Resiliency and Loss: A Case Study of Two Clusters of High Elevation Ice Patches in the Greater Yellowstone Ecosystem, USA

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Introduction

Ice patch archaeology refers to the study of high-elevation perennial patches of ice and snow, some of which contain ice that is thousands of years old (fig. 1). They are of interest to archaeologists because they are relatively stable and therefore have the potential to preserve ancient organic artefacts and palaeobiological material (for example, Hare et al. 2004; Lee 2012; Reckin 2013). This differentiates them from mountain glaciers, whose dynamic flow can destroy artefacts and whose ice is often less than 500 years old (Cronin 2010). To date, the oldest ice patch artefact recovered in the world is approximately 10,300 years old, a dart shaft from the Beartooth Mountains of the Greater Yellowstone Ecosystem (GYE) in the central Rocky Mountains (Lee 2010). As anthropogenic climate change causes melt in the cryosphere, recent years have seen ice patch artefacts, including leather, basketry and hunting implements, melting free all over the world, particularly in Canada, Norway and the Alps (Reckin 2013). Ice patch researchers are in a race against time to identify productive ice patches and recover any fragile artefacts or palaeobiological material they may contain before they melt completely. For many of these patches, this would be their first complete melt since the early Holocene.

Fig. 1. Transverse ice patch in the Absarokas. Note the dark organic and nonorganic material on the ice surface (photograph by Rachel Reckin).

Yet we know very little about the internal structure of ice patches, how they melt or how resilient they may be to years of low snowpack and high melt. A few pioneering studies address these questions (notably Haeberli et al. 2004; Ødegård et al. 2017), but we are not certain about how representative these results may be. That said, our understanding of the age of high elevation ice, its preservation potential and its resilience is vital as we continue to refine our prioritization of ice patches to visit for detailed survey (see Dalmas et al. 2016; Rogers et al. 2014). In most years, what we consider to be a single ice patch is actually made up of snow and ice in a variety of compaction states, possibly including one or several ancient cores of ice. Therefore, we cannot presume that all of these types of snow and ice will melt at the same rate; glacial ice, for example, certainly does not melt at the same rate as snow does (for example, Benn and Evans 2010).

In addition, we have virtually no scientific understanding of how ice patches contribute to and interact with the ecosystems that surround them. Particularly during hot and dry years, ice patches often maintain a green halo along their lower edge; these are slow-release watering mechanisms for entire valleys below. They are places animals are known to frequent in order to drink water, eat green grass and escape insects. Ice patches may

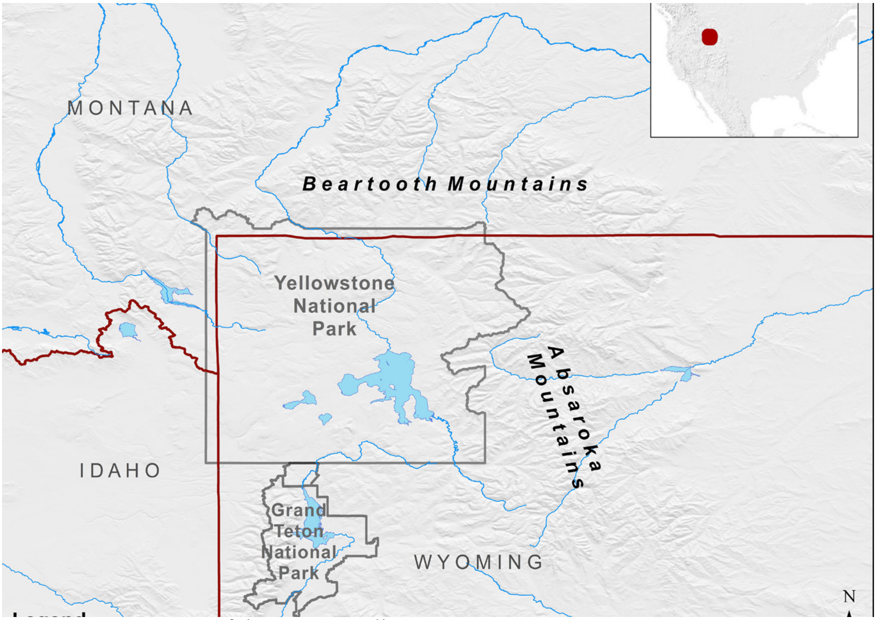

Fig. 2. Overview map of the Greater Yellowstone Ecosystem.

even offer a specialized habitat to sensitive species of plants and animals. Recent research has shown that the glaciers of the Wind River Range, in the south of the GYE, contribute more than 50 per cent of streamflow on the mountains' eastern slopes (Cable et al. 2011). We do not know how much ice patches contribute to streamflow, either at the regional level or within particular drainages. Yet these kinds of contributions to the ecosystem and the place of ice within that system are vital to our archaeological understanding of how humans have interacted with the ice over the millennia.

This paper seeks to better understand how two clusters of ice patches in the Greater Yellowstone Ecosystem (fig. 2) are responding to anthropogenic climate change. My broad hypothesis is that the compacted core of ancient ice that an ice patch contains will be more resistant to melt than the less compacted, younger layers of snow and ice that may blanket it during cooler, wetter years. I use georectified historic aerial photos to measure the area of the ice patches and then compare those results across the years in relation to historic climatic data. Specifically, this paper seeks to test the following three sub-hypotheses: firstly, ice patch area has declined overall from the time of the earliest available imagery to the present, even when comparing the respective highest melt years, which indicates that ancient ice is melting; secondly, the largest ice patches lose a smaller percentage of their overall mass in high melt years than do smaller ice patches, thanks to the greater quantity of more resilient ancient ice the larger patches may contain; and, thirdly, ice patches melt back to roughly the same size and shape during each high melt period, which likely represents their ice core. At this point, dark organic material on the ice surface and permafrost below may slow further melt.

Background

Ice Patch Morphology

Unfortunately, we know relatively little about the internal morphology of ice patches, but recent research is beginning to shed some light. Generally, what Lewis (1939) called 'transverse ice patches' appear to have the best conditions for organic preservation and artefact recovery (Lee et al. 2009; Reckin 2013). Their long axis lies perpendicular to the line of drainage, meaning they are more likely to offer a flatter forefield, where organic material may collect. Figure 1 shows a classic transverse ice patch. Longitudinal ice patches, on the other hand, lie roughly parallel to the line of drainage, and circular ice patches often occur in small, glacially-formed circular depressions.

Ødegård et al. (2017) provide a rare in-depth geomorphological study of one of the most archaeologically productive ice patches in the world: Juvfonna, in the Jotunheimen region of central Norway. The ice core in Juvfonna is cold, consistently -2°C to -4°C at a 5–10m depth of ice. This may be the result of both permafrost underlying the ice and some insulation provided by the organic layers it contains. Indeed, it appears that perennial ice patches are often underlain by their own permafrost, possibly even in situations where permafrost does not otherwise exist in the surrounding landscape (Haeberli et al. 2004). This may contribute to their resilience during high melt years. In addition, while the ice contains distinct layers, including ancient organic lag deposits, it also experiences internal deformation such as shear stress, which can cause curved layering in basal ice.

Fig. 3. 2015 aerial photograph of a Beartooths ice patch with an overlay of the 1953 ice extent. Note the lichen-free zone surrounding the ice patch.

Unlike glaciers, over time, ice patches must exist roughly at equilibrium in terms of net gain/loss of snow and ice, or they will either become glaciers or disappear. In fact, the monitoring results at Juvfonna found thermal regimes similar to those at the equilibrium line of nearby glaciers. The study also found unevenly distributed rates of precipitation accumulation across the ice. However, because the ice patch is roughly at equilibrium, those areas of increased accumulation also experience increased melt. Otherwise, the areas of consistently higher precipitation would grow. On the other hand, in the case of Juvfonna, vulnerability to melt in specific portions of the ice patch was controlled by local ice thickness and wind direction. In particular, sensible heat from the surrounding landscape blowing across the upwind edge of the ice patch appeared to increase melt. Many of these factors are very difficult to determine from aerial photographs alone, but they suggest that snow and ice do not melt in a simple, linear fashion. Instead, Juvfonna contains a cold, layered core of ancient ice that seeks equilibrium, much like a glacier, and is more resistant to melt than is the newer snow it accumulates.

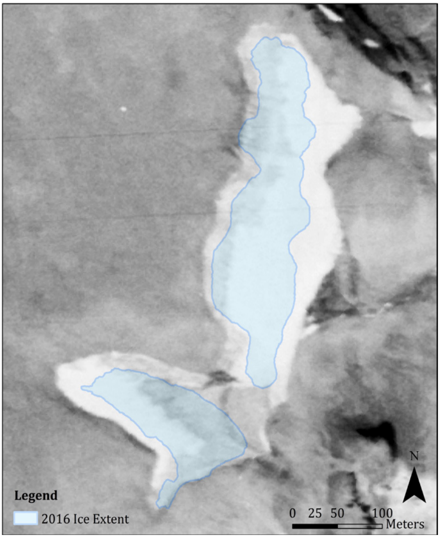

Fig. 4. 1954 aerial photograph of an Absarokas ice patch with an overlay of the 2016 ice extent.

Data

In the late 2000s, Lee et al. (2009) manually searched available imagery from high melt years in the Greater Yellowstone Ecosystem in order to pinpoint high-altitude patches of ice and snow that might have archaeological potential. Lee et al. (2009) based their analysis on factors including the presence of an ice patch in high melt years, flatness of its forefield and visibility of dark organic material on the ice, which can act as an indicator of age. In contrast, ice patches located on cliffs, where any archaeological or palaeobiological material they contain would be washed away downslope, were not included. Neither were those with clear moraines, indicating that they were active glaciers at one time. Based upon this analysis, researchers in the GYE have begun visiting identified ice patches and surveying them for palaeobiological and archaeological material (see Lee and Puseman 2017; Reckin 2013; Sgouros and Stirn 2016). This paper focuses on two clusters of these ice patches in particular: one in the Beartooth Mountains of the northern GYE and the other in the southern Absaroka Mountains in the eastern GYE. In both cases, researchers have visited these ice patches and recovered archaeological artefacts in addition to palaeobiological material. Maps and images in this paper are limited in order to protect the precise locations of these ice patches (figs. 2–4).

I selected the ice patches analyzed here because they are known to contain archaeological and palaeobiological material, they persist even during the highest-recorded years of melt to date, they exist in a cluster and they appear consistently in historical aerial photographs. Descriptive information about each cluster of ice patches is provided in Table 1.

Ice Patch Number	Elevation (m)	Morphology	Outlook
Beartooths			
HR1	3247	transverse	NE
HR2	3109	longitudinal	S
HR3	3200	circular	NE
HR5	3042	circular	E
Absarokas			
GL1	3450	transverse	E
GL2	3505	circular	NE
GL3	3520	longitudinal	S
GL4	3468	transverse	E
GL5	3420	transverse	E
GL6	3440	longitudinal	E
GL7	3435	transverse	E
GL8	3425	transverse	E
GL9	3401	longitudinal	NE
GL10	3450	longitudinal	NE
GL11	3444	circular	E

Table 1. Basic data on each cluster of ice patches. HR4 is now an extinct ice patch, so was not included in this analysis.

In both case studies, the aerial photographs come from a variety of sources, indicated in Table 2. Aerial photographs are not necessarily dated to the same years for each area, as coverage for both areas was not always available in the same year. Additionally, in one case, for 1969 in the Beartooths, only a portion of the group of ice patches is shown in the aerial photographs. Overall, when possible I used images from years known to be relatively high melt, as my interest is in the potentially ancient core of the ice. It is important to note that these images were taken on different days of the year, which impacts the quantity of melt that had occurred (table 2). I limited the analysis to images from very late August into early October, but, under the right conditions, significant melt can take place between these two dates. Most of the images were taken in September. They also vary widely in scale, as shown in Table 2. Ideally, all of the images would be at the highest-possible resolution, but the limitations of historical data mean that my analysis must be relatively coarse-grained to account for the variance in image resolution. The ice patch area for the Absarokas in 2016 is based on walking the perimeter of the ice in the field using high-resolution GPS units (fig. 4).

Historic climatic data are from the National Oceanic and Atmospheric Administration (NOAA). Specifically, the data come from two high-ele-

Beartooths								
Date of photograph	12/09/1932	15/09/1953	26/08/1969	12/09/1975	13/09/1983	24/08/1994	2/09/2006	23/09/2015
Source	US Army Corps	Army Map Service	NASA Johnson Space Center	USGS	USGS	USGS	USDA	USDA
Scale	N/A	1:60,000	1:12,639	1:8000	1:58,000	1:40,000	1.0m resolution	0.5m resolution
Absarokas								
Date of Photograph	20/09/1954	17/08/1969	13/09/1983	27/08/1990	5/09/1994	20/09/2001	2/09/2006	21/08/2016
Source	Army Map Service	USGS	USGS	USGS	USGS	USGS	USDA	Field Connection
Scale	1:59,000	1:36,000	1:80,000	1:40,000	1:40,000	1:40,000	1.0m resolution	0.4m resolution

Table 2. Data on source and scale of aerial photos used in the analysis. USGS stands for US Geological Survey, and USDA for US Department of Agriculture.

vation Snotel observation stations near the ice patches in question: Fisher Creek Station in the Beartooths (2774 m.a.s.l.) and Kirwin Station in the Absarokas (2911 m.a.s.l.). In the available data, the most relevant factors for predicting ice melt are snowfall and summer temperatures (table 3, figs. 5–6). In this analysis, I use the spring date on which Snow Water Equivalent (SWE) equals zero at each Snotel site as an indicator of the quantity of winter snowfall and a measure of early spring melt. Later dates when SWE equals zero are presumably the result of more winter snow and/or a cooler spring. In addition, I averaged summer temperatures for each year from 1 May through 30 September, when the majority of ice patch melt occurs. These numbers are based on average daily temperatures (table 3). Modern Snotel observation points in the wilderness areas

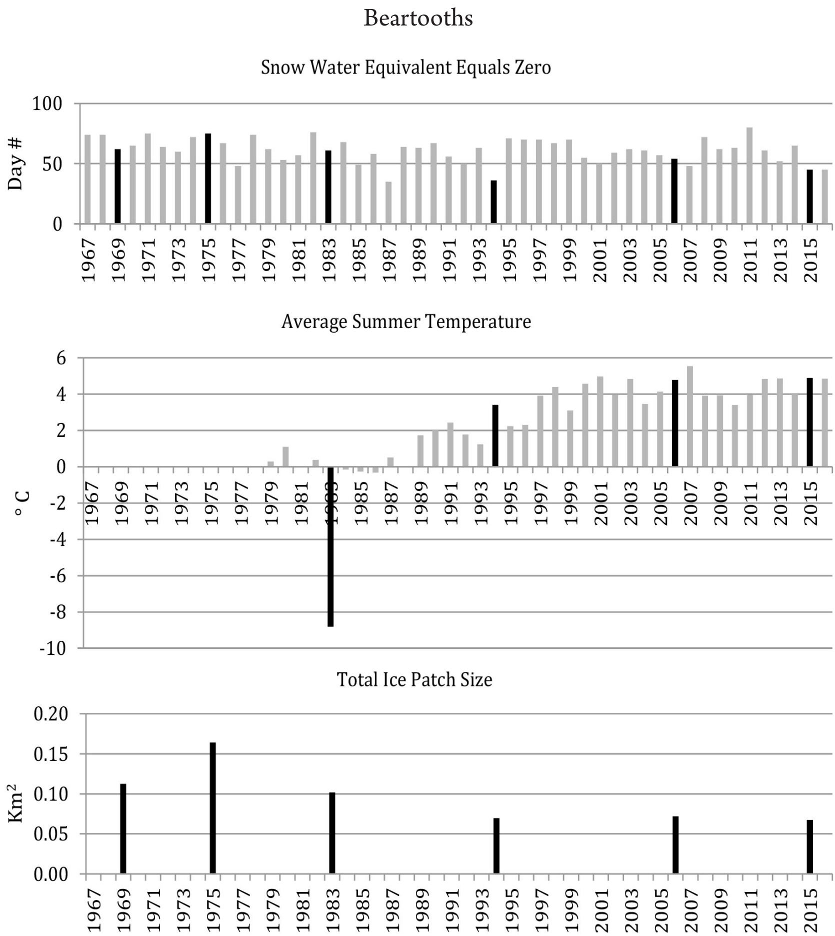

Fig. 5. Climatic data and ice extent for the Beartooths, taken from the Fisher Creek Snotel Station. Years with aerial photos used in the analysis are shown in black. Years that have no column did not have data available.

were not fully installed until the late 1970s or early 1980s, so these data are, unfortunately, not available for the entire period of the study. Older climatic data exist from nearby towns like Red Lodge, Montana, and Dubois, Wyoming, but do not correlate well with a precise understand-

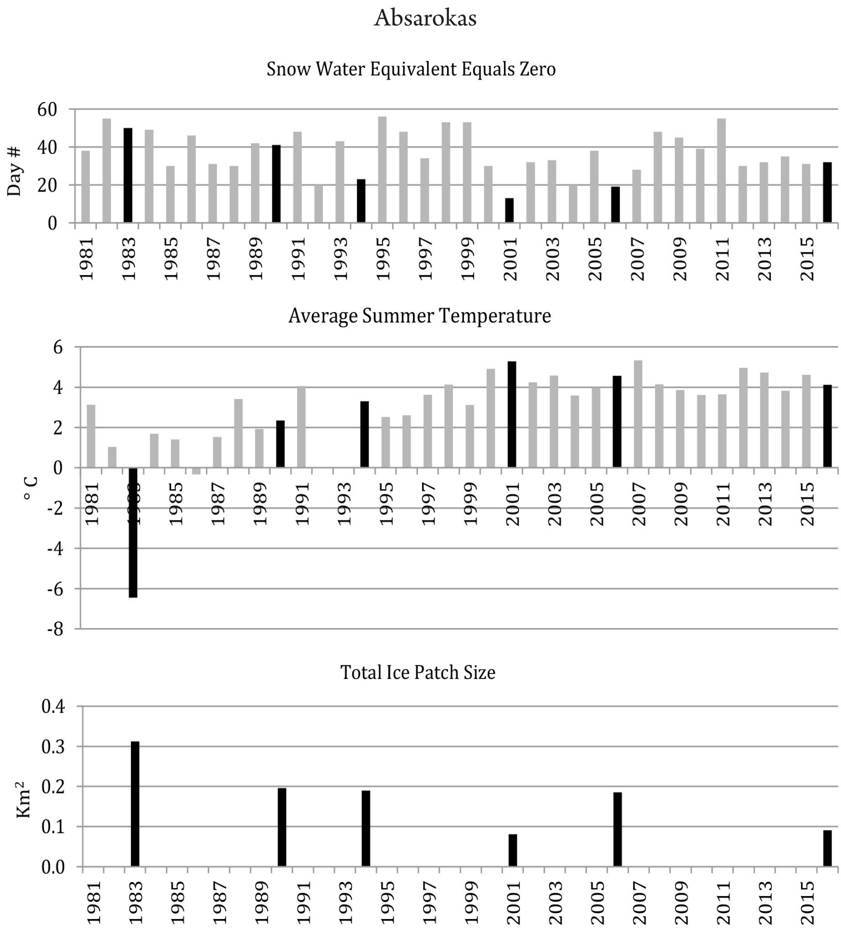

Fig. 6. Climatic data and ice extent for the Absarokas, taken from the Kirwin Snotel Station. Years with aerial photos used in the analysis are shown in black. Years that have no column did not have data available.

ing of changing ice extents, as the precipitation patterns and temperatures can be very different in the valleys than they are at high elevations

Beartooths					
Year	Date SWE=0	Average Summer Temp (°C)	Aerial Photograph date	Total Ice Patch Size (m^2)	HR 1&2 Ice Patch Sizes (m^2)
1932	N/A	N/A	256	80,098	75,323
1953	N/A	N/A	258	131,381	124,805
1969	7/01	N/A	238	N/A	112,458
1975	7/14	N/A	255	173,621	164,072
1983	6/30	-8.93	256	108,244	101,773
1994	6/05	3.42	236	73,274	69,553
2006	6/23	4.77	245	77,081	71,817
2015	6/14	4.89	266	70,811	67,523
Absarokas					
Year	Date SWE=0	Average summer Temp (°C)	Aerial Photograph Date	Total Ice Patch Size (m^2)	
1954	N/A	N/A	263	404,212	
1969	N/A	N/A	229	432,526	
1983	6/19	-6.45	256	312,382	
1990	6/10	2.35	239	196,034	
1994	5/23	3.30	248	189,500	
2001	5/13	5.28	263	80,906	
2006	5/19	4.57	245	185,346	
2016	6/1	4.12	234	90,511	

Table 3. Summary data, including the spring date that Snow Water Equivalent (SWE) equals zero, average temperature from 1 May to 30 September, and the date the photo was taken, counted from January 1. Climate data for the Beartooths is from Fisher Creek Snotel station, and for the Absarokas is from Kirwin Snotel station. The 1969 aerial photo for the Beartooths did not include all of the ice patches, so there is an additional column with just HR1 and HR2, which are included in all aerial photos.

Methods

I georectified the aerial photographs in ArcGIS by hand to a modern (2015 or 2016) geotiff of the area, projected at NAD1983, UTM 12. I then digi-

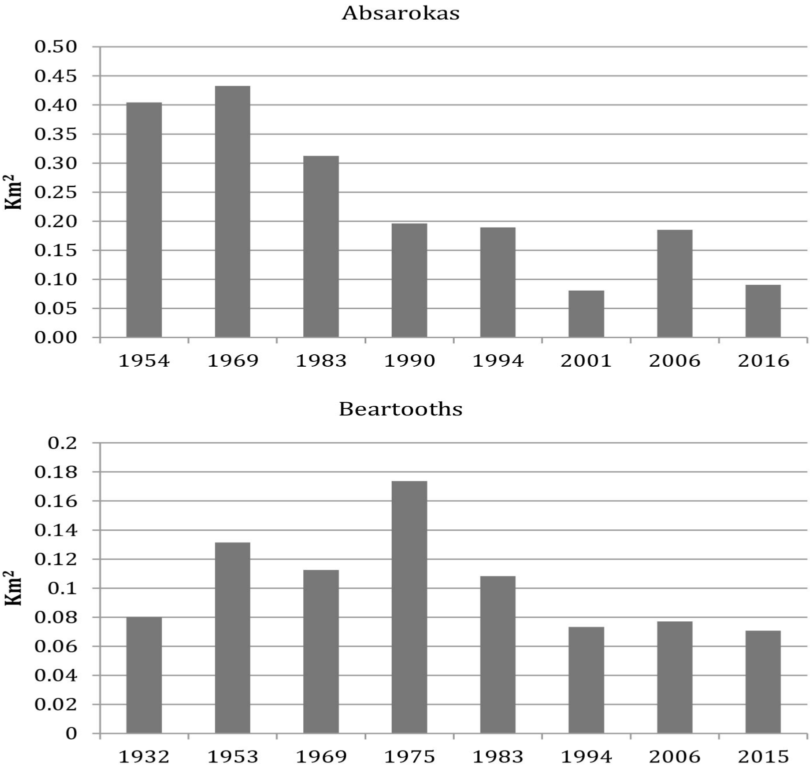

Fig. 7. Comparison of total ice extent through time for each cluster. Note that in 1969, two of the smaller ice patches in the Beartooths are not in the aerial photo, so the total shown here for 1969 is artificially depressed. The 2016 measurement for the Absarokas also slightly underrepresents the ice's actual size as we could not fully walk the boundary of two of the ice patches safely.

tized the perimeters of the perennial ice patches identified and numbered in Lee et al.'s analysis (2009), ignoring other snow patches in the area that persist during lower melt years. Because the area surrounding perennial ice patches is often clear of lichen and bleached by the sun, it can be difficult to tell the edge of the ice from the light-colored rocks surrounding it. On the other hand, the dark organic material and sediment that can cover the surface of old ice can also make deciphering its precise edge difficult (figs. 3–4). I used careful consideration and best judgment, however, and believe mistakes in drawing to be minimal, though pixels are quite large in some years.

Discussion and Conclusions

First sub-hypothesis: Ice patch area has declined overall from the time of the earliest available imagery to the present, even when comparing the highest melt years, thereby indicating that the ancient ice is melting.

In both the Beartooths and the Absarokas, ice patch area has declined overall (fig. 7). However, this does not necessarily mean that the lost ice mass is all ancient ice. In the Beartooths in 2015, the four clustered ice patches in question are 44 per cent of their maximum-recorded size in 1975. However, most of the mass lost between 1975 and 2015 is not ancient ice. In fact, in 1932, the Beartooths ice patches were smaller than in 1953, 1969 or 1975, though still larger than in 1994, 2006 or 2015 (fig. 7). We know, therefore, that the ancient ice in those patches cannot be larger than what we see in the aerial imagery in 1932. Yet the ice in 2015 is even smaller—26 per cent smaller—than the ice in 1932, and that loss may well be ancient ice. The presence of 10,300-year-old artefacts in the ice in the Beartooths suggests some ice patches there may be of early Holocene age (Lee 2010). But others may have melted out during the warm, dry Altithermal (~8000–5000 cal BP), and all would likely have shrunk substantially during that period. On the other hand, glacial research suggests that alpine ice was at its largest extent in the recent Holocene, during the Little Ice Age (~450–100 cal BP) (Cronin 2010). Taken together, all of this suggests that the relatively small ice extents documented by the aerial photographs of the Beartooths in 1932 may, indeed, have been exposing old ice. And, if so, approximately 9287 square meters of that ancient ice have since melted.

We unfortunately do not have aerial images of the Absarokas from the 1930s for similar comparison. However, we can say that, when at their smallest in 2001, the 11 ice patches in question were 16 per cent of their size in 1953. Interestingly, they have lost more of their mass than the Beartooths cluster has since 1994 (fig. 6). We also unfortunately do not have a reliable aerial photograph of the Beartooths cluster for 2001, a year that experienced early melt and high summer temperatures throughout the GYE (figs. 5–6). In

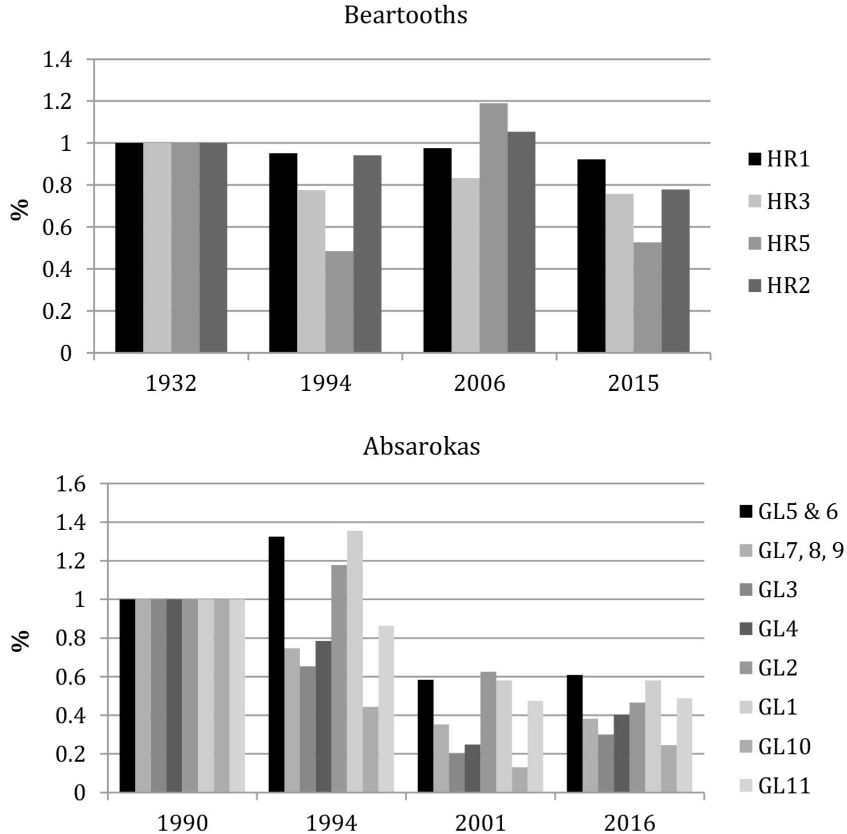

Fig. 8. Percentage of ice mass in high melt years, with 1932 and 1990, respectively, held as 1.00. In each chart, the ice patches are ordered, from left to right, from largest to smallest. The 2016 measurements for GL1 and GL2 slightly underrepresent their size as we could not walk their full boundaries safely.

addition, the two clusters' melt differences from 1994 until today cannot be entirely attributed to the date the photographs were taken. In 1994, the Beartooths photograph was taken 12 days earlier, meaning the Absarokas ice patches actually had 12 more days to melt (table 3). And we mapped the Absarokas ice patches in person in 2016 a month earlier than the date when the aerial photo of the Beartooths ice patch was taken in 2015. This means that the Absarokas ice patches likely melted back even more before consistent winter snows began, and their loss of mass between 1994 and 2016 should be even more substantial than what is shown in Figure 7. Indeed, it may be that the Absarokas ice melted past the 2001 threshold after our measurements were taken in 2016. Ultimately, the Beartooths ice patches genuinely seem to have lost less mass than have the Absarokas ice patches since 1994. This is likely due to differing ice thickness or other factors of ice patch morphology difficult to discern from aerial imagery.

Second sub-hypothesis: The largest ice patches are the most resilient to high melt years, losing a smaller percentage of their overall mass than do smaller ice patches.

Ice patch size does not, in fact, appear to be a good proxy for resilience to high melt years in either the Beartooths or the Absarokas. If this were the case, in Figure 8 we would expect the highest percentage of ice retention to consistently be with the largest ice. Figure 8 specifically compares very high melt years, when ancient ice was likely exposed, pinning the earliest of those years as 100 per cent for comparison. And, clearly, the largest ice patches do not consistently retain the highest percentage of their mass. In fact, thickness is likely a much better predictor of ice patch resiliency, as Ødegård et al. (2017) find for Juvfonna, though thickness is very difficult to determine from aerial photographs.

Third sub-hypothesis: Ice patches melt back to roughly the same size and shape during each high melt period, at which point dark organic material on the ice surface and permafrost below may slow further melt.

As predicted, ice patches do appear to have a size and shape to which they return consistently in high melt years. This size and shape likely corresponds with the ancient, compacted ice they contain and with the permafrost underlying that ice (Ødegård et al. 2017). In the Beartooths, ice patch size and shape in 1994, 2006 and 2015 are markedly similar, given that the local date of snowmelt, the summer temperatures and even the dates the photographs were taken vary significantly between the years (fig. 5). If there were a simple linear relationship between an early melt at the Snotel site, warmer average summer temperatures and a respectively late date when each photograph was taken, we would expect the image from 2015 to show even smaller ice patches than it does. The lack of such a relationship suggests some resiliency to that inner core of ice and further suggests that snow from recent years does melt much more quickly than the inner core of ice does. In addition, Figure 6 shows that the years leading up to 2015 included years of relatively late melt. But the additional snow from those years blanketing the ice patches was unable to withstand the consistently higher summer temperatures of the 2010s, and, cumulatively, the ice still lost mass. In fact, the data suggests that 1994 may have been a pivotal year of melt in the Beartooths: summer temperatures leapt upward that year, and the melt date was among the earliest recorded. If there was ancient ice exposed in 1932, by 1994 we had lost 6824 square meters of that ice, and the climatic data suggests much of that melt took place during the summer of 1994.

In the Absarokas, the very similar ice extents documented during high melt years in 1990 and 1994 are also evidence for a moderately resilient ice core (fig. 6). Though the ice in 1994 is 6534m^2 smaller than in 1990, the earlier melt date, the higher summer temperatures and the later photograph date in 1994 suggest that this difference should have been even greater. The year 2001, on the other hand, provides striking evidence for the vulnerability of that central core of ice to an exceptionally early melt date and an especially warm summer. The Absarokas ice patches lost a staggering 108,594 square metres of potentially ancient ice between 1994 and 2001, which is 43 per cent of their overall mass. They rebounded in 2006, and current data suggests we have not lost a major portion of ancient ice since then. However, the measurements for 2016 were taken 29 days earlier than the photograph in 2001, and the ice in 2016 may have melted past its 2001 size after our measurement.

Ultimately, while the cores of these ice patches may be more resistant to melt than are their broader boundaries of seasonal snow, the cumulative years of higher summer temperatures and earlier spring melts are taking their toll. Yet it is not a simple downward trajectory of size—local climates are variable, and it is still unclear exactly how local snow regimes will change with the global climate. Therefore, in some more favourable years, these ice patches may be able to maintain insulative layers of new snow even in the midst of other high melt years, as happened in the Absarokas in 2006. Taken independently, the melt dates and the summer temperatures of 2015 and 2016 do not suggest that these should have been extreme melt years for either the Absarokas or the Beartooths; yet, in both cases, the ice is extremely small relative to earlier years. Together, these data suggest that ancient ice patches in the Greater Yellowstone Ecosystem are ultimately losing their battle with earlier spring snowmelt and warmer temperatures, even in the midst of some years with higher snowpack. And they may be losing that resiliency as they lose its source: their ancient ice. These results also suggest that, for researchers and land managers, survey of these features does not always have to wait for the most optimal melt years. It is increasingly likely that even a relatively normal modern melt year may expose ancient ice as that ice becomes ever more vulnerable. As we continue to work to increase our understanding of ice patch morphology and melt, studies like this one emphasize the danger anthropogenic climate change poses to ancient alpine ice and the trove of archaeological and palaeobiological data it contains. It is important that we continue to consider the applications of remote sensing, including aerial photography, in our study of alpine ice in the GYE in particular, as the vastness of the wilderness and the quantity of alpine ice requires us to prioritize survey and research resources carefully.

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