 2013) maintained at 190 soil-surface sites across the elevation gradient of Mount Rainier NP from 2009 to 2015 (Figure 2b). The best model for predicting snow disappearance date, as judged by the difference in the Akaike Information Criterion, corrected for small samples (ΔAICc = 8.29; WebTable 2), incorporated fixed effects of elevation, year, longitude, slope, and relative elevation (the difference between site elevation and the average elevation within 30 m of the site), as well as a random effect of site (WebTable 2). The model's fixed effects explained 91% of the variation in snow disappearance date, and had an average absolute prediction error of 12.9 days. The residuals from the model were approximately spatially independent (WebFigure 3, b and c), and the model's predictions strongly aligned with our observations of qualitative patterns of snow disappearance. Model fitting was performed using the R v3.1 (R Core Team 2016) package *lme4* (Bates *et al.* 2015).

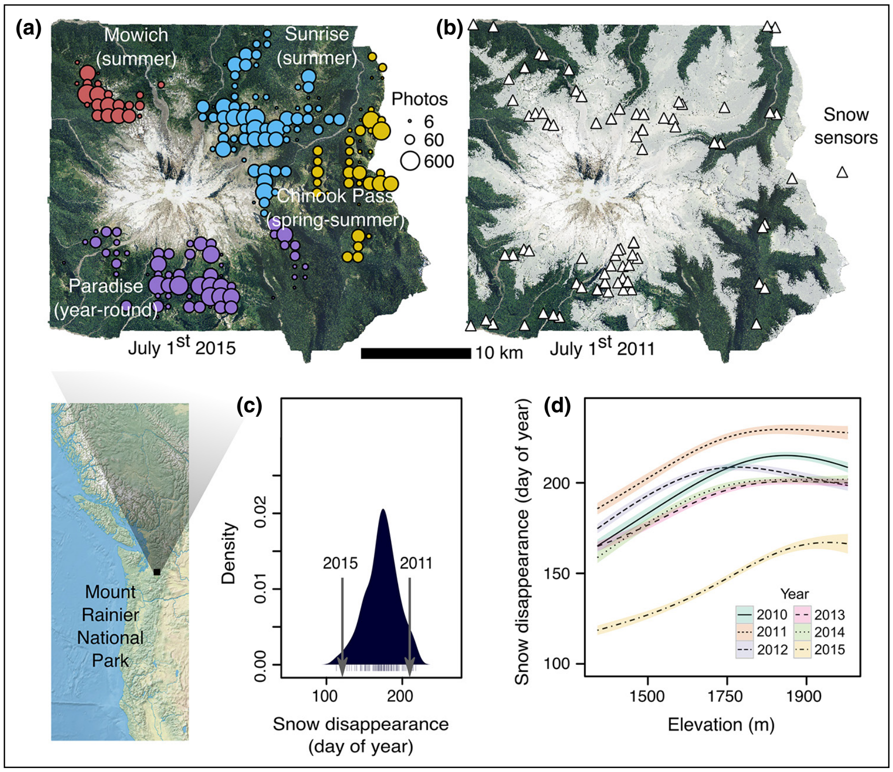

Figure 2. (a) Distribution of geolocated Flickr photos used in the analysis. The colors correspond to different centers of activity in Mount Rainier National Park (NP). The photo locations are overlaid on a map of predicted snow cover on 1 Jul 2015, one of the earliest snow disappearance dates on record. (b) Distribution of snow duration sensors used to estimate the date of snow disappearance for each photo location. There are 3–16 sensors installed at each site to account for small-scale heterogeneity in snow accumulation and melt. The sensor locations are overlaid on a map showing predicted snow cover on 1 Jul 2011. (c) Distribution of modeled snow disappearance dates in the vicinity of Paradise from 1918 to 2015. (d). Statistically estimated mean dates of snow disappearance across the lower slopes of Mount Rainier for different years of the study when other covariates are held at their median values (WebTable 2; WebFigure 3). Shading represents 95% confidence bands in the mean fit.

Modeling flower phenology

We modeled flowering phenology as a function of snow disappearance using a Bayesian generalized non-linear mixed-effects model, assuming the presence or absence of any focal species in a photo is distributed as a Bernoulli random variable with probability P. We chose a unimodal, quadratic functional form to model the relationship between the probability of encountering a flower in a photo and the day of year (DOY):

$$\text{logit}(P) = w * (o - \text{DOY})^2 + h \qquad \text{(Equation 1).}$$

We allowed the optimum (o) and height (h) of each curve to be linear functions of estimated snow disappearance day (SDD), with slopes and intercepts according to the following:

$$o = o_{\text{intercept}} + o_{\text{slope}} * \text{SDD} \qquad \text{(Equation 2),}$$

and

$$h = h_{\text{intercept}} + h_{\text{slope}} * \text{SDD} \qquad \text{(Equation 3).}$$

The width of each curve (w) was modeled as a negative exponential function of SDD:

$$w = -1 * \exp\left(w_{\text{intercept}} + w_{\text{slope}} * \text{SDD}\right) \qquad \text{(Equation 4).}$$

We allowed the height of the fit curve (h) to have a fixed intercept, as well as a zero-centered random intercept that varied by user, which allows each Flickr user to have a different intrinsic probability of capturing a flower in a photo. In all models, true SDD was represented as a latent (unobserved) random variable with a variance equal to the prediction variance of the snow model to account for uncertainty in snow disappearance date. Parameters were fit via Markov chain Monte Carlo (MCMC) in JAGS v4.2 (http://mcmc-jags.sourceforge.net) using diffuse priors (truncated normal distributions for slopes and intercepts, gamma distributions for random effect variances). Model convergence was confirmed visually, as well as by using the Gelman-Rubin statistic (upper 95% credible interval [CI] for all parameters < 1.1). Parameters of the fit model are described in WebTable 4.

Modeling visitor phenology

We took a similar non-linear approach to modeling daily visitation to Mount Rainier NP, except that we modeled the number of unique Flickr users per day with a negative binomial distribution and a log link. We allowed the height of each curve to have a random intercept for each year, day of week, and park access point, with all other parameters in common in the aggregate analysis (Figures 2 and 3; WebFigure 6; WebTables 3 and 4). For the analysis that compared different access points (Figure 4; WebTables 3 and 4), we allowed the width and optimum to have fixed intercepts and slopes that varied by access point. Modeling details (ie methods, priors, convergence) were the same as for flowering phenology models, and parameters are also described in WebTable 4.

Measuring phenological mismatch

We measured phenological matching between visitors and wildflowers by numerically computing the area of overlap in the two phenology functions normalized by the area under each curve. Computing overlaps of normalized phenological curves provides an estimate of phenological mismatch that varies between zero (complete mismatch) and one (perfect matching) with uncertainty bounds generated by overlap estimates from each of 1000 posterior MCMC samples of the fit parameters for each model. The computation for this analysis was done in R using the base function 'integrate()'. Data and code for this analysis are available on GitHub (https://github.com/ibreckhe/social_ecological_phenology).

Results

Social and ecological sensitivities to climate

We found that the phenology of both park visitors and wildflowers was sensitive to the date of snow disappearance (Figure 3a). In this linear relationship, for every 10 days earlier snow disappearance, seasonal peaks of human visitation came approximately 5.5 days earlier (Figure 3a; 95% CI = 3.86–7.08 days), while peaks of wildflower blooms came approximately 7.1 days earlier (95% CI = 6.56–7.83 days). Early snow disappearance conditions were accompanied by a lengthened season of human visitation, with earlier snow disappearance of 10 days associated with a lengthening of the peak period (including 50% of the total season's visitors) of 4.1 days (95% CI = 2.63–6.12 days). By contrast, earlier snow disappearance was associated with a shortening of the period when wildflowers were common (encompassing 50% of the probability density of observing wildflowers) by 0.36 days (95% CI = 0.28–0.52 days) for every 10 days earlier snow disappearance. Additional details can be found in WebTables 3 and 4, as well as in WebFigures 5 and 6.

Effects of climate on phenological matching

The lengthening visitor season, the shortening wildflower season, and the differing sensitivity of peak visitation and peak flowering to snow disappearance date caused the match between people and wildflower blooms in this system to decrease by 35% in early snow disappearance conditions typical in 2015 versus late snow disappearance conditions typical in 2011 (95% CI = 17.4–48.9%; Figure 3, b and c). In all, we observed decreased overall visitor exposure to subalpine ecosystems in peak flower in 2015 compared to years with more typical climatic conditions. This mismatch was accompanied by a significant decrease in the proportion of early-flowering species such as avalanche lily and western anemone

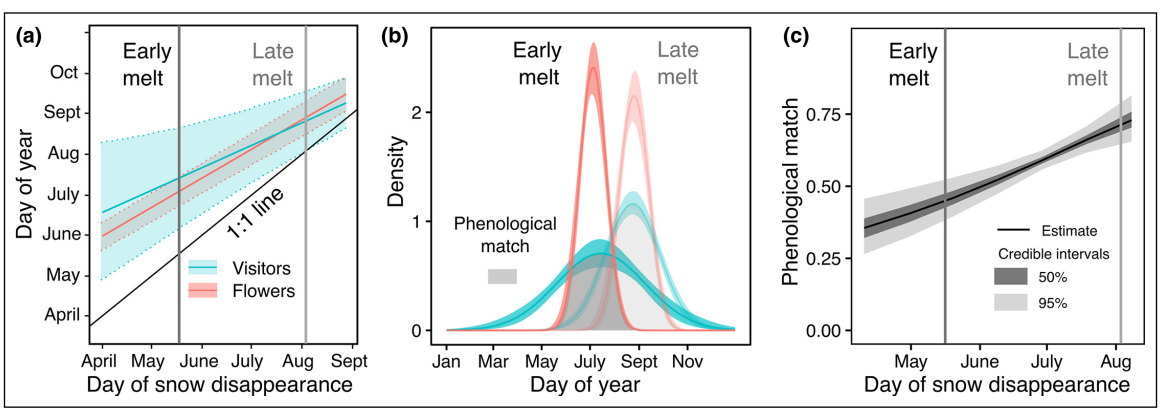

Figure 3. (a) Changes in visitor phenology (blue) and flower phenology (red) driven by changes in snow disappearance date. The shaded regions represent the periods that include 50% of seasonal visitors, or 50% of the probability density of observing wildflowers in photos. Solid lines indicate the phenological peaks. (b) Mean predictions (solid lines) and 95% credible intervals (CIs) (shading) from the fit models when snow disappears on 28 Jul ("late melt", typical of conditions in 2011) and on 19 May ("early melt", typical of conditions in 2015). Gray shading represents the phenological overlap discussed in the text. (c) Changes in phenological matching between people and wildflowers driven by changes in snow disappearance date. Vertical lines indicate snow conditions depicted in panels (a) and (b). Dark and light shading indicate 50% and 95% CIs, respectively.

(*Anemone occidentalis*) observed in photos (χ^2: 19.655, $P <$ 0.0001). These results are robust to uncertainties introduced by using estimated rather than measured snow disappearance dates, and variation in focal species selection (WebFigure 6).

Effects of visitor management and ecological context

We also found that seasonal constraints on vehicle access and geographic variation in wildflower sensitivity to climate had strong influences on the ability of visitors to track wildflower blooms (Figure 4). Human activity in the subalpine zone of Mount Rainier NP is centered around four points of vehicle access, two of which are open to visitors year-round, and two of which are open only during the summer (Figure 2a). Access to Paradise, on the southwest slopes of Mount Rainier, remains open throughout the winter. Chinook Pass, on the east side of Mount Rainier NP, closes seasonally, but opens early in the spring season (average open date: 6 May), and visitors can access the area year-round through the adjacent Crystal Mountain Ski Area. Two other subalpine sites, Sunrise and Mowich Lake, are open only during summer (approximately July–September). These access restrictions result in greater potential for phenological mismatch between park visitors and wildflower blooms under early snow disappearance conditions in these areas (49.1%, 95% CI = 35.3–61.2%; Figure 4, a and b) as compared to areas where visitor use is less seasonally restricted (21%, 95% CI = 3.3–36.9%; Figure 4, c and d). Potential mismatch was also more severe at west-slope locations, where wildflower blooms are more sensitive to the date of snow disappearance (Figure 4, a and c).

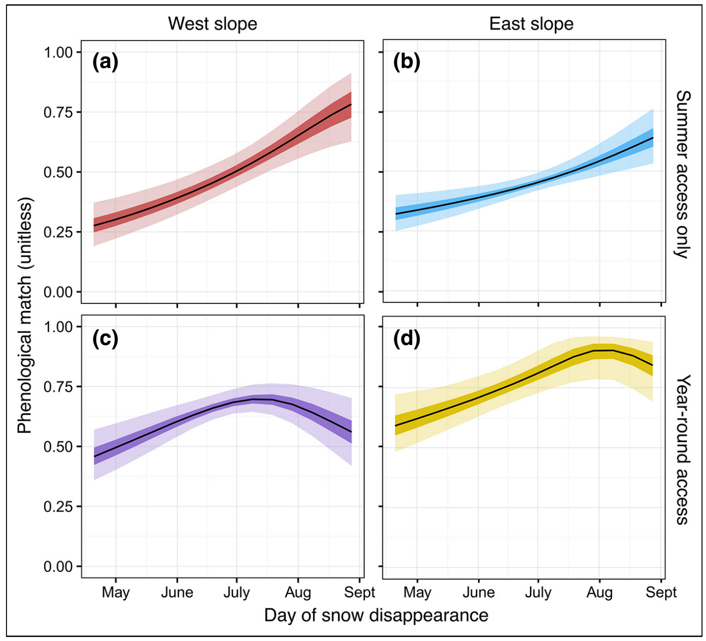

Figure 4. Geography and seasonal restrictions on visitor access affect the potential for mismatch between wildflower and visitor phenology at Mount Rainier NP. The potential for mismatch is greater in areas (a) and (b), where visitor access closes seasonally, than in areas (c) and (d), where visitors have vehicle access year-round. Colors correspond to the geographic areas depicted in Figure 1. Dark and light shading indicate 50% and 95% CIs, respectively.

Discussion

Ecological theory and substantial empirical evidence suggest that climate-driven phenological mismatch should be more common when different groups of interacting organisms have access to different sets of phenological cues (Rafferty *et al.* 2015; Usui *et al.* 2017) and are subject to different non-climatic constraints (Kappeler *et al.* 2013). Both factors appear relevant to the mismatch between visitors and wildflowers that we observed at Mount Rainier NP in 2015. For example, out-of-town visitors were unlikely to have information on seasonal snowpack when planning their trips, presumably relying on published typical dates of wildflower blooms. This means that such visitors would have arrived 5–6 weeks too late to appreciate peak wildflower displays in 2015 (Figure 3a). In addition, the timing of opening park roads and facilities to visitors in spring, also determined by typical snow disappearance dates, imposed direct behavioral constraints on park visitors that acted to even further reduce their exposure to seasonal wildflower displays in 2015, especially at Mowich Lake (Figure 4a), where vehicle access was closed until near the peak of the wildflower season that year. Over the long term, these temporal mismatches between people and wildflower displays could become more common and more severe as the climate warms. These impacts would play out in the context of other rapid changes to subalpine ecosystems, including treeline advance (Cansler *et al.* 2018) and the rapid reassembly of plant communities (Bueno de Mesquita *et al.* 2018).

Collectively, these changes could reduce the status of wildflower meadows as iconic features of Mount Rainier NP, affecting public knowledge of these systems and potential support for conservation measures to preserve them (Fazey *et al.* 2007; Cetas and Yasué 2017). Although the contribution of wildflower displays, like many other seasonal ecosystem services of recreational value (eg bird migrations, deciduous forest fall colors), is difficult to quantify, people's stated preferences indicate that these values are substantial (Breeze *et al.* 2015).

Fortunately, this study also suggests that such potential negative outcomes can be averted. For instance, shifting road openings of summer-access wildflower meadows to track snow disappearance and/or updating visitor materials to reflect current snowpack conditions and peak wildflower bloom timings could reduce the potential for social–ecological mismatch. The feasibility of these strategies depends on their costs, as well as on how closely aligned they are to existing management mandates (Colwell *et al.* 2012) in the context of increasing visitation to Mount Rainier NP (visitation increased by 30% from 2008 to 2018; NPS 2019), which puts additional pressure on infrastructure and natural resources. Our results also suggest that social learning and altered visitor management in the social system (Fazey *et al.* 2007; Tschakert and Dietrich 2010), much like phenotypic plasticity and evolutionary changes in ecological systems (Johansson *et al.* 2015), could minimize changes in social–ecological matches (eg visitors encountering flowers) in a warming climate. Like many studies that use spatial and annual climate variation as proxies for anthropogenic climate change (Elmendorf *et al.* 2015; Fisichelli *et al.* 2015), our approach cannot account for such long-term adjustments in the climate responses of either visitors or wildflowers. Moreover, the crowd-sourced photos that we used did not allow us to directly measure visitors' knowledge or appreciation of subalpine meadow ecosystems, or to ascertain whether these factors affect how sensitive visitors are to snow or bloom timings (an area ripe for further investigation).

Conclusions

Wildflower displays are a major draw for visitors at Mount Rainier NP (Manni *et al.* 2013), and to mountain environments worldwide. To the best of our knowledge, our study is the first to empirically demonstrate a climate-driven phenological mismatch in a coupled social–ecological system such as this one. With climate change, we believe that such socioecological mismatches could be widespread in natural areas where seasonal biological events are a visitor draw, influencing visitors' experiences and potentially their long-term investment in these natural areas or their understanding of ecosystem services. With the widespread adoption of social media, passively collected digital records are a promising resource for detecting social–ecological mismatches in phenology and other important feedbacks between ecosystem management and social–ecological systems (Miller *et al.* 2014; Sessions *et al.* 2016). Such analyses have the potential to both inform management strategies that can mitigate the negative consequences of mismatches, as well as suggest new areas of research relevant to the coupling between social and ecological systems.

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Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.2142/suppinfo

