Using community photography to investigate phenology: A case study of coat moult in the mountain goat (Oreamnos americanus) with missing data

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Abstract

Participatory approaches such as community photography can engage the public in questions of societal and scientific interest. We combined data extracted from community-sourced, spatially-explicit photographs with research findings from 2018 fieldwork in the Yukon, Canada, to evaluate winter coat moult patterns and phenology in mountain goats (Oreamnos americanus), a cold-adapted, alpine mammal. Leveraging the community science portals iNaturalist and CitSci, in less than a year we amassed a database of several hundred unique photographs spanning some 4500 kms between latitudes 37.6°N and 61.1°N from 0m to 4333m elevation. Using statistical methods accounting for incomplete data, a common issue in community science datasets, we evaluated effects of intrinsic (sex and presence of offspring) and environmental (latitude and elevation) factors on moult onset and rate and compared our findings with published data. Shedding occurred over a 3-month period, May 29-September 6. Effects of sex and offspring on the timing of moult were consistent between the community-sourced and our Yukon data and with findings on wild mountain goats at a long-term research site in west-central Alberta, Canada. Males moulted first followed by females without offspring (6.4 days later in the coarse-grained, geographically-wide community science sample; 23.7 days later in our fine-grained Yukon sample) and lastly females with new kids (5.5; 17.9, respectively). Shedding was later at higher than at lower elevations. Northern latitudes had slightly later but shorter shedding periods. We detected a possible shift in moult timing in recent years (2015-2018) that warrants additional investigation. Despite data limitations, such as bias towards recent photographs, our findings establish a basis for employing community photography to examine broad-scale questions about the timing of ecological events, as well as sex differences in response to possible climate drivers. As such, community photography can inspire public participation in environmental and outdoor activities with reference to iconic wildlife.

Introduction

Phenology, the seasonal timing of life history events, is increasingly relevant in the framework of global change studies (Cohen et al., 2018; Staudinger et al., 2019; Horton et al., 2020). In general, species are predicted to exhibit phenological shifts across wide geographical scales in response to climate change. Phenological responses are predicted to be particularly important for high elevation communities (Hodkinson, 2005; Stewart et al., 2019), wildlife at northern latitudes (Berger et al., 2018) and cold-adapted species (Sarmento et

1

al., 2019) prone to seasonal mismatches, for example in coat colour (e.g., white snowshoe hares on a brown background; Mills et al., 2013, Zimova et al., 2014, Pedersen et al., 2017; Zimova et al., 2018) or arrival at calving grounds (e.g., caribou arriving after spring vegetation flush; Post & Forchhammer, 2008).

Many mammals of temperate zones experience high seasonal variance in exposure to ambient temperature; pelage that offers heat retention in winter is shed in summer, but for most species little is known about rates of shedding or the extent it varies by sex or across broad latitudinal or altitudinal gradients. Among these species are mountain goats (*Oreamnos americanus*), inhabitants of mountainous terrain in northwestern North America (White et al., 2018). Mountain goats use high, windy slopes above the treeline during summer (Chadwick, 2002) and make use of snow patches for cooling (Sarmento et al., 2019). If they did not shed their thick, two layered winter coats, which can grow over ten centimeters long (Foresman, 2012), these would likely pose a liability in summer. Across the late Holocene, their ranges diminished in accordance with warming temperatures from northern Mexico to Idaho (Festa-Bianchet & Cote, 2008).

Much remains to be learned about the triggers of shedding and differences between the sexes in mammals, despite the noted high visibility of massive chunks of hair hanging from species like bison (*Bison bison*) and muskoxen (*Ovibos moschatus*) (Wilkinson, 1974; Berger and Cunningham, 1994). Most mammals moult to replace worn out hairs and provide different summer and winter coats (Ryder, 1965), including moose (*Alces alces*), bison, elk (*Cervus canadensis*), and thinhorn sheep (*Ovis dalli*). While moult is a relatively understudied life history event (Beltran et al., 2018), it is well-established that photoperiod and, to a lesser extent temperature, control moult onset (Murray, 1965; Lincoln and Ebling, 1985; Mo et al., 2006; Zimova et al., 2018). Moult is known to occur latest in lactating mountain goat females (Déry et al., 2019) likely because, as documented in red deer (*Cervus elaphus*), the costs of milk production affect female body condition even though food may be most abundant in summer (Clutton-Brock et al., 1982).

Mountain goats offer an unusual opportunity to examine ecological predictions about moult because they occur along latitudinal gradients that vary in ambient condition including elevation. Because of their stature as an iconic mammal of the mountains, there is likely to be high interest from community scientists. Further, they occur in captive settings including at the far northern extent of their range providing opportunity for individual-level and repeated observation and comparison with southern, better-photographed populations.

Community generated datasets offer a promising way to test hypotheses about moult across broad geographical ranges in part because some historical data are available and because volunteer monitoring is growing in popularity (Taylor et al., 2019). This community-based approach is intended to complement rather than replace long-term research. For instance, community science data have been combined with satellite data to examine how bird migration (arrival time at breeding grounds) responds to advancing vegetation green-up dates (Mayor et al., 2017). Community science data have also been explored across multiple projects to assess climate change effects on American pika (*Ochotona princeps*) with reasonably reliable results (Moyer-Horner et al., 2012). In addition to mammals and birds, community-contributed photographs have been used to document glacial retreat, and show promise to shift climate change conversations and enhance public education and engagement (Mullen et al., 2013).

Here, we assess the utility of community photography, un underutilized resource, to detect phenological patterns of moult in mountain goats within and between a geographical gradient and between the sexes. We employed a comparative study design involving detailed fieldwork of our own that concentrated on captive and adjacent wild populations, with decades of community scientist photos of moulting goats along gradients of latitude and elevation (Figures 1-2). If the community science data are commensurate with those from our own focal research, then it seems plausible to explore long-term phenological patterns of moult across the entire geographical range of a species using photographs. Collation of a more complete photographic data base, and then using it to quantify long-term and spatially extant patterns of shedding, provides a barometer for detecting patterns and developing inferences regarding impacts of climate change (Hetem et al., 2014; Vieira et al., 2017). We might also expect greater community engagement with climate science outcomes when communities are actively in involved in data collection.

However, there are issues to consider when relying on community sourcing of data that may be influenced by variation in identification skills, sampling effort and efficiency (Dickinson et al., 2010). Large data sets and applying appropriate statistical models may help account for potential bias (e.g., including observer error in assigning sex to an animal and variation in sampling effort). Data are also often missing from community science datasets (e.g., sampling some locations but not others). The best way to deal with missing data often associated with community science projects has received relatively little attention, and the most common approach is to simply filter out such data (Dickinson et al., 2010), despite it being well known that non-random filtering of data can lead to bias and poor inference (Nakagawa, 2015). However, we might expect that patterns in observed data provide information about likely values of missing data (i.e., information is shared across observations) (see Nakagawa, 2015).

Missing data is an issue for our study because animal sex is not always clearly distinguishable in community sourced photographs nor is whether or not a female is associated with a kid. Here, we develop a statistical model of coat shedding that infers the most likely state of an animal when unknown, and so, even the photographs with incomplete information are still included in the model fit. This general approach could be applied to other community science data sets, reducing the need to remove seemingly uninformative data. Using this approach, we show how community science data can help identify important environmental predictors of shedding rates (e.g., elevation and latitude), the role of the state of the animal (e.g., sex, whether caring for young), and quantify the extent of geographical variation.

Methods

We used data extracted from photographs of adult mountain goats, estimated to be at least two years old. We focused our analysis on photographs taken between the months May and September. The data were obtained from community science and our focal research in the Yukon, Canada.

Community Science

Photographs were sourced from members of the public including staff, researchers, and visitors to parks and protected areas, professional photographers, hunters and guide-outfitters, and other outdoor enthusiasts. Criteria for photos included: known date and location, animal clearly visible and ideally from the side, high enough image resolution (desired value of 300 dpi) to use pixel counts to estimate shed extents.

We used the online platforms CitSci and iNaturalist, posters hung in public places, social media, and word of mouth to crowd-source images. We also used forums such as those of the Yukon Fish and Game Association, British Columbia Wildlife Federation, as well as radio (Mountain FM and Canadian Broadcasting Corporation), and local newspapers (e.g., *Hungry Horse News*) to encourage photograph submissions. Since all photographs submitted via CitSci become party to a Creative Commons license, we also gave the option to email us photos, and this was often preferred by professional photographers. If sourcing from iNaturalist, we contacted the photographer and asked for permission before including their photo in our analysis. We also received (by mail) slides and photographs developed from film from both photographers and visitors to protected areas, as well as (digital) photographs from remote cameras, particularly from agency staff and researchers working in parks. Photos submitted from hunters were limited since the hunting season spans the period when mountain goats are in full winter coats (between October and April). Some professional photographers also expressed preference for photographing goats in winter months when the animals are "more photogenic".

Fieldwork in southern Yukon

We deployed remote cameras between mid-May and early September 2018 to develop sex and latitudinal chronologies of goat moult for contrasts with more southern goat populations. Our study areas included three locations at which mountain goats are wild (Mount White (60.2, -133.9), Montana Mountain (60.0, -134.6), and Kluane National Park (60.7, -137.7)), and a fenced facility, the Yukon Wildlife Preserve (YWP) (60.8, -135.3), where 20 goats (in two herds, one breeding, one non-breeding) roam large enclosures and are viewed by the public. We deployed 16 cameras along active mountain goat trails in these four locations. Our

data from the wild (opportunistic camera trap photographs) were added to the community science dataset, whereas our repeated samples data on 14 adult mountain goats in YWP were analyzed separately.

Sample of photographs

We amassed 693 photographs of which nearly 80% were community-sourced and spanned years 1948 to 2018 from the entire distributional range of mountain goats (Figure 1) with the exception of Nevada and the Northwest Territories (NWT). Broken down by sources of data, professional photographers were our main source of photographs (N=203) followed by the CitSci platform (185), iNaturalist (126), researchers (Caw Ridge, Alberta, and Glacier National Park (GNP), Montana: 58), members of the public by e-mail to the lead author (15), members of professional societies including B.C. Mountain Goat Society, Wilderness Society, Summit Post (13), and other sources (4). Our 2018 southern Yukon sample included 58 photographs from YWP and 31 from the three wild sites. Mountain goats at GNP (where mountain goats are habituated in some locations) were most photographed by the public and by one professional photographer in particular (Sumio Harada), followed by Mt. Evans, Colorado (where mountain goats are introduced and also habituated to people) while Caw Ridge and Yukon were third and fourth with data provided by researchers (including the authors and inclusive of camera trap photos). Most but not all of these photographs (635 of the 693) were included in the analysis (see Statistical Analysis and Results). Finally, and even if photographs were submitted with elevation data, we used provided geo-referenced locations of all photographs to source elevation in meters for each photo from the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010).

Photo analysis

To estimate the extent of winter coat shed, we compared pixel counts of shed versus unshed areas of mountain goats' coats in each photograph using Adobe Photoshop. First, we outlined the entire animal, typically using a combination of the quick selection and lasso tools (omitting hooves, eyes, nose, mouth, and horns), copied the animal, separated from its background, into a new layer (total layer). Second, we duplicated this layer, and outlined the shed and unshed areas and cut these as new layers (shed and unshed layers). We selected all pixels in the layers and used the histogram tool to obtain counts of both shed and unshed areas. Lastly, to create quick visuals, we filled the unshed area with red and the shed area with black; a video tutorial of one of our approaches can be found here: https://www.youtube.com/watch?v=h9cWl9Z1Odw. Our non-invasive, photo-based moult analysis is not without precedent: Vieira et al. (2017) used photos to evaluate feather moult in black skimmers (*Rynchops niger*) and Beltran et al. (2019) used photos to study moult in Weddell seals (*Leptonychotes weddellii*).

Statistical analysis

A statistical model was developed to assess whether the public-sourced photographs provide evidence of long-term and/or wide-spread variation in patterns of mountain goat shedding. We assumed that the progression of the amount of coat shed within a season could be described by the logistic equation. Let $f(t)$ denote the mean fraction of coat shed on day of year (DOY), t. In its simplest form our model is given by:

$$f(t) = \frac{e^{\alpha(t-\tau)}}{1 + e^{\alpha(t-\tau)}}$$

where τ is the DOY when 50% of the coat has been shed, and a describes the rate of shedding. Rate of change in f has maximum value $a/4$ and occurs when $t = \tau$. We refer to τ and a as the shedding date and shedding rate, respectively. These two parameters may be affected by animal state or environmental variables. Here, the state of an animal is defined by its sex and, if female, the presence of a kid. Although animal state is known for the YWP study it is often not clear from community photographs. Animal state is described by a letter pairing; the first letter describes the sex of the animal (F = female, M = male, X = unknown) and the second letter describes the presence of kid (Y = yes, N = no, X = unknown). Assuming only females may be associated with kids, there are six animal states, three of which are unambiguous: FN (female without a kid), FY (female with a kid), and MN (male without a kid). We assume that animal state

may affect the timing of shedding. Let τ_0 be the shedding date of a female without kid, and suppose the shedding date of males differs to females by τ_M. Shedding date of females when with kid differs by τ_K.

Shedding date and shedding rate may also correlate with elevation (E) and latitude (L), due to their relation with temperature and photoperiod. Specifically, for an animal photographed in year y at elevation x_E and latitude x_L, we assume

$$\alpha = \alpha_0 + \alpha_E x_E + \alpha_L x_L + \alpha_Y y + \alpha_{[y]},$$

and

$$\tau = \tau_0 + \tau_M x_M + \tau_K x_K + \tau_E x_E + \tau_L x_L + \tau_Y y + \tau_{[y]},$$

where x_M and x_K are binary predictors indicating whether the animal is male, or with kid (e.g., if animal state is FY then $x_M = 0$ and $x_K = 1$). Year factors into the model as both a continuous predictor and a random effect. Parameters a_Y and τ_Y describe long-term, smooth trends in shedding date and rate, which we might expect to differ from zero under climate change. Alternatively, the $a_{[y]}$ and $\tau_{[y]}$ are random effects associated with year y, drawn from normal distributions with mean zero and standard deviation σ_a and σ_τ, respectively, and represent any year-specific stochastic effects on the timing of shedding that are common to all locations (e.g., large-scale weather fluctuations).

We fit our model to the observed estimates of shedding fractions by first converting the fractions into integers. If fraction f had been shed then the response variable is set to $n = \text{round}(fN)$, where N is the number of shedding bins, implying $0 < n < N$. We chose $N = 25$ bins; our statistical findings are robust to the choice of N. The probability of observing n bins shed at time t when the expected fraction shed is $f(t)$, is given by the beta-binomial distribution, denoted $P_{\text{BB}}(n)$. The beta-component accounts for over-dispersion in the observations relative to the binomial distribution (e.g., due to observation error, animal differences, or unknown environmental variation). We formulate the beta-binomial using the parameter φ (common to all observations) so that its variance inflation factor, relative to the binomial distribution, is $v = 1 + (N-1)\phi/(1+\phi)$ (Richards, 2008).

The model described above can be fit to observations of shedding where animal state is unambiguous. We can also fit this model to observations when animal sex or presence of kid is unknown. Suppose at any time proportion p of animals are female and proportion q of the females are associated with a kid. These assumptions imply that the average proportion of animals in states: FN, FY, and MN, are $p(1-q)$, pq, and $(1-p)$, respectively. When animal state is ambiguous (i.e., FX, XN, or XX) the probability of observing n shed bins is a weighted sum of the three beta-binomial distributions associated with the unambiguous states, where the weights are calculated using p and q. Specifically,

$$\Pr(n|\text{FX}) = (1-q)P_{\text{BB}}(n|\text{FN}) + qP_{\text{BB}}(n|\text{FY}),$$

$$\Pr(n|\text{XN}) = \frac{p(1-q)P_{\text{BB}}(n|\text{FN}) + (1-p)P_{\text{BB}}(n|\text{MN})}{p(1-q) + (1-p)},$$

and

$$\Pr(n|\text{XX}) = p(1-q)P_{\text{BB}}(n|\text{FN}) + pqP_{\text{BB}}(n|\text{FY}) + (1-p)P_{\text{BB}}(n|\text{MN}),$$

where $P_{\text{BB}}(n|j)$ is the probability of observing n bins shed when the animal is in an unambiguous state j, which is calculated according to the beta-binomial distribution, as described above.

This model has 15 parameters (see Table 1) and we estimate them using Bayesian methods based on Monte Carlo sampling. Specifically, we implemented the model using the R programming language and the package rstan (Supplementary Materials). We specified relatively uninformative priors for all parameters so that

the posterior distributions were strongly dependent on the data (Supplementary Materials). We used three sampling chains to visually check that our model formulation converged and posterior parameter distributions were based on 1000 samples after a 1000 sample burn-in.

For the YWP portion of our study we fit a simpler form of the model. As this study was conducted at a single site, and within a single season, we did not estimate effects of elevation, latitude or year (i.e. $a_E = a_L = a_Y = \tau_E = \tau_L = \tau_Y = 0$). An important difference with sampling design between both studies is that animals were identified and repeatedly surveyed in the YWP study. To account for repeated measures, we used a random effect term associated with each animal; however, given the limited number of animals in the study (14) we only included a single random effect and associated it with shedding date. These random effect terms were drawn from a normal distribution with mean zero and standard deviation, σ_{ID}. The model of shedding that we fit to the YWP study had six parameters (Table 2).

Results

We had 651 photographs where shedding fraction could be well-estimated. Photographs provided good spatial coverage as they spanned latitudes 37.6°N to 61.1°N and elevations between 0 at Glacier Bay, Alaska and 4333m in the southern Rocky Mountains of Colorado, USA. However, these two environmental variables (latitude and elevation) were negatively correlated (Figure 2). Community-submitted photographs were taken between 1948 and 2018; but, as expected, dates were heavily biased towards the latter few years (Figure 3). Sex and status with/without kid could only be attributed to 55% of the photographs, and most photographs were of females with kids (sample sizes: FN = 94, FY = 202, FX = 61, MN = 104, XN = 2, XX = 188).

Animals predominantly shed over a 3-month period between day of year (DOY) 150 (May 29) and DOY 250 (September 6) (Figure 3). We noted that shedding estimates for 16 animals were unusually low and late in the season (i.e., after DOY 220, see Supplementary Materials). These photographs may be associated with incorrect dates and were removed from the statistical analysis, as they will likely result in biased parameter estimates; our final sample size was 635.

The photographs indicate that, on average, males shed earlier than females and females with kids tend to shed later than females without kids (Figure 3). There was no clear pattern of long-term trends in shedding (Figure 3). Our statistical model was able to reproduce the observed patterns of shedding (Figure 4) and supported these conclusions (Table 1). The model estimated that about two-thirds of animals photographed were female and half of those had a kid. There was strong evidence that males shed before females by about 6.4 days, and that females shed later when with kid by about 5.5 days.

The model did not find evidence of a long-term trend in either the date or rate of shedding; 80% credible intervals (CIs) for τ_Y and a_Y contained zero (Table 1). There was also not strong evidence that the rate of shedding varied stochastically between years (Figure 5). However, there was some evidence that in recent years (2015-2018) the date of shedding may have been begun earlier by up to a week, relative to the long-term average (Figure 5A). Note that the model also predicts earlier shedding for 1999 and 2004, however these estimates should be treated with caution as in these years sample size was low and animal state was always unknown (i.e., sex, female status with/without kid).

Shedding date was positively associated with elevation and latitude (i.e., delayed), and shedding rate was greater at higher latitudes (Table 1). The negative correlation between elevation and latitude resulted in positive correlations between model parameters associated with elevation and latitude (Supplementary Materials). Nonetheless, posterior parameter estimates resulted in the model predicting slightly later but shorter shedding periods at higher latitudes (Figure 6).

Although the number of animals observed during the study at YWP was very low (animal numbers: FN = 9, FY = 3, MN = 2), the 58 photographs suggest that males shed before females and females with kids had delayed shedding (Figure 7). The model fit strongly supported animal state as being an important determinant of the timing of shedding (Table 2). In this case, on average, males were estimated to shed 23.7 days earlier than females and the presence of a kid delayed female shedding date by 17.9 days. These

6

offsets are greater than those predicted by the community science analysis and may be the result of biases due to low sample sizes for the YWP study, or uncertainty in animal state inherent with the community data. Interestingly, the shedding date estimate of alone females, τ_0, for the YWP study, is later than the population-wide estimate associated with the community study, however these two estimates are consistent because YWP is at the extreme northerly latitude, and latitude is predicted to be associated with delayed shedding date.

Discussion

Our results demonstrate that community photography, including old and recent images, has potential for investigating phenological differences across wide spatial areas. In particular, we have shown that statistical analyses can be informative even when a significant fraction of the photographs are missing information (e.g., animal states), which is often inevitable with community science data. We were able to incorporate nearly all of the community science photographs that were associated with uncertainty into the statistical analysis by building missingness explicitly into the statistical model expectations. Conclusions drawn from the community science analysis are supported by similar conclusions drawn from the analysis of our Yukon Wildlife Preserve data that included complete data and repeated observations of individuals.

Our findings (using both crowd-sourced and field-sourced data) on sex differences and effects of new (current year's) kids are also consistent with earlier published results from Caw Ridge, west-central Alberta (Déry et al., 2019) as well as with the recorded knowledge of a Tlingit weaver (Rofkar, 2014) who observed that nannies finish moulting only after weaning their kids. The stage of hair moult has also been used to make assumptions about sex and reproductive status in the field (Chadwick, 2002).

Community-sourcing of photos was generally successful; every naturalist with existing mountain goat photos already uploaded on iNaturalist granted us permission to have their photos included in our analysis and some people uploaded additional photographs after learning about our study. More than 100 people submitted photos via our designated CitSci platform. That we detected sex and kid effects using photos crowd-sourced over approximately one year demonstrates that community science can be leveraged to boost research scope, scale and speed especially if it can be validated against long-term and/or carefully field-sourced data.

While our sample had broad spatial coverage (Figure 1) directly inferring the effects of latitude and elevation on moult was difficult due to their negative correlation. Where mountain goats have access to a range of elevations (e.g., in the southern Rocky Mountains) there are presumably advantages as the climate warms as average temperature drops by approximately six degrees Celsius for every 1000-meter increase in elevation. However, as observed in cashmere goats (*Capra hircus*) wool is also thicker at higher elevation, so presumably there is also more to shed if animals shift higher up, a pattern noted by British military officer Cecil Rawlins when above 4000m in Tibet in 1905 (Berger, 2018). We found later and slower rates of moult in mountain goats where they were photographed in high mountains / higher elevations, although we acknowledge this does not account for their vertical movements as photographs are mere snapshots of locations and not indicative of long-term responses or behaviour (Beever et al., 2017), for example shade-seeking or timing of activity.

We found later moult at higher latitudes in contrast to findings in muskoxen where earlier shedding occurred in animals at 69 degrees N than at 57 degrees N (Wilkinson, 1974). Whereas photoperiod is considered to be a primary cue for moult (Lincoln and Ebling, 1985; Zimova et al., 2018), temperature also plays a role; for example, cattle populations at the same latitude but different temperatures show earlier moult where lower and warmer (Murray, 1965). In northern mountain goats, delayed moult may be warranted if a warm coat is still needed for the late spring cold. Rate of moult was faster at the lower elevation, higher latitude sites, which might also be explained by northern mountain goats' need to put winter coats on more quickly in time for winter.

We found no clear long-term climate signal, however, consistent with our hypothesis that moult may occur earlier in the year in recent years because of climate warming, we detected some evidence of earlier moult in 2015-2018 (Figure 5A). Our inability to tease apart long-term change with random but recent shifts to

earlier shedding may be partly due to a limited sample of historical photographs. Specifically, more than 90% of our 650 photos were from the year 2000 and later. Further outreach and time would be required to meet the objectives of boosting sample sizes and reducing bias, especially for the acquisition of historical images. However, such data are necessary to enable a more rigorous assessment of the extent to which climate is driving shedding schedules. Analyzing shed extent from photographs by hand is slow, thus as data accumulate an important research focus will be how best to employ automated processing of photographs (e.g., Artificial Intelligence, machine learning).

One further caveat, and an indirect effect of climate change, was the prevalence of ticks (*Dermacentor andersoni*) and their effect on moult patterns. We noted visible hair loss in mountain goats' shoulder areas associated with active rubbing, especially at Glacier National Park (the locale of most crowd-sourced photographs) and where others, notably Douglas Chadwick and Sumio Harada observed these tick-affected bare patches (personal communication, 2018). As moult starts at the face, loss of hair and irritated skin at the shoulder area when the face and neck are not yet shed can most likely be attributed to ticks and not to moult onset. However, we did not attempt to distinguish tick-related loss of hair from regular moult. Our Yukon data offer a tick-free baseline for the far north; while ticks were first detected in the Yukon in the early 1990s and have also been found on ungulates in the NWT, these ticks are cervid-specific and it is highly unlikely that they have reached mountain goat range in the Yukon. Future moult research would still more carefully distinguish between regular moult and tick-affected hair loss resulting from rubbing.

Our future work will explore the potential to reduce analysis effort and time by linking the CitSci platform with Zooniverse, where community scientists engage with image classification tasks. From a community science theory perspective, such a linkage offers opportunities to study cross-over motivations between volunteers submitting photos and those classifying images. Given opportunity for additional field research, it would be valuable to compare the captive herds of the YWP with adjacent wild mountain goats (at the same latitude) to explore the roles played by nutrition and relative safety from predators in moulting.

Conclusions

We show that, in a general sense, there is power in combining community sourced data and appropriate analytic techniques to understand ecological trends across broad areas and environments. Both the community science component and our detailed study of captive mountain goats provided consistent predictions regarding the effect of animal state, demonstrating that community science data can identify the same ecological patterns available from a planned research study. Other photo-based community science engagements using resources from museum and newspaper archives, personal collections, and automated photo processing methods have also been useful, including for understanding the demise and re-expansion of black bears (*Ursus americanus*) into desert environments (Lackey, Beckmann, and Sedinger, 2013). Our project contributes to this knowledge base and substantiates a potential way for researchers and the public to showcase collaborative approaches to address specific scientific questions across large geographical areas.

Data Availability Statement

We plan to archive our data, after removing longitude for data privacy reasons and so as not to reveal locations of sensitive areas such as mineral licks, on https://datadryad.org/.

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Author Contributions

K.N. designed the research; K.N. and A.P. crowd-sourced and analyzed photographs; K.N. and D.R. carried out fieldwork in the Yukon; G.N., K.N. and A.P. managed and monitored the CitSci project platform; K.N. managed the iNaturalist project page and sought permissions for use of photographs; N.Y. extracted elevation data; S.R. analyzed the data; J.B., J.B., A.J., K.N. and D.R. institutions provided funding, administrative support, and/or outreach assistance. All authors contributed to the writing of the manuscript and approved the final version.

Table 1: Descriptions and estimates of model parameters based on photographs taken between 1948 and 2018 as part of the community science project. Note: DOY= day of year, and CI = credible interval. σ-terms describe random variation between years. [*] indicates that the parameter is associated with the z-transformed predictor variable.

Parameter	Description	Mean	10% CI	90%CI
p	Proportion of animals being female	0.666	0.640	0.692
q	Proportion of females with kid	0.500	0.472	0.528
τ_0	DOY when 50% shed for females without kid (days)	193.8	188.7	199.1
τ_M	Shift in shedding date when male (days)	-6.4	-8.4	-4.2
τ_K	Shift in shedding date when with kid (days)	5.5	3.7	7.3
τ_Y	Logit of long-term trend in shedding date[*]	0.005	-0.004	0.015
τ_E	Logit of elevation effect on shedding date[*]	0.009	0.005	0.014
τ_L	Logit of latitude effect on shedding date[*]	0.005	0.000	0.009
a_0	Shedding rate (% per day)	1.489	1.399	1.582
a_Y	Logit of long-term trend in shedding rate[*]	-0.024	-0.992	1.011
a_E	Logit of elevation effect on shedding rate[*]	0.054	-0.803	0.877
a_L	Logit of latitude effect on shedding rate[*]	1.101	0.169	2.046
φ	Beta-binomial overdispersion term	0.265	0.246	0.286
σ_τ	Standard deviation of inter-annual shedding date (days)	13.5	9.3	18.0
σ_a	Standard deviation of inter-annual shedding rate (% per day)	0.182	0.097	0.276

Table 2: Descriptions and estimates of model parameters based on our summer 2018 research at Yukon Wildlife Preserve. σ-term describes random variation between animals.

Parameter	Description	Mean	10% CI	90%CI
τ_0	DOY when 50% shed for females without kid (days)	198.2	194.4	201.7
τ_M	Shift in shedding date when male (days)	-23.7	-31.4	-15.8

Parameter	Description	Mean	10% CI	90%CI
τ_K	Shift in shedding date when with kid (days)	17.9	10.8	25.4
a_0	Shedding rate (% per day)	1.602	1.442	1.765
φ	Beta-binomial overdispersion term	0.180	0.120	0.254
σ_{ID}	Standard deviation of among individual shedding date (days)	4.6	0.9	8.6
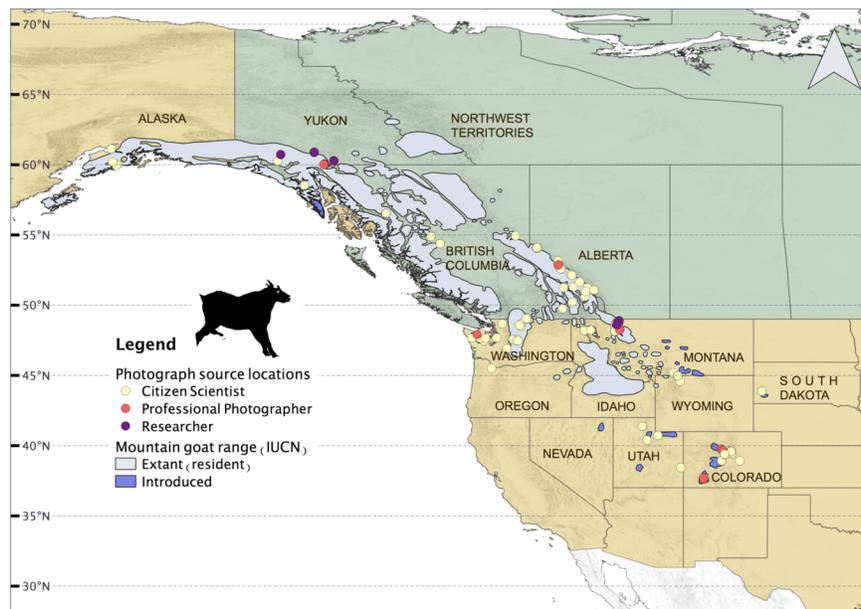
Figure 1: Map showing mountain goat range (IUCN Red List shapefile 2008) and locations of photographs from citizen scientists (yellow), professional photographers (also considered community scientists but shown separately here, in red), and researchers (purple).

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image2.emf available at https://authorea.com/users/320699/articles/450156-using-community-photography-to-investigate-phenology-a-case-study-of-coat-moult-in-the-mountain-goat-oreamnos-americanus-with-missing-data

Figure 2: (A) Locations of photographs analyzed. Cross indicates the location of the Yukon Wildlife Preserve. (B) Relation between latitude and elevation for all photographs. Colours show what is known about the sex and presence of a kid for each animal photographed. There are six possible animal states described by a pair of letters: [first pair] F = female, M = male, X = sex unknown; [second pair] Y = with kid, N = without kid, X = kid status unknown.

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Figure 3: Fraction of coat shed estimates from all photographs collected during the community science project. See Figure 2 for explanation of animal state. Light grey circles depict all shedding estimates.

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Figure 4: Observed and predicted shedding patterns. Panels correspond to the three animal states where sex and kid status are known. Each panel contains 40 lines that depict shedding patterns predicted by the model when parameters are randomly drawn from their posterior distribution; thus, their spread describe prediction uncertainty associated with the mean. Predictions are for 2018, for an animal at latitude 50 and elevation 2000m, which is consistent with the observed data (Figures 2B, 3). Circles depict shedding status from all photographs (i.e., across a range of years, latitudes and elevations) and are grey if sex or kid status is unknown. See Figure 2 for explanation of animal state.

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Figure 5: Estimated annual stochastic deviations in (A) mean shedding date (positive values imply shedding occurred later in the year), $\tau [y]$, and (B) mean maximum shedding rate, $a [y]$. These estimates depict the random effect terms in the model. Error bars indicate 80% credible intervals.

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Figure 6: Solid coloured circles depict predicted dates when a female without kid is expected to have shed 50% of her coat and vertical lines depict dates when between 5% and 95% of her coat has been shed. Colours indicate the latitude at which the photograph was taken. Vertical bars indicate all photographs included in the model fit, irrespective of whether they were male or female. Open symbols show dates when animals were photographed and how much they had shed: phase 1 ($< 33\%$ shed), phase 2 (33%-66% shed), and phase 3 ($> 66\%$ shed). Vertical bars missing a shedding estimate coincide with an animal that had yet to shed at all ($f = 0$), or had completely shed ($f = 1$).

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Figure 7: Observed shedding patterns for 14 animals repeatedly observed at the Yukon Wildlife Preserve in 2018. See Figure 2 for explanation of animal state.