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Parks as Proving Grounds:

Research Tools and Techniques

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Cover photo: Measuring the height of Denali. A 2015 resurvey of Denali showed the mountain is growing by about 0.04 inches/year.
COMPASSDATA TEAM/BLAINE HORNER

Parks as Proving Grounds: Research Tools and Techniques

Jeff Rasic, National Park Service

Parks in Alaska pose special challenges to researchers: they are large, remote, and less is known about them. This makes it all the more important that tools and techniques we use here are practical, effective, and impactful. While researchers often focus on sharing the findings from their work, here we shine a light on the devices and approaches used by researchers with attention to the innovation needed to work in Alaska.

Alaska's national parks are laboratories for scientific research and monitoring, but they present special challenges to scientists. Alaska's parklands are typically large, remote, and little-studied compared to conservation lands in more populated and developed regions. Just getting to a base camp from which to mount a scientific study in most Alaskan parks can be a costly endeavor requiring travel in boats and small aircraft, followed by lengthy stays in remote camps, and requiring an ability to work detached from the power and data grid.

This, of course, represents not only a challenge, but also rewarding opportunities. Swapping an office cubicle and a constant stream of email for a quiet camp in a mountain meadow or coastal bay no doubt makes for an incredible workplace. More importantly, the exceptional natural and cultural resources in parklands represent special opportunities for novel research and an encouraging mandate to conduct the work in practical, effective, and impactful ways. This places an especially high premium on the use of the right tools and best methods for research and monitoring. Sometimes this means new, cutting-edge technologies that minimize impacts to resources or visitor experience. Other times it means, simple, tried-and-true methods that are guaranteed to deliver results when a follow-up visit to a study site is impractical.

This volume of *Alaska Park Science* highlights a wide range of high and low tech, of novel and well-tested methods, and in all cases demonstrates the unparalleled collection of data about the natural and cultural resources preserved in Alaska's national parks, preserves, and historical parks.

Denali South District ranger servicing a high-altitude (14,200') weather station at Kahiltna Glacier's Genet Basin, on Denali. This is the highest-elevation weather station in Alaska and is maintained year-round as a collaborative project of the Central Alaska Inventory and Monitoring Network and the Denali National Park and Preserve mountain rescue team.
NPS/MICHAEL LOSO


Eskimo
QUICKFISH 6
FRABILL

New Approaches to Study Interactions Among Climate, Environment, and Humans in Arctic Alaska

Richard S. Vachula, Karen J. Wang, and Yongsong Huang, Brown University
Jonathan A. O'Donnell, National Park Service

Lake sediments accumulate for thousands to hundreds of thousands of years, serving as a geological record or environmental archive of long-term climate change and ecological variability. Paleoclimatologists and paleoecologists are examining lake sediment cores to deduce environmental changes of the past. This understanding will allow us to make more informed predictions about future change.

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The lake sediment coring process on Imuruk Lake, Bering Land Bridge National Preserve.
SKYDANCE AVIATION/SCOTT AMY

The Arctic is rapidly changing, with air temperatures rising nearly two times faster than those of lower latitudes over the past 150 years (Bekryaev et al. 2010). Rapid and pronounced warming in the Arctic is caused not only by rising emissions of greenhouse gases from human activities (fossil fuel burning, land use change), but also by *Arctic amplification* (Serreze and Barry 2011), a phenomenon by which the magnitude of climate change occurs more strongly in the poles. Alaska and its national parks are among regions bearing the brunt of climate change's effects (Gonzalez et al. 2018). The negative consequences of climate change include permafrost thaw, sea ice loss, more severe wildfires, coastal erosion, changing habitat (including human habitats), and animal and plant species distributions. But how do we know that the recent climate change in the Arctic is exceptional and outside the natural range of climate variability? What are the sensitivities of various landscape processes to changes in temperatures and what does this tell us about how the Arctic will change in the future? Geological records like lake and ocean sediments can help us understand how various factors (e.g., greenhouse gases, solar insolation) have driven these changes in the past, which therefore allow us to make more informed predictions of future changes.

Lake sediments accumulate for thousands to hundreds of thousands of years, recording environmental archives that can provide context for long-term climate and ecological variabilities as well as short-term observational records. In this way, understanding the Arctic's past is a key to understanding and providing context for what we see today, and also for predicting what we can expect for the future. As paleoclimatologists and paleoecologists, we can deduce environmental changes of the past by examining lake sediment cores. By using a piston coring system afloat a raft or atop of ice (Figure 1), we can extract sediment cores from lakebeds. The techniques we use to date sediment horizons depend on the age of the sediment (Figure 2). For example, for sediments deposited within the last 200 years or so, we can determine ages by measuring the lead isotope (^{210}Pb) content of sediments (Binford 1990). For sediments deposited within the last 45,000 years, we can assign ages by measuring the radiocarbon (^{14}C) content of organic matter preserved in sediment layers. To date sediments beyond 45,000 years in age, we can use paleomagnetics, thermoluminescence, and tephra (ash layers ejected by local and far-off volcanic eruptions) deposits of known ages. After determining the age of the sediments as a function of depth, we analyze the fossils and chemicals from past plants and animals that are stratigraphically archived and available to understand the nature and timing of environmental changes of the past (Figure 2).

In this article, we highlight scientific tools and methods we are using to understand the climate

Figure 1. The lake coring process. A hole is drilled through the ice and a coring platform and a winching apparatus is placed above the hole. Sediment cores are extracted from the lakebed and extruded from the corer for later analysis in the laboratory.
SKYDANCE AVIATION/SCOTT AMY

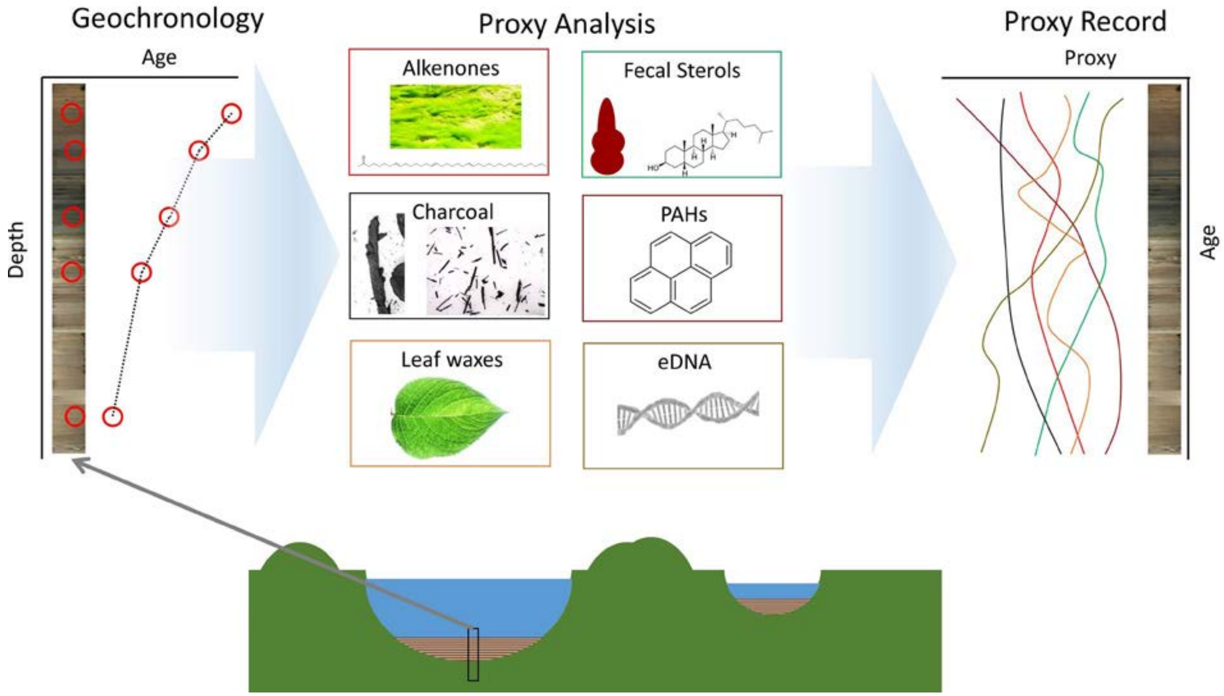

Figure 2. Summary of paleoenvironmental analysis of lake sediment records. First, the age-depth relationships of sediment cores are established using geochronological techniques. Next, proxies in the sediment, such as alkenones, fecal sterols, charcoal, polycyclic aromatic hydrocarbons, leaf waxes, or eDNA, are analyzed to develop proxy records. These proxy records are then used to infer how climatic and/or environmental conditions have changed through time.

and ecological history of Arctic Alaska. We have recently collected lake sediment cores from two lakes, Imuruk and Whitefish, in Bering Land Bridge National Preserve in northwest Alaska (Figure 3), to determine how temperature, plant ecology, and water chemistry have changed on the Seward Peninsula in the geologic past.

The lakes where we collected sediment cores are *maars*, meaning they formed when volcanic activity superheated ground ice or groundwater in permafrost terrain, building up pressure and eventually causing an explosion that formed the lake basin (Shackleton 1982, Begét et al. 1996). The exact ages of these lakes are debated, but recent evidence indicates that Imuruk may be more than 200,000 years old (Shackleton 1982, Burgess et al. 2019), meaning its sediments would offer the longest terrestrial sedimentary record of environmental change in Alaska from lakes and ocean sites (the ocean around the Bering Strait has no sediment during glacial times due the sea level drop and exposure). Imuruk may also have sediments older than most nearby marine records. To our knowledge, only one marine record, Integrated Ocean Drilling Program site U1343 on the Bering Sea shelf, contains sediments older than the last Glacial Maximum ca. 21,000 years ago (Westbrook 2014). However, even site U1343 sediments are limited to 150,000 years in age (Westbrook 2014), making Imuruk a truly exceptional archive. Our preliminary geo-chronological data from Whitefish Lake suggest it may have one of the highest sedimentation rates of all Alaskan lakes, which would offer one of the highest-resolution paleoenvironmental records in this region.

We hope that these sediment records can answer some very important questions about Alaska's environmental history. These questions include: How has Alaska's climate varied over time? How do

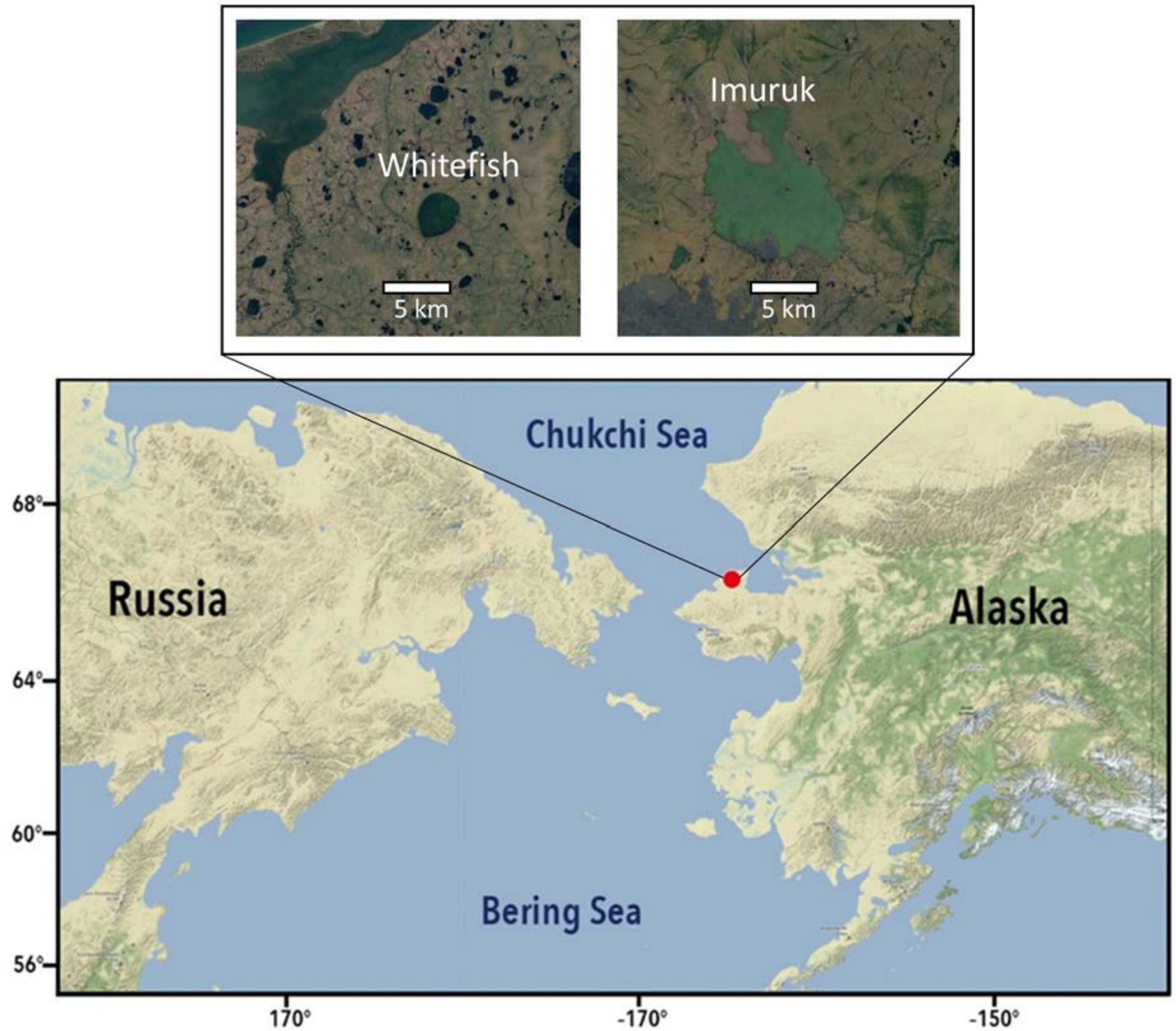

Figure 3. Location of study site. Insets depict aerial views of Whitefish and Imuruk lakes. [Map adapted from Wang and others 2019.]

fire regimes respond to climate variability? How do subsistence resources respond to climate changes? When did the first Americans arrive to Alaska and what was their impact on the environment?

How has Alaska's climate varied over time?

There are several organic compounds preserved in lake sediments that can be used to reconstruct climates of the past. Alkenones are a class of organic molecules produced by certain algae living in these lakes (Wang et al. 2019). Alkenones are stable, or slow to degrade, and can be preserved for millennia in lake sediments. The relative amounts of different alkenones produced by these algae depend upon the water temperature of the lake during spring algal bloom (Longo et al. 2016). By measuring the relative concentrations of different alkenone molecules preserved in individual lake sediment horizons, we can reconstruct spring temperature changes.

Leaf waxes are another class of organic compounds preserved in lake sediments that can be measured to reconstruct past climatic conditions. Plants use leaf waxes to help conserve water and protect their tissues and their chemistry records the environmental conditions that the plant was exposed to (Eglinton and Hamilton 1967). Leaf wax compounds are composed of hydrogen and carbon atoms that originate from the water the plants take up, and the isotopic composition of water varies with climatic factors (e.g., wet versus dry time periods, temperature). By measuring the isotopic composition of plant leaf waxes preserved in lake sediments, we can reconstruct changes in climate (aridity) over time.

By reconstructing the climate, we can gain a better understanding of how climate in Alaska responds to external forcings, such as insolation or greenhouse gases, and we can assess the abnormality of rates of change for climatic changes like temperature and aridity. This is especially important in Alaska, where reliable instrumental records are far apart and brief relative to other places in the world. Using alkenones, we hope to extend the temperature record of this region past the earliest instrumental records. Additionally, by reconstructing climate, we can better understand ecosystem sensitives to changing climate by comparing our paleoclimate records with paleoecological data.

How do fire regimes respond to climate variability?

Wildfires produce numerous byproducts that can be preserved in lake sediments and used to reconstruct fire history. Charcoal particles produced by wildfires are transported to lake sediments by wind and water (Higuera et al. 2007, Vachula et al. 2018). By sieving lake sediments, we can isolate these tiny particles (greater than 125 microns in size; about the thickness of a human hair) and count them under a microscope. The changes in charcoal particle accumulation over time are a record of fire history. Like charcoal, polycyclic aromatic hydrocarbons (PAHs) are molecules that are produced by fire and preserved in lake sediment records (Argiriadis et al. 2018, Denis et al. 2012, Vachula et al. 2019). Total PAH abundance reflects fire activity and the relative amounts of different PAHs offer information about fire severity and the type of vegetation burned (conifers, deciduous plants, or moss; McGrath et al. 2003, Oros et al. 2006, Oros and Simoneit 2001a and 2001b,Yunker et al. 2002). In combination with the climate records reconstructed from alkenones and leaf waxes, these fire markers are used to infer how fire respond to climate.

Recent boreal forest and tundra fire seasons in Alaska have been particularly severe and are thought to be driven by increasing temperatures and aridity (Young et al. 2017). However, given the limited number of observational records, our understanding of fire-climate relationships could certainly be improved. For example, in 2007, the Anaktuvuk River Fire burned more than 250,000 acres (100,000 ha) of tundra on the North Slope of Alaska (Jones et al. 2009). At the time, it was thought that this fire was unprecedented (Hu et al. 2010, Higuera et al. 2011, Mack et al. 2011). But then researchers discovered that two similarly sized fires had burned on the supposedly fire-free North Slope between 1880 and 1920 (Jones et al. 2013). These new results suggest that fire activity may have been more common in the past than previously thought. It also suggests that the temperature sensitivity of tundra fires may be lower than what fire models predict (Higuera et al. 2009, Young et al. 2017). Fire frequency is generally higher in tundra regions of western Alaska (e.g., Bering Land Bridge National Preserve) than on the North Slope (e.g., northern reaches of Noatak National Preserve or Gates of the Arctic National Park and Preserve; Racine et al. 1985, Sae-Lim et al. 2019), highlighting the need for regionally specific studies of fire-vegetation relationships (e.g., Racine et al. 2006). In this way, comparing tundra fire and climate reconstructions will be very helpful in understanding how fire activity, severity, and frequency respond to climate variability and change.

How do subsistence resources respond to climate changes?

Lakes provide crucial fish habitat, particularly for overwintering, rearing, and spawning. Anadromous fish species, such as salmon, are a critical component of both commercial and subsistence fishing throughout Alaska. Observation and modeling studies have predicted that as temperatures warm, subarctic fish may expand into Arctic waters (Fossheim et al. 2015, Wisz et al. 2015). However, the lack of long-term fish community records hinders our future conservation decision making because we have not observed this migration occur in recent decades. How did fish communities change on longer time scales in the Arctic before modern human intervention? Can we use past changes in the rate and extent of fish species migration as the basis to predict future changes and adapt to them accordingly?

Fortunately, similarly to alkenones, leaf waxes, and charcoal particles, DNA shed by fish and other organisms living in the lakes can also be preserved in sediment, even if there are no visible macrofossils present (Pansu et al. 2015). Those DNA fragments are called environmental DNA (eDNA) and are composed of DNA fragments from a variety of organisms living inside and nearby the lake. Recent advances in DNA sequencing techniques present unprecedented opportunities to identify the presence of macroorganisms using eDNA in lake sediments. After eDNA is isolated from the sediment, it is purified, then amplified by polymerase chain reactions (PCR). During amplification, specific primers are used to target and replicate DNA fragments belonging to a particular species or other taxa of interest. Then, the DNA sequencer returns massive DNA sequence data from the amplicons and, by comparing those sequences to a DNA library, we can identify which species contributed to the eDNA over time and reconstruct the ecology of the lakes. Though there are uncertainties regarding ancient eDNA preservation, studies in upstate New York have successfully recovered yellow perch eDNA in 2,200 year-old lake sediment sample (Stager et al. 2015). It is possible that eDNA in Alaska lakes can provide a time series of fish community change as well as information on other organisms.

When did the first Americans arrive to Alaska and what was their impact on the environment?

Beringia, the ancient landmass that connected northeastern Asia and northwest North America during episodes of lower sea level, is thought to be the pathway by which humans arrived in the Americas (Goebel et al. 2008, Hoffecker et al. 2014). However, the timing of this human migration is hotly debated in archaeology and anthropology (Vachula et al. 2019, Waters 2019). The existing paradigm suggests that humans arrived in the Americas via the Bering Land Bridge in the late-Pleistocene (ca. 14,000 years ago; Goebel et al. 2008, Waters 2019). However, recent genetic research has suggested humans arrived in Beringia much earlier, during the height of the last ice age (ca. 30,000 years ago), and lived there for several thousand years before migrating south into the continents (Hoffecker et al. 2016, Tamm et al. 2007). Importantly, there is no archaeological evidence that unequivocally supports this genetically-inferred early human presence in Beringia (Hoffecker et al. 2020). At other lakes on the North Slope, we found sedimentary, albeit not archaeological, evidence of ice-age humans as early as 32,000 years ago in the form of fecal sterols, polycyclic aromatic hydrocarbons, and charcoal (Vachula et al. 2019). Fecal sterols are a class of molecules that are produced in animal feces and can be preserved in lake sediments (Argiriadis et al. 2018, D'Anjou et al. 2012). Animals, including humans, have unique fecal sterol signatures, so the composition of fecal sterols preserved in sediments can offer insight into the presence of humans in the past. By measuring fecal sterols preserved in sediments, we hope to determine when humans arrived to our study area and, subsequently with the paleofire records, what their environmental impact was over time.

Conclusion

Lake sediment cores from two lakes in Bering Land Bridge National Preserve in northwest Alaska are valuable environmental archives that can be used to better understand the geologic past of the Seward Peninsula. By analyzing proxies preserved in the sediments, such as alkenones, fecal sterols, charcoal, PAHs, leaf waxes, and eDNA, we can reconstruct how climate, ecology, and subsistence resources have varied through time as well as deduce the early environmental impacts of humans in this region. In light of the increasingly pronounced impacts of anthropogenic climate change in Arctic Alaska, a more thorough understanding of the past is the key to understanding what we see in the modern and what we can expect for the future.

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Clues from Glacier Debris: Dating and Mapping Glacial Deposits Since the Last Ice Age in the Western Alaska Range

Joseph P. Tulenko and Jason P. Briner, University at Buffalo and Nicolas E. Young, Columbia University

Moraines are the footprint of past glacier positions and, if the age of the moraine is known, they can record the timing and rate of glacier change. Carefully reconstructed glacier histories are used as archives of past climate change. Cosmogenic isotope exposure dating is a new technique being used in the Revelation Mountains that could tell us about glacier and climate history of the Alaska Range.

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During the cold times of the last ice age—roughly 26,000-19,000 years ago (Clark et al. 2009)—glaciers in Alaska and elsewhere accumulated snow, growing to tremendous size, spilling out of mountain ranges and into adjacent lowlands. Ice-age glaciers worldwide, although now gone or reduced in size, left behind signs of their former selves including moraines.

Glaciers act like bulldozers. *Moraines* are the piles of glacial debris (fine sediments like sand and mud, and large sediments like boulders) that were collected, transported, and deposited by glaciers. Moraines are features easily identified from the ground, on topographic maps, and from aerial images. Sometimes narrow, sometimes broad and lumpy, moraines are ridges of glacial debris draped over the landscape. For glacial geologists, moraines are an exciting archive of past glacier change, full of possibilities. Moraines are the footprint of past glacier positions and, if the age of the moraine is known, they can record the timing and rate of glacier change. In turn, carefully reconstructed glacier histories are used as archives of past climate change since glacier growth and decay are so closely coupled to climatic factors such as temperature and precipitation.

Here, we describe one cutting-edge technique for dating moraines, the challenges associated with using the technique, and how we are applying the method to a promising site in Alaska: the Revelation Mountains. Lessons learned from studying glacial deposits in the Revelation Mountains are valuable for understanding the glacial history of nearby parks and throughout Alaska more generally. Together with the iconic landscapes preserved in frequently visited parks like Denali, our research results can provide park visitors with important geologic context for currently retreating glaciers.

Evidence of past glacier advances throughout Alaska is abundant and has been noted for decades. In 1964, Thor Karlstrom published one of the first state-wide maps of surficial geologic deposits—including moraines—in Alaska. The map was a culmination of decades of careful and dedicated work by over 25 Alaska state geologists (Karlstrom 1964). Yet some of the earliest recorded observations and links between glaciers and the deposits they leave on the landscape date as far back as 150 years ago in Alaska (Blake 1867, Meehan 1884). Since that time, generations of glacial geologists have improved our understanding of the glacial record in Alaska through collaborative projects, workshops, seminars, and hundreds of scientific reports, papers, and maps. Maps of past glacier size across Alaska (e.g., Figure 1) are kept up to date (e.g., Kaufman et al. 2011) and made available for widespread use.

Past Glaciers and Climate

Evidence for multiple glacier advances occurring over the last ~2.5 million years exist all over the state of Alaska (e.g., Kaufman et al. 2011). Some of the

Moraine deposited in the North Swift River Valley of the Revelation Mountains, Alaska, located between Denali and Lake Clark national parks and preserves. The boulder-rich moraine ridge in the foreground crosses the valley floor and tracks up the side of the hill across the valley, highlighted with the white lines outside of the moraine with hash marks pointing inward.
UNIVERSITY AT BUFFALO/JASON P. BRINER

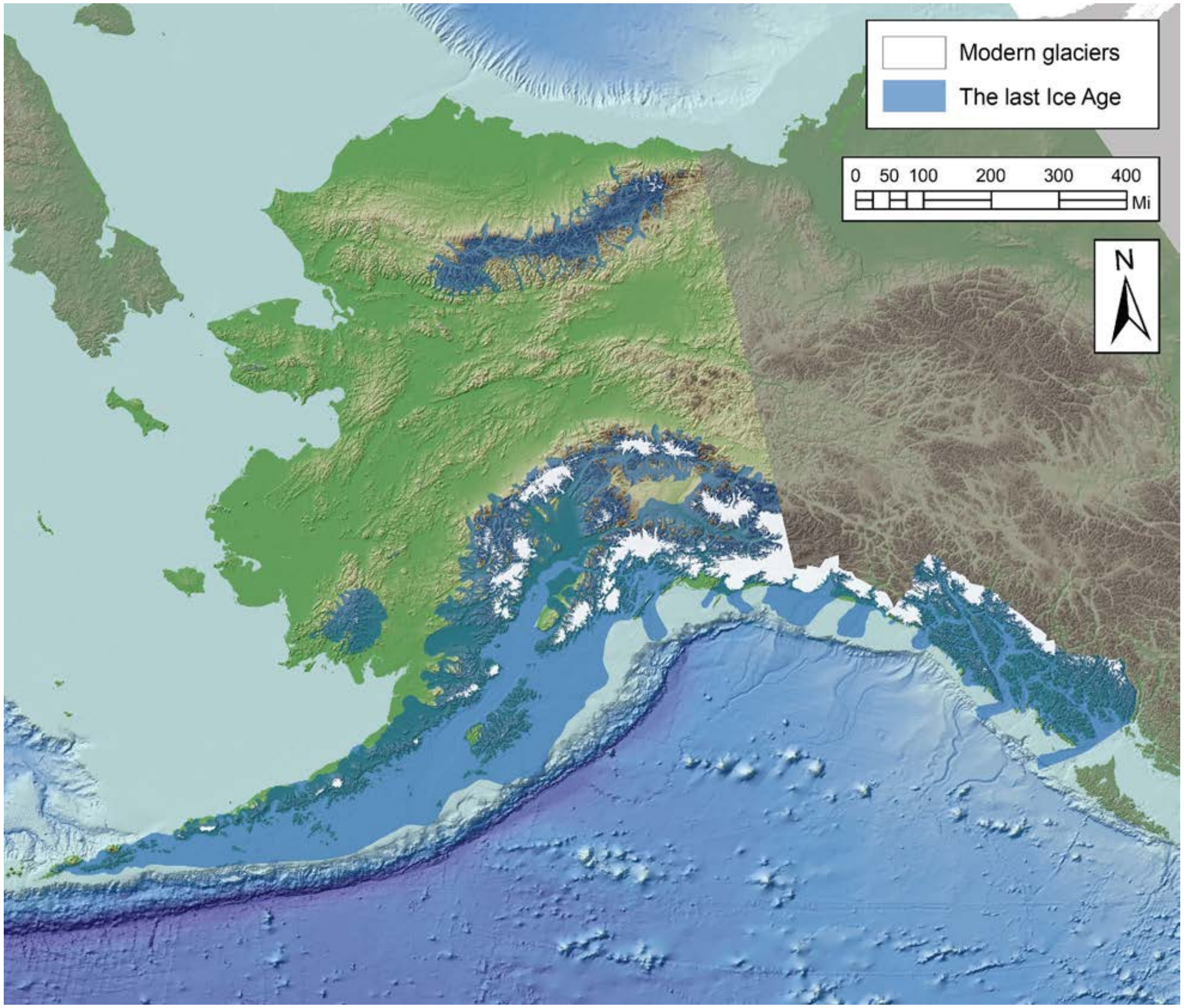

Figure 1. A map of glacial extents in Alaska now and during the last ice age.
ALASKA PALEOGLACIER ATLAS

best-preserved and, therefore, most easily observable deposits were formed during and following the last ice age (spanning in age from approximately 20,000 years ago to less than a few hundred years old). During the last ice age, temperatures in Alaska may have been 2-4 degrees (Celsius) colder than today (Viau et al. 2008, Kurek et al. 2009), and glaciers covered roughly 42% of Alaska (Kaufman 2011; Figure 1). Compare that to the roughly 3.5% of Alaska that is covered by glaciers today (Kienholz et al. 2015; Figure 1). Between the last ice age and present, from 19,000 to 11,000 years ago, the global climate warmed and glaciers in Alaska (and worldwide) underwent a period of substantial retreat. This episode of glacier retreat is referred to as the last deglaciation and is a key period in Earth's history. The last deglaciation provides glacial geologists with a natural experiment to see how glaciers behave when global climate warms significantly. Determining how glaciers responded to climate warming in the past provides essential insight into how glaciers will respond to climate warming today and in the future.

The key to reconstructing glacier histories is two-fold: (1) there needs to be meticulous mapping of glacial deposits to know where glaciers have been, and (2) there needs to be precise dating of those mapped glacial features to know when glaciers formed the deposits. Opportunities for continued glacial geologic mapping improvements arise as high-quality satellite images and geographic maps are frequently published. Examples include the [Arctic Digital Elevation Model] provided by the Polar Geospatial Center, which we used to make some of the maps in this paper. However, dating glacial deposits in the state, and worldwide, has only recently been seriously attempted (in the last 50 years or so). Furthermore, dating techniques for glacial deposits need to be exceptionally precise to make meaningful comparisons between past glaciers and other climate archives (such as ice core records from Antarctica and Greenland, ocean sediment records, and lake sediment records, among other archives), and it has only been in the last few decades that advancements to new dating techniques have made those comparisons possible.

Glacial geologists now use a technique known as cosmogenic isotope exposure dating to date moraines deposited during the last deglaciation and we have applied this technique in the Revelation Mountains of the western Alaska Range. This dating technique has been applied with varying degrees of success to other sites in Alaska—including Denali National Park and Preserve—(see Kaufman et al. 2011). Yet after two decades of research across the state, paired with continued improvements to field sampling and lab techniques, we believe that the Revelation Mountains site will provide the best chance of reconstructing a precise and complete post-ice age history of glaciers anywhere in the Alaska Range. The ultimate goal of this research is to use the information gained from studying past glaciers in the Alaska Range to improve our understanding of how and why glaciers in Alaska are responding to current climate change.

Cosmogenic Exposure Dating

Our planet is constantly bombarded with high-energy particles that originate from outside of our solar system, known colloquially as *cosmic rays*. These charged particles enter Earth's atmosphere with enough velocity that they strike gas atoms in our atmosphere and burst them apart, like a cue ball breaking racked balls at the start of a pool game. There is so much energy from cosmic rays entering our atmosphere that a giant chain reaction of atoms bursting apart and colliding with other atoms makes its way down to shower the Earth's surface. At this point, there is still enough remaining energy that particles in the atmosphere penetrate Earth's crust and burst apart some atoms that make up the minerals in rocks. The leftover pieces of atoms become new *isotopes* (a term used to distinguish atomic elements with a varying number of neutrons within their nucleus), referred to as cosmogenic isotopes. These *cosmogenic isotopes* accumulate over time in the surfaces of rocks exposed at Earth's surface at a relatively steady rate. The longer rock surfaces are exposed, the greater the accumulation of isotopes.

For cosmogenic isotopes to be a useful dating tool, there needs to be some sort of geologic event that exposes fresh rock surfaces from deep below Earth's surface so that cosmogenic isotopes may begin accumulating on that surface. In other words, there needs to be a "clock starter." Conveniently for glacial geologists, glaciers grind off previously exposed parts of Earth surface and expose new, fresh rock surfaces that do not contain any cosmogenic isotopes. Glaciers produce beautiful landscapes by carving broad valleys and fjords in mountain ranges, like so many of the iconic landscapes found in Alaska. To form moraines, glaciers collect and transport large boulders and sediments that are both plucked from below the ice and that fall from the steep, carved valley walls onto the glacier. In many cases, these sediments and boulders were not previously exposed to the surface prior to being collected by the glacier. Thus, once the glacier forms a moraine or retreats out of a mountain valley, fresh sediments and bedrock are exposed and the clock starts. In these new surfaces, cosmogenic isotopes begin accumulating and the isotopes on the rock surfaces build. After a long period of time, glacial geologists can collect surface samples from bedrock or from boulders sitting atop moraines and measure the amount of cosmogenic isotopes in those surfaces. From that information, we can calculate the time at which the glacier left those moraine boulders and bedrock surfaces behind by applying known rates of cosmogenic isotope production.

Challenges

There are a certain set of requirements when using cosmogenic isotopes to date moraines. In an ideal situation, a glacier would (1) build a moraine using freshly scraped boulders and other sediments, (2) leave that moraine exposed at the surface once it retreated, and (3) that moraine would then remain perfectly intact for millennia until a glacial geologist collects a sample (Figure 2A). However, glaciers do not always adequately grind down rock surfaces. In some regions on Earth (although not commonly in Alaska), glaciers move very slowly and fail to erode away all of the previously exposed rock surfaces. In this case, there might be leftover cosmogenic isotopes in rock surfaces. Extra cosmogenic isotopes in these rock surfaces would mean that ages appear to be older-than-expected (i.e., *inheritance*; Figure 2B).

Landscapes on Earth rarely remain perfectly preserved and, in fact, moraines slowly degrade through time. During that process, boulders sitting on top of moraines sometimes tumble over or rise from inside the moraine as mud washes away around them in a process known as *boulder exhumation*. These processes alter or delay the start of the cosmogenic clock and result in an incorrect age of moraine formation. The ages derived from these boulders appear to be younger than expected (Figure 2C).

The Alaskan landscape is exceptionally dynamic. Active faulting that causes earthquakes and landslides, the freeze-thaw cycle of the active layer in permafrost, and even volcanism all lead to enhanced erosion and degradation of relatively fragile landforms like moraines. Thus, moraine degradation is a serious issue for glacial geologists wishing to use cosmogenic isotope exposure dating in Alaska. For

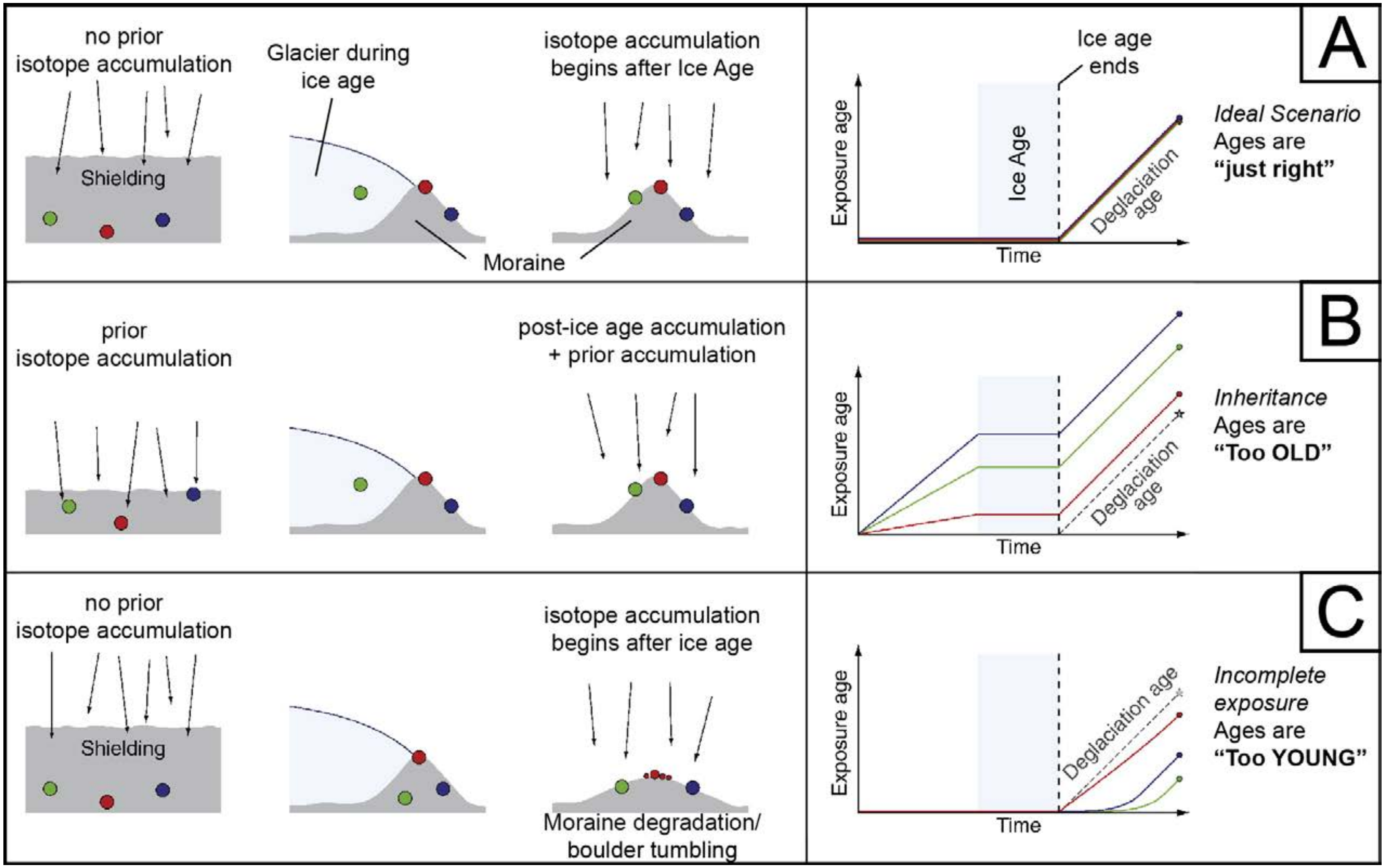

Figure 2. Different possible scenarios for cosmogenic exposure dating. (A) The ideal scenario is where a glacier removes any prior accumulated isotopes, deposits a moraine, and then the moraine remains relatively intact. (B) The inheritance scenario is where glaciers do not fully erode out the prior accumulated isotopes and ages from the moraine appear to be too old. (C) The incomplete exposure scenario is the largest challenge in Alaska. The glacier is sufficiently erosive, but after deposition, the moraine degrades, resulting in ages that are too young. [Figure modified from Heyman et al. 2011.]

this reason, although there have been many studies using cosmogenic isotopes in Alaska, results from moraine dating studies in Alaska vary.

Not all moraines are created equally. Typically, moraines contain a mixture of both large- and fine-grained sediments (e.g., Figure 3A). However, the composition of a moraine can range from almost completely boulder-sized sediments (i.e., *clast-supported moraine*; Figure 3B) to almost completely clay or mud-sized sediments (i.e., *matrix-supported moraine*; Figure 3C). While the rate of moraine degradation is dependent on environmental factors, the rate is also dependent on moraine composition. In other words, a moraine is more likely to degrade if it is mostly composed of fine-grained sediments instead of being mostly composed of large boulders. This has to do with the fact that fine sediments, like clays, trap ice (Figure 3C) and water. If the ice trapped inside a moraine were to melt, the moraine would not hold its shape but would slump or settle out (like the moraine depicted in Figure 3C). In contrast, moraines mostly built of large boulders do not trap ice very well and are less affected by slumping due to ice melt-out. That said, it is extremely valuable to find moraines on landscapes that appear to be more clast-supported (Figure 3A and 3B) than matrix-supported (Figure 3C), for it is these types of moraines that provide the best chance to sample boulders that have been stable throughout time.

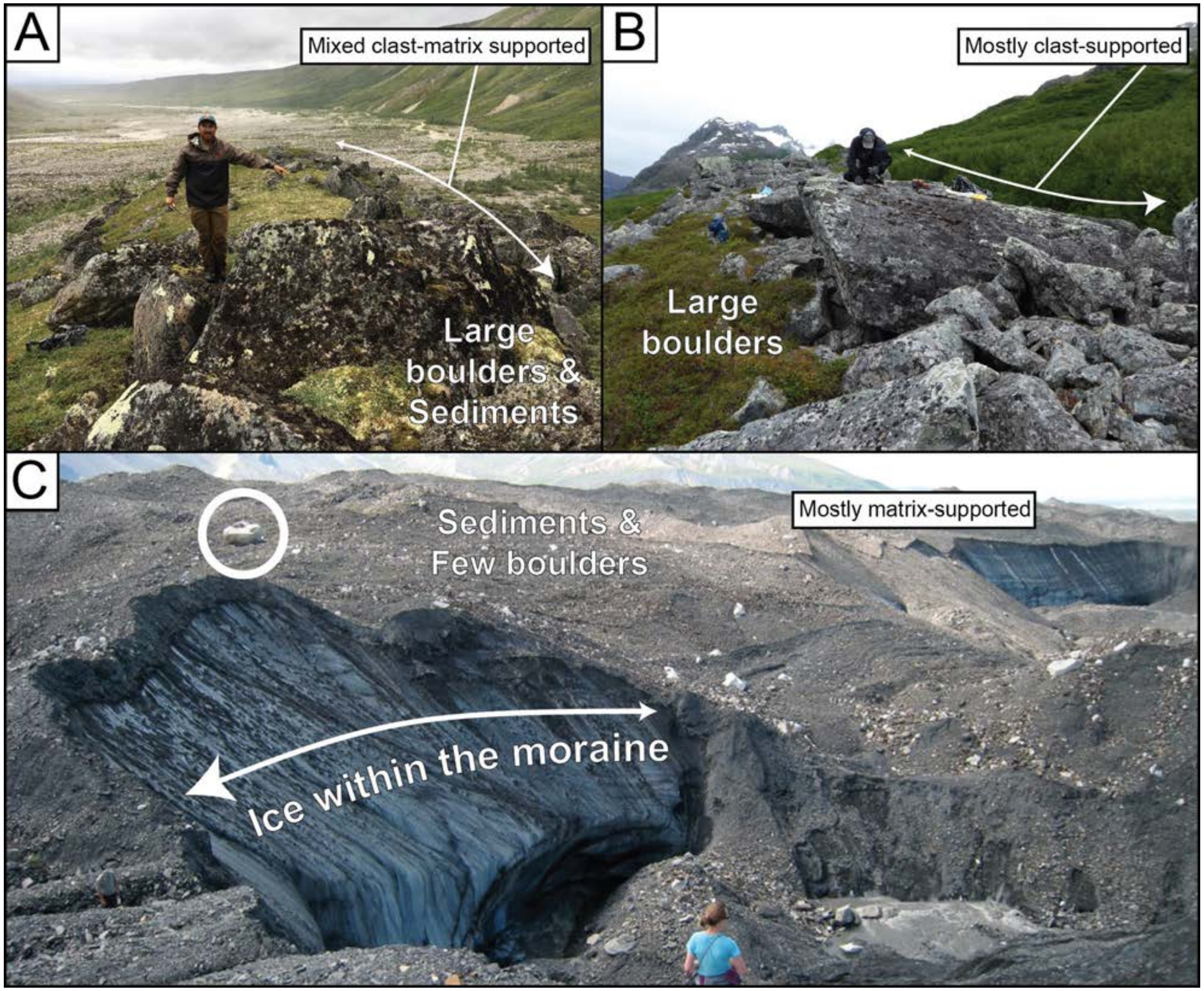

Figure 3. Different types of moraines. (A) Moraine from the North Swift River valley in the Revelation Mountains composed of soil and tundra lightly covering and surrounding mostly large boulders. (B) Moraine near Waskey Lake in the Ahklun Mountains completely composed of large-to-medium sized boulders (Young et al. 2019). (C) Moraine deposited by the Muldrow Glacier in Denali National Park and Preserve. Note the very few boulders sitting atop/within the moraine, which is composed primarily of fine-grained sediments. Note also the presence of glacier ice trapped within the moraine that will likely eventually melt out and cause the moraine to degrade even further. This ice is often referred to as "dead ice" and can result in erroneous moraine ages.
(A) UNIVERSITY AT BUFFALO/JASON P. BRINER, (B) AND (C) COLUMBIA UNIVERSITY/NICOLAS E. YOUNG

Ages from clast-supported moraines are more likely to represent the true date of moraine deposition.

For the past few decades, since near the time when cosmogenic isotope exposure dating was first applied to moraines in California (Phillips et al. 1990), glacial geologists have been attempting to use the method on moraines in Alaska (Kaufman et al. 2011). There have been a few successful attempts, but there have also been failures. Both have been critical to further our understanding. It has been only through these past attempts that glacial geologists have learned the importance of meticulously selecting moraines for dating *before* collecting samples. For example, moraines deposited in Denali National Park and Preserve by the Muldrow Glacier have significantly degraded because they are mainly matrix-supported, with only a few large boulders sprinkled throughout (Figure 3C). In addition, these moraines are located near the Denali Fault and may have degraded over time in response to the steady occurrence of powerful earthquakes. For these reasons, previous work has shown that cosmogenic isotope exposure ages from Denali National Park and Preserve likely do not represent the time when the glacier built the moraine, but rather multiple phases of moraine stabilization after the glacier had already significantly retreated (Dortch et al. 2010). While the popular landmark that attracts visitors worldwide is a stunning visual of how glaciers shape landscapes, glacial geologists have found that other sites in Alaska are more suitable for cosmogenic exposure dating.

The Revelation Mountains

Despite the previously mentioned challenges, some sites in Alaska do exhibit properties that more accurately record the timing of moraine formation. Glaciers existed in the Revelation Mountains during and following the last ice age, and the moraines these glaciers formed are preserved on the landscape. In the early 2000s, Dr. Jason Briner and his colleagues Dr. Darrell Kaufman, Dr. Al Werner, and others visited multiple sites across Alaska, including a site known as the Swift River Valley in the Revelation Mountains. They were searching for the ideal site to generate a precise glacier chronology for Alaska (Briner et al. 2005). This reconnaissance work produced some promising, yet incomplete, results. They found that unlike the moraines in Denali and elsewhere in Alaska, the moraines in the Revelation Mountains were less degraded and contained many large, stable boulders with moraines that were not predominantly matrix-supported.

Beginning in 2016, following more than a decade of continued research in Alaska, and improvements to both sampling and lab techniques by the global community of glacial geologists, our team revisited the Swift River Valley. The goal was to generate a reliable chronology of the oldest moraines from the last ice age to both demonstrate a successful application of cosmogenic exposure dating in Alaska and compare glacier change in Alaska to past climate. In the example shown in Figure 4, we found one moraine that was likely deposited sometime around 17,800 years ago based on four reliable exposure ages (note the two outliers that are significantly older than the rest; we suspect those are samples affected by inheritance). The rest of the moraine ages from that site may be found in Tulenko and others (2018). Since we were able to produce a well-constrained dataset from a collection of stable moraine boulders, we were able to discuss how Alaska's glacier history related to climate change. We found that even though global temperature and atmospheric carbon dioxide (CO_2) concentrations remained relatively low toward the end of the last ice age, glaciers in Alaska began retreating prior to some other glaciers around the world. We suggested this warming was due to steadily increasing solar radiation in the Arctic.

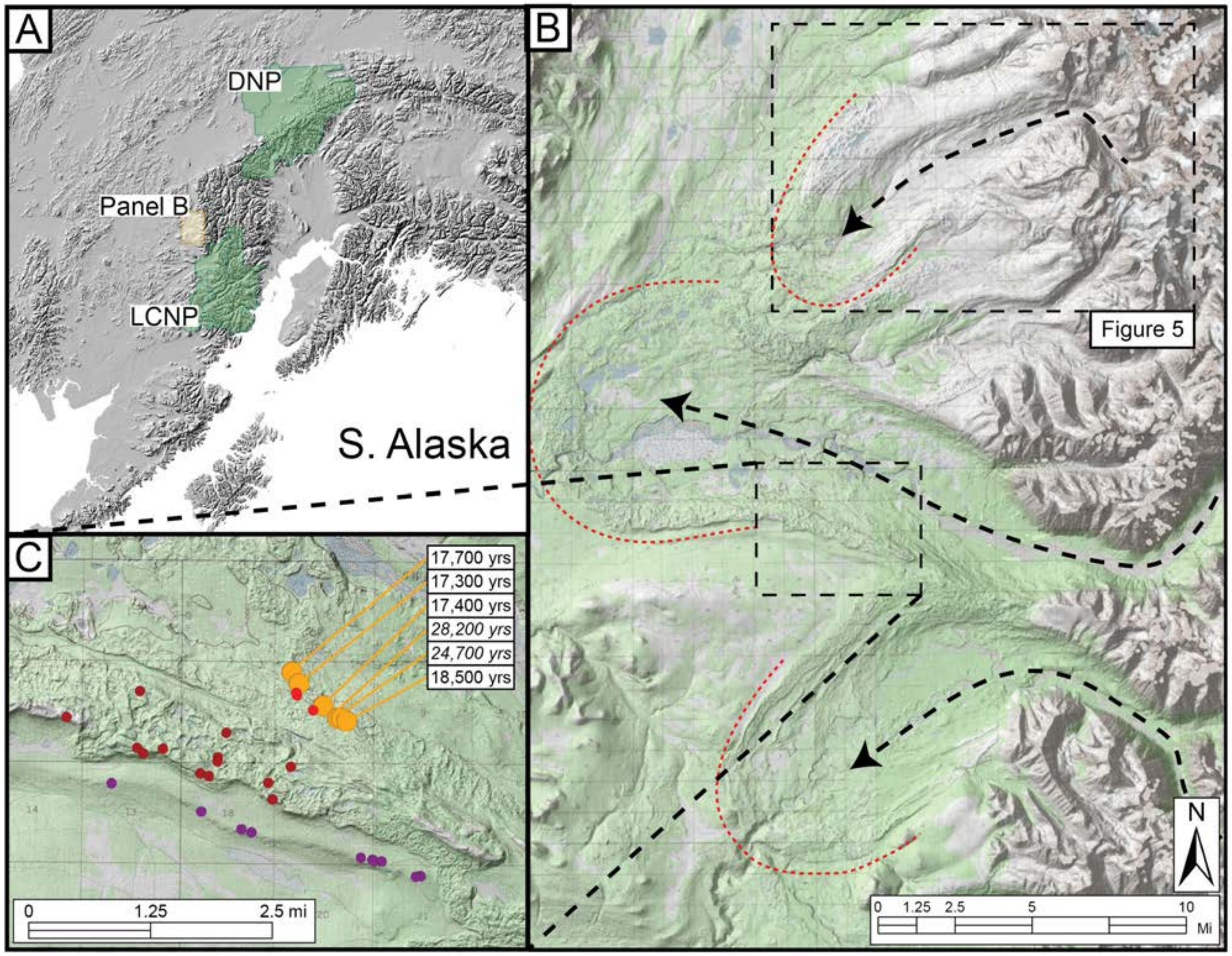

Figure 4. Clockwise from top left. (A) Hillshade image of Southern Alaska: DNP = Denali National Park and Preserve, The Revelation Mountains field site highlighted in yellow and shown in detail in Panel B, LCNP = Lake Clark National Park and Preserve. (B) Hillshade and topographic map of the Revelation Mountains field site: General ice flow directions in black dashed lines, and maximum last ice age extents of each glacier denoted by red dashed lines. The "rough" textures of the land surface seen in this map and zoomed image are moraines. (C) Zoomed image of lateral moraines lining the Swift River Valley: All samples collected in 2016 denoted by colored dots and an example of boulder ages on one moraine sampled in 2016 (four reliable ages and two ages suspected of showing inheritance that are italicized). See Tulenko and others (2018) for more details and ages on the other moraines at that site.
[Revelation Mountains field maps created from data freely available from the Polar Geospatial Center's ArcticDEM product overlain by a topographic map available from the ArcGIS online database.]

However, the dataset we produced is incomplete; we still do not know what happened to the glaciers in the Revelation Mountains through the last deglaciation. Was this relatively early retreat at the end of the last ice age sustained?

In the summer of 2019, we visited the Revelation Mountains once again. This time we had a second goal: to investigate the detailed retreat of a glacier following the last ice age. Our specific study glacier in the north Swift River Valley deposited multiple discrete moraines since the last ice age, and to date them, we collected surface samples from 79 boulders (Figure 5). Based on moraine mapping and the chronology generated from our 2018 paper, we hypothesize that these moraines were deposited sometime between the last ice age and today, with many deposited during the last deglaciation interval. As with the site we visited in 2016, we hope we will be able to precisely date these moraines. This time however, we hope to use the chronology to characterize the rate of retreat of this glacier through the last deglaciation. This will allow us to make a direct comparison between our glacier chronology and other climate records to determine exactly why the glacier—and glaciers across Alaska—retreated after the last ice age.

Summary and Future Project Directions

Although our work is ongoing, we hope to soon contribute data to help answer several big questions in the climate science community:

1. Is there one single mechanism of climate change (such as greenhouse gases) that controls how glaciers behave worldwide, or are Arctic glaciers different?

2. The last deglaciation was one of the most recent times in the geologic record that the climate warmed

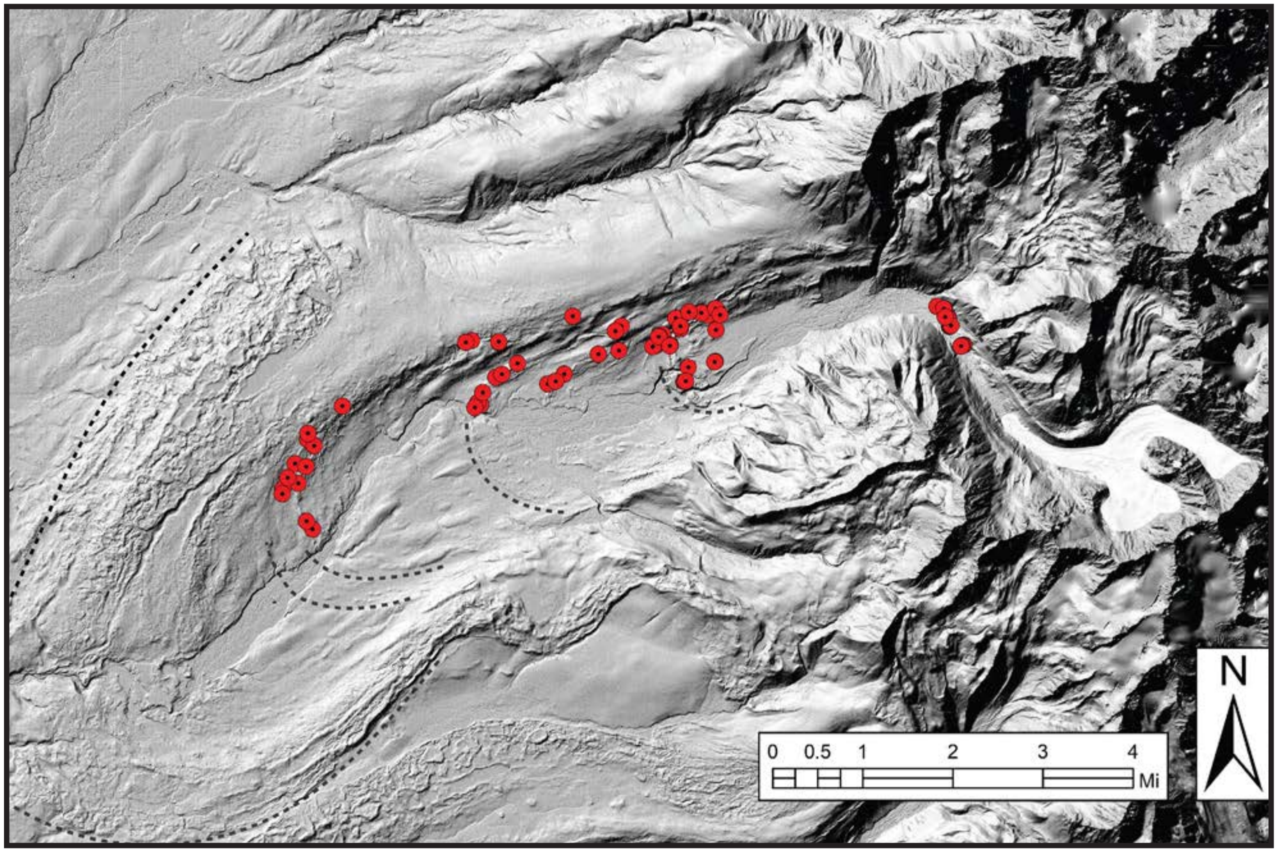

Figure 5. Samples collected from the north Swift River Valley in 2019. Sample locations for all 79 samples collected in 2019 in red dots and some major moraine crests in the valley highlighted with dashed lines. Modern glacier shaded in white. [Hillshade map created from data freely available from the Polar Geospatial Center's ArcticDEM product.]

quickly. How fast did glaciers in Alaska melt away during this interval?

3. Do these past changes provide some useful context and comparison to how quickly glaciers are currently retreating, and will continue to retreat, as the climate is once again warming rapidly?

There are precise records of glacier retreat during the last deglaciation for many sites across the globe, but not yet in Alaska. With this project, we aim to generate a retreat chronology with precision comparable to other chronologies elsewhere to determine if alpine glaciers in the Arctic behaved similarly to glaciers in other regions and what climatic factors caused these similarities or differences. We hypothesize that lessons learned from studying interactions between glaciers and climate of the past will provide valuable context for current and future warming and glacier retreat. Visitors to parks across Alaska are able to see firsthand how quickly glaciers are retreating. It is our hope that providing some geologic context will demonstrate why current glacier retreat is so alarming.

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N. Young (left) and J. Tulenko (right) sampling a large granitic moraine boulder for cosmogenic isotope exposure dating in the Revelation Mountains of the Alaska Range.
UNIVERSITY AT BUFFALO/JASON P. BRINER

High-definition Laser Scanning for Documenting Cultural Resources

John Wachtel, National Park Service

High-definition laser scanning is a recently adopted technology to collect highly accurate and detailed spatial data that can be processed into a three-dimensional digital model. It is a powerful tool to quickly and accurately document historical buildings and sites, which can facilitate conservation and restoration of these cultural resources.

Citation:
Wachtel, J. 2021. High-definition laser scanning for documenting cultural resources. *Alaska Park Science* 20(1): 20-27.

Historic American Engineering Record photograph with high-definition laser scan data overlaid.

The National Park Service's (NPS) Heritage Documentation program has been documenting historic sites for more than 85 years and the collection of drawings, photographs, and written histories has grown to more than 200,000 pieces stored at the Library of Congress. The Historic American Buildings Survey (HABS) was initiated in 1933 as the first of the three Heritage Documentation programs and as a "make work" program for unemployed architects and draftsmen. The objective of the HABS program was to document structures that represented American history through accurate line drawings. Using tape measures and building levels, documentation teams spent weeks measuring buildings to within 1/8" accuracy (Figure 1). The field notes would be transcribed onto ink on Mylar or vellum providing accurate plans, sections, elevations, and details of the subject building. The Heritage Documentation Program expanded in 1966 to include the Historic American Engineering Record (HAER) and in 2000, the Historic American Landscape Survey (HALS). As their names suggest, HABS focuses on documenting buildings and structures, HAER records sites and structures related to engineering and industry, and HALS documents historic landscapes.

Figure 1. A HABS team taking dimensions in 1934.
LIBRARY OF CONGRESS, PRINTS & PHOTOGRAPHS DIVISION, KY-20-19-7

Documentation Advancements

The process to document historic sites has evolved in recent years with the introduction of new tools and technologies. One of the most notable advances occurred with the introduction of Computer Aided Drafting (CAD), making it possible to transfer field notes into digital files and expanding the potential uses for drawings.

More recent technological advances include High-Definition Laser Scanning, which greatly increases the amount of information that can be acquired on site. High-Definition Laser Scanning (or laser scanning) is the process of collecting highly accurate and detailed spatial data resulting in a three-dimensional (3D) digital representation of the site or structure, commonly called a *point cloud*.

Some sites may pose safety concerns with traditional documentation methods. Others may require teams of multiple people and several site visits to obtain the basic information necessary to begin documentation. In some cases, laser scanning may address both issues. The speed at which data can be collected (thousands, even millions of points per second), paired with long-range scanning (up to 300 m depending on make and model) means that the operator can collect more information from safer vantage points.

Of course, with the increased ease of data collection comes the need to process, manage, and store all those data back in the office. Processing data generally requires a desktop computer with relatively high-end specifications. Solid-state hard drives (SSDs), a central processing unit (CPU) with as many cores as possible, a minimum of 32 gigabytes (GB) of random access memory (RAM), and a dedicated graphics card with a minimum of 2 GB of video RAM (VRAM) are all recommended. Depending on the computer used for processing and skill level of the user, the amount of time spent in the office may be double what is spent in the field collecting the data. The amount of storage space required to process a project can vary, but averages around 50-100 GB. Understanding the processing demands as well as the storage requirements may help inform the scope of a project.

Laser Scanning, a Treatment?

Although there are many benefits of conducting laser scanning for documentation purposes, it should not be thought of as a preservation treatment itself because it is only collecting information. Simply laser scanning a building does little to preserve it. It is simply data on a flash drive until it can be processed back in the office. Having a plan for the data is critical to producing meaningful and useful documentation that captures the character-defining features of a site or structure that can then be used for preservation, maintenance, and interpretive purposes. Laser scan data can become meaningful documentation through a process of informed interpretation using CAD software, and in turn that documentation can be used to facilitate treatment.

Why Drawings?

Production of a set of architectural or interpretive drawings using CAD is still the gold standard for documentation. Drawings are a simple and convenient way to communicate general and specific information in a format that has well-established standards. There is relatively little effort and cost required to read a set of full-size architectural drawings, when compared to the computer hardware and software requirements necessary to interpret laser scan data on the computer in a meaningful way. Additionally, when plotted on materials such as vellum and stored appropriately, drawings can far outlast digital files, which tend to have a much shorter shelf life.

Drawings from point clouds are the result of careful review and classification of the scan data (Figure 2). Using specialized software, drafters are able to isolate certain portions of the data, making it easier to visualize. From there, a process of tracing key features with clean vector line work begins. Vector images are different from raster images in that they can be scaled to any size without losing quality, as opposed to raster images that have a fixed resolution and lose fidelity when scaled up. Once completed, the line drawing provides a crisp, legible, and accurately scaled representation of the subject.

Added Benefits

Traditional HABS/HAER/HALS documentation projects produce a set of drawings, large format photography, and a written historical component. Each component contributes important context to the other, resulting in a comprehensive resource for managers, facility and maintenance staff, architects, historians, students, and stewards of historic properties.

In addition to the pairing of CAD and laser scanning, additional products can be derived alongside the traditional drawings. These include scaled orthographic images of the point cloud, rendered flythrough animations, 3D models, and virtual or guided online tours. When produced individually, these products tend to have a shorter shelf life, but can increase exposure, awareness, and understanding of the resource.

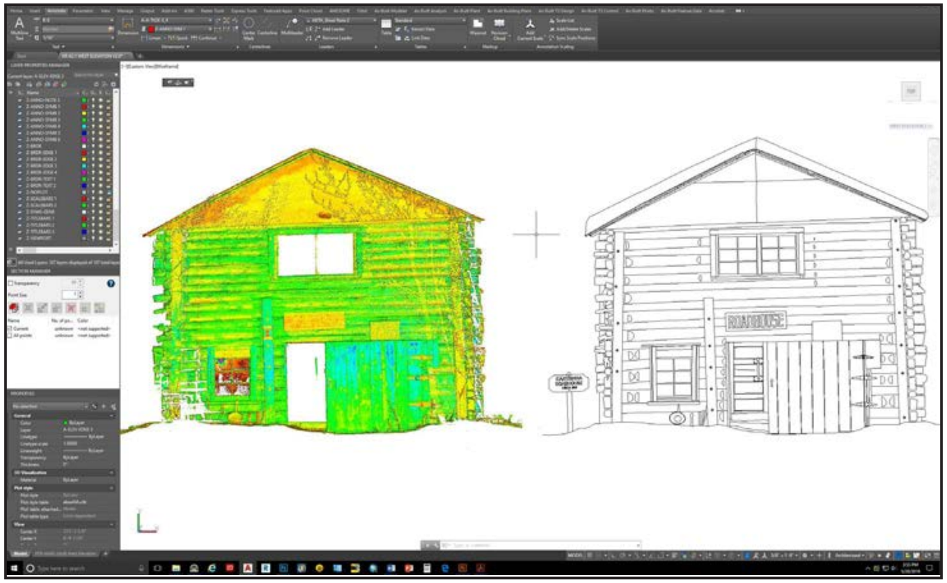


Figure 2. West elevation of the Kantishna Roadhouse in Denali National Park and Preserve (built from 1919-1920). The point cloud is brought into CAD software and cropped in various ways to isolate specific elevations and details. A draftsperson can then trace over the features of the point cloud, creating a line drawing. The line drawing is more legible than a point cloud, which is best viewed using computer software to rotate and examine from all angles.

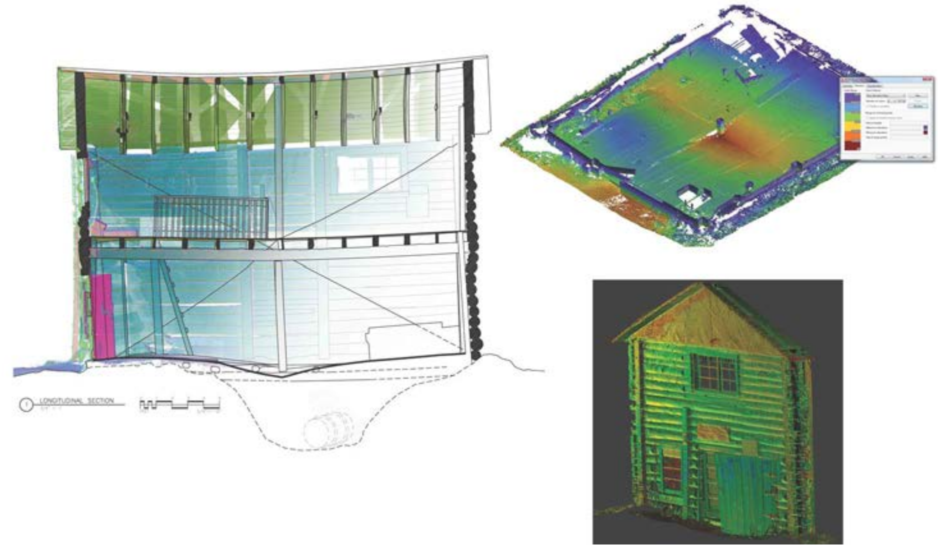


Figure 3. Kantishna Roadhouse CAD and Scan Data. Clockwise from left: Longitudinal section through point cloud with an overlay of the line drawing; Point cloud shown isolating the ground floor and its deflection using a colorized elevation ramp; Point cloud showing the west elevation of the roadhouse.

Sample Projects

Kantishna Roadhouse

In the spring of 2017, high-definition laser scanning was conducted on the Kantishna Roadhouse (Figure 3), located within Denali National Park and Preserve (built from 1919-1920). The building is a significant example of the exploration and settlement theme from early twentieth century Interior Alaska. The project objectives were to obtain laser scan data of the building and surrounding site in order to produce a set of architectural drawings to HABS standards.

Located near the end of the Denali Park Road, the remote setting provided some unique challenges. The project originally called for two days of scanning on site, but this time was reduced to one day due to weather conditions. The ability to scan at high speeds and high resolutions affords flexibility in these situations.

In normal scenarios, multiple scans at multiple resolutions are acquired in order to reduce the number of unnecessary points collected, reserving the higher-resolution settings for the focal subject. By being selective of the data acquired in the field, overall file size is reduced and time is saved back in the office. However, if time becomes limited in the field due to unforeseen circumstances, such as inclement weather, the technician has the option in the field to modify the collection method in favor of time. Processing the data back in the office may take slightly more time and effort as a result of the increased file sizes, but this is likely more cost effective than planning a second site visit.

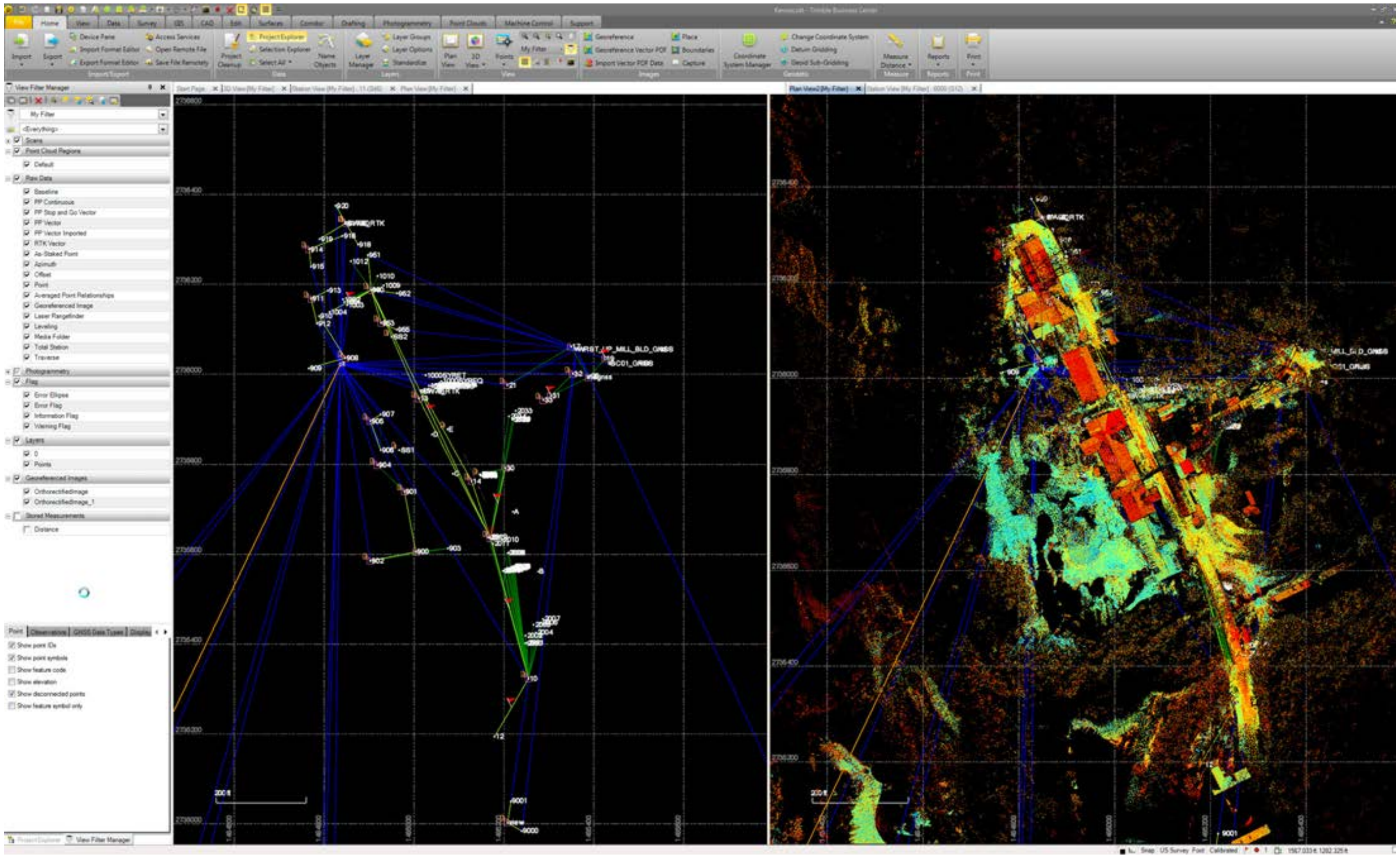


Figure 4. Overview of the combined dataset for the Kennecott Mill Site. The overall site shown here is approximatley 50 acres, with the mill site occupying approximately 15 of those acres. Data on the left side shows the scan positions and RTK (Real Time Kinematics) vectors for the site. The right side shows the scan data overlaid. This project was tied to real-world coordinates using Survey Grade GPS and a local Bureau of Land Management control network.

Kennecott Scanning Effort

In the fall of 2017, a pilot project was initiated by a multidisciplinary team, in partnership with Trimble, Inc. and local survey company Frontier Precision. The project sought to test the capabilities of two laser scanners at the Kennecott Mines National Historic Landmark (NHL) site, located within Wrangell-St. Elias National Park and Preserve. The NHL includes the Kennecott mill town, a sprawling collection of structures built for the purposes of processing copper ore and sustaining a workforce necessary to accomplish this task in a remote location. Five objectives were set and prioritized for a three-day on-site survey: General survey and scan of (1) the mill building from street level, (2) the upper tram deck, (3) ore chute, (4) interior spaces, (5) and adjacent glacier. The mill site spans nearly 15 acres of complex terrain and provides generally narrow line of sight corridors, which required careful planning by the team to make the most of the time available on site.

The equipment being evaluated was the Trimble SX10 Scanning Total Station and the Trimble TX8 3D Laser Scanner. The remote setting of the location, combined with the scale and topography of the site, presented an interesting challenge and opportunity to put the devices to the test. While the SX10 excels at long range, the TX8 excels at speed and high-resolution scanning. By incorporating both units on the same project, the team was able to register and compare the resulting data while still in the field and present their findings to park staff.

The project resulted in a successful achievement of all five objectives, as well as a satisfactory evaluation of the benefits and drawbacks in certain applications for both devices (Figure 4). The pilot project also served as an extreme example of what a documentation project could attempt. The objectives were broad and ambitious by design in order to produce a widely applicable technique that could be adopted by a range of professionals and modified for various sites and scenarios.

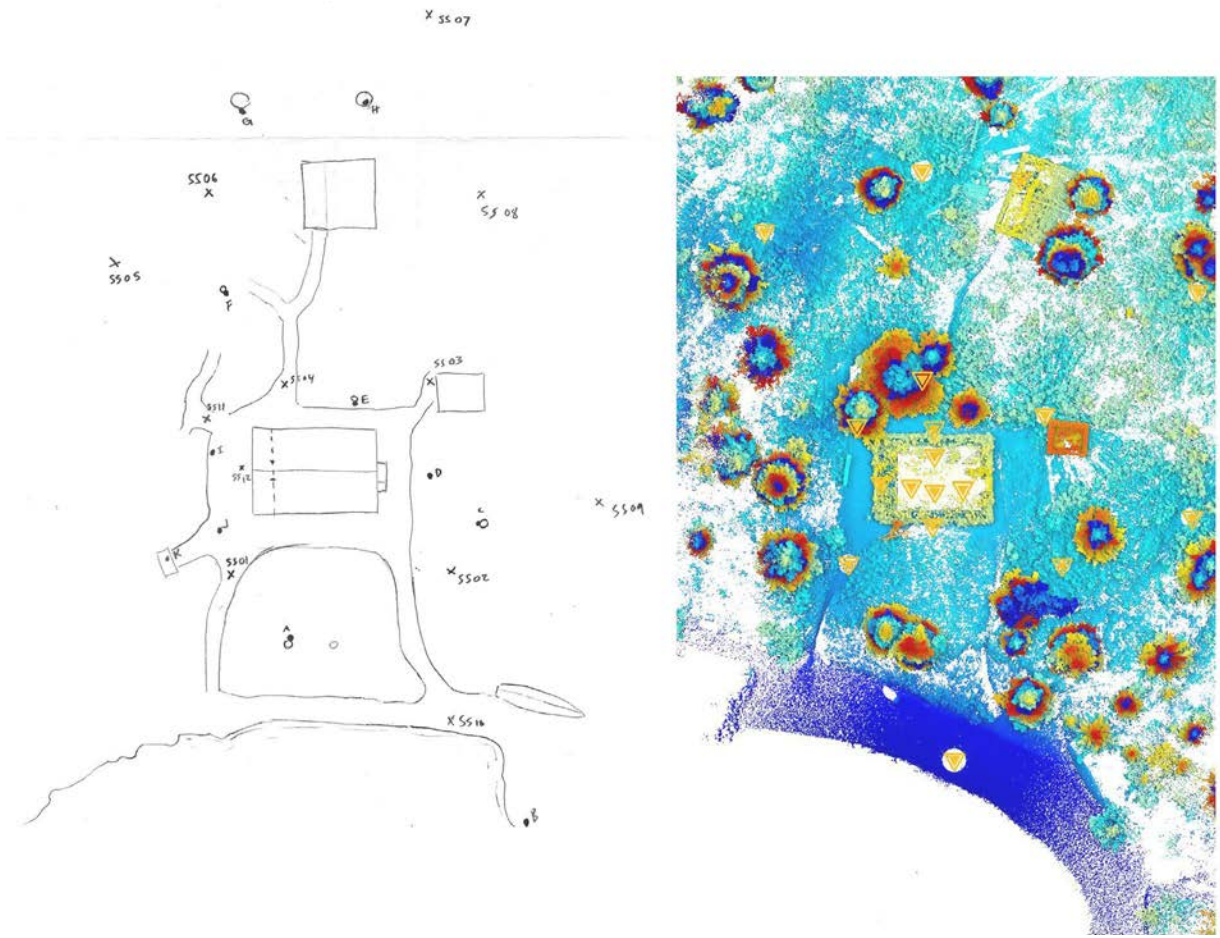


Figure 5. Site plans of the Richard Proenneke Cabin and Site, located in Lake Clark National Park and Preserve. This image compares the field sketch of the site, which includes the planned locations of scan positions and targets. This facilitates both fieldwork and data registration back in the office. The right image shows the final registered data in plan view using an elevation-based color scheme.

Richard Proenneke Cabin and Site

While high-speed scanning is certainly useful in reducing time spent on site, it does not help if you are unable to get to the site itself. In order to document the Richard Proenneke cabin and site located on the shore of Upper Twin Lake within Lake Clark National Park and Preserve, transportation by float plane is required.

The size and amount of equipment necessary for conducting laser scanning has decreased over the years, and is now at a point where the bare minimum equipment required is the scanner itself (in a 50-pound hard case) and a survey tripod. For certain projects, targets are also set up around the site to assist in the alignment of different scan positions. However, if significant overlap exists between scans, then alignment can be achieved without targets. For the Proenneke project, targets were used as a backup for alignment, but were only needed to align interior and exterior scan data (Figure 5). Due to the relatively small amount of equipment needed (compared to earlier versions of this technology), regional transportation such as float planes can be used without exceeding weight and space limitations.

St. Nicholas Chapel

The NPS Alaska Regional Office's Heritage Assistance Program (HAP) provides technical assistance to stewards and owners of historic properties listed, or eligible for listing, on the National Register of Historic Places. Often these stewards of historic buildings are pursuing funding grants to assist preservation work and these groups may not possess baseline documentation or condition assessments for these resources, which is typically required for grants of this nature.

Working with the non-profit ROSSIA, Inc. (Russian Orthodox Sacred Sites in Alaska), an organization dedicated to the preservation of Alaska's Russian Orthodox Churches and iconography, the HAP staff provided technical assistance in the form of laser scanning (Figure 6). During the fall of 2017, high-definition laser scanning was conducted on the Holy Assumption Russian Orthodox Church and nearby St. Nicholas Chapel, a National Historic Landmark site in Kenai, Alaska.

Scanning was conducted in a single afternoon while driving to a professional conference in Homer, Alaska to present on laser scanning. The ability to conduct laser scanning documentation within existing travel highlights potential cost savings, as well as the mobility of the equipment. Not only was the dataset useful for ROSSIA in applying for a Historic Preservation Fund grant the following year, but they were also incorporated into the presentation for the conference the following day. The scan data of the St. Nicholas Chapel helped to estimate material costs, provide accurate dimensions for developing schematic drawings, and facilitate planning efforts for the re-roofing of the historic chapel.

Figure 6. Laser scan data of the St. Nicholas Chapel in Kenai, AK. This section cut of the chapel highlights the unique roof construction and facilitated the planning efforts to maintain character defining features, such as the exposed rough sawn skip sheathing inside.

A Powerful Tool

The use of high-definition laser scanning to document historic resources has proven a powerful tool in the field and in the office. Benefits include high speed, long range, sub-millimeter precision, and ease of operation in the field. Drawbacks include high upfront cost, demanding computer resources, and significant time spent processing the data before production of drawings can begin.

There is also a difference in how the resource is experienced by the team when in the field. Traditional hand measuring techniques generally require three people (one to hold the tape at zero, one to call out the dimension, and one to record), whereas scanning can be conducted by a single person. Having multiple individuals on site allows the team to split up after measurements are taken and collect profile details of windows, doors, and other small-scale features. These features are best measured by hand while in the field using a profile gauge (Figure 7). With laser scanning, these smaller-scale features may not be captured satisfactorily from the distances that are typical for exterior scanning. The method used to collect information in the field has an effect on the collector's ability to recreate it in the office. For this reason, there is a balance that must be struck between the tools used to collect the data and the time and staff available to conduct the work.

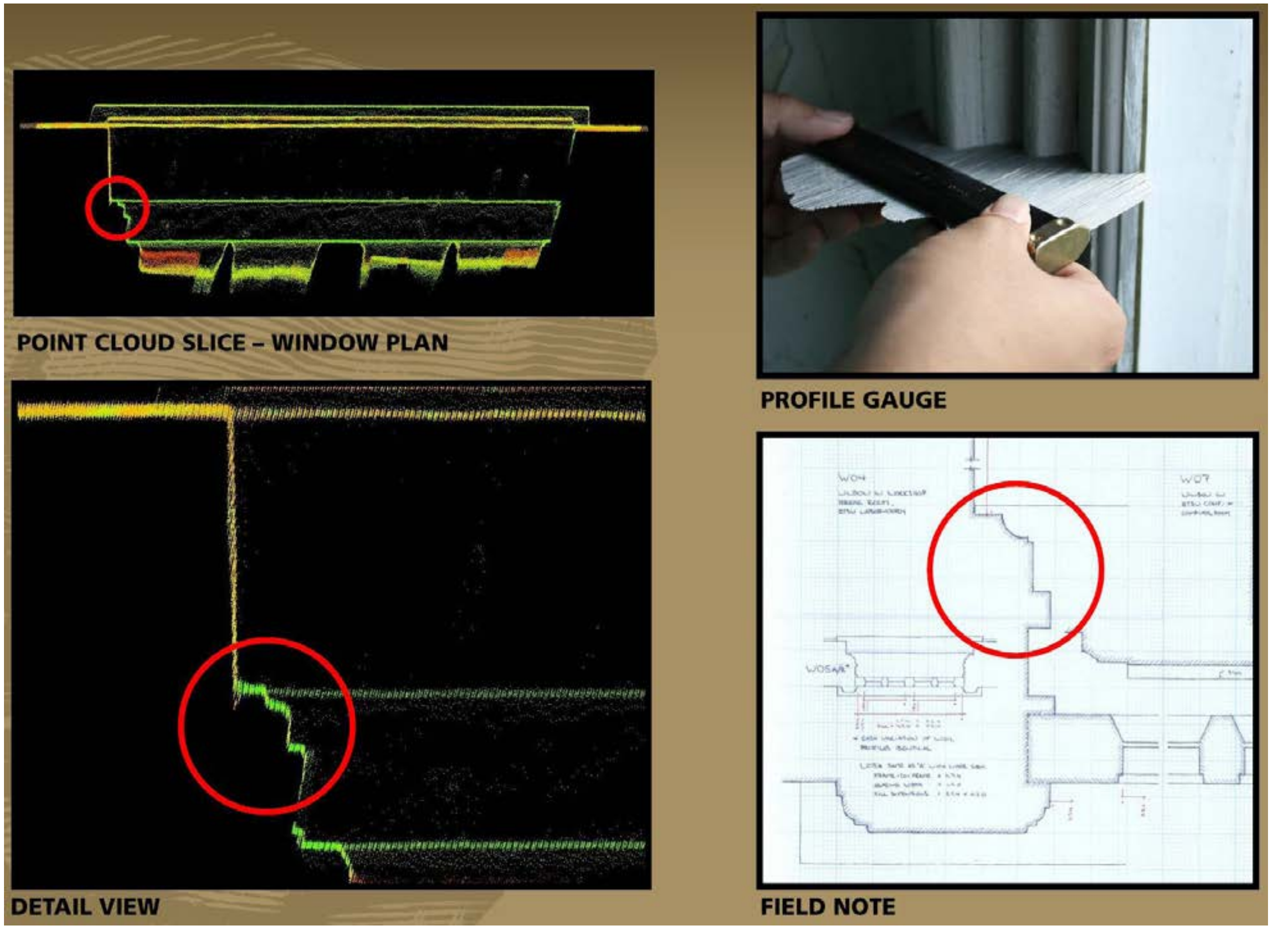


Figure 7. Capturing small-scale details such as window and door profiles will often require supplemental field measurements using a profile gauge and transferring to a field sketch for later reference alongside the scan data. Field photographs are also critical in providing context when drafting in CAD.
NPS/HERITAGE DOCUMENTATION PROGRAMS

Unmanned Aerial Systems as a Tool for Natural Resource Applications

Jamie N. Womble, Parker Martyn, and Britta Schroeder, National Park Service

The use of unmanned aerial systems (UAS) is rapidly expanding as a tool for resource management. Employing UAS to collect data can result in more accurate mapping, decreased cost, and increased personnel safety. Applications of UAS in Alaska parks are demonstrating the benefits and defining best practices for its continued and enhanced use.

Citation:
Womble, J. N., P. Martyn, and B. Schroeder. 2021. Unmanned aerial systems as a tool for natural resource applications. *Alaska Park Science* 20(1): 28-35.

Unmanned Aerial Systems (UAS) have emerged as valuable tools for natural resource management, science, and geospatial applications. UAS are unoccupied aircraft that are controlled by a combination of a radio-linked interface and an onboard autopilot. UAS can be used in lieu of manned aircraft to collect natural resource data, increase safety, reduce costs, and provide an aviation resource where manned aircraft may not be appropriate, available, or able to fly. UAS missions can be accomplished through a variety of ways, including using fleet operations, contractors, and through partnerships with universities or federal and state agencies.

In June 2014, the National Park Service (NPS) Director issued Policy Memorandum 14-05, which outlined the use of UAS for administrative or research purposes. Since 2016, parks and NPS programs in Alaska have used UAS to inform science, natural resource monitoring, and provide park managers with information for decision making. The advantages of UAS technologies are especially promising in the NPS mission areas of inventory and monitoring (I&M), natural and cultural resource management, law enforcement, and search and rescue. By developing UAS capabilities in these areas, the NPS can inform decisions to better understand and protect park resources and values.

Benefits of UAS as a Tool

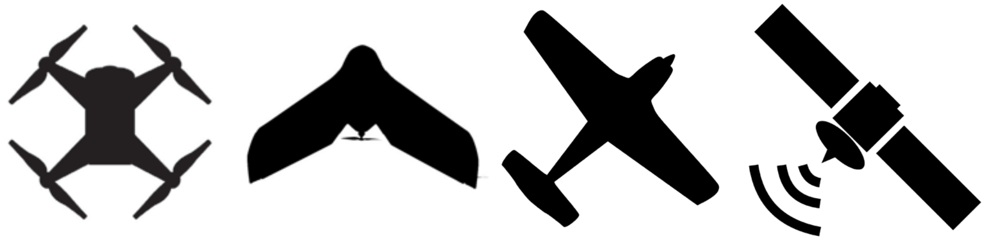
Platforms for collecting remotely sensed data include satellite, occupied aircraft, and UAS (Table 1). Factors to optimize platform usage depend upon the question of interest, geographic scale, and desired data product and resolution. Traditionally, occupied aircraft have been used to conduct surveys to collect relatively high-resolution data over large geographic areas. However, surveys that are conducted using occupied aircraft can pose significant safety risks for scientists and pilots, may be costly, and may have limited availability in many regions of Alaska. Depending on the scale of the research question and study area, UAS may be more cost-effective, particularly for projects that are limited in geographic scope. UAS may also provide the ability to assess aspects of animal behavior that are not feasible with occupied aircraft and potentially reduce disturbance to wildlife during surveys. In addition, UAS have the ability to fly at lower altitudes beneath the clouds (e.g., Sweeney et al. 2015), can be pre-programmed to conduct systematic surveys, and, in most cases, rely upon battery power as opposed to fossil fuels (DOI OAS 2015, Johnston 2019).

UAS Platforms and Sensors

The airborne system of unmanned aircraft is composed of two primary components: a platform and a sensor. Platforms include multi-rotor, fixed-wing, or transitional aircraft that vertically take-off and land (VTOL). Multi-rotor UAS have the benefit

Parker Martyn operating a 3DR Solo with an optical camera over the intertidal zone at Takli Island in Katmai National Park and Preserve.
NPS PHOTO

Table 1. Typical characteristics and applications of remote-sensing platforms for natural resource applications.



Platform	Multi-rotor UAS	Fixed Wing UAS	Manned Aircraft	Satellite
Altitude	Surface to 1,200′ AGL	Surface to 12,000′ AGL	100′ AGL to 15,000′ MSL	> 200 miles AGL
Area	1-50 acres (single flight/day)	1-640 acres	1-1,000 sq. miles	> 1,000 sq. miles
Typical Resolution (Ground Sample Distance)	0.5″- 3″	1″- 3″	3″- 40″	> 6″
Speed	slowest	slower	faster	fastest
Examples of Applications	vertical 3D modeling, structural/habitat evaluations	mapping	wildlife surveys, Lidar	vegetation index, sea surface temperature and ocean color

of hovering; fixed-wing have the benefit of using lift generated by the airfoil as opposed to thrust (power), thus providing longer flight endurance; VTOL aircraft can launch and land in smaller areas and have the ability to hover over an area.

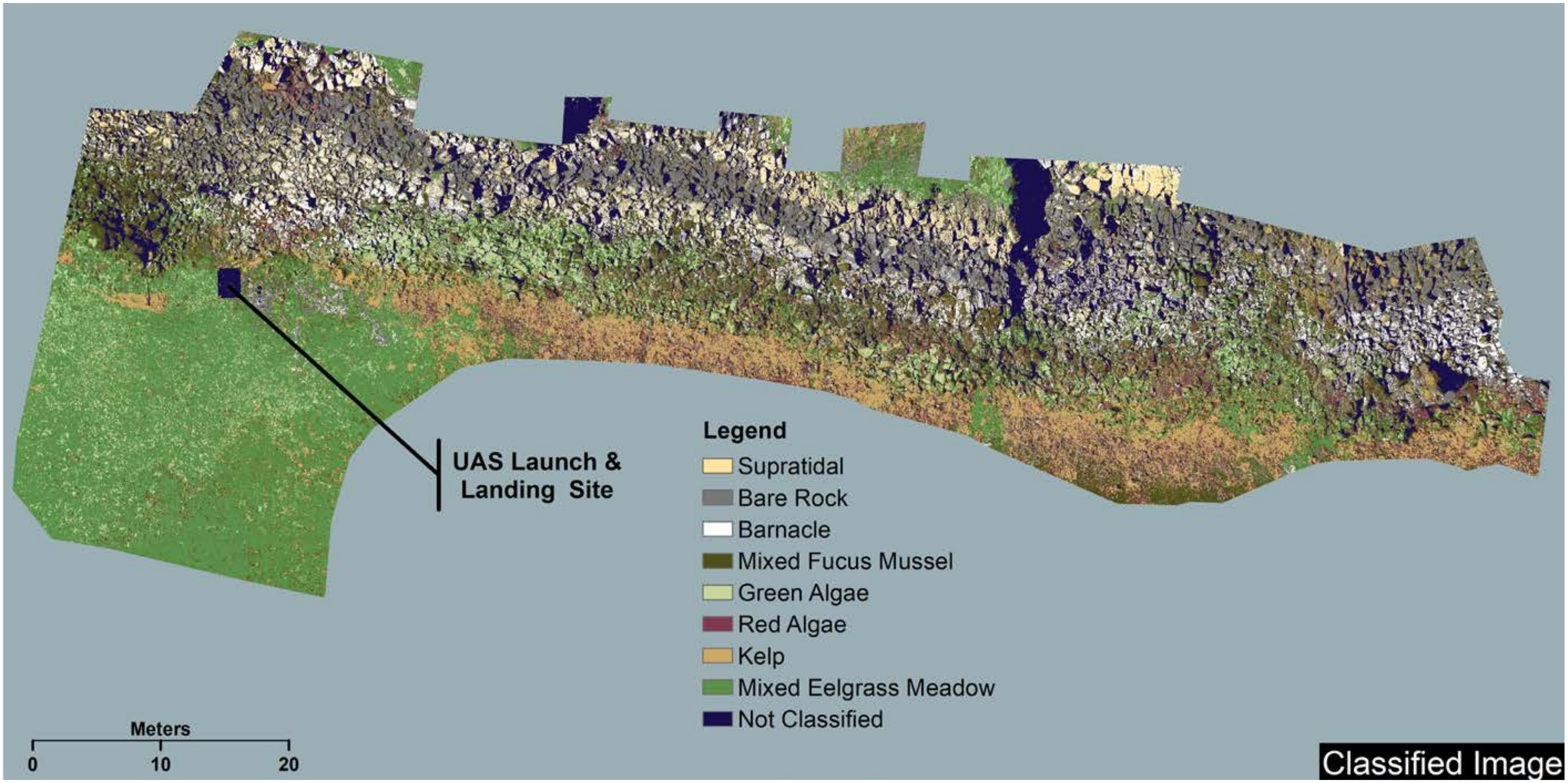
UAS can carry a variety of inexpensive commercial-off-the-shelf (COTS) payloads without requiring modification. Payloads can include, but are not limited to, mapping cameras, real-time high-definition (HD) video cameras, thermal-infrared sensors, multispectral cameras, Lidar sensors, and a variety of other data collection sensors (e.g., aerosol monitors; Table 2). Data resolution is a function of sensor lens, data capture rate, and flight altitude. Data streams can include video, digital images, and thermal images. Processed products can include orthomosaics, digital surface models, and time-series data.

Examples of Natural Resource Applications

Since 2016, UAS have been used as a tool in Alaska parks for a variety of physical and biological science related projects. The NPS UAS program has also supported all-hazard assignments, inter-agency projects, and continues to develop best practices for future UAS integration into parks to help managers determine safe, efficient, and effective ways to integrate UAS operations with park missions.

In Denali National Park and Preserve, multi-rotor UAS platforms have been used to map streams affected by mining activities for restoration and trail project planning, to generate elevation models for monitoring volumetric changes of mass wasting sites, and to create 3D models of historic districts to assess land instability due to permafrost melt, along with thermal imaging to identify ground temperatures. Denali National Park and Preserve has also used UAS to map permafrost and fire ecology sites with multi-spectral and thermal sensors to assess plant growth in burned areas, identify spatial patterns in permafrost thaw dynamics, and map elevation. UAS have also been used in partnership with the University of Alaska Fairbanks to map paleontological specimens in Denali National Park and Preserve and to conduct glacier mapping in Kenai Fjords National Park.

The NPS Inventory & Monitoring Program has conducted UAS surveys of the intertidal zone in Katmai and Lake Clark national parks and preserves in collaboration with Gulf Watch Alaska and the U.S. Geological Survey-Alaska Science Center. The resulting data are being evaluated to assess intertidal species distribution and abundance and create multi-spectral orthomosaics for land cover and topographic change analysis along the coastline. A pilot project in Denali National Park and Preserve collected real-time video streams of nesting Canada jays to quantify chick health.



Classified image produced from imagery of the intertidal zone at Takli Island, Katmai National Park and Preserve. [Source imagery was collected by Parker Martyn using a 3DR Solo.]

Table 2. Examples of sensor types and products for natural resources applications.

Examples of Sensors	Optical	Thermal	Multi-spectral	Other Data Collection Sensors
Types	visual (red, green, blue) color-infrared (red, green, near-infrared)	radiometric (longwave thermal infrared)	red-edge (red, green, blue, red-edge, near-infrared)	aerosol, temperature, particulate, UV, Lidar
Resource Applications	wildlife, habitat	hydrology, geology, wildlife	botany, archaeology, habitat	volcanology, hydrology, air quality, wildlife, astronomy
Products	digital image, orthomosaiced photos, live-stream video	orthomosaiced photos, live-stream video	orthomosaiced photos	time series, physical and biological samples

3DR Solo with Micasense multispectral camera flying over intertidal zone, Katmai National Park and Preserve.
NPS PHOTO

Future Applications

Several UAS projects are in the planning stages that will support natural resource applications in NPS units. For example, UAS technologies are expected to provide valuable information on the current condition and long-term trends of vegetation and other natural resources to determine how well management practices are sustaining park ecosystems. Through a partnership agreement with the U.S. Forest Service, NPS fleet operations within the Alaska I&M Program will provide high-resolution baseline imagery for vegetation map accuracy assessments of forested areas in Alaska.

Population assessment surveys for terrestrial and marine wildlife species present unique challenges for transitioning to small UAS platforms, given the large geographic areas and remote regions in which they occur (e.g., Schmidt et al. 2017, Womble et al. 2020). Nonetheless, innovation in UAS platforms with longer battery endurance will have the ability to transform the field for wildlife population assessment over large geographic areas (Christie et al. 2016, Johnston 2019). Plans to map thermal refugia with infrared sensors and stream turbidity with multi-spectral sensors for hydrologic surveys, as well as detect fish presence with optical sensors, are planned for Denali National Park and Preserve. Trial surveys conducted by the U.S. Fish and Wildlife Service and NPS for nest surveys of birds may hold promise for future NPS projects (Magness et al. 2019).

Transitioning from manned aircraft to UAS platforms will substantially increase safety for biologists and pilots as wildlife surveys are typically low, slow, and often over water or ice, which presents substantial risks. There are plans for a forthcoming project to evaluate UAS as a platform for population assessment of harbor seals, sea otters, and their habitats with the goal of improving the safety and efficiency of future data collection efforts. This project will take advantage of recently developed statistical designs combined with aerial photographic methods that were developed in occupied aircraft (Williams et al. 2017, Womble et al. 2020). Additionally, aerial surveys for Dall's sheep require flights in narrow box canyons in turbulent conditions and in close proximity to terrain. A UAS equipped with thermal and optical sensors may serve as an alternative platform and would reduce human exposure to aviation hazards.

Challenges and Future Directions of UASs

Advances in UAS platform and sensor technology, regulatory and policy development, and a balanced integration of the tool provides future opportunities for Alaska parks. While there are many benefits of using UAS, the adoption of new technology also comes with challenges. Battery technology and endurance can be limiting; however, as innovation continues, battery capacity for longer flights should increase while also decreasing costs. For example, Department of the Interior call-when-needed contracted UAS are available with 16-hour flight times, while engineers are currently designing a quad-biplane for the National Oceanic and Atmospheric Administration (NOAA) with long-endurance (multi-day), heavy-payload, and agile flight response for atmospheric profiling and meteorological data collection.

UAS have exposed mechanical parts, making them more susceptible to rain and snow, cold temperatures, and wind. Smaller UAS are also limited in the weight they can carry, which typically means smaller sensor size and limited sensor resolution. UAS that provide weatherized and ruggedized bodies, as well as the ability to maintain radio signals at greater distances, are in the development and approval phases.

Similar to other natural resource projects, workflows that include identifying the question of interest and the appropriate tool, project planning, data collection, statistical analysis, data management, and publication are essential for success. Like satellite and manned aircraft surveys, UAS surveys can generate large amounts of data and imagery and the post-processing workload can be time-consuming, technical, and costly. Properly accounting for the post-processing workload is essential and will require efficient workflows, data management, and technical expertise.

Continued research and development related to semi-automated or automated methods, such as machine learning, for automated image processing and detection of target species (e.g., Seymour et al. 2017) will be essential for improving the efficiency of post-processing. For example, NOAA Fisheries is currently leading an initiative with industry and academic partners to create end-to-end open-source software for automated analysis of optical data streams collected from vessels, occupied aircraft, and UAS for use in fisheries and marine mammal stock assessments (Angliss et al. 2020).

Federal regulations for UAS operations have evolved with the technology and use of UAS, and safe integration of UAS in the national airspace now allows for more opportunities to fly beyond line-of-sight. There are concerns related to potential impacts on wildlife, soundscapes, and visitor experience, as well as potential privacy or sensitivity incursions. For example, using UAS for monitoring and research of protected species, such as marine mammals, requires federal research permits from managing agencies. In addition, there are plans by the U.S. Department of the Interior (DOI) Office of Aviation Services (OAS) to evaluate "Blue" UAS, which would allow for enhanced cybersecurity for future DOI missions.

Use of UAS for natural resource monitoring will continue to benefit from collaboration with other agency, academic, and industry partners that have the ability to develop, test, and extend UAS capabilities and post-processing techniques for natural resource monitoring and research. The application of UAS in parks has helped define best practices, processes, and procedures for operations in Alaska national parks, as well as establishing interagency relationships with other DOI bureaus, and developing additional partnerships with local, state, federal and academic entities. By expanding existing aviation capabilities and integrating cost-efficient UAS as a survey platform, the NPS has access to a versatile tool for monitoring the status of natural resources in Alaska.

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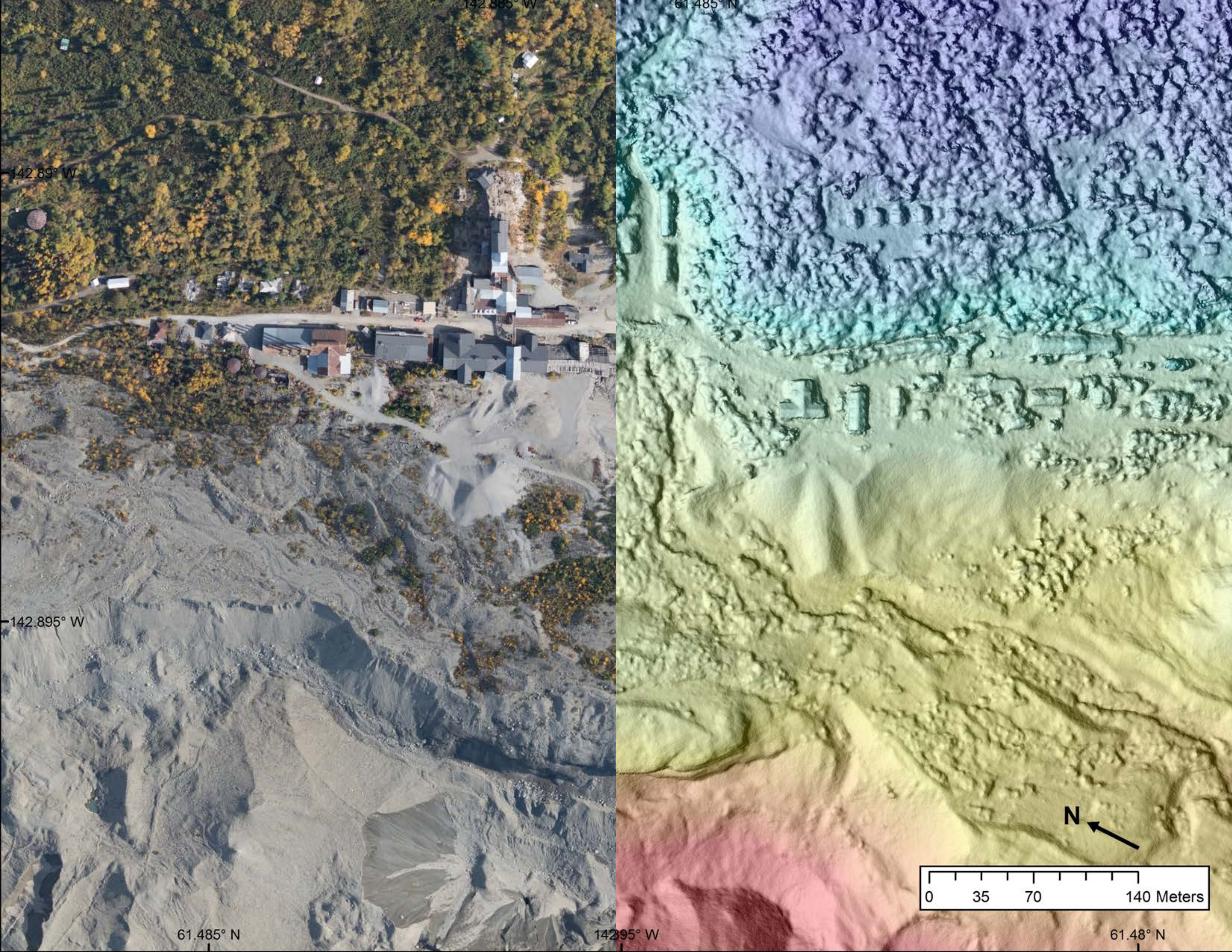
Britta Schroeder operating a 3DR Solo to collect orthophotos to create a digital elevation model to monitor displacement at Pretty Rocks in Denali National Park and Preserve.
NPS PHOTO


142.885° W
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Mapping and Monitoring Landscape Changes Using Structure from Motion from Aircraft

Chad Hults, Tahzay Jones, Britta Schroeder, Denny Capps, Dana Hansen, Celia Miller, Michael Hannam, and Deb Kurtz, National Park Service

Aerial SfM is an accessible tool for mapping and monitoring landscape changes for a wide range of applications and disciplines across parks in Alaska. The success of the Alaska Region aerial SfM system during the first four years of testing and deployment has demonstrated its value to park mangers to address rapidly changing park landscapes.

Citation:
Hults, C., T. Jones, B. Schroeder, D. Capps, D. Hansen, C. Miller, M. Hannam, and D. Kurtz. 2021. Mapping and monitoring landscape changes using structure from motion from aircraft. *Alaska Park Science* 20(1): 36-47.

To address Alaskan-sized issues in remote parks, remote sensing is often the most useful and efficient tool. Boots-on-the ground collection of biological or physical features is time-consuming and often spatially restricted relative to the vast extent of habitats and size of the physical features of interest. Extrapolations from small sample areas to large areas is often statistically tenuous. As such, remote sensing is useful for monitoring changes on the landscape scale.

Satellite imagery is used for many landscape-scale applications but typically has a maximum resolution of approximately 40 cm. Satellite imagery is useful for parkwide-scale projects (1,000s km^2) such as parkwide imagery, a park land cover map, and even detecting elevation changes at larger scales such as in the Arctic digital elevation models. Unmanned Aircraft Systems (UAS) mapping is increasing in use, but UAS flights are commonly restricted to less than 400 feet above ground level and flying line-of-sight, which results in a resolution of about 1-10 cm and constrains them to small-scale projects (<10 km^2). They are useful for modeling changes of individual landslides, mapping detailed land cover at a vegetation transect, or making three-dimensional (3D) models of unique landforms (Arches, for example). Aerial photography in aircraft fits in the niche between those two remote sensing systems with typical pixel ground resolutions of 10-60 cm. Aerial structure from motion (SfM) is useful for medium-sized projects (100s km^2), such as mapping intertidal environments, detecting landslides over a large area of interest such as an entire park road, and monitoring glacier changes on large glaciers or icefields.

In Alaska, SfM from agency aircraft has provided a cost-effective tool for high-resolution mapping and monitoring of landscape changes to help manage natural resources. Applications so far include monitoring coastal erosion, sea level rise, glacial outburst floods, fires, volcanic eruptions, permafrost thaw, landslides, glacier recession, oil spills, developments, and mining.

Structure from Motion (SFM) Technology

Structure from motion (SfM) technology is the driver behind the recent explosion of unmanned aerial systems (UAS) used for mapping. SfM provides the ability to create high-resolution and accurate orthophoto mosaics and digital elevation models (DEM) using consumer-grade cameras and survey-grade Global Navigation Satellite System (GNSS) equipment. Traditional photogrammetry relied on precisely engineered cameras with known geometry; whereas, SfM technology consists of algorithms that make it possible to use consumer-grade cameras without accurate sensor geometry to generate 3D models. SfM uses multiple overlapping photos to solve for all the variables of a camera geometry, camera orientation and location, and the 3D shape of the object being photographed (Furukawa and Hernandez 2015).

Orthophoto mosaic (left) and digital elevation map (DEM; right) of the Kennecott area, Wrangell-St. Elias National Park and Preserve. Structure from Motion (SfM) of the toe of the Kennicott Glacier was completed in 2018 to support a project to prepare for the retreat of the Kennicott Glacier. The area acquired was expanded to include the Kennecott mine site to produce a high-resolution basemap of the Kennecott Historic Landmark. The orthophoto mosaic is 16 cm resolution and the DEM is 32 cm resolution.

In Alaska, SfM use from aircraft was spearheaded by Dr. Matt Nolan, previously a geophysicist at the University of Alaska Fairbanks (Nolan et al. 2015). The National Park Service (NPS) Alaska Region has worked with Dr. Nolan to apply SfM to various geohazards projects; most notably developing basemap imagery and DEMs for the Denali Park Road and monitoring retrogressive permafrost thaw slumps in Gates of the Arctic National Park and Preserve and Noatak National Preserve (Swanson and Nolan 2018).

With assistance from the U.S. Fish and Wildlife Service and the Bureau of Land Management Cadastral group, the NPS has deployed an aerial SfM system that uses high-resolution digital cameras and survey-grade GNSS units to map and monitor changes using agency planes. The system is shown mounted in a plane in Figure 1 and primarily consists of two digital cameras (standard red-green-blue [RGB], and near infrared [NIR]). The NPS Alaska Regional Office also provides an SfM processing server that can be run remotely by trained park staff.

The NPS Alaska Region is well positioned to deploy aerial SfM because we have numerous agency planes and pilots located in parks near project areas. Area covered in a typical day is about 100–300 km^2. For perspective, the city of Anchorage is 250 km^2 and can be mapped at a resolution of 15 cm in about 5 hours of flying. If processed just for the DEM and orthophoto mosaic, the project can be completed in less than a week. The primary constraint on the deployment of SfM is weather (Table 1). The Alaska Region is working on outfitting existing NPS planes to be SfM capable and training park employees across the region on the operation of the aerial SfM system. With park planes and personnel trained in acquiring SfM, response times to map and monitor geohazards will be quicker.

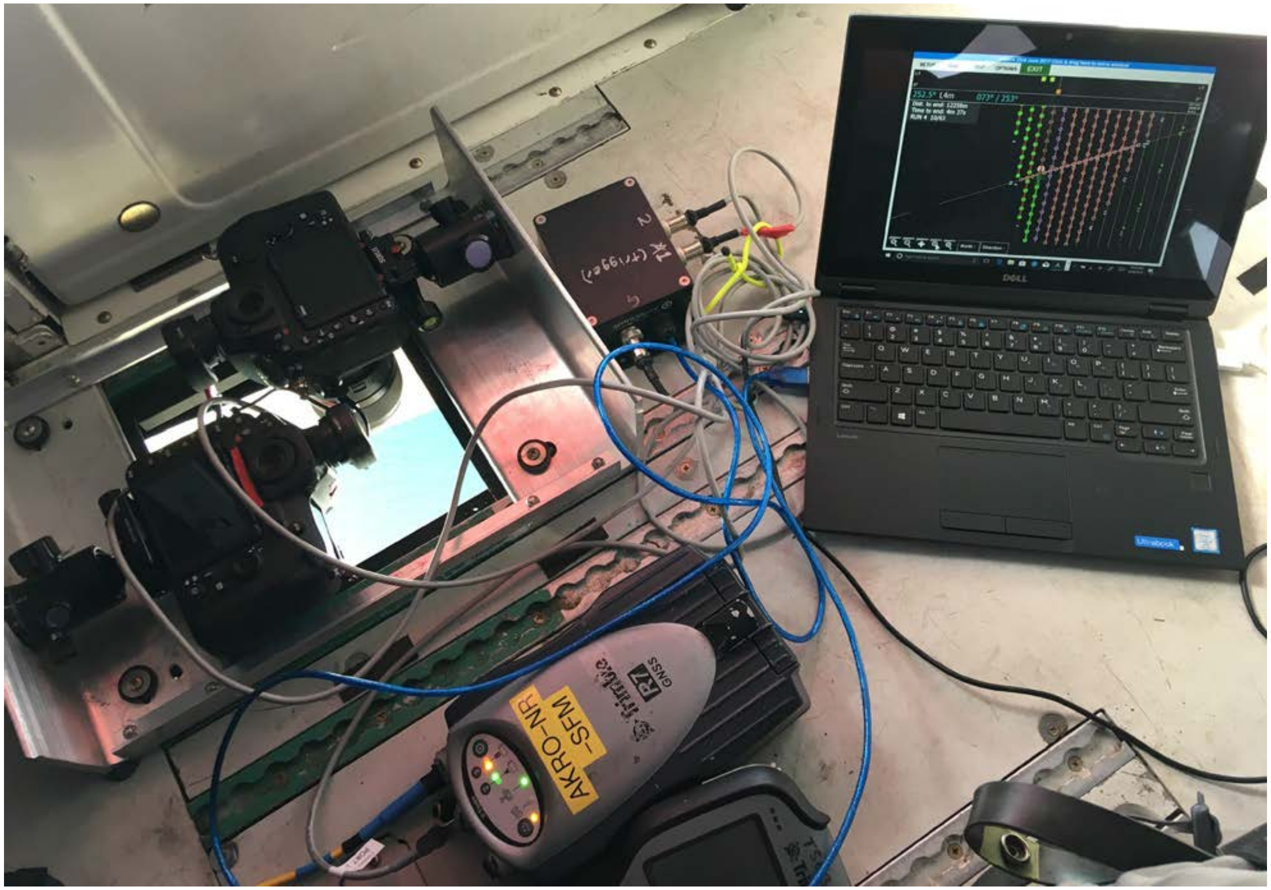

Figure 1. Photograph showing the Alaska Region aerial SfM system installed in a camera port. The two cameras are triggered using Aeroscientific™ flight software running on a laptop. The screen of the laptop shows a flight plan in action with the gridded flight lines of camera locations. As the pilot follows the flight lines, the cameras are triggered when the plane reaches the camera locations. The shutter flash in the hot-shoe sends an event signal to the running GNSS unit (Trimble™ R7) that records the time of the camera trigger. This precise time record for each photograph allows the interpolation of the event along the recorded flight lines.

An important caveat is that SfM isn't useful for measuring ground surface elevations where vegetation is thick, as can be done with LiDAR. Fortunately, many of the parks have high-altitude or high-latitude areas with little to no vegetation. For these places, SfM is as good as LiDAR for elevation mapping (Figure 2; Salach et al. 2018). SfM has the added benefit of producing precise orthorectified imagery, which can be used for vegetation classification.

Table 1. Table showing the mission results for the last three years of SfM acquisitions. 2017 was the year we developed the system and tested deploying it, so we had fewer days planned than the last two years.

	2017	2018	2019
# Days Planned	14	42	48
# Days Flown	6	23	20
Success Rate	43%	54%	42%
# Photos*	12,315	29,996	30,106
Area Mapped (km^2)	603	2,197	2,242

*Number of photos is doubled when including near infrared (NIR).

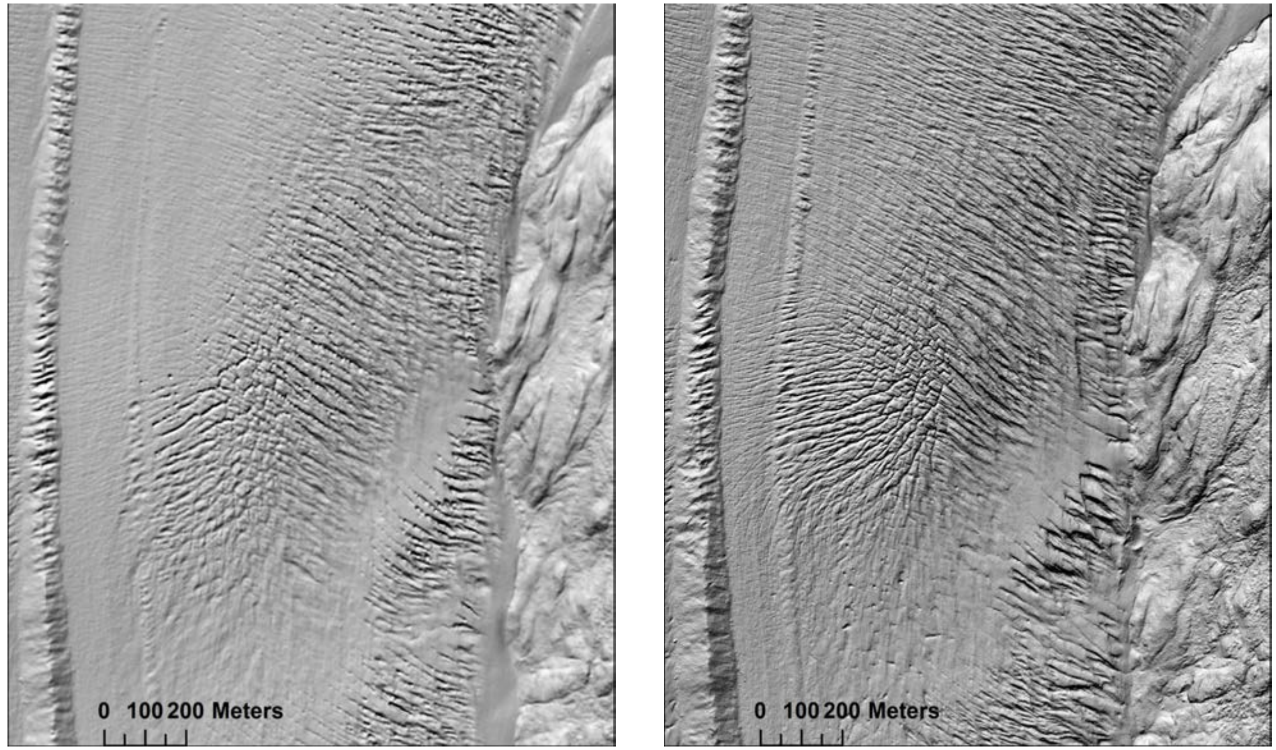

Figure 2. Comparison of digital elevation models (DEM) produced by LiDAR (left) and the Alaska Region aerial SfM system (right) for a section of Bear Glacier in Kenai Fjords National Park. On bare ground (or ice, in this case) SfM can provide resolutions comparable to LiDAR.

Mission Planning and Execution

Missions are developed based on multiple factors: available funds, fuel availability, remoteness, time available, and project purpose. Project purpose dictates the resolution needed, the lighting or seasonal timing constraints, and extent necessary to meet the goals. For example: intertidal mapping projects are planned for the lowest tides of the year, which only last a few hours in a day, whereas land cover classification projects require peak growing season and consistent lighting throughout the acquisition. Project purpose also dictates the accuracy and accuracy validity needed. Ground control points (GCPs) are placed when projects require greater vertical accuracy and validity of the vertical and horizontal accuracy. As such, aircraft landing locations within the area of interest (AOI) are necessary if GCPs are to be placed using the fixed-wing aircraft used to fly SfM, or GCPs and vertical check points can be measured before or after an acquisition by other means.

Flight planning software is used to develop gridded camera locations (shutter events) in order to assure that the photo spacing is optimal for SfM processing. The desired resolution, camera type, and lens are entered into the flight planning software with an outline of the AOI from which a gridded flight plan is generated at the necessary altitude. A user chooses the flight direction (e.g., east–west) to reduce the overall flight time or to follow the orientation of the adjacent terrain for safety. An alternative intervalometer method is used in situations where the object to be mapped is narrow and sinuous like roads, trails, rivers, and shorelines. For this method, we use a synchronized remote shutter control for the two cameras that has a time interval function. When properly executed, both methods create extremely accurate orthophoto mosaics and DEMs.

Processing Protocols and Accuracy Assessments

To create 3D models of landscape features, or digital elevation models (DEM), precise camera shutter event locations or visible GCPs are necessary to reference the 3D model to real-world coordinates.

Most UAS work relies on ground control marks to georeference the model, because most don't have a survey-grade GNSS unit onboard. The Alaska Region aerial SfM system relies on precise (to the scale of centimeters) locations of the camera positions to accurately georeference the imaged landscape. We use GNSS base station (Trimble™ R10) that is ideally located less than 50 km from the project area. Using a local base station to correct the aerial GNSS unit (Trimble™ R7) measurements using the post-processing kinematic (PPK) technique, results in GNSS positions accurate to within 5 cm (90%) resulting in a camera position accuracy of approximately 15 cm. SfM processing is completed in Metashape™ software without using GCPs to inform the model. Survey-grade GNSS measurements on visible GCPs are used to test the horizontal accuracy of the resulting orthophoto mosaics, which show they are accurate to ±15 cm (95%). GCPs and/or vertical check points placed on flat, open bare ground are used to adjust DEMs. After testing accuracy of numerous projects, the DEMs have a precision of about ±10 cm (95%), but all DEMs have a vertical shift of approximately -25 to -70 cm (DEM minus GCP elevations; see Alidoost and Arefi 2017). As such, when vertical accuracy is critical for the project, GCPs or vertical check points are used to adjust the DEMs to account for the vertical shift. With the low vertical error, repeat SfM acquisitions over the same AOI can detect changes of about 20 cm or greater.

Example Applications

Figure 3 shows the areas that the Alaska Region aerial SfM system has been deployed from 2017 through 2020. Although the system was developed for natural resource projects, it has been used for a wide-range of applications, including:

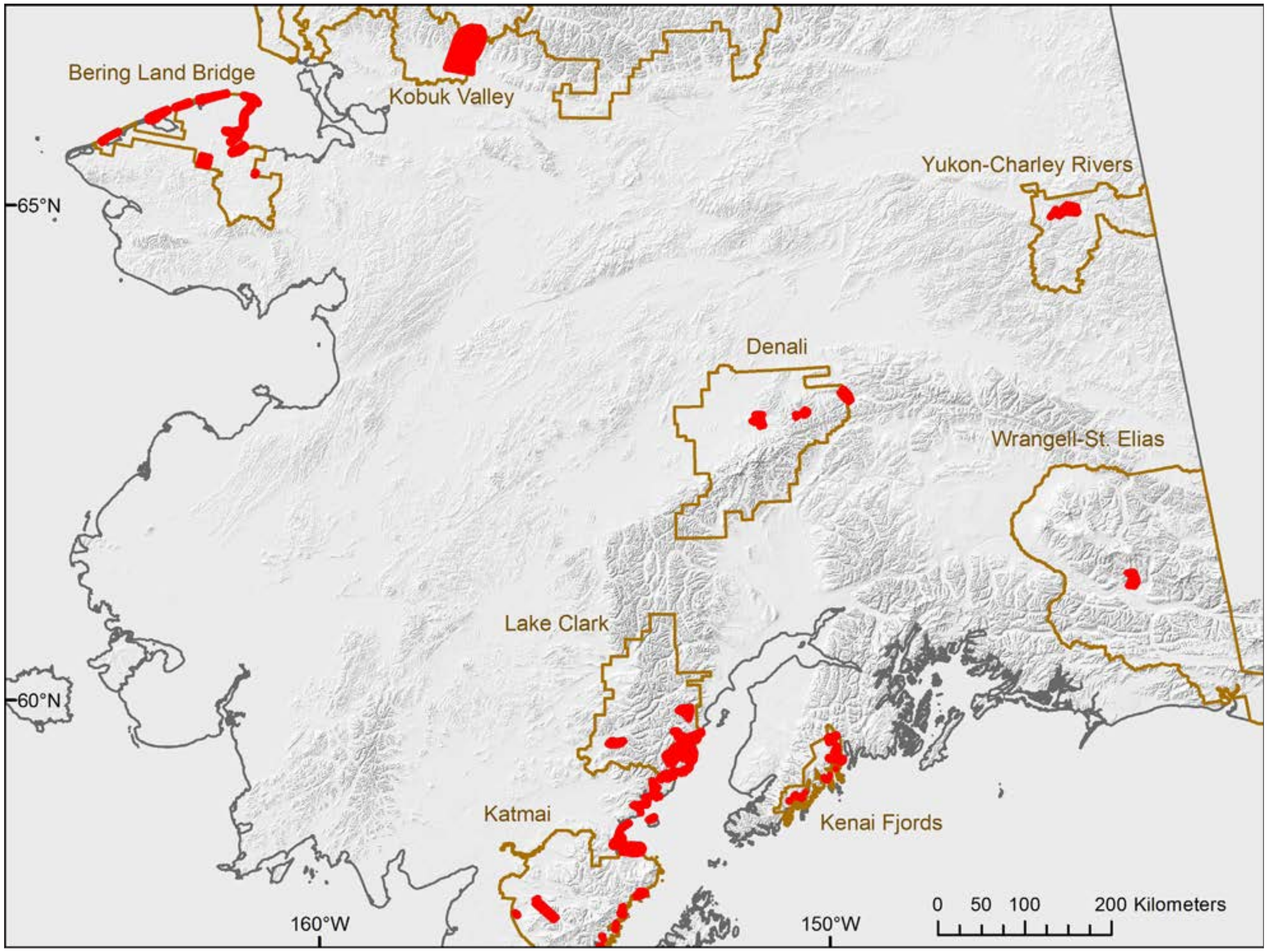

Figure 3. Map indicating the areas where SfM has been flown from 2017 to 2020.

- coastal ecological and geomorphic mapping;
- intertidal habitat mapping and salt marsh landcover change detection;
- coastal erosion monitoring;
- developing landform maps for archeological sites;
- monitoring landslides;
- monitoring mining;
- mapping abandoned mineral lands;
- mapping rivers for planning stream restoration;
- mapping park infrastructure developments;
- monitoring landcover and permafrost changes after fires;
- monitoring glacier retreat; and
- responding to glacier outburst floods.

Kenai Fjords National Park Glacier Change Monitoring

Exit Glacier in Kenai Fjords National Park is one of the most visited and easily accessible land-terminating glaciers in North America, yet it is becoming less accessible. Until very recently, the toe of the glacier was easily accessible with a short walk along a flat riverbed. Today, the toe is not accessible because it is constrained in a cliff-sided gorge. As the glacier recedes up the mountainside, the interest for viewing the glacier is receding with it (Moser 2016). SfM is being used by park managers to help monitor and project the rate of retreat in order to make informed decisions about maintaining the infrastructure and managing use in the Exit Glacier area.

Beginning in 2016, SfM has been deployed annually to measure the volume changes for Exit Glacier. Figure 4 shows the vertical change between the 2018 SfM DEM and a 2008 LiDAR-derived DEM. The higher elevation Harding Icefield area has dropped 10–20 meters vertically; whereas, 100 meters of ice has melted from the toe of Exit Glacier. The vertical change shows a net loss of 12.6 m of glacier ice, which equates to an annual average loss of 1.26 m of ice per year. The annual water equivalent gains or losses at the index sites in Figure 5 show that the highest-elevation sites have a slight gain to no change in accumulation and the lower-elevation sites have a net loss. Assuming glacier ice density of 0.9 kg/l, the mean annual meters water equivalent is 1.13 m per year. These data show that the loss of ice at higher elevation, detected using SfM, indicates that the Harding Icefield is losing mass from outlet glaciers faster than it is receiving snow in the accumulation zone, which is leading to the recession of Exit Glacier and all other outlet glaciers.

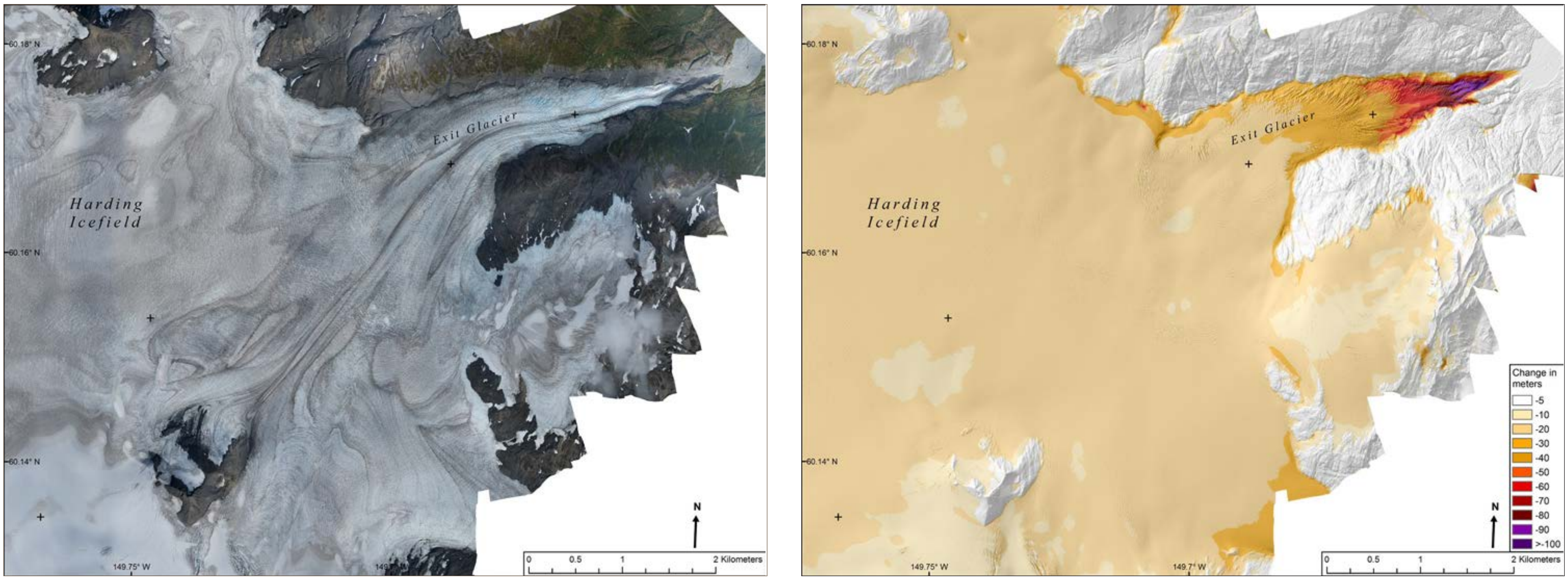

Figure 4. Aerial image (left) and DEM difference analysis (right) for a portion of the Harding Icefield and Exit Glacier. The orthophoto mosaic is from the 2018 September SfM acquisition showing much of the icefield is barren of annual snow. The DEM from the 2008 LiDAR was subtracted from the 2018 SfM DEM to show vertical change of the icefield and Exit Glacier over the 10-year period. The black crosses on the image show the locations of the annual index stakes where snowpack thickness and density are measured in the spring and melt is measured in the fall. Compare these glacier changes to the index stake mass-balance measurements shown in Figure 5.

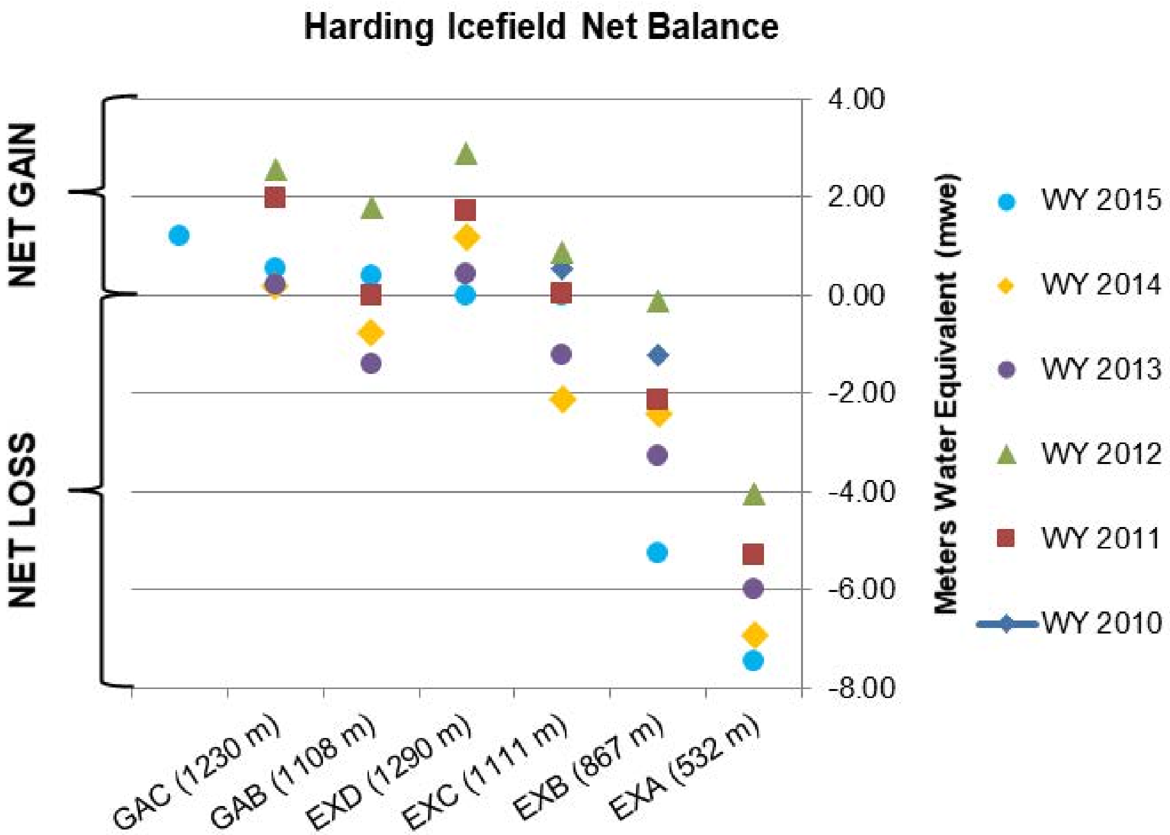

Figure 5. Chart showing the annual water equivalent gains or losses at the Harding Icefield index sites. (WY=water year, 1 October–30 September).

Preparing for Oil Spills through Ecological Classification and Geomorphology of the Western Arctic Coasts

Bering Land Bridge National Preserve and Cape Krusenstern National Monument have approximately 1,600 km of predominantly soft-sediment Arctic coastlines rich in biological resources. These shorelines include lagoons with richly patterned interiors, estuaries that are key waterbird breeding areas, extensive salt marshes and brackish wetlands, and sediment transport-driven barrier islands and capes. Over the past decade, marine vessel traffic through the Bering Strait has grown exponentially to take advantage of new ice-free, Arctic summer shipping routes. A new deep-water port servicing the Arctic is planned for Nome, and other oil-related infrastructure is expected. Given the proximity of shipping and nascent industrialization to these formerly remote conservation units, the NPS has embarked on an ambitious coastal research and stewardship plan. A project is underway to develop an ecological classification of coastal vegetation based on geomorphologic and vegetation units defined through remote sensing and field work. SfM was identified as an effective tool for high-resolution mapping of geomorphic features and vegetation classification.

Figure 6 shows a short section of the Bering Land Bridge National Preserve coastline that has been mapped using SfM. Difference analysis of elevations from 2004 LiDAR (flown by the National Oceanic and Atmospheric Administration) to the 2018 SfM shows that along this stretch of coast, the dune ridges and shoreline are progressing inland. Notice that the gross shape of the dunes is preserved, but the crests are shifted a few tens of meters to the south-southwest. Work is underway to conduct a difference analysis along the entire preserve coast.

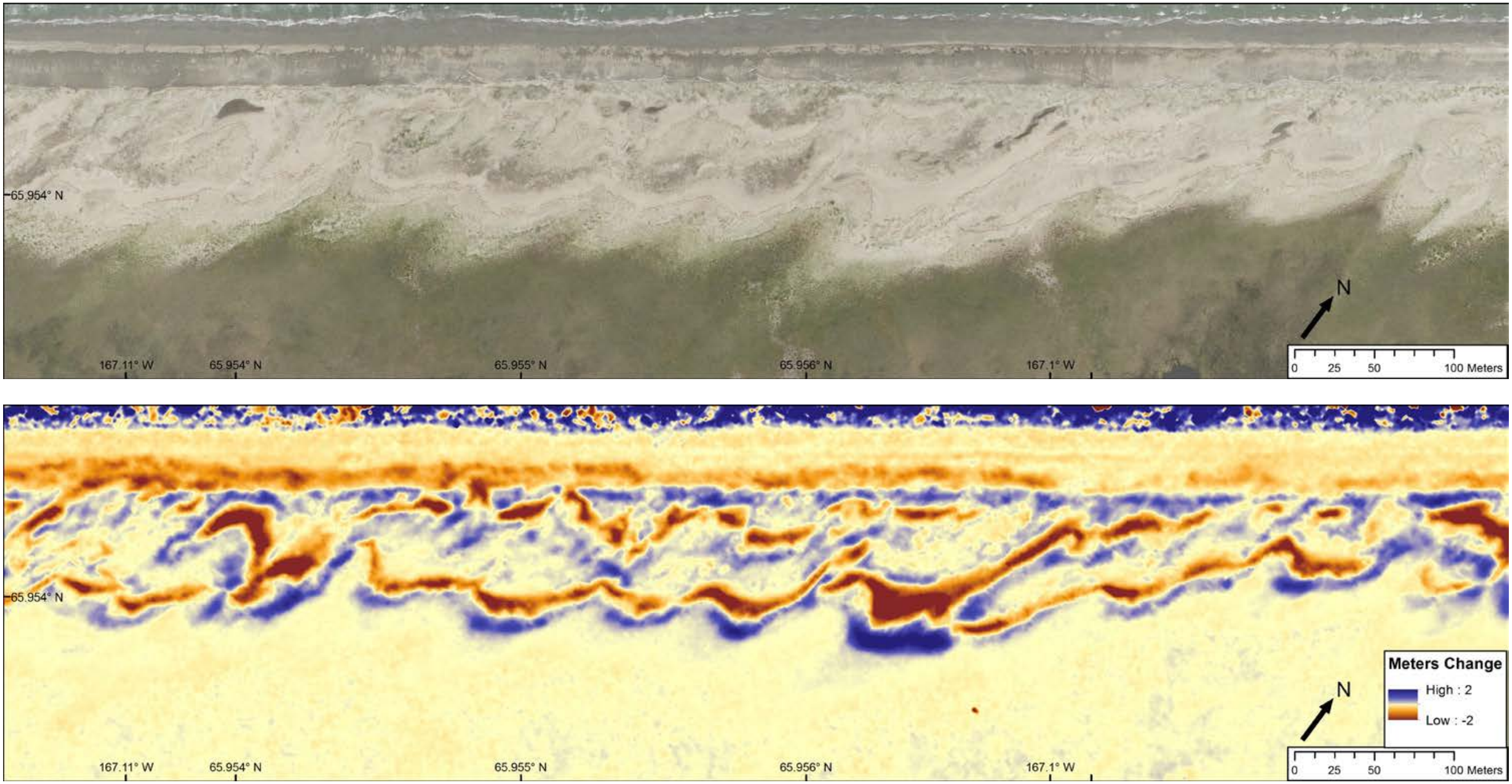

Figure 6. Aerial image (above, top) and DEM difference analysis (above) showing coastal changes of a beach ridge (dune) complex along the Ikpek lagoon area of Bering Land Bridge National Preserve. The underlying orthophoto mosaic is from the 2018 SfM and the vertical difference layer is the 2018 SfM minus the 2004 LiDAR. The blue areas are where material has been gained and red areas is where material has eroded, which shows the dunes migrating south in the direction of the prevailing winds.

Coastal Landcover Classification

Over the last two years, the Southwest Alaska and Arctic inventory and monitoring networks have partnered with the Alaska Regional Office Natural Resources staff to test using SfM for mapping coastal areas and development of landcover classification routines. Both networks contain abundant productive coastal habitats that could be impacted by oil spills from oil and gas development or marine vessel traffic.

To map intertidal habitats, we have used both satellite-based and SfM-based landcover classification techniques in order to compare the two resolutions (5 m vs. 20 cm, respectively). Preliminary results for classifying land cover types along the coasts of the two networks are encouraging. Figure 7 shows an example of landcover classification in Bering Land Bridge National Preserve. The combination of RGB and NIR imagery and high-resolution DEM were processed using spectral and object-based classification techniques for land cover types. High-resolution imagery can be tricky for classification because of lighting changes, shadows, and fine details. The example-based classification routine included all four spectral bands (RGB+NIR), NDVI, DEM, topographic position index (TPI), object-based segmentation, and random-forest classification. The imagery mosaics were created using the average of all the 10+ images overlapping every place within the AOI. Using these combinations of layers and averaged mosaics helps reduce the effects of lighting changes throughout the acquisition. It also helps reduce the effects of shadows and the variation in objects when using very high-resolution imagery and increases the contrast between class types. The classes were defined through a multi-year vegetation survey and image interpretation to create hundreds of training points. These tests have proven that SfM can provide a high-resolution tool for quantifying vegetation changes over large areas to better understand and monitor changes to coastal habitat due to tectonic uplift, sea level rise, and climate change in addition to providing a basemap useful for developing oil spill response plans.

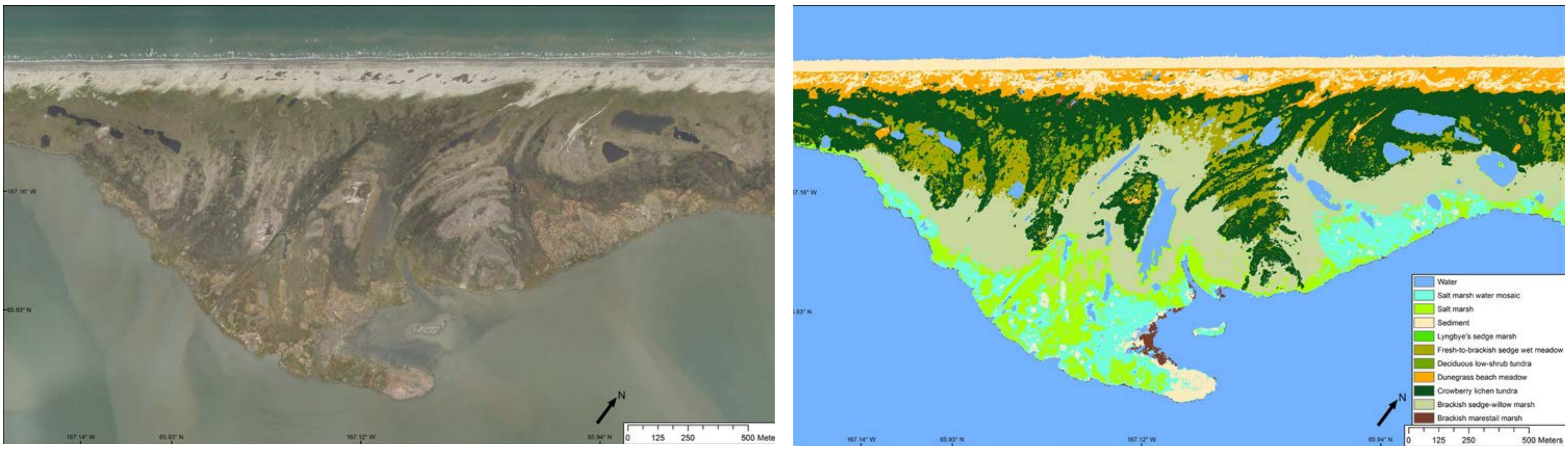

Figure 7. Orthophoto mosaic (left) with landcover classification (right) overlain for the barrier bar between the Bering Sea and Ikpek Lagoon.

Denali National Park and Preserve Landslide Detection Along the Park Road

In 2017, Denali National Park and Preserve had approximately 600,000 visitors, most of whom traveled on tour buses along the Park Road. However, with increased warming, the road is increasingly unstable. As of 2018, the road had about 30 known unstable slopes along the Polychrome section (miles 44 to 46). Recent climate records indicate that the mean annual temperatures are increasing (Sousanes 2016). This anticipated warming is causing permafrost thaw, which is increasing landslide activity in the park (see Capps et al. 2019). Landslides, rockfalls, and debris flows have frequently blocked and damaged the Park Road. The greatest concern is the Pretty Rocks landslide, which has a displacement rate of approximately 8 cm/day where the road crosses the landslide.

To address the increasing landslide threat to the park road, park management has initiated an unstable slope management plan and brought numerous tools and partners together to monitor the motion of the landslides (see Capps et al. 2019). Aerial SfM was used in 2018 and 2020 to monitor ground motions in the Polychrome area by flying repeat SfM to detect changes. Figure 8 shows the results of the difference in elevations in 2018, which detected slumping of the road over the Pretty Rocks landslide and intra-slide failures. These vertical changes are only the vertical part of the 3D motion of the landslide; if the landslide moves horizontally, with no change in height, the motion won't be detected by the DEM differencing. However, the eye can better detect motion of objects; Figure 9 shows an animation made by toggling between the spring and fall 2018 DEMs. In this animation, you can see motion along most of the length of the landslide. Repeating aerial SfM over the greater Polychrome area over the next few years will provide park managers with a tool for detecting

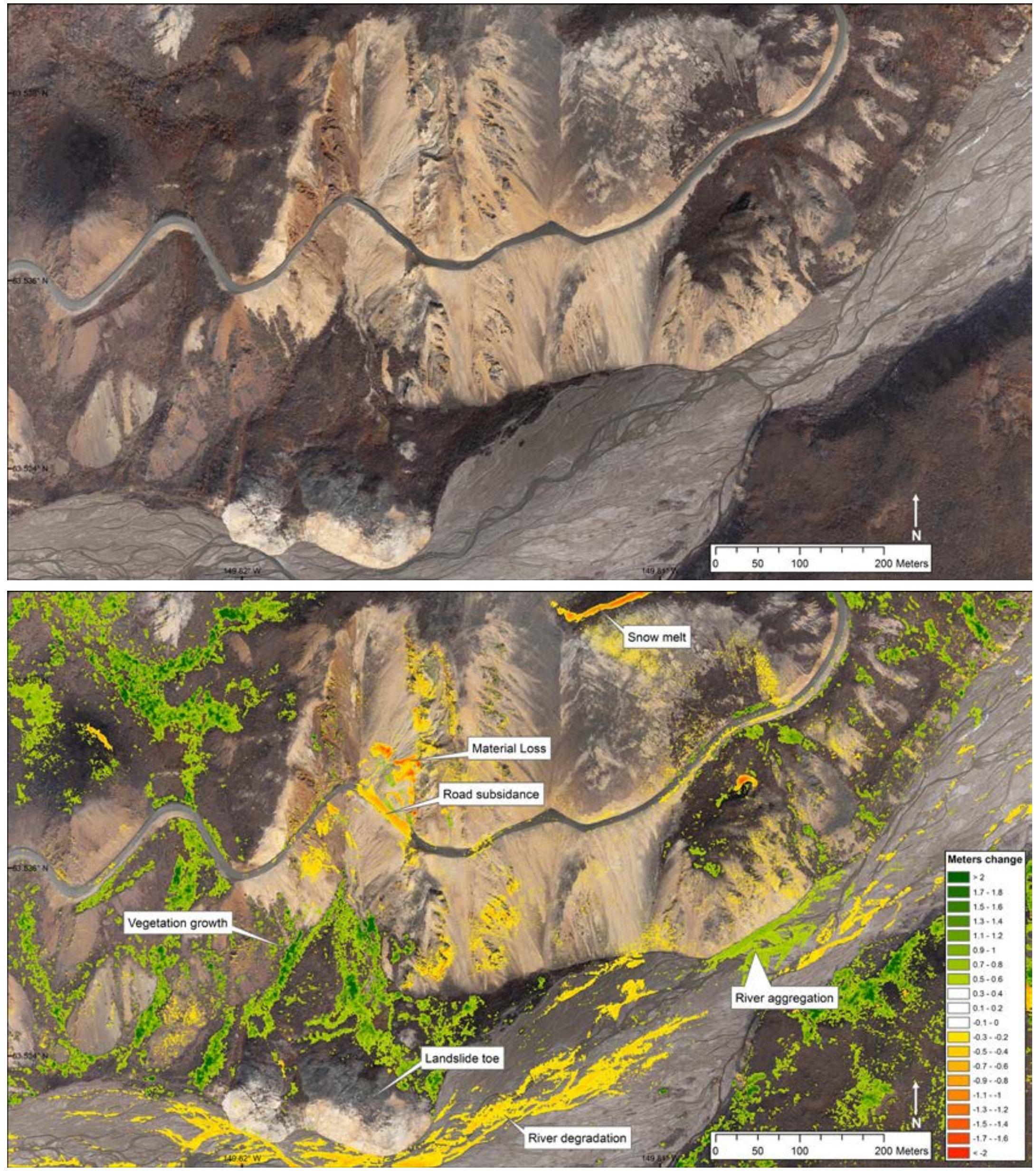

Figure 8. Aerial image (above, top) of the Denali Park Road, Polychrome-Pretty Rocks landslide, with an overlay of DEM vertical difference analysis of SfM flown in 2018 between June 6 and September 27 (above). The green colors depict positive vertical change, mostly due to vegetation growth, and yellow to red colors for negative change. Where the park road crosses the Pretty Rocks landslide, the road subsided up to 1.0 m in three months with slumps occurring above the road. Braided river aggregation and degradation and snow melt were also detected.

Figure 9. An oblique view of the Pretty Rocks landslide between the June 6 and September 27 DEMs. An animation shows that there was down-slope movement over nearly the entire extent of the landslide. The vertical elevations may not have changed enough to be detected in Figure 8, but the eye can capture the motion of the features down slope.

landslide motions over the entire area, which will be helpful for making decisions on how to address the road instabilities.

Summary

Aerial SfM is an accessible tool for mapping and monitoring landscape changes for a wide range of applications and disciplines. Using standard consumer-grade cameras and geotagging the images precisely using GNSS hardware is relatively straight forward and most agency pilots have experience flying transects for wildlife surveys. In addition, the rapid growth of SfM using UAS platforms is increasing the number of NPS staff with experience conducting SfM projects. Merging these tools and techniques to develop accurate orthophoto mosaics at the landscape scale is a natural progression. The success of the Alaska Region aerial SfM system during the first four years of testing and deployment has greatly increased the demand for the system. Meeting the growing interest of Alaska park mangers to address the rapidly changing landscapes is the greatest challenge to applying the Alaska Region aerial SfM system to map and monitor Alaska's dynamic park landscapes.

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Geoscientist-in-the-Parks intern Claire Schmidt securing cameras into an external box attached to the belly of a Top Cub airplane on the coast of Bering Land Bridge National Preserve.

Repeat Photography: A Visually Compelling Tool for Documenting Natural Resource Change

Ronald D. Karpilo, Colorado State University

Repeat photography is an effective method to qualitatively and quantitatively assess landscape change over time. From shrinking glaciers to changing vegetation to changes in the built environment, comparing historical and contemporary photos can help us identify specific features or processes that may require more intensive monitoring and research and can serve as a valuable tool for education, outreach, and resource management.

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The breathtaking beauty of Alaska inspires visitors and residents alike to reach for their cameras and document the view before them. In that euphoric moment, it feels like photography was specifically invented to capture and preserve our memories of extraordinary places like Alaska's national parks. The early explorers, scientists, and visitors who ventured to Alaska around the turn of the 20th century felt the same urge that we do to document and share their experiences. Beginning in the late 1800s, cameras rapidly became standard equipment for expeditions to Alaska. Many of the early explorers and scientists recognized the utility of photography for documenting natural and cultural resources and as a result, thousands of high-quality images were produced during this time. Pioneer photographers captured Alaska on film at the turn of the century. A few of these early photographers recognized the value of systematically revisiting sites and using repeat photography to create long-term records of natural resource change.

Geophysicist Harry Fielding Reid (pictured in Figure 1) was one of the early proponents of repeat photography. Reid made expeditions to Glacier Bay in 1890 and 1892 and, during these visits, he quickly recognized the effectiveness of repeat photography for monitoring landscape changes in Alaska. In 1896 Reid wrote:

> *All photographs of the end of a glacier are useful, especially those taken from a station easily accessible and easily described; photographs taken from the same station at a future date will show what changes have taken place in the interval.* (Reid 1896: 867)

In the 125 years that have elapsed since Reid wrote those words, scores of researchers and photographers have used repeat photography techniques to leverage the treasure trove of historical photos to document and study the past century of environmental changes in Glacier Bay and many other areas currently managed by the National Park Service (NPS).

It is important to understand how the natural resources of Alaska's national parks have changed during the past century and how the ecosystems and landscapes of the parks are responding to drivers such as climate change, human visitation, and development. This information and data are critical for effective park management and public safety. It is well established that repeat photography is an effective method for qualitatively and quantitatively documenting and evaluating complex changes in natural and cultural resources over time (Jorgenson et al. 2006, Karpilo and Venator 2015, Molnia 2010, Webb et al. 2010). Additionally, numerous studies

1897 photo by Frank La Roche of prospectors and packers resting on the Chilkoot Trail one mile north of Sheep Camp overlaid on a repeat image made in the same location on August 5, 2014. Notable changes include growth of thicker shrubs and larger trees along the trail and the establishment and growth of moss and lichens on the boulders. Cultural changes include erosion-reducing improvements to the Chilkoot Trail by the NPS Trail Crew.
PHOTOS COURTESY OF F. LA ROCHE, LIBRARY AND ARCHIVES CANADA, C-28645 AND R.D. KARPILO JR./S.C. VENATOR

Figure 1. August 20, 1890, Group photo at Muir's cabin of John Muir and the field party led by Harry Fielding Reid (professor at the Case School of Applied Science) and Henry Platt Cushing (professor at Western Reserve University) to study and map Muir Glacier in Glacier Bay. Left to right, John Muir, H.P. Cushing, R.L. Casement (on roof), C.A. Adams, J.H. McBride, and H.F. Reid.
PHOTO WAS TAKEN BY J.F. MORSE. PHOTO COURTESY OF JOHNS HOPKINS UNIVERSITY SHERIDAN LIBRARIES

have demonstrated the value and efficiency of repeat photography as a tool for studying landscape-scale changes and communicating the complex effects of climate change in national parks to diverse audiences including park visitors, resource managers, and scientists (Adema et al. 2007, Fagre and McKeon 2010, Karpilo et al. 2006, Molnia et al. 2004, Molnia et al. 2007, Roland and Stehn 2013).

Repeat Photography Methods

Over the past two decades, I have been fortunate to conduct repeat photography projects in Denali National Park and Preserve, Gates of the Arctic National Park and Preserve, Glacier Bay National Park and Preserve, and Klondike Gold Rush National Historical Park. During these projects, my project partners and I have relocated and repeated hundreds of historical photos and developed a well-tested repeat photography project workflow and protocol. My approach is a result of the combination of the application of techniques found in literature, guidance and support from other experts, and an abundance of trial and error. In general, a repeat photography project can be divided into five phases: (1) historical photo collection, (2) project planning, (3) photography fieldwork, (4) photo pair assembly, and (5) photo analysis.

Phase 1: Historical Photo Collection

This step consists of visiting various archives and collecting historical images depicting the targeted subjects (glaciers, vegetation, or other resources) in the area of interest. To make relocation possible, the photos must include identifiable features, such as mountain peaks, rock outcrops, or other static landmarks, that are unlikely to significantly change in the time since the photo was made. It is also beneficial to gather additional material such as photographer field notes, journals, personal letters, maps, and publications that may assist in finding photo locations and provide context for the images. I have collected thousands of historical images made in Alaska's national parks from the following sources: Alaska NPS park archives, Library and Archives Canada, Library of Congress, National Archives, National Snow and Ice Data Center, Royal BC Museum, University of Alaska Fairbanks, University of California Riverside, University of Washington, U.S. Geological Survey, Yukon Archives, and various private photo collections.

Phase 2: Project Planning

The second phase is evaluating and prioritizing potential photos based on criteria relevant to the project goals. Examples of prioritization criteria are: quality of original photograph, depiction of natural resources (or other subject of interest), seasonality of original photograph (most projects have a preference for snow-free summer images), photo location access and safety, and repeatability (Karpilo and Venator 2015). Once the high-priority photos are selected, the locations of the photo sites should be identified and mapped. Park staff, shuttle bus drivers, pilots, local residents, or anyone with intimate knowledge of the field area should be consulted to help pinpoint photo locations and identify landmarks visible in the images. Using Google Earth, GIS data, and topographic maps, it is often possible to digitally simulate the view of the historical photo or use triangulation to determine a general location of the photo site. Other project planning tasks include printing field copies of photos and planning fieldwork transportation and logistics.

Phase 3: Photography Fieldwork

The third phase involves visiting high-priority historical photo locations and making modern images. One technique that has served me well in finding photo locations in the field is the "think like a photographer technique," in which I look at the local area and ask myself: "If I were a photographer, where would I want to go to make a photo?" This simple technique often leads to prominent overlooks, hills, or other obvious photo-taking locations. Once the general photo location is found, the camera position is fine-tuned by moving around and comparing the apparent position of key temporally stable foreground and background elements, such as identifiable rocks, ridges, and peaks with the position of those same features in the printed field photo (Figures 2 and 3). After making a modern repeat of the photo, a GPS is used to record the latitude, longitude, and elevation of the photo stations (Figure 4). Additionally, the camera height and bearing for each photo is recorded. Reference photos of each photo site should be made to aid in finding the site in the future. To extend the utility of the photo station, a high-resolution, 360-degree panoramic image should be made at each photo location. For more detailed descriptions of repeat photo-monitoring methods, see Hall 2002, Jorgenson et al. 2006, Karpilo 2009, Karpilo and Venator 2015, and Webb et al. 2010.

Figure 2. September 11, 2003, Ron Karpilo holds a photo of Muir Glacier near the site where the image was made in June 1899 by G.K. Gilbert in Muir Inlet, Glacier Bay National Park and Preserve.
PHOTO COURTESY OF R.D. KARPILO JR.

Figure 3. June 30, 2011, Ron Karpilo and David Tomeo locating and repeating a 1919 photograph taken by U.S. Geological Survey geologist Stephen R. Capps in the East Fork Toklat Valley in Denali National Park and Preserve.
PHOTO COURTESY OF LACY KARPILO

Figure 4. Sarah Venator using a Trimble GeoXH 6000 GPS with external antenna mounted on the camera tripod to record the location of a photo station on Chilkoot Pass.
PHOTO COURTESY OF R.D. KARPILO JR.

Phase 4: Photo Pair Assembly

To assemble the photo pairs, the historical and modern photos are imported into image editing software as separate layers. The historical photo is overlaid on the repeat photo and made partially transparent and then the historical photo is rotated and resized (with the aspect ratio locked so the image is not distorted) to best align with the repeat photo. The modern photograph is then cropped to the field of view of the historical photograph.

Phase 5: Photo Analysis

The photo pairs are then examined and the notable changes summarized. Each person who views a photo pair, views it through the lens of their own experience and expertise. Therefore, it is often beneficial to consult with specialists from different fields. Several individuals can view the same photo pair and they may all notice different details and nuances that otherwise would have gone undetected. Depending on the objectives of the project, the pairs can be analyzed to identify variations in vegetation density and distribution, ecosystem composition and connectivity, fluvial morphology, glacier dynamics, geomorphic change, anthropogenic impacts, and other changes. Contingent on the quality of the images and precision of the repeat, both qualitative and quantitative analyses are possible. Brodie and others (2019) provides a good example of the use of photo pairs to analyze landcover change in Denali National Park and Preserve. See Webb and others (2010) for other examples of analysis techniques.

Discussion

Repeat photography is a unique method of scientific investigation because of the broad range of subjects that can be studied and the fact that the resulting products are interesting and understandable for both children and subject-matter experts. Projects can use repeat photography as the primary investigative method or it can easily be added as a complimentary component to other projects or fieldwork. Repeat photography is a low-cost tool, requiring only basic camera and GPS equipment and skills. The low technical and financial barriers to entry make repeat photography a good fit for citizen science projects and field courses (Tomeo 2013).

The photo pairs or series that are produced are useful for illustrating and analyzing changes over time in a wide range of physical or cultural resources. The resulting data can assist in identifying specific features or processes that may require more intensive monitoring and research and can serve as a valuable tool for education, outreach, and resource management. The high-resolution photo pairs and well-documented photo stations serve as a baseline and can be easily revisited and rephotographed to detect and monitor future changes in park resources.

The significant communication and educational value of repeat photo pairs is apparent in how quickly viewers comprehend the information being presented and are often drawn in to learn more about subjects that are complex or difficult to conceptualize. The adage that "a picture is worth a thousand words" certainly applies and one could argue that a photo pair or series has a multiplying effect making them worth much more. Repeat photography satisfies an innate human yearning for time travel. On a basic level, photo pairs serve as virtual time machines that afford researchers and viewers that desired ability to transcend time and see a snapshot of how things used to be.

Select Alaska National Park Repeat Photography Links

Klondike Gold Rush National Historical Park

Glacier Bay National Park and Preserve

Gates of the Artic National Park and Preserve

Kenai Fjords National Park

Denali National Park and Preserve

August 9, 2019, Chris Allan and Sarah Venator searching for a photo location in Gates of the Artic National Park and Preserve.
PHOTO COURTESY OF R.D. KARPILO JR.

Panoramic view of the terminus of Reid Glacier in Glacier Bay National Park and Preserve.

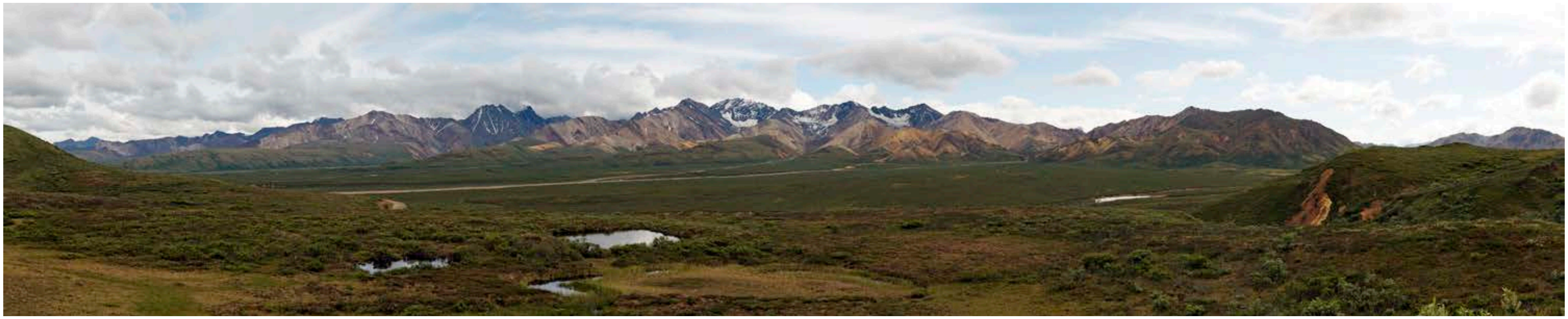
UPPER PHOTO: June 12, 1899, G.K. Gilbert, U.S. Geological Survey.
LOWER PHOTO: June 27, 2004, R.D. Karpilo Jr.

NOTABLE CHANGES: Reid Glacier has retreated several kilometers and vegetation has colonized the deglaciated area.

View north-northwest of Grand Pacific glacier (center) and Margerie glacier (left) in Tarr Inlet, Glacier Bay National Park and Preserve.

UPPER PHOTO: Summer 1931, C.W. Wright, U.S. Geological Survey.
LOWER PHOTO: June 26, 2004, R.D. Karpilo Jr.

NOTABLE CHANGES: Margerie Glacier has advanced into Tarr Inlet. Grand Pacific Glacier has thinned and stagnated and the terminus is now debris covered. Vegetation now covers the foreground.



View south from a small hill north of the park road near Polychrome Pass, Denali National Park and Preserve.

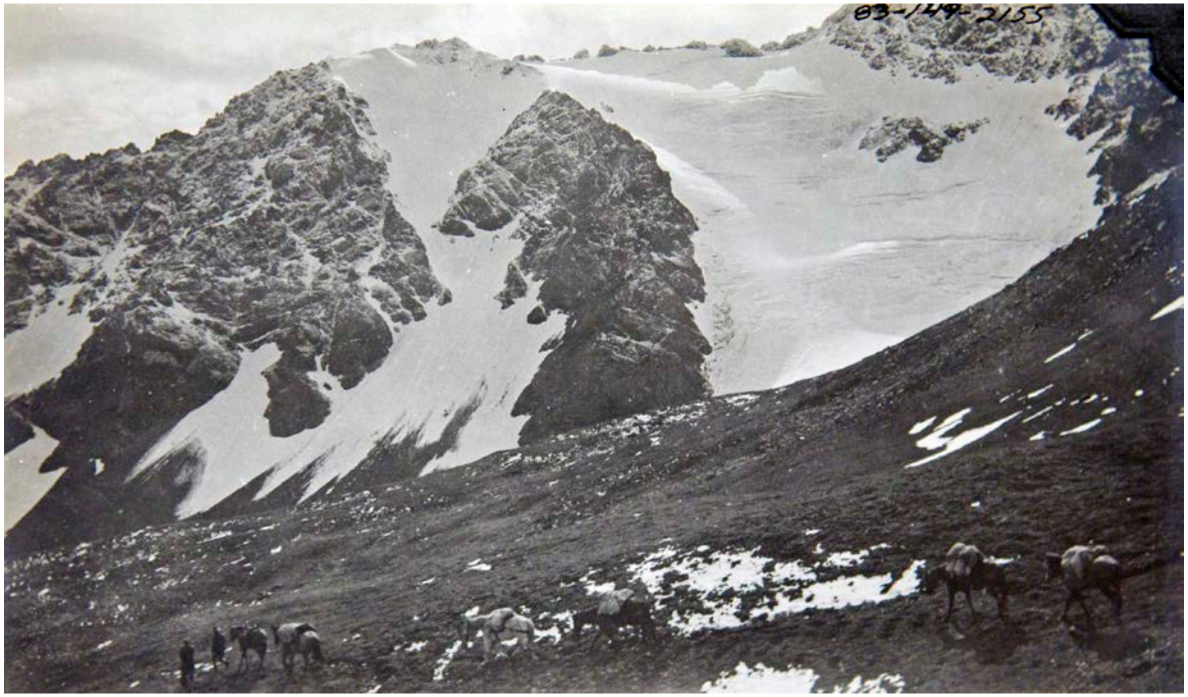
UPPER PHOTO: July 18, 1916, S.R. Capps, U.S. Geological Survey.
LOWER PHOTO: June 26, 2011, R.D. Karpilo Jr.

NOTABLE CHANGES: There has been significant melting of the Polychrome Glaciers, drying of the large pond in the foreground and development of several new ponds (related to permafrost melting), shift in vegetation from primarily low tundra to brush, and construction of the park road (a glimpse of a curve of the dirt road is visible above the left-most pond).

Panorama of the East Fork Toklat River and Glacier, Denali National Park and Preserve.

UPPER PHOTO: August 22, 1919, S.R. Capps, U.S. Geological Survey.
LOWER PHOTO: June 30, 2011, R.D. Karpilo Jr.

NOTABLE CHANGES: There has been significant retreat and thinning of the East Fork Toklat Glacier as well as melting of several cirque glaciers in tributary valleys. The East Fork Toklat River has migrated from the east bank of the outwash plain to the west bank.



U.S. Geological Survey geologist Stephen R. Capps' field party crossing into Windy Creek from the Sanctuary River Valley, Denali National Park and Preserve.

UPPER PHOTO: August 31, 1919, S.R. Capps, S.R. Capps Papers #83-149-2155, APR Collections, University of Alaska Fairbanks.
LOWER PHOTO: July 30, 2011, R.D. Karpilo Jr.

NOTABLE CHANGES: There has been significant melting of the cirque glaciers at the head of Windy Creek.

View north of Nutuvukti Lake from small peak between the lake and Kobuk River in Gates of the Arctic National Park and Preserve.

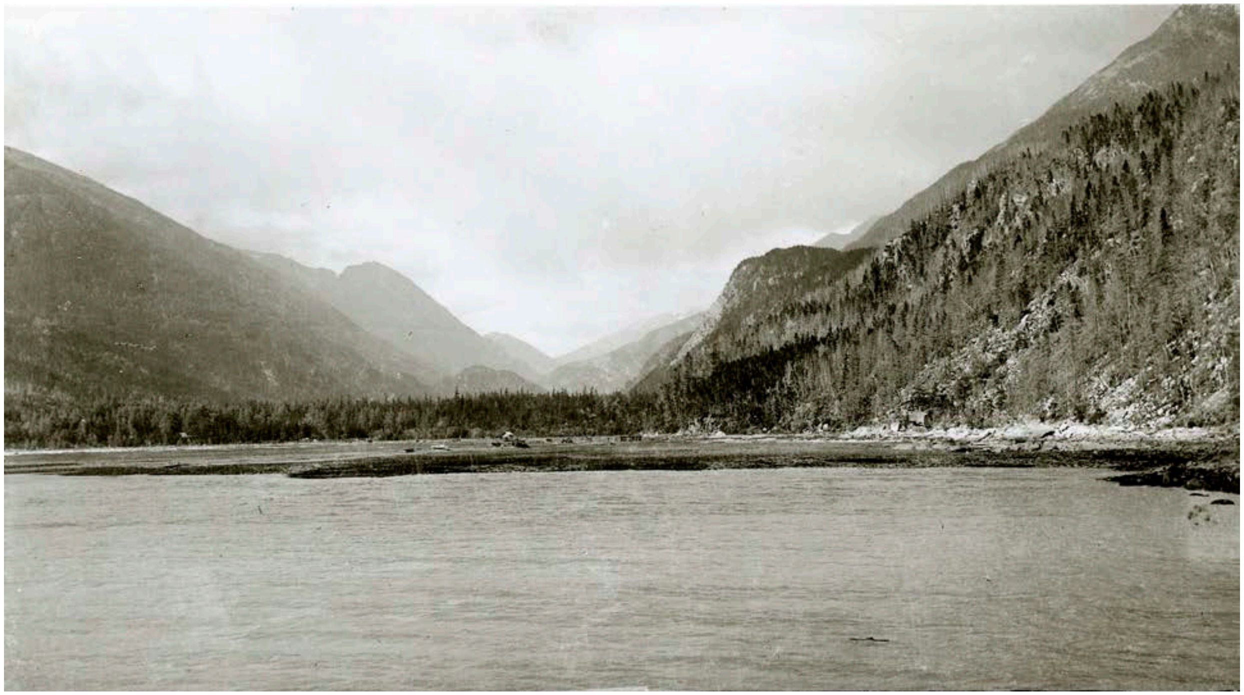
UPPER PHOTO: August 13, 1901, W.C. Mendenhall, U.S. Geological Survey.
LOWER PHOTO: August 9, 2019, R.D. Karpilo Jr.

NOTABLE CHANGES: There has been an Increase in density and size of white spruce (*Picea glauca*) on the slope in the foreground and on the midground ridge.

View north from Swan Island, Walker Lake, Gates of the Arctic National Park and Preserve.

UPPER PHOTO: August 12, 1901, W.C. Mendenhall, U.S. Geological Survey.
LOWER PHOTO: July 12, 2018, R.D. Karpilo Jr.

NOTABLE CHANGES: Photo pair shows variations in density, distribution, and size of vegetation such as white spruce (*Picea glauca*), black spruce (*Picea mariana*), balsam poplar (*Populus balsamifera*), and willows (*Salix* spp.). Specifically, the trees have increased in size and number and there is a general increase in shrub density. Shrubs have filled many of the previously open areas and thickened along the lakeshore and in stream channels.



View north of the waterfront in Skagway.

UPPER PHOTO: July 26, 1897, F. La Roche, Library of Congress, LC-USZ62-122304.
LOWER PHOTO: August 15, 2013, R.D. Karpilo Jr. and S.C. Venator.

NOTABLE CHANGES: Vegetation on the slopes around the town has thickened and the shoreline and tidal area have been altered by dredge and fill operations. Additional changes include residential and commercial development and infrastructure improvements such as construction of the Skagway Small Boat Harbor.

View to the south of the East Fork Skagway River and train on the White Pass and Yukon Route Railway rounding the curve at Rocky Point, Klondike Gold Rush National Historical Park.

PHOTO ABOVE: August 3, 2014, Ron Karpilo repeats a historic photo near Inspiration Point on the White Pass and Yukon Route Railroad, Klondike Gold Rush National Historical Park. Photo courtesy of Sarah Venator.
UPPER RIGHT PHOTO: August 1899, H.C. Barley, Yukon Archives, H.C. Barley Collection, #5509.
LOWER RIGHT PHOTO: August 3, 2014, R.D. Karpilo Jr. and S.C. Venator.

NOTABLE CHANGES: Rock has been blasted and removed along the railroad, there is an increase in the density of vegetation along the East Fork Skagway River, regrowth of vegetation in the area disturbed by the railroad construction, a shift from predominantly spruce forest to a deciduous species dominated environment, and slight shrinking and thinning of the ice on the peak in the background.

Panorama of Chilkoot Pass from north of Boundary Monument 121 with view of Crater Lake and glaciers on both sides of the United States-Canada boundary. The Chilkoot Trail and structures on the pass are also visible.

UPPER PHOTO: Late summer 1906, G. White-Fraser, International Boundary Commission, Library and Archives Canada, PA-162894-5 and 162901-3.
LOWER PHOTO: August 5, 2014, R.D. Karpilo Jr. and S.C. Venator.

NOTABLE CHANGES: Glaciers on both sides of Chilkoot Pass have significantly retreated, there is a slight change in lake level, and deterioration of historic structures at the pass.

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August 27, 2013, Sarah Venator locating a photo site on AB Mountain, overlooking the Taiya River and Chilkoot Trail, Klondike Gold Rush National Historical Park.
PHOTO COURTESY OF R.D. KARPILO JR.

Making Sound Decisions Using Bioacoustics in Alaska's National Parks

Davyd Betchkal, Paul Burger, and Chris Gabriele, National Park Service

Animals are continuously immersed in acoustic signals. Acoustic recording devices allow us to extend our sense of hearing to remote places, times, and even frequencies we normally cannot access. By studying the sounds animals make, and the sounds in their environment, we can better understand their conservation needs. Presented here are examples from bats, birds, frogs, and whales.

Citation:
Betchkal, D., P. Burger, and C. Gabriele. 2021. Making sound decisions using bioacoustics in Alaska's national parks. *Alaska Park Science* 20(1): 66-73.

Animals are continuously immersed in acoustic signals. Physical processes of Earth's surface—such as flowing water, earthquakes, or weather—produce sounds. Fundamental animal behaviors—such as breathing, moving, or eating—produce sounds. And of course, animals deliberately produce sounds to communicate. On top of this are the sounds that humans produce with vehicles, machinery, and other activities. Considering the continuous flow of information that *acoustic environments* represent, it is no surprise that every animal species has some form of ear (Horowitz 2012). The National Park Service (NPS) protects acoustic environments, meaning all the sounds occurring at a location over time plus the physical capacity of the landscape to transmit them (NPS 2006).

Western culture historically considered audible sounds to be intangible, emotional, and formless. As a result, sound was long overlooked as scientific information (Sterne 2003). The invention of audio recording devices in 1877 contributed, in part, to a paradigm shift. If sound could be documented, it could be analyzed. Since then, recording devices have become recognized as keen instruments of field science.

Acoustic recording devices allow us to extend our sense of hearing to remote places and times where we would otherwise not be listening. Instruments can document conditions on a remote mountainside continually for months at a time. They extend sensitivity beyond physiological limits, revealing sounds above (i.e., *ultrasonic frequencies*) or below (i.e., *infrasonic frequencies*) the range of human hearing. Submersible instruments can listen underwater without having to hold their breath or wear a wetsuit. The purpose of this article is to provide examples of how we use acoustics to understand wildlife and their environment (Figure 1).

Terrestrial Sounds: From Familiar Voices, Renewed Understanding

To realize the potential of audio recording devices, the NPS is focused on analysis tools. The right tool depends on the scientific question, management issue and staff capacity. Most acoustic environments have varied, overlapping sounds. Separating, categorizing, and summarizing them is often the way to analyze sound and interpret biological significance. Many analyses proceed by a basic approach: methodical, technical listening in headphones. Listening methods are time consuming, but offer detailed results.

Purely numeric approaches are flexible enough to answer diverse questions and allow greater analysis speed. With appropriate care, numeric acoustic indices have shown great promise for biologists seeking to estimate biodiversity in time or space (for example Towsey et al. 2014, Buxton et al. 2018, Bradfer-Lawrence et al. 2019). For questions involving specific taxa, advances in technology have recently enabled identification of animal sounds at close-to-human levels. Computerized detection is

Bob Peterson packs up after deploying an acoustic recorder at JoJo Lake, Katmai National Park and Preserve. The equipment was part of a parkwide inventory, and documented activity of common loons and other birds.
NPS PHOTO

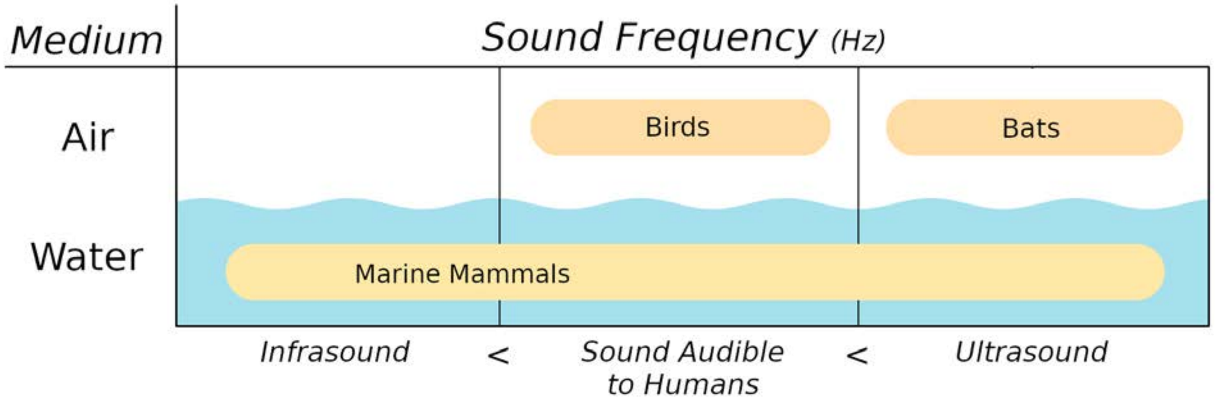

Figure 1. Bioacoustic technique depends on the acoustic frequency of animal sound (in Hertz; Hz) and the medium it travels through. This article provides updates on research within each of the three acoustic domains. Article focal taxa are shown within their respective domain.

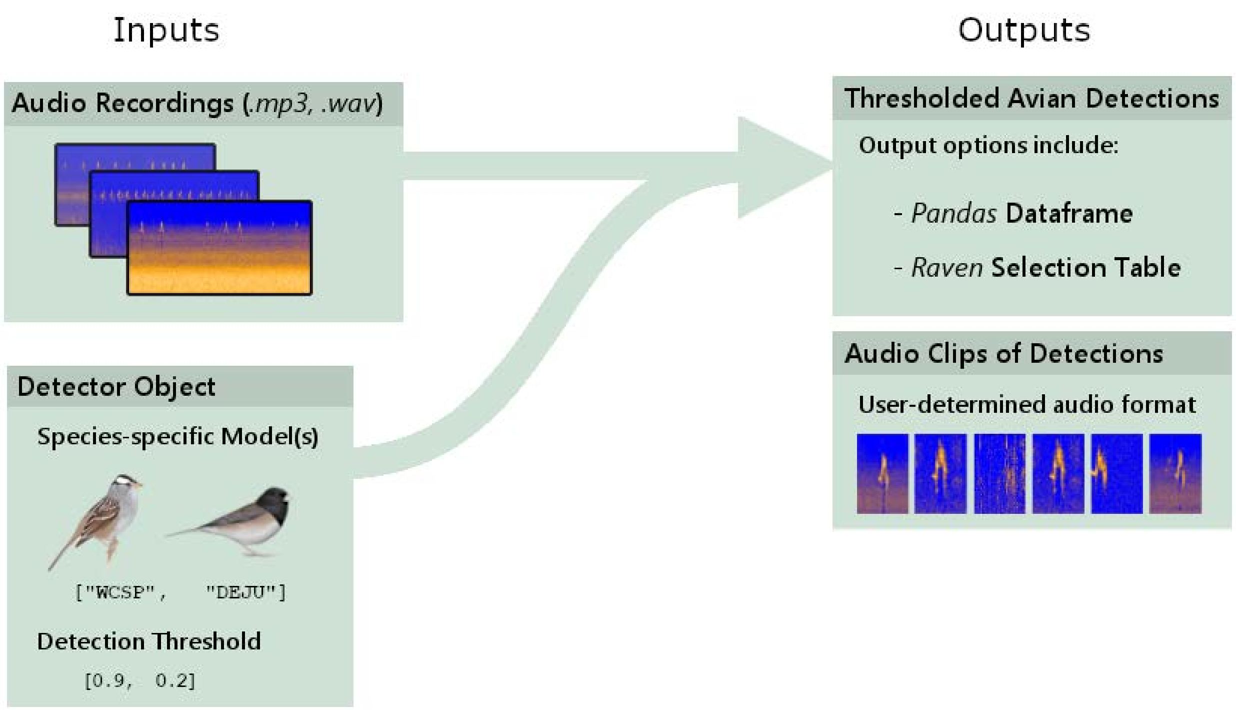

Figure 2. Intended use of the *Avian Acoustic Discovery* Python library. Species-specific models sweep through input audio under a sensitivity threshold. Outputs allow users to continue working with detections in Python or in Cornell's Raven software. The tool can also save short audio clips of detections.

currently well-defined for some taxa (for example, bats, described below) and in development for others. Software programs like Cornell Lab of Ornithology's Raven, Wildlife Acoustics Kaleidoscope, Oregon State University's Ishmael, or University of Costa Rica's warbleR allow users to develop their own wildlife detectors. Fine tuning can result in a moderate-to-high level of performance.

Given a large library of example sounds, machine learning is another way to develop high-quality detectors. One such machine-learning-based tool is now available to parks. Avian Acoustic Discovery: Alaska (Summers and Betchkal 2019, Figure 2) is an open-source detection tool trained using Alaskan bird dialects. The current release includes 20 different species. Many inclusions, like white-crowned sparrow (*Zonotrichia leucophrys*), are abundant, while others, such as orange-crowned warbler (*Vermivora celata*), are experiencing rapid declines in abundance (Audubon Alaska 2017). Most of the included species are migratory, but a few, like willow ptarmigan (*Lagopus lagopus*), are year-round residents.

Automatic detection speeds analysis of the entire audio record. Using this technique, we can track biological events across an entire season, or over several years. Records show the beginning, ending, peak, or abrupt changes in the rate of sounds. Glacier Bay National Park and Preserve has been using audio recordings to monitor the timing of bird migration since 2012 (Buxton et al. 2016). The Central Alaska Inventory and Monitoring Network's shallow lakes monitoring program has used recorders to document the reproductive timing of wood frogs (*Lithobates sylvaticus*) since 2011 (Larsen 2012). Both efforts are well-suited to analysis with automated detectors.

Phenology research is one among many fields that benefit from the advancement of acoustic data tools. Consider a remarkable example: In 1974, researchers at the University of Alaska Fairbanks distinguished metapopulations of Gambel's white-crowned sparrow (*Z. leucophrys gambelii*) using only acoustic properties of their song (DeWolfe et al. 1974). To do this, they required an expensive spectrograph machine that would cost over $13,000 in 2019 dollars. With Acoustic Discovery, any computer can rapidly extend the spatial extent of their work. A recording with a GPS coordinate and a white-crowned sparrow song becomes a population biology study site.

This underscores an important point: To advance the field of biology, it is critical for publicly funded recordings to be accessible for research. This involves parks working with archival institutions like the National Oceanic and Atmospheric Administration's National Centers for Environmental Information, the Cornell Lab of Ornithology's Macaulay Library, Xeno Canto, and others.

Ultrasonic Sounds: Bat Monitoring in Alaska

If you've never heard a bat call, there's a good reason why: their sounds are *ultrasonic* (i.e., higher frequency than the range of human hearing). Several Alaska parks are monitoring the ultrasonic calls of bats to better understand their distribution, migration, and behavior.

Many people are surprised to find out that there are bats in Alaska. These elusive animals forage for insects late at night and are rarely seen other than when they end up inside people's attics or cabins. There are six bat species in Alaska (little brown, *Myotis lucifugus*; silver haired, *Lasionycteris noctivagans*; hoary, *Lasiurus cinereus*; Yuma myotis, *Myotis yumanensis*; California myotis, *Myotis californicus*; and long-eared myotis, *Myotis evotis*), with most of the diversity in the southeast where the climate is more temperate. In southcentral and interior Alaska, the only species that has been found is the little brown bat.

Bats are small, fly quickly, and are only out for a few hours each night, so direct observation and identification is very difficult. Thankfully, bats use echolocation for navigation and hunting prey and these calls can be detected with ultrasonic microphones. Bat calls have been characterized and collected into vocal libraries for different bat species, which allows researchers to identify bats from recordings, at least to major species groups. Studying the calls also allows researchers to determine bat activity levels each night and throughout the year.

Bats in Alaska are poorly understood with regard to their habitat, prey, life cycle, and migration patterns. Though many parks have documented little brown bats in park structures and, in some cases, overwintering in structures outside the parks, very little is known about the presence of bats in natural habitats. Knowing what habitats are being used by bats helps park managers make important resource management decisions, such as leaving old-growth tree stands and snags in place because bats are using them for day roosts.

There is some acoustic and recapture data to support the idea that some bats in interior Alaska migrate to the coast in the fall, but it is not known whether all Alaska bats migrate or if some overwinter in the parks. Migration to the coast and southward would increase the opportunities for Alaska bats to interact with southern populations and carry diseases such as White Nose Syndrome northward.

Since 2015, we have placed 82 detectors in 10 parks for over 4,500 nights of acoustic monitoring (Figure 3). The detectors were established across

Little brown bat captured in Klondike Gold Rush National Historical Park in 2014.

White Nose Syndrome is a fungal disease that has decimated bat populations in the eastern parts of the U.S. and Canada and has been spreading west and north since 2002. In some cases, bat colonies have lost more than 90% of their population. Bats provide nearly 4 billion dollars a year in natural pest control and are vital to many ecosystems. Understanding the types of bats, their habitat, and migration patterns is vital for developing long-term strategies to protect bat populations from disease, habitat destruction, and other direct threats.

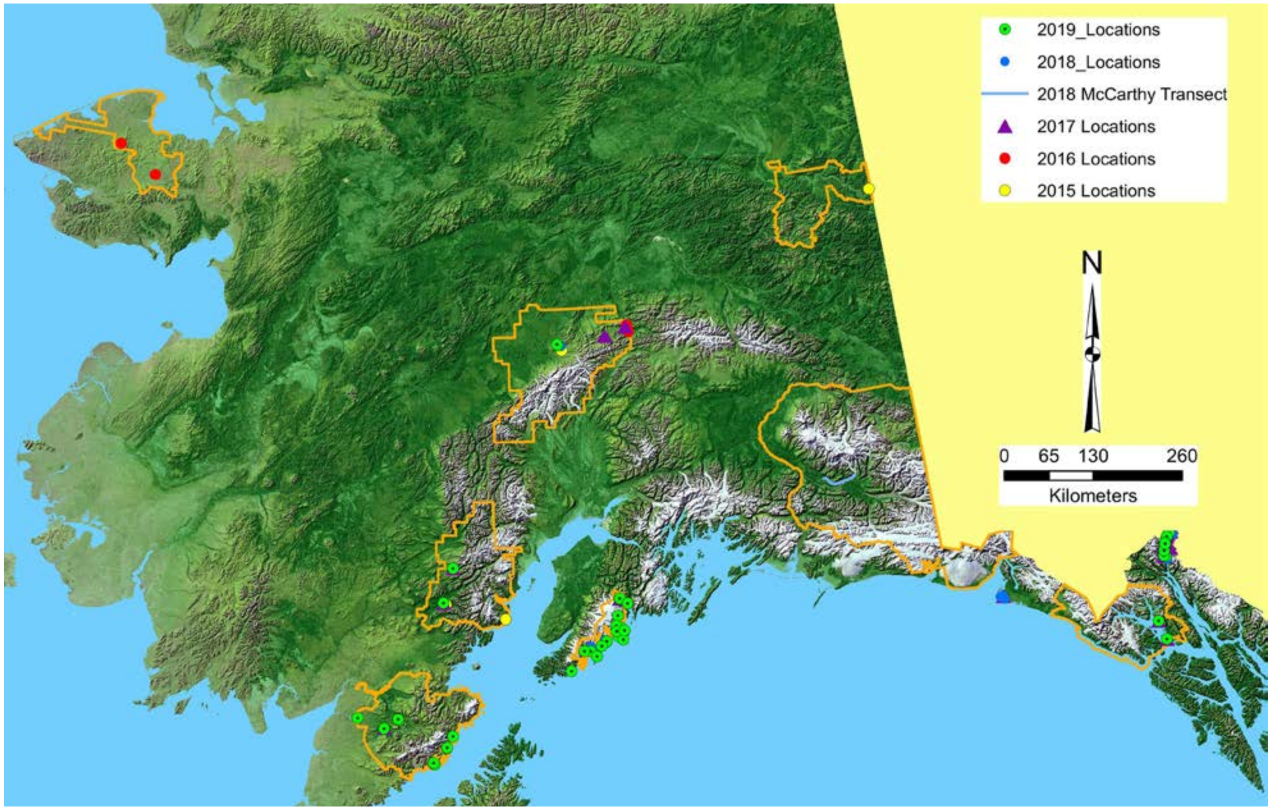

Figure 3. Points indicate bat monitoring locations in Alaska from 2015 to 2019. The road-based transect route in Wrangell-St. Elias National Park and Preserve is also shown.

a wide range of habitats from coastal to forested interior and tundra. We have conducted 4 driving transects in Wrangell-St. Elias National Park and Preserve and several hiking transects from the U.S .into Canada and back along the Chilkoot Trail in Klondike Gold Rush National Historical Park.

As expected, bats are most active during the warmer months. What was unexpected is that they feed intensely for much shorter periods on a given day than predicted, frequently in the range of only two hours. This may be due to the short-to-nonexistent darkness in northern Alaska that makes it difficult to avoid predation by owls and other animals.

We have also found bats active over saltwater in Glacier Bay National Park and Preserve and Kenai Fjords National Park. It is not clear whether they are actively foraging or just using the open space to transit between feeding and roosting areas, but these were also unexpected results.

The acoustic monitoring has shown a spike in calls in the late fall in the coastal area of Klondike Gold Rush National Historical Park that roughly corresponds to when calls diminish in the interior of Alaska and Canada, suggesting that at least some bats may be migrating from those areas to the coast. We have started coordinating with the Alaska Department of Fish and Game and researchers in Canada to conduct mist netting and banding of bats to verify this, but do not have results yet.

Bioacoustic monitoring has proven to be a very effective tool to explore bat activity over a broad area with little impact on staff time. We plan to continue using acoustic monitoring long term and to use the data to guide effective mist net placement for species identification and disease screening.

Diving Into Underwater Sound: Lessons from Glacier Bay

Aside from the occasional scuba diver, humans do not directly experience underwater sound environments in Alaska parks. However, underwater acoustic habitats are essential to the basic life functions of many aquatic animals that are ecologically important and of high interest to park visitors. Effective conservation requires that we document the underwater sound environment, how animals use it, and how management decisions affect it. Work we conduct in Glacier Bay National Park and Preserve illustrates the use of underwater acoustics to inform park management and provides a useful example of how other parks may successfully use these tools.

The story of underwater sound monitoring in Glacier Bay centers on a long-standing concern that vessel-generated noise has the potential to disturb whales and other wildlife. Knowing that animals rely on underwater listening in their daily life and that park vessel-management actions affect the underwater soundscape, our studies focus on describing natural and man-made underwater sounds and how vessel management actions, such as vessel quotas and speed limits, change the underwater soundscape.

Thinking deeply about what information is needed to answer a particular basic research or management-related question is an essential first step in bioacoustics study design and methodology. If you're planning to make quantitative measurements, it's important to use standard metrics that will allow you to compare your findings with those from other researchers or geographic areas.

Finding the right partners at the start is an essential ingredient to successfully using bioacoustic tools. The complexity of acoustics can be intimidating, potentially creating a formidable deterrent to using the resulting information in management decisions. The NPS Natural Resource Science and Stewardship (NRSS) Natural Sounds Program is an excellent resource for finding the right equipment and the right collaborators to collect, process, and interpret acoustic results.

Malme and others (1982) first quantified Glacier Bay's underwater soundscape using portable hydrophones (underwater microphones) deployed temporarily off the side of a boat (Figure 4a). Regular monitoring of ambient underwater sound began in 2000, when park scientists in collaboration with U.S. Navy acousticians installed a calibrated hydrophone near the mouth of Glacier Bay, connected by a 5-mile (8-km) cable to a custom computer system at park headquarters (Figure 4b). With this system, we created the first comprehensive description of sound sources (wind, rain, animals, and vessel engines), how often, and what their pitch and duration characteristics were (McKenna et al. 2017). We also used this system to make calibrated measurements of specific vessels that transited past the hydrophone at a known distance determined by GPS (Kipple and Gabriele 2004). Next, using autonomous recorders from Cornell University's Bioacoustics Research Program in 2007, we broadened our efforts to listening mid-Glacier Bay to see if the sound characteristics were different there (Figure 4c).

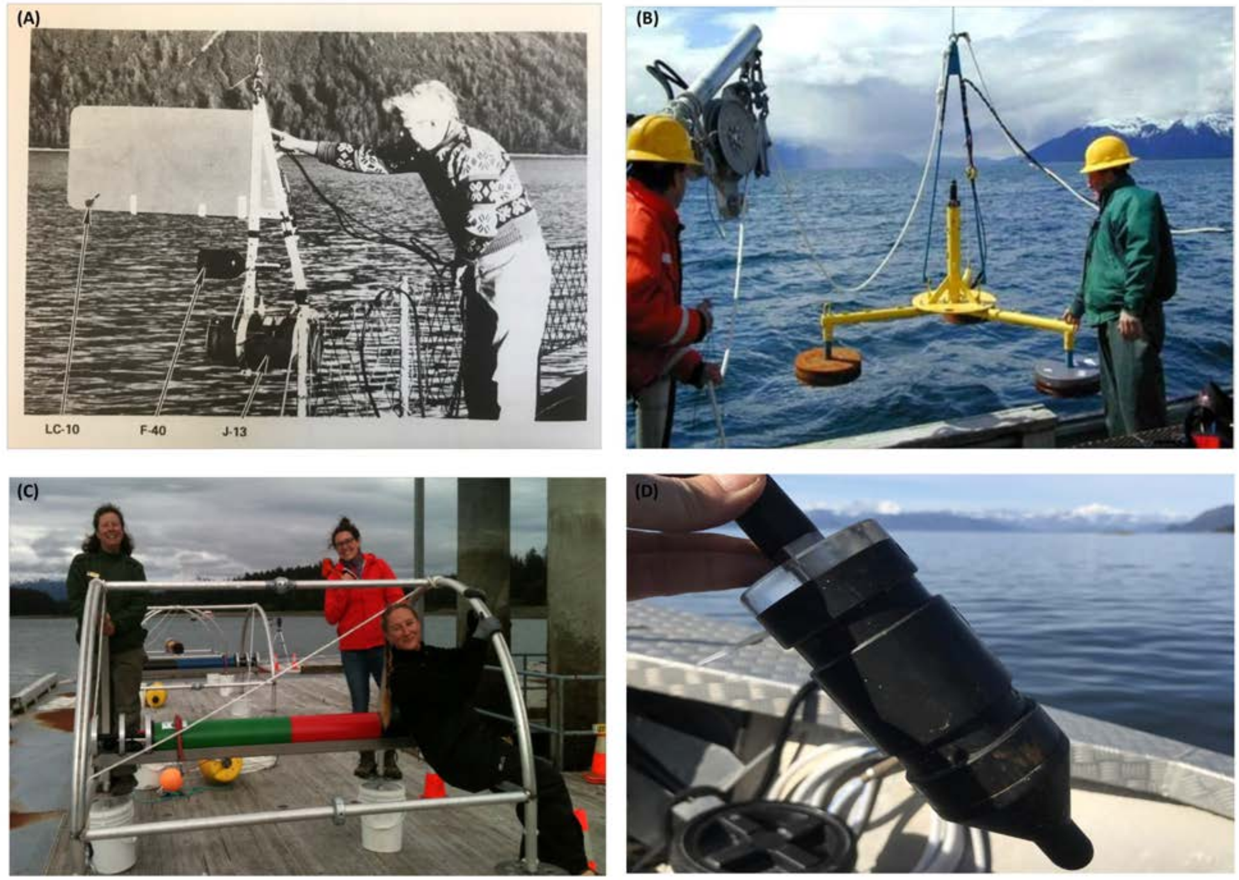

Figure 4. Choosing the right hydrophone for the job: (a) In 1980-1982, contractors from Bolt, Beranek, and Newman used underwater speakers to measure how much sound dissipates as it travels in seawater. (b) In partnership with the U.S. Navy, a long-term monitoring hydrophone was installed in 2000 and is still in use today. (c) In 2015-2016, we worked with graduate students from Syracuse and Oregon State Universities using an array of four anchored hydrophones to study the vocalizations of harbor seals and humpback whales. (d) In summer 2019 and 2020, we deployed a small Sound Trap® automated recorder in the middle of Glacier Bay for a month at a time.

Autonomous systems, that can record for weeks or months before being retrieved, become more powerful and affordable every day, and are the right tool for most applications in Alaska parks.

Bioacoustic studies have been vital to a better understanding of how humpback whales communicate and rely upon Glacier Bay's underwater soundscape.
NPS PHOTO

Most recently, in a 2015-2016 study funded by the Coastal Marine Grant Program, we worked with Oregon State University to deploy an array of hydrophones (Figure 4c) that allowed us to acoustically locate each vocalizing animal, allowing us to measure the loudness of harbor seal (*Phoca vitulina*) roars and humpback whale (*Megaptera novaeangliae*) calls (Matthews et al. 2017, Fournet et al. 2018a). This study also allowed important insights into how whale and seal vocalizations change in the presence of motorized noise (Fournet et al. 2018b). In summer 2019 and 2020, we deployed a Sound Trap® autonomous recorder to replicate the soundscape measurements made back in the 1980s in Glacier Bay and Frederick Sound to determine how the underwater sound environment has changed over time (Figure 4d).

Simple metrics and visualizations help managers understand the relative contributions of different natural and anthropogenic noise sources and how they reduce the opportunities of animals to communicate. For specialized tasks, it is often necessary to team up with collaborators who have the tools that allow us to model and visualize the results. For example, incorporating all our knowledge of Glacier Bay's sound environment and the loudness of individual vessels into the Acoustic Integration Model (AIM), we found that cruise ship speed was the dominant factor affecting how much noise whales were exposed to in Glacier Bay, and that noise exposure is lower when ships are scheduled to synchronize their arrival times (Frankel and Gabriele 2017). We recently completed work that allowed the first assessment of the extent to which vessel-generated noise decreases the distance over which humpback whales and harbor seals can communicate, relative to how far they can communicate under naturally quiet conditions (Gabriele et al. 2018). In quiet conditions, two whales can hear each other and vocalize back and forth at a distance of about a mile and a half (2.3 kilometers). But with the noise from vessels on a typical day in the tourist season, that communication distance shrinks to about 75 yards (70 meters) or even less.

A study done in collaboration with Oregon State University under an Alaska Coastal Marine Grant showed that whales vocalized more loudly when natural or man-made background noise got louder and were less likely to vocalize when there was vessel noise than when only natural sounds were present (Fournet et al. 2018b).

Working with Cornell University's Center for Conservation Bioacoustics, we created a visualization of a day in the life of Glacier Bay shows the sound footprints of calling humpback whales and vessels on a peak summer vessel traffic day. Using computer models, we were able to estimate and quantitatively compare how far a whale or seal's vocalizations could travel in quiet conditions vs. during wind and vessel noise (Gabriele et al. 2018). The results suggested that synchronizing vessel entries into the bay is one way that managers can improve the underwater acoustic environment and benefit the marine mammals that rely on it. Using these powerful visualization tools on an ongoing basis is one of the most important next steps toward effective conservation of underwater sound environments. A key step that managers can take to prepare is to begin collecting representative vessel sound signatures and baseline ambient noise measurements that can later be used to inform models.

Important Links

Check out these links to experience sounds in Alaska parks.

- Soundscapes, Denali National Park and Preserve
- Voices of Glacier Bay National Park and Preserve
- Humpback whales, Glacier Bay National Park and Preserve
- Acoustic monitoring, Glacier Bay National Park and Preserve
- Wood frog, Gates of the Arctic National Park and Preserve
- Natural sounds across the National Park System

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An Introduction to Some of the High-flying Technology Used to Study the Movements of Alaska's Migratory Birds

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There are many tools available to study the movements of birds and the technology is evolving rapidly. Explore how satellite telemetry, global system for mobile communications telemetry, archival light-level loggers, and GPS data loggers are used in migratory bird research and what we are learning as a result.

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Alaska's national parklands are home to an amazing diversity of birds ranging from black-capped chickadees (*Poecile atricapillus*) and Canada jays (*Perisoreus canadensis*) that remain relatively close to their natal areas throughout their entire lives to Arctic terns (*Sterna paradisaea*) and blackpoll warblers (*Dendroica striata*) that migrate tens of thousands of miles annually. Many species of migratory birds nest in Alaska's national parklands, while others migrate through them or spend time in them during the non-breeding season or winter.

Brown and Elder (1982) eloquently stated in their book, *This Last Treasure, Alaska National Parklands*, "the national parklands in Alaska, some 50 million acres of them, hold in trust the closest approximation to complete ecosystems left on this planet." As such, these areas are likely to become increasingly important for migratory birds as indirect and direct impacts of human activities spread across our planet. However, protecting migratory birds requires us to think and act far beyond the boundaries of these parklands; we need to work collaboratively with others to identify and protect the areas and resources they use throughout the year (Runge et al. 2014, 2015). Protecting our migratory birds also requires us to understand how events at any one stage of the life cycle, or the combined events at all stages, affect their population dynamics (Bowlin et al. 2010). Overall, we need to be proactive and apply life-cycle stewardship approaches for protecting our migratory birds. One step in doing so is learning more about the areas and resources they use throughout the year and their lives.

In this article, I review just a few of the recent advances in electronic tracking devices (or *tags*) that scientists are using to study migratory birds and highlight the results of a few recent studies that are providing new information on their movements. Tags provide new opportunities to identify the areas used by migratory birds throughout the year and assess how conditions and events at distinct geographic locations that are thousands of miles apart interact to affect their survival and reproductive success. Kays and others (2015) and McKinnon and Love (2018) suggested that we are in the golden age of animal tracking and bio-logging, where smaller and more sophisticated tracking technology allows the unprecedented study of animal movements. Others have suggested that tracking technology is still in its infancy, with many new advances being made every year (Bridge et al. 2013). Regardless, we hope that the results of studies using new tracking technology can be used to enhance conservation of migratory birds (Weidensaul 2017), including those found in Alaska's national parklands.

New Technology Provides New Opportunities

The tools and technologies used to study bird movements is a rapidly evolving field. In this article, I briefly introduce four types of tracking devices (tags), that scientists are currently using to study the movements of wide-ranging migratory birds.

A gyrfalcon in Denali National Park and Preserve. Gyrfalcons nest throughout the circumpolar Arctic and Alaska contains the only nesting populations of gyrfalcons in the United States.
NPS/JARED HUGHEY

A golden eagle hunts the slopes in Denali National Park and Preserve.
JARED HUGHEY

The first two types of tags, satellite telemetry and global system for mobile communications (GSM) telemetry, remotely transmit data and do not require researchers to recover them to obtain data. The second two types of tags, archival light-level loggers (also known as *geolocators*) and global positioning system (GPS) data loggers, store data on board and require researchers to recover the tags to obtain data.

Over the past decade, tags available for studying the movements of birds and other wildlife have decreased in size, but in many cases increased in their data collection capabilities (see Kays et al. 2015). While these tags have been used to study the movements of a wide range of bird species, they are still limited to species that are large enough to carry the tag. For birds, a general rule is that the tag and materials used to affix it must be less than 3% of the weight of the bird (Caccamise and Hedin 1985).

The methods used to attach or affix tags to birds vary by species and by study; readers wanting to learn more about the various types of attachment methods should refer to specific studies. Further, tags are designed and sold by many different manufacturers; a list of the type of tags and their manufacturers is not included in this article.

Satellite and Global System for Mobile Communications Telemetry

Satellite telemetry systems rely on a series of polar-orbiting satellites to obtain data. Global System for Mobile Communication (GSM) telemetry systems rely on existing mobile cellular networks to obtain data. Both satellite and GSM tags can be equipped with many types of sensors including altimeters, thermometers, accelerometers, battery voltage meters, and solar-charging meters. Most current models of satellite Platform Transmitting Terminals (PTTs) and GSM tags also include a GPS sensor. Both types of tags can be programmed with specific duty cycles (the fraction of one period in which a signal is active) to allow researchers to collect and transmit data to their specification. Older PTT models were powered by batteries that had a limited life, but most newer models of PTTs and GSMs use solar rechargeable batteries that provide opportunities for tracking individuals for many years.

Satellite telemetry. Satellite telemetry was a major technological advancement for studying the movements of wide-ranging animals, including birds. This technology allowed researchers to remotely track tagged individuals nearly anywhere they traveled across Earth. Satellite tags (or PTTs) for birds became commercially available in the early 1990s. NPS scientists were among the first to use PTTs in Alaska to study bird movements (Britten et al. 1995). This system includes a PTT that is attached to the bird, a receiving system in space (the satellite), and a data receiving and transfer system on Earth. Today, most PTTs provide for highly precise locations determined by GPS.

GSM telemetry. GSM telemetry systems use cellular data networks to collect GPS-derived location and other (i.e., speed, heading, altitude) data. Tag locations are determined using GPS or Global Navigation Satellite Systems (GNSS). This technology became commercially available for use on birds about ten years ago. The system includes a transmitter/data logger that is attached to the bird and a receiving system, usually an existing cellular data network. GSMs can collect a tremendous amount of data and provide it to the user very quickly when a tag connects to a cellular network. When the tag cannot make a connection to a cellular network, the data are stored on board and sent when the tag makes the connection. GSM tags are very useful for studies that require large sample sizes of highly precise data for birds that pass within cellular networks.

A Sample of Studies Using Satellite and GSM Telemetry

Pre-breeding hotspots of Denali's golden eagles on Alaska's Arctic coastal plain. Golden eagles (*Aquila chrysaetos*) are a relatively long-lived species, but individuals most likely do not enter a breeding population until they are at least four to five years old (Watson 2010). Identifying areas used by younger golden eagles before they enter a breeding population is essential to the conservation of the species. Using lightweight battery-powered PTTs, McIntyre and others (2008) described the annual cycle movements of juvenile golden eagles that were raised at nests in Denali National Park and Preserve (Denali). These younger eagles were not members of the breeding population, but they returned to Alaska each spring to forage and perhaps prospect for future nesting opportunities. One of the most important, and surprising, results of the study was that some of the tagged eagles used portions of Alaska's Arctic coastal plain in the summers before they entered a breeding population (McIntyre et al. 2008). In 2014, National Park Service (NPS) scientists in collaboration with scientists from the U.S. Fish and Wildlife Service, U.S. Geological Survey, and Conservation Science Global, LLC, continued studying the movements of golden eagles raised in Denali, this time instrumenting them with light-weight PTTs or GSM units with solar-rechargeable batteries just before they fledged (Figure 1; McIntyre 2015, McIntyre and Lewis 2018). The solar rechargeable PTTs and GSMs allowed scientists to track the movements of these younger eagles for multiple years. Like the eagles tagged in the earlier study, many of the eagles tagged in Denali after 2013 used portions of Alaska's Arctic coastal plain during the summer (Figure 2; McIntyre and Lewis 2018). While use of this area by younger age classes of golden eagles was documented by Mauer (1985), Ritchie (2014), and Shook and Ritchie (2017), the historical and contemporary tracking studies demonstrated the strong link between golden eagles from Denali and Alaska's Arctic coastal plain over decades.

Figure 1. Eight week old golden eagle nestling wearing 45 g solar rechargeable satellite transmitter (PTT), Denali National Park and Preserve, Alaska. The PTT is attached to the eagle using a backpack harness constructed of Teflon ribbon.
US FISH & WILDLIFE SERVICE/ STEPHEN B. LEWIS

Trans-continental movements of juvenile gyrfalcons. Gyrfalcons (*Falco rusticolus*) nest throughout the circumpolar Arctic and Alaska contains the only nesting populations of gyrfalcons in the United States (Anderson et al. 2017). Using lightweight, battery-powered PTTs, McIntyre and others (2009) described the movements of juvenile gyrfalcons that were raised near Bering Land Bridge National Preserve and in Denali during their first few months of independence. The most significant findings of this study were that the tagged gyrfalcons exhibited a wide range of movement patterns during this period, including repeated movements from Alaska to Russia and use of coastal areas along the Chukchi and Bering seas.

Identifying the importance of off-shore waters for wintering long-tailed ducks. The coastal waters off many Alaska's national parklands provide important staging and wintering areas for many species of migratory birds including waterfowl. Long-tailed ducks (*Clangula hyemalis*) nest in the circumpolar Arctic and migrate to cold, temperate coastal waters for the non-breeding season (Robertson and Savard 2020). Using lightweight battery powered PTTs, Bartzen and others (2017) studied the movements of 58 long-tailed ducks from nesting areas in Northwest Territories, Canada. The study identified important migration corridors, molting areas, and wintering areas in Alaska, including several near Alaska's national parklands in southwest Alaska. The study's findings suggest that conservation of long-tailed ducks requires cooperation among Canada, the USA, Russia, Japan, and South Korea—all countries that the tagged ducks used during their annual cycle (Bartzen et al. 2017).

The East Asian connection of Alaska's red-throated loons. Red-throated loons (*Gavia stellata*) are migratory waterbirds. They breed at high

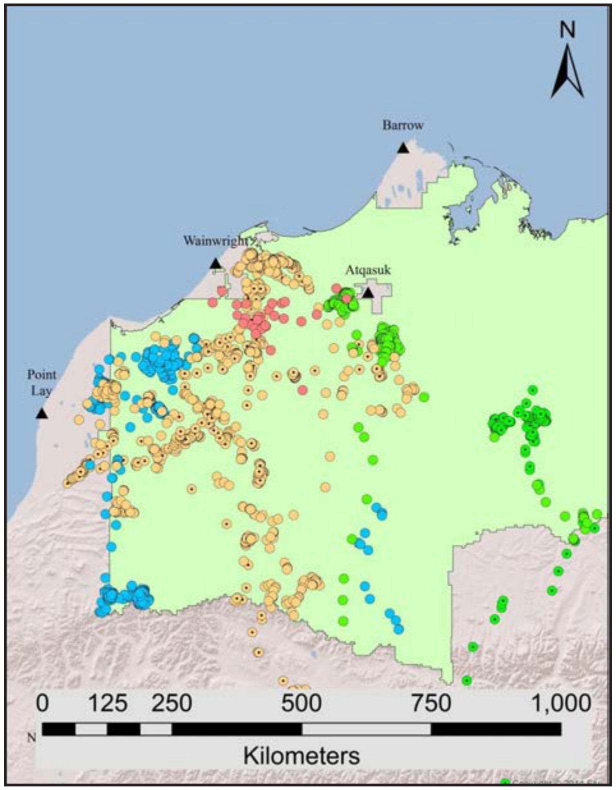

Figure 2. Relocations of golden eagles from Denali National Park and Preserve in the National Petroleum Reserve, Alaska during the nesting season (June to early September). The eagles were telemetered as fledglings in Denali in 1999, 2014, and 2015. Different colored circles represent individual eagles. Circles with the same color but with a black dot in the center represent the same individual but in different nesting seasons.
[Figure from McIntyre and Lewis 2018.]

latitudes, nest in low densities on small ponds in coastal tundra ecosystems and spend most of the remaining year (about 8 months) on coastal marine waters (McCloskey et al. 2018). Using lightweight, battery-powered PTTs, McCloskey and others (2018) studied the annual movements of 38 red-throated loons from four breeding populations in Alaska. They discovered that the most northerly breeding population from the Arctic coastal plain, which has also exhibited population declines, generally migrated along the East Asian flyway, used stop-over sites on the northern edge of the Seward Peninsula near the Bering Land Bridge National Preserve, and overwintered in eastern Asia (Figure 3). In contrast, tagged loons from other nesting populations in Alaska migrated along the west coast of North America. These findings suggest that during much of the year, red-throated loons live in coastal and marine systems, including those that are often inundated with terrestrial-, atmospheric-, and marine-derived contaminants and pollutants (McCloskey et al. 2018). Identifying how these contaminants and pollutants affect survival and reproductive success is a key to understanding and mitigating them.

A red-throated loon in Bering Land Bridge National Preserve.
NPS/JARED HUGHEY

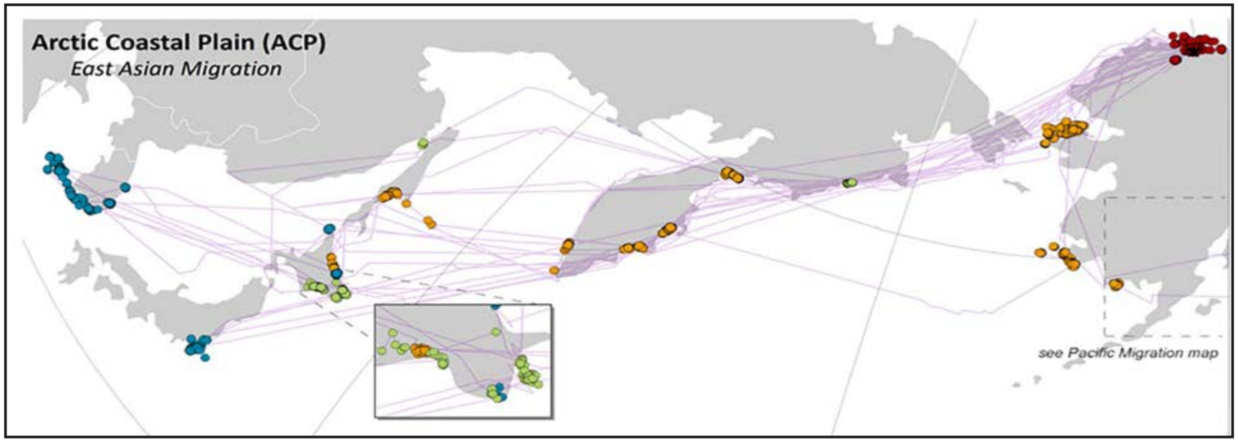

Figure 3. Migration paths (dotted lines), autumn stopover sites (yellow dots), wintering locations (blue dots) and spring migration stopover sites (green dots) of radio-tagged red-throated loons breeding on the Arctic coastal plain.
[Figure from McCloskey et al. 2018.]

Archival Data Loggers: Light-level Geolocators and GPS Data Loggers

Light-level geolocators and GPS data loggers became commercially available for use on birds in 2007. McKinnon and Love (2018) suggested that the availability of these smaller tags revolutionized the study of movements of birds that are too small (less than 0.7 ounces or 20 g) to carry PTTs or GSMs. Researchers attach these tags to birds using a variety of techniques (e.g., leg-loop backpack harness, nylon harness). Unlike PTT and GSM tags, these tags must be recovered to obtain the data stored on board.

Geolocators (Miniature Archival Light-level Logger). These tags currently range in weight from about 0.01-0.3 ounces (0.35 to 0.8 g) and offer scientists a tool to study the broader-scale movements of smaller birds (McKinnon and Love 2018). The tag includes a light sensor, internal clock, data- logging computer, and battery. Geolocators record light levels at regular intervals and store data on board; the archival data are obtained when the tag is recovered and locations are estimated by inferring solar positions (Bridge et al. 2013). Geolocators do not provide precise location data; because of error associated with unknown degrees of shading, a bird's exact position cannot be determined using geolocators (Bridge et al. 2013). Estimates of the location accuracy vary but range up to 124 miles (200 km) in latitude and 93 miles (150 km) in longitude (Bridge et al. 2013). Further, latitudinal location estimates are unreliable on either side of the vernal and autumnal equinoxes (Hallworth and Marra 2015). Thus, these small tags are useful for answering questions that do not require highly precise location data.

Archival GPS Data Loggers. The smallest available GPS data logger weighs about 0.035 ounces (1 g) and are programmed to collect location data at specific times and dates. The locations are estimated by GPS, resulting in very high-resolution spatial data. However, the number of locations provided by the tag varies, depending on the model and the duty cycle. Overall, GPS data loggers provide highly precise locations but fewer locations than geolocators. The location data are stored on board and the tags must be recovered to obtain data.

A Sample of Studies Using Geolocators and GPS Data Loggers

Hemispheric movements of blackpoll warblers. Blackpoll warblers are tiny (0.4 ounces or 12 g) passerine birds. Their breeding range spans the entirety of North America's boreal forests. DeLuca and others (2019) described the movements of tagged blackpoll warblers from two study areas in Alaska (Nome and Denali) and two study areas in Canada (Whitehorse, Yukon, and Churchill, Manitoba; Figure 4). The study demonstrated that blackpoll warblers nesting in these areas undertake one of the longest migrations ever recorded for a passerine (DeLuca et al. 2019). After the nesting season, the tagged birds flew eastward across North America in 7 to 29 days, then laid over on the Atlantic coast in the United States for 18 to 41 days (Figure 5) as they prepared for the next stage of their autumn migration. They then embarked on a non-stop transoceanic flight to the north coast of South America—a trip ranging from 1,400-2,113 miles (2,250 to 3,400 km) that took just 48 to 96 hours to complete. The tagged birds overwintered in the northern Amazon basin. In spring, the tagged birds migrated back to their breeding grounds along what

Figure 4. Blackpoll warbler wearing a 0.5 gram geolocator, Denali National Park and Preserve, Alaska. The geolocator is attached to the warbler by a leg-loop harness.
NPS PHOTO

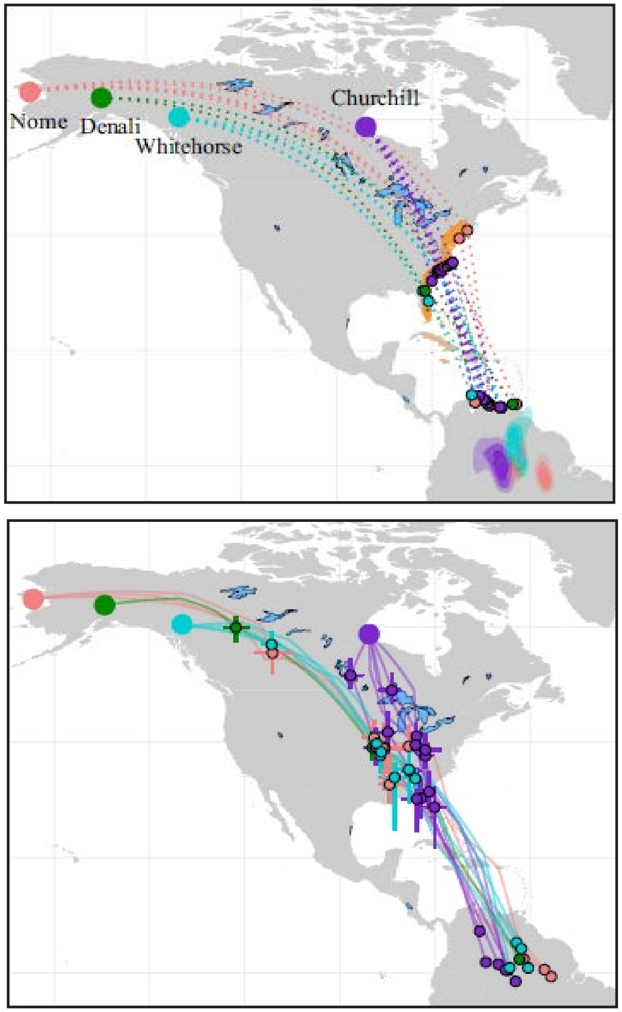

Figure 5. The four study sites, each indicated by a different colored dot, where 0.5 g geolocators were deployed on blackpoll warblers (top panel). Autumn migration pathways (dotted lines), estimated stopover locations on eastern coast of North America, and estimated arrival locations on coast of South America (top panel). Spring migration of individuals, with points showing stopover sites (> 4 days) (bottom panel).
[Figure from DeLucca et al. 2019.]

is close to the most direct route and completed the migration in 17 to 49 days (Figure 5). DeLuca and others (2019) suggested that loss or degradation of stopover habitats along the Atlantic coast of the U.S., northern Venezuela, and the Great Lakes basin could result in disproportionately wide-ranging effects on blackpoll warblers since they are used by individuals from across the breeding range.

Continental movements of American robins and their behavioral response to environmental conditions during spring migration. Two recent studies used GPS data loggers to study the movements of American robins (*Turdus migratorius*), one of the most widespread birds in North America (Jahn et al. 2019, Oliver et al. 2020; Figure 6). Jahn and others (2019) studied the difference in migratory behavior of a very small sample of male American robins (n=7) in several study areas in North America. As predicated by encounters of banded birds (Brown and Miller 2016), four tagged male American robins from Denali migrated further than a female tagged in Massachusetts and a male and female tagged in Washington, DC, with Denali birds wintering from eastern Montana to northern Texas (Jahn et al. 2019; Figure 7). The timing of autumn migration events

Figure 6. American robin wearing a 1 gram GPS data logger, Denali National Park and Preserve, Alaska. The GPS data logger is attached to the robin using a leg-loop harness. The robin also wears an USGS aluminum leg band (on right leg) and color-coded plastic bands (on left leg). The color bands are visible using binoculars and help field staff identify which individuals should be targeted for recapture efforts when they return to Denali.
NPS PHOTO

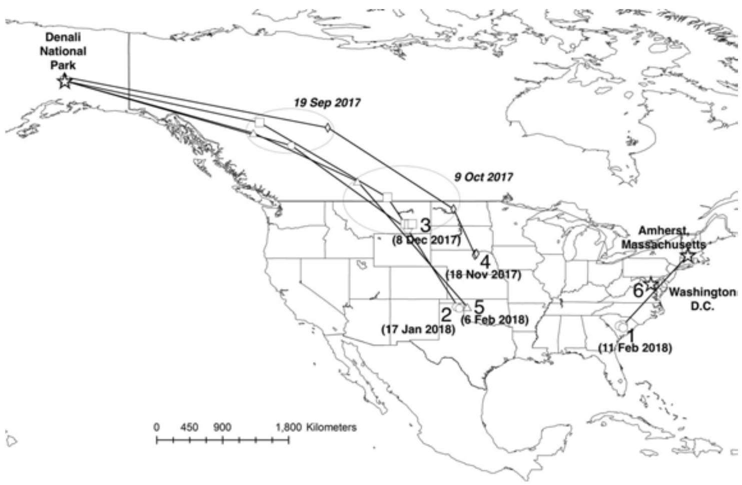

Figure 7. Map of American robin capture locations (stars), estimated autumn migration routes (solid lines), and estimated wintering locations (numbers) as determined using 1 g GPS data loggers.
[Figure from Jahn et al. 2019.]

for the Denali birds was similar; all were in western Canada in mid-September and in the northern Great Plains in early October (Jahn et al. 2019).

Oliver and others (2020) documented migration routes and wintering areas of robins nesting in northwest North America, but also investigated if individual robins adjusted their migratory behavior in response to environmental conditions. Their study included 42 robins that were tagged and recaptured during migration in Alberta, Canada. The study results suggested that robins may fine-tune their northward rates of migration based not only on local environmental conditions along the way, forging ahead when and where environmental conditions permit, but also adjust their departure from overwintering grounds and migration rates according to broad-scale climatic conditions including snow cover, snow depth, and precipitation (Oliver et al. 2020).

Considerations for Wildlife Tracking

This article provides a brief introduction to four relatively new tracking tools that scientists are using to study movements of migratory birds that spend at least part of the year in Alaska. Weidensaul (2017) and McKinnon and Love (2018) provide excellent summaries of these and the many other tools that scientists are using to study bird movements including high-definition radar, stable isotope analysis, digitally coded radio-tags (very high frequency (VHF) nanotags), high-resolution genetic markers, and eBird. Wildlife tracking technologies are evolving rapidly, and readers should expect to see further advances and new technologies. For example, the collaborative and international MOTUS tracking system, while not described in this article, is providing many new opportunities for studying the movements of birds. Further, the newly develop ICARUS project also holds potential for studying the movements of wide-ranging birds.

Results of many tracking studies are providing new, and often exciting, results. However, it is extremely important for anyone thinking about tagging an individual with a tracking device to: (1) ensure that they are using the best methodology for answering the study questions; (2) review the literature to understand how the tags and attachment methods may affect individuals and, in turn, the study results; and (3) consult a biometrician to estimate the sample size of tagged individuals needed to answer the study question (Lindberg and Walker 2007). While we have made great advances in tracking the movements of wide-ranging birds, we still do not fully understand all the potential detrimental effects that birds may experience due to carrying tracking tags (Taff et al. 2018, Green et al. 2019). For example, return rates of birds tagged with geolocators may be lower than for birds that do not carry them and birds carrying tags may behave differently than untagged birds (Taff et al. 2018). Assessing the effects of a tag is an essential step in any movement study where tags are used. For tags that require the researcher to recapture the bird to obtain the data, it is also essential for researchers to understand the effort needed to recapture the bird, including the amount of area that should be included in recapture efforts. For example, two of the four tagged American robins in the Denali study were recaptured a mile or more (2 and 3.6 km) away from their original capture location (Jahn et al. 2019). Knowing the maximum distance that a robin would move between the initial capture and the recapture site provided researchers with information essential for adequately searching their study area for recapture efforts in subsequent year.

Beyond the Technology: Taking a Proactive Approach to Bird Conservation

While there are many new tools available for studying the movement of birds, it is important to remember that collecting the data is just one step toward conserving birds. We often get caught up in the excitement regarding new technology, but we need to be careful not to be blinded by it. A more important step happens long before the tags are ordered or deployed on birds. That step includes identifying the issue, developing questions, and designing a study (complete with a peer-reviewed study plan) that can answer those questions. Another essential step is sharing the data, either through publications, collaborations, or via online resources such as Movebank. A proactive approach to bird conservation that could be applied to Alaska's national parks, is the concept of life-cycle stewardship. *Life-cycle stewardship* is defined as managing natural resources such that ecological processes or species' full life cycles are sustained over time. For example, the North American Waterfowl Management Plan (has used range-wide and annual cycle approaches for management and conservation for decades. This approach is also being used and recommended by many other groups including Partners in Flight, the U.S. Shorebird Conservation Plan, Pacific Americas Shorebird Conservation Strategy, the East Asian-Australasian Flyway Partnership, and the Pacific Seabird Group. By applying a life-cycle stewardship approach using effective study plans and by collaborating with others, we can proactively work toward effective conservation of Alaska's migratory birds. A proactive approach can help identify the impacts of environmental catastrophes such as the Deepwater Horizon oil spill that may have directly or indirectly impacted migratory shorebirds (Henkel et al. 2012) that nest in Alaska. A proactive approach may also provide opportunities for estimating how many of the estimated 599 million birds killed annually by collisions with buildings (Loss et al. 2014) or the 1.4 to 3.7 billion birds killed annually by free-ranging domestic cats in the U.S. (Loss et al. 2013) nest in Alaska's national parklands. And, a proactive approach may allow us to estimate how many of the 12,000 to 35,000 shorebirds harvested annually in Barbados (Reed et al. 2018) nest in Alaska's national parklands. These are examples of the types of issues we must investigate using well-designed scientific studies (National Parks Science Committee 2009) if we are to effectively protect the migratory birds that nest in Alaska's national parklands.

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New Insights from an Enduring Tool: Using GPS Data to Detect Calving Events in Alaskan Caribou Herds

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Since movement is the norm for caribou, it is noticeable when an animal changes its movement pattern—especially when it slows down or stops. By using GPS collar data, biologists have been able to detect when female caribou slow down long enough to give birth to a calf.

Citation:
Cameron, M. S., K. Joly, and J. Hepler. 2021. New insights from an enduring tool: Using GPS data to detect calving events in Alaskan caribou herds. *Alaska Park Science* 20(1): 84-87.

The life of a caribou is defined by movement and Arctic, barren-ground caribou (*Rangifer tarandus granti*) exemplify this lifestyle at a staggering scale. Caribou of the Western Arctic Herd, living in northwest Alaska, travel an average of ~1,900 miles (3,000 km) in a year and some individuals cover an astounding ~2,500 miles in a single year (4,000 km; Joly and Cameron 2019). This places caribou among the farthest walking mammals on the planet (Joly et al. 2019). Since movement is the norm for caribou, it is noticeable when an individual changes its movement pattern—especially when it slows down. This observation was the basis for recent developments using GPS collar data to detect when a female caribou delivers a calf (referred to as *calving*), which is a fundamental component of caribou monitoring and management.

In the early days of caribou management, knowledge of where caribou were located was obtained by biologists flying in small aircraft and tracking animals outfitted with VHF (radio) collars. This limited tracking to daylight hours with good flying weather. The use of GPS collars began replacing older VHF technology in Alaska in the 1990s and is now the standard for wildlife monitoring. They allow for tracking of animals 24 hours a day, 7 days a week, and 365 days a year. Even with the increased use of GPS collars, biologists still rely on aerial VHF tracking to monitor reproduction during the calving season, typically following protocols similar to Whitten and others (1992). Biologists locate collared females via airplane and count the number of females with calves; these collared females act as a representative sample of the population that are used to estimate calving success for the herd. Monitoring calving provides insight into the condition of individuals, since caribou have a higher probability of getting pregnant if they have larger body mass the previous fall (Cameron et al. 1993, Cameron and Ver Hoef 1994). When considered at the herd level, low reproductive rates could signify poor range conditions and potential future herd decline. While these surveys are straightforward, they still rely on extensive periods of good flying weather, which can be unpredictable and are costly for very remote herds such as the Western Arctic Herd and the Porcupine Herd in northeast Alaska.

Recent analytical methods developed in Canada offered a potential solution to this problem. The idea was that during calving, the movement of a female caribou that delivers a calf slows down more than a female that does not deliver a calf, owing to the fact that newborn caribou calves are initially limited in their mobility. To analyze this potential difference, two approaches were developed using GPS collar data (DeMars et al. 2013). One approach, the Individual Method, fits two movement models to the GPS data using the distance covered by an individual between locations. The first movement model represents a female that did not have a calf, therefore the model is expressed as a constant rate of movement across the time span analyzed. The

A female caribou of the Western Arctic Herd with her newborn calf.
NPS/MATT CAMERON

second model represents a female that delivered a calf and the model is expressed as a sudden decrease in movement followed by a steady increase (as the calf develops) until movement reaches the pre-calving rate. Both models are fit to an individual caribou's observed movements (tracked by GPS) and compared to each other to see which best represents what was observed. If identified as having a calf, the model returns an estimate (date) for when the calf was delivered (Figure 1), based on the date of the sudden decrease and slowest movement.

The second approach is called the Population Method. This approach still analyzes the movement of an individual caribou, but in a different way: a moving average is applied to the speed of each individual, which results in a smoothed rate of travel. The first step in applying this approach is to obtain a group of individual females with a verified calving date. With the assumption that females slow down after calving, the smoothed movement rate of these known females directly after calving is used to generate a threshold for the herd being analyzed (the threshold indicating a calving event). Next, the movement data for the rest of the females without a verified calving date is analyzed by the model and if any of their smoothed movement rates slow down below this threshold, then the female is labeled as calving on that date (Figure 1).

These methods were developed for woodland caribou subspecies (*Rangifer tarandus caribou)* that seek isolation in the boreal forest to have their calves and were not expected to work for gregarious migratory barren-ground caribou (the subspecies native to Alaska) that deliver their calves on the open tundra. Researchers from the National Park Service, University of Alaska Fairbanks, and Alaska Department of Fish and Game set out to test this assumption for Alaskan herds and found that the Individual and Population methods correctly identified whether calves were born with nearly 90% accuracy across six years of data for the Western Arctic Herd (Cameron et al. 2018) and across two years of data for the Porcupine Herd (Hepler 2019). These results are striking because they indicate that despite congregating on the calving ground, individuals are moving independently at the time when they deliver a calf. This is supported by observations on the calving ground—pregnant females are often left behind the group when they deliver their calf (Lent 1966).

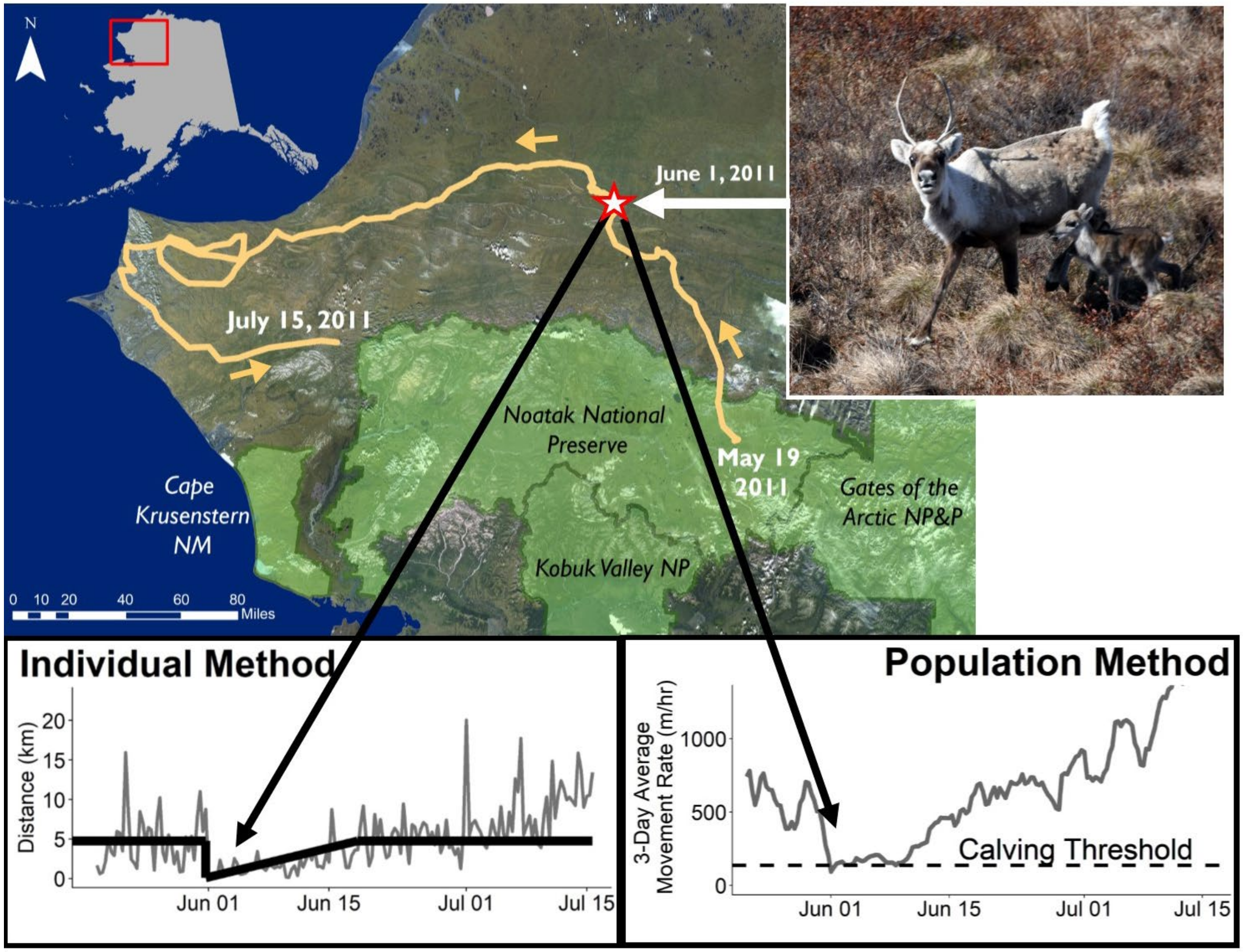

Figure 1. A collared female caribou's path (map) and movement rate (two lower plots) analyzed for calving in 2011. The Individual Method is depicted in the lower left and the Population Method the lower right. Both methods identified the female as having a calf near June 1, in the heart of the calving ground for the herd.
NPS/MATT CAMERON

These two recent studies highlight the utility of GPS collars to analyze animal behaviors beyond simply tracking animal locations and movement. Recent work with moose (*Alces alces*) has found similar success in detecting calving events from GPS movement data (Nicholson et al. 2019), suggesting that identifying reproductive events from movement data is applicable beyond just caribou. While we do not expect these methods to completely replace aerial surveys for calving caribou, they do provide an additional option to managers in the event that weather conditions or logistics do not permit an aerial survey in a given year. These methods were employed in follow-up research that investigated the spatial trends of the calving ground for the Western Arctic Herd and found that caribou rely on memory to guide them back to the general area each year (Cameron et al. 2020). Additional research is being conducted to more broadly apply these methods to herds across the Canadian Arctic and Alaska.

These results also highlight the truly incredible rate at which calf mobility develops. Considering the calving threshold (the smoothed speed indicating a female had a calf) of the Porcupine Herd, calves could conceivably cover over 1.2 miles (2 km) in their first day of life. Lent (1966) observed that by the second day after birth, calves were able to maintain their mother's running pace for an extended distance and swim across streams. Caribou are remarkably well adapted, even in their first days, to a life constantly on the move.

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For further reading, see:

Movement of caribou and their calves

Why do caribou calve where they do?

Monitoring caribou in the Arctic Network

About the Porcupine Caribou Herd

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Using GPS Units to Understand Where Backpackers Travel in Denali National Park

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Visitor use in national parks is dynamic. By examining different aspects of visitor use, such as where people go, managers are better prepared to address issues such as potential resource damage and crowding. But learning where people go in a large wilderness park poses some challenges. When backpacking parties used GPS tracking devices, the data clearly showed where they went, how far they traveled, and how long they stayed.

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A backpacker admiring the view of Denali.
NPS/KENT MILLER

Visitor use in national parks is dynamic and can be challenging to understand. One important aspect of visitor use is to understand where people go. Knowing *where* visitors travel within a park helps park managers allocate resources more effectively, identify potential environmental impacts such as vegetation trampling and soil erosion, and preserve the experience of other park visitors. Tracking use in remote and expansive wilderness areas is challenging as there are few reliable methods to record detailed use patterns. However, a growing body of research uses Global Positioning System (GPS) technologies to track visitor use in remote and wilderness settings (Gundersen and Andersen 2010, Gundersen et al. 2019, Hallo et al. 2004, Stamberger et al. 2018). In Denali National Park and Preserve, we used GPS units to track backpackers' locations (Stamberger et al. 2018) as part of a larger project focused on front and backcountry visitor values and pro-environmental behaviors (van Riper et al. 2019). The aim of this paper is to provide a detailed description of the methods of GPS visitor tracking used in Denali in 2016. We point the reader to van Riper and others (2017, 2019, and 2020) and Stamberger and others (2018) for descriptions of the characteristics of backcountry users who participated in GPS tracking.

Backpacking in Denali National Park

Denali National Park and Preserve covers six million acres of subarctic land in the Alaska interior. Denali provides a multitude of recreational experiences for visitors in untrammeled settings within its two million acres of designated wilderness. An especially unique experience for visitors is the fact that most of the park is trailless. In the backcountry, visitors are instructed, in most instances, to avoid using informal (or *social*) trails and to "Find Your Own Trail." This slogan is used as a purposeful management strategy to disperse visitor use in fragile tundra ecosystems.

Backcountry visitors to Denali have the freedom to travel within the park. However, the park's unit quota system affects dispersion of use. Denali is segmented into 87 backcountry units, and the units in the "old park" (Mt McKinley National Park) have specific visitor quotas per night. During peak season (June through August), the quotas are often met and aid in dispersing campsites and foot traffic, especially in popular backcountry units. The 92-mile road into the park also influences travel patterns. The road is often used as a launching point into the backcountry. Due to the immense size and trailless qualities of Denali, understanding the geographic extent of backpackers' travel is challenging.

Need for Visitor Use Dispersion Tracking

In Denali, managers have expressed concern over a growing network of informal trails and concentrated impacts of camping areas along popular routes. Routes can become popular due to reasons related to topography and vegetation where higher elevations involve less bushwhacking, length of time to get into the heart of the park, recommendations made by staff, and social or other media. The specific motivations for why backpackers choose the route they do is less understood, but general motivations include experiencing pristine nature, quiet and solitude, and adventure (Keller and Toubman 2019). Rising numbers of park visitors over the last decade has increased pressure to both facilitate and preserve quality experiences related to landscapes, species, and sense of place (including wilderness character) that national parks are mandated to protect.

Denali has had an informal trail monitoring program using trail counters, patrols, photographs, and erosion monitoring for over a decade. Additionally, backcountry patrols have a protocol in place to identify and locate impacts within the backcountry, adapted from the problem assessment survey method (Leung and Marion 1999). Currently, park managers primarily rely on this seasonal monitoring effort to understand where backpackers disperse into the backcountry. Also, these occasional backcountry patrols are the only means to enforce dispersion. Thus, little is known about where visitors travel and if dispersed hiking and camping guidelines are being followed. Our study provided the park with season-long spatial data of backpackers' trip extent, access points, camping locations, and use densities to assist in backcountry patrols and give park managers an overview of common visitor pathways.

Visitor Tracking Technologies

Researchers have used a variety of technologies to track visitor use trends for planning, regulation, and mitigation purposes. Trail counters, for example, are useful for their consistent data collection and, if calibrated regularly, their reliability (D'Antonio et al. 2010). However, trail counters are only as good as an install, and installation sites are determined *a priori* of where people go. In other words, trail counters do little to capture dispersed and highly variable recreation (Beeco and Hallo 2014) or monitor trends in these contexts. Denali has used passive infrared trail counters for years to establish a broad sense of use on established and known informal trails in the park, but these counters are necessarily rotated among sites and calibrated infrequently.

Starting in the early 2000s, GPS units became widely popular for navigation in wilderness and other recreational settings (Hallo et al. 2004). Human dimensions researchers capitalized on this trend, especially when GPS units shrank to a size that fit into pockets. This tracking technology, unlike passive counters, captures on-the-ground travel patterns and creates detailed and accurate spatial data (Edwards and Griffin 2013, Kidd et al. 2015). More importantly, this technology provides a link between spatial data and social data collected with social science surveys (Stamberger et al. 2018). Due to the richness that spatially linked social data can provide for planners, managers, and practitioners, this study has wide-ranging applicability.

Data Collection

During the peak season of 2016 (June-August), we distributed GPS units to backpackers who agreed to participate in the study. One person in each group was responsible for carrying the GPS unit the entirety of the trip and then dropping it off upon their return. Backpackers were usually responsible for turning on the units themselves. We provided a drop-box outside of the park's backcountry office to ensure the GPS units could be returned at any hour. If willing, backpackers provided contact information so the researchers could meet them upon their return out of the backcountry to collect the units and administer a follow-up survey. In large parks with dispersed use, this re-intercept method ensures the GPS units are returned. We administered a survey to individuals who took tracking units into the backcountry in order to ascertain attributes such as trip motivation, backpacking experience, and park knowledge. Our sample also included GPS trackers returned from guided hikes in the backcountry (NPS and other educational groups) to compare dispersion, use, and distance between guided and independent hikers.

We used Canmore GT-740 FL units due to their size, design, spatial and temporal accuracy, and battery life (Table 1). The units are small and have a simple design (Figure 1). The Canmore model has good spatial accuracy, detailed temporal data abilities (timestamp intervals), (see for model review White and others 2015), and extended battery life capabilities. These units are able to capture multi-day trips—a key component of this study. From our research, we found the Canmore units lasted approximately three days. If groups planned to be in the backcountry longer than this, they were given multiple GPS units in order to record the entire trip.

Data Cleaning and Management

During the 2016 field season, spatial data were systematically downloaded from the units and cleared for redistribution. On a weekly basis, the tracks were extracted and converted into .csv files. Following the field season, the .csv files were uploaded into ArcGIS 10.4. The spatial point data were then converted from the WGS 1984 to the NAD 1983 Alaska Albers coordinate system. As noted by others (Peterson et al. 2016), extracting the data from these units and into ArcGIS software is a multiple-step process and less streamlined than when using other units. Models that export the tracks as .gpx rather than .csv files may result in a more efficient data management process.

In all, 147 GPS units were distributed to 132 independent backcountry groups, but data cleaning processes trimmed the total number of recorded trips

Table 1. Characteristics of the Canmore GT-740 FL GPS unit.

Characteristic	Details
Small unit	Unit is about 2.75 inches (7 cm) long, weighs less than half an ounce, and is similar in size to a USB flash drive.
Ease of use	Unit has a simple design with two buttons on the top, one to power on and the other to set manual waypoints. Buttons are stiff to press, making the unit difficult to accidentally power off.
Spatial accuracy	Unit is accurate to 8 feet (2.5 meter) CEP (circular error probably).
Timestamp interval	Timestamp intervals are set by the user and can be as short as 1 second between recorded waypoints. Note that setting shorter timestamp intervals will decrease battery life. We collected waypoints every 15 seconds.
Battery life	Battery life is about 48-72 hours per use (Stamberger et al. 2018).

Figure 1. The GPS unit used to collect tracking data from backpackers.

to 113. Three of the units were never returned and the remaining units not included in our sample had no or incomplete data and were therefore discarded. When units were returned with no data, backpackers often forgot to turn on the units at the start of their trip. Trips were deemed incomplete by researchers if the backpacker(s) did not enter the backcountry during any part of their trip. For example, a group may have decided to stay at a designated campsite or take a bus trip into the park.

The tracks in our sample (N=113) were cleaned for a more accurate representation of where and how far backpackers traveled. Three factors guided our decision to cut data points in the cleaning process. The first factor was frontcountry travel (i.e., visitor centers, along road/established trail networks or in tourist areas outside of the park). We assumed backpackers had started their trip in the backcountry when the GPS points diverged from the park road and into backcountry units. Thus, points not located in the backcountry were removed. Second, we

A backpacker on the Savage River Trail.
NPS/LIAN LAW

removed points that were not physically feasible (e.g., a consecutive point in a 15 second span located several miles away). Third, we removed points that formed a dense cluster when backpacker movement appeared to be stagnant. This final cleaning step reduced the total trip distance for each group by an average of 4.7 miles (7.6 kilometers; $t = 11.52$, $p < 0.01$).

Data Analysis

After the data were cleaned and prepared for analysis, the routes taken and campsite locations chosen by backpackers were examined using ArcGIS 10.4 software (Table 2). Routes were created using the point-to-line conversion tool, and campsites were delineated by placing a point in the location where backpackers were stationary from one day into the next. The spatial analyses described in Table 2 were driven by several motivations: (1) concentration of use (density, access point distribution, and distribution by backcountry unit), (2) impact on natural resources (land-cover overlay), and (3) adherence to park rules and regulations (viewshed analysis).

Route and Campsite Characteristics

On average, the backpacking trips lasted about three days, covering approximately 11 miles (17.84 km). The lengthiest trip recorded was ten days long. We found the GPS tracks were concentrated in specific locations of the park (Figure 2). Tracks were densest near the Eielson Visitor Center and the Toklat River Rest Area. There were less dense pockets of GPS tracks at the park entrance and near the end of the road by the Kantishna and Wonder Lake areas. Access points into the backcountry were also highly concentrated as over one third of backpackers (37.5%) accessed the backcountry from two stretches of the 92-mile park road (between miles 50-55 and miles 65-70). Backcountry Unit 13 (Mount Eielson) was most popular with 149.9 miles (241.2 km) hiked in this unit followed by Units 9 (East Toklat, 126.2 mi; 203.1 km) and 10 (West Toklat, 117.6 mi; 189.3 km).

The spatial distribution of campsites (n=203) exhibited a similar pattern to the density of GPS tracks with the majority of backpackers choosing to camp from the middle sections of the park road between Toklat Rest Area and the Eielson Visitor Center. The viewshed analysis (using ESRI's Viewshed Analysis Tool) showed that about half of the campsites recorded were within view of the park road although NPS staff urge backpackers to camp outside of the road's view (Figure 3). Lastly, we conducted an overlay between the campsites and land cover. This

Table 2: GIS analysis of route and campsite data (adapted from Stamberger et al. 2018).

Element	Variable	Research Questions	Spatial Analyst Tool(s)	Description of Analysis
Route	Density	Where were low- and high-density areas located?	Kernel density	Spatial diffusion of GPS routes was analyzed using kernel density estimation (KDE; Korpilo et al. 2017).
	Access point distribution	At which point did users access the backcountry? How were the access points distributed?	Create routes Locate features along routes Point density	The park road access corridor was converted into a route layer and point features were located along the road to capture where backcountry users departed from the park road and moved into the backcountry.
	Distribution by backcountry unit	How many miles were hiked in each backcountry unit?	Spatial join	The routes (line layer) were spatially joined to a polygon layer of the park's backcountry units. The sum of miles hiked in each unit was calculated during the join.
Campsite	Density	Where were low- and high-density areas located?	Kernel density	The campsite data were analyzed to show concentration of use, particularly "hotspot" locations (Alessa et al. 2008).
	Viewshed analysis	Which campsites were located within the park road viewshed?	Viewshed Select by location	The viewshed tool calculated the raster cells that were visible from the park road (Carver et al. 2012). Campsites within the viewshed were spatially selected and mapped.
	Land-cover overlay	On what types of surfaces did most users camp?	Raster to polygon conversion Spatial join	A Denali land-cover layer, including 23 land-cover classifications, was spatially joined to backcountry campsite locations (Marion and Cole 1996).

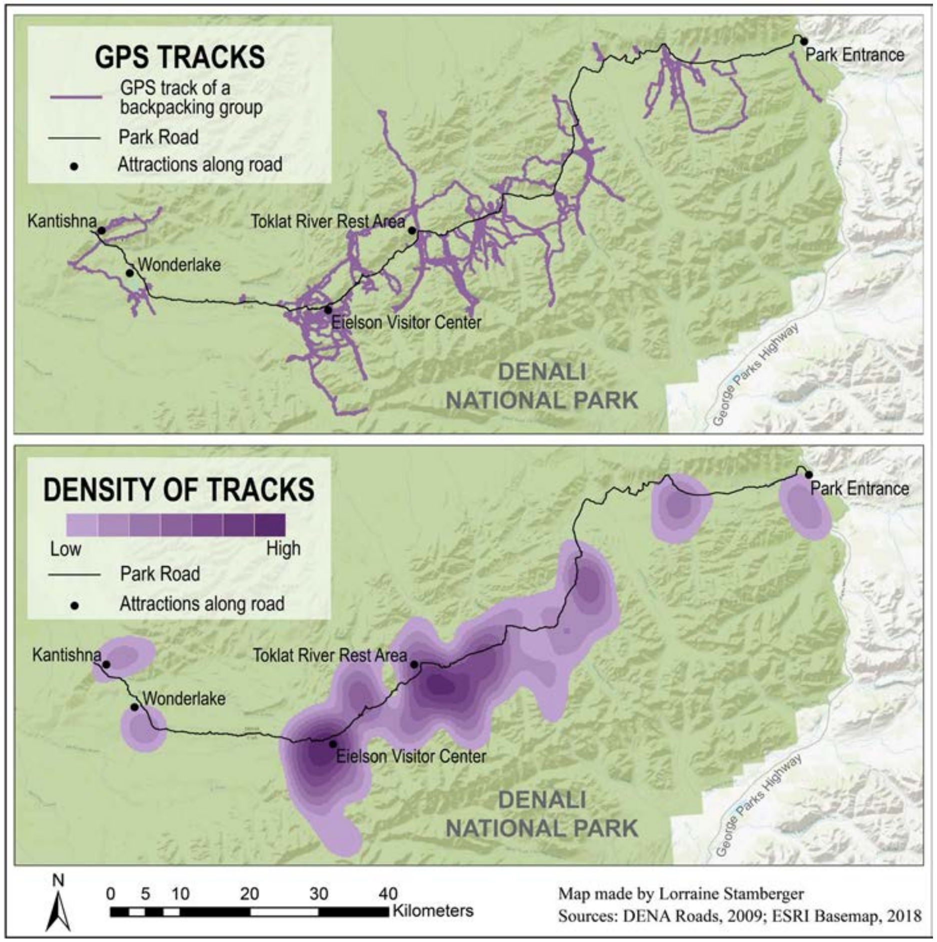

Figure 2. Maps of GPS tracks (top left) and density of tracks (left) based on 113 separate backpacking groups.
[Adapted from Stamberger 2018]

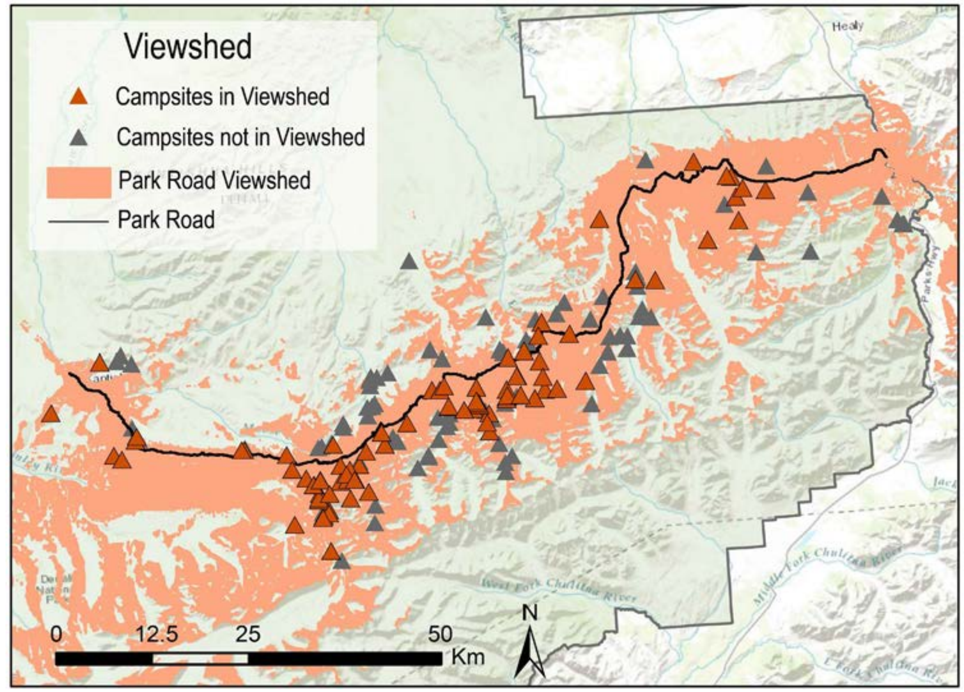

Figure 3. Campsite location related to the Park Road Viewshed.
[Sources: Esri Basemap 2017, DENA Roads 2009, DENA Park Road, Viewshed Analysis 2011]

analysis illustrated that the majority of backpackers camped on vegetated surfaces. Backpackers most commonly camped on a low shrubby land-cover type (41.9%) followed by bare ground (17.7%).

Independent vs. Guided Trip Characteristics

In addition to our GPS tracking dataset, tracks of guided backcountry trips led by NPS staff and other educational groups were independently recorded during the 2016 peak season. We compared the characteristics of these guided trips to the independent backpacking trips we analyzed (Stamberger et al. 2018). Unguided independent travelers spent the most days in the backcountry (mean (M)=2.89, standard deviation (SD)=1.37). For this subgroup, two-day trips were most common. The NPS-led day hikes lasted only one day while guided educational tours averaged 2.30 days (SD=1.36). For the educational trips, two-day trips were also most common, followed by one-day trips with the longest trip lasting six days. Unguided independent travelers not only spent the most time in the backcountry but also traveled the farthest, averaging 11.08 miles. However, mileage was highly variable with the minimum being 0.39 miles and the maximum distance a group traveled being 37.34 miles. NPS-led day hikes averaged 2.67 miles (SD=1.09), and guided educational tours averaged 5.97 miles (SD=7.07).

Understanding the Findings

Despite the strong “Find Your Own Trail” messaging in Denali National Park and Preserve, backpackers’ GPS tracks were concentrated in a few locations. This concentrated pattern of tracks might occur for a few reasons. First, the densest track locations were at relatively high elevations. Hiking at

Backpackers in Denali National Park and Preserve finding their own trail.
NPS/ALEX VANDERSTUYF

higher elevations in Denali tends to be easier due to drier conditions compared to the boggy and brushy conditions at lower elevations. Second, backpackers were likely pursuing similar scenic vistas. Third, tracks were densest in renowned popular units (that is, people knew to go there; Keller and Toubman 2019). Finally, visitor use may have been more concentrated near established stops along the road, such as the Eielson Visitor Center, so backpackers could use amenities from these sites, such as bathrooms and water before starting their trip.

Tracking visitor use in the backcountry in Denali has been a priority since the adoption of the Denali Backcountry Management Plan in 2006 (NPS 2006). This long track record has shown park managers that use has changed in some areas (e.g., decreased visitation to Sable Pass), but others remain key attractions and have a potential for deterioration. Monitoring studies such as GPS tracking of visitor use in the backcountry are important for managers because they provide season-long (or multi-season) datasets. Our study provides guidance to backcountry staff when administering permits to reinforce the messaging of Find your Own Trail, and camp out-of-sight from the road. Campsite densities from this study furthermore provide direction of where to monitor landscape changes, especially in alpine tundra settings, for impacts related to human use and concentration: key indicators in the Denali Backcountry Management Plan (NPS 2006). This study also provided data comparing dispersion of NPS-led hikes, guided educational hikes, and independent hikers which suggests that these subgroups have very different experiences of Denali's backcountry regarding time and distance covered.

Future Research

Evidenced by this research, GPS trackers can be used to understand use patterns in remote and expansive areas where use is often less known. This studied expanded on previous GPS tracking research by capturing use patterns for multi-day trips. The future of GPS tracking has wide-reaching potential as the technology continues to improve and expand. Studies like these will continue to aid in the betterment of managing our public parks and protected areas.

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Using Aquatic Invertebrates to Measure the Health of Stream Ecosystems: New Bioassessment Tools for Alaska's Parklands

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Macroinvertebrates (aquatic insects) are good indicators of stream ecosystem health because they are common, reasonably well understood, easy to collect and analyze, and sensitive to the environment in which they live. We can determine the relative health of a stream by comparing what insects we find to what we would expect to find in a similar healthy stream. This straightforward approach can be used in all kinds of settings and compared across a region.

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Although the popular image of Alaska and its national parks is one of vast tracts of unspoiled wilderness, in fact, human disturbance has had significant impacts on stream ecosystems in many areas, particularly in interior Alaska. Over a century of mining, primarily for gold, has been the main source of this disturbance. Mining took place in all three interior Alaska parks (Denali National Park and Preserve, Wrangell-St. Elias National Park and Preserve, and Yukon-Charley Rivers National Preserve) as well as in much of the surrounding area. Although mining in the parks largely ended in the 1980s, some activity continues to this day, and mining continues in many other areas. In some cases, hydraulic dredge mining has led to drastic alteration of entire valleys (Figures 1 and 2), whereas other impacts to mined streams have been smaller and more localized. Mining activity may lead to a variety of detrimental changes to stream ecosystems, including habitat simplification, removal of riparian vegetation, channelization, altered hydrology, excessive sedimentation, acidification, and increased levels of toxic compounds such as heavy metals (e.g. Bernhardt and Palmer 2011, Brim Box and Mossa 1999). Any or all of these changes may negatively affect the biological communities that live in streams, and lead to impairment of ecosystem function. Biological responses to human disturbances like mining may include changes in biodiversity, food web structure, productivity and nutrient cycling (e.g., Wagener and LaPierrere 1985, Van Nieuwenhuyse and LaPerriere 1986, Wedemeyer 1987, Niyogi et al. 2002, Maret et al. 2003, Daniel et al. 2004, Milner and Piorkowski 2004). Other types of human disturbance such as roads, logging, urbanization, and agriculture can impact the biota and function of stream ecosystems in similar ways. The authors and others have been working on developing methods to allow us to quantify the effects of these disturbances on the ecological integrity of streams throughout interior Alaska, including in national parks.

Figure 1. An aerial photo of Woodchopper Creek, Yukon-Charley Rivers National Preserve showing the effects of extensive dredge mining.
NPS PHOTO

Trey Simmons sampling aquatic invertebrates in an unnamed stream in Denali National Park and Preserve.
NPS PHOTO

Figure 2. Hydraulic mining in the Yukon River Basin.
U.S. GEOLOGICAL SURVEY PHOTO

There are several reasons why it is important to be able to quantify these effects on the integrity of stream ecosystems. In parks, the National Park Service is mandated to protect, and improve if necessary, park resources, which includes streams and the organisms that depend on them (National Park Service 2006). As part of this mandate, it is important that national park managers be able to understand the effects of both past human activity and current management actions on the integrity of park ecosystems, including streams and rivers. In addition, the core objective of the Clean Water Act of 1972 is to "restore and maintain the chemical, physical, and biological integrity of the nation's waters" (USEPA 1972). The Clean Water Act requires that states report on the physical, chemical and biological condition of their waterbodies, determine whether they meet the designated use criteria that the state has established, and develop plans to improve the condition of any that are deemed to be impaired. In order to do so, states must develop defensible methods for determining whether waterbodies meet the criteria they have established. Finally, the ability to quantify ecological integrity will be critical for both prioritizing disturbed sites for restoration and for monitoring the degree to which those restoration efforts succeed in the future.

Historically, water quality assessment focused on the chemical aspects of water quality; for example, whether concentrations of nutrients or toxic compounds exceeded levels thought to be safe for aquatic life or human consumption. However, starting in the 1980s water quality practitioners began to move away from strictly chemical measures, and to attempt to consider a more holistic approach that also included measures of biological and physical integrity, as originally spelled out in the Clean Water Act. Methods that use various measures of the status of the biological community as indicators of the health of stream ecosystems have been the predominant focus of these more holistic ways to assess water quality (although similar methods are used to assess lake and wetland ecosystems, this article is focused on stream applications). The fundamental idea behind this approach is that the biological community reflects overall *ecological integrity*—that is, when the biological components of an ecosystem are healthy, then the physical and chemical components are also in good condition. These methods are collectively referred to as *biological assessment*, or *bioassessment*, and are in widespread use by water quality agencies around the world (e.g., Wright et al. 2000, Bailey et al. 2004, Carter and Resh 2013).

There are a number of reasons why assessing the status of the organisms that inhabit a stream or river (collectively referred to as the biota) is a powerful approach to determining the condition of a stream ecosystem. The primary advantage is that the biota is always present in the ecosystem. That means that it integrates conditions over time, and can respond to intermittent effects (for example, pulses of toxic compounds released during high flows) that may be missed by typical periodic sampling efforts. Similarly, the biota can respond to the chronic effects of low levels of stress, to stressors that we can't easily measure, and to the aggregate effects of multiple stressors. Finally, the biota integrates conditions over space, in that it can respond to conditions or stressors upstream of the sampled site, as well as in the riparian and upland zones surrounding the site. We can use this approach to quantitatively assess the ecological condition of a stream site, allowing us to determine whether human activity has in fact had a negative impact on that ecosystem, and to potentially identify the particular stressors responsible.

Assessment approaches that use biological indicators to measure stream ecosystem condition have been in use for over a century (Kolkwitz and Marsson 1908, Metcalfe 1989), but in recent years have become much more widely applied and grown increasingly sophisticated. In principle, a bioassessment could be based on measuring the condition of any species assemblage that is present in a stream, including aquatic macroinvertebrates, fish, amphibians, algae, or aquatic macrophytes, or multiple assemblages in combination. However, the vast majority of these methods in fact rely on assessing aquatic macroinvertebrates (Figure 3). There are several reasons why macroinvertebrates are the preferred indicators of stream ecosystem health. First, they are ubiquitous, being found in every stream and river, no matter how small or extreme, meaning that macroinvertebrate-based assessments can be applied universally. They are also typically abundant and diverse in streams, making them relatively straightforward and cheap to collect and analyze. In Alaska, as many as 70 unique macroinvertebrate taxa (aquatic macroinvertebrates can often only be identified to the genus or family level; so we refer to *taxa* rather than "species") may be present at a single stream site, and densities may be as high as 20,000 individuals per square meter. Due to this diversity, the macroinvertebrate assemblage as a whole is sensitive to a wide variety of potential stressors. Because macroinvertebrates typically live no more than a year or two, they tend to respond to the current state of the ecosystem. And finally, macroinvertebrates are relatively sessile; that is, they don't tend to move long distances during their lifetimes, meaning that they are responding to local conditions (whereas salmon, for example, may be responding to changing conditions in the ocean rather than at a site we are interested in assessing).

Although a wide variety of methods exist for using macroinvertebrates to assess stream ecological integrity, there are two main approaches, both of which use the *reference condition approach* (Bailey et al. 2004, Stoddard et al. 2006), in which the status of the macroinvertebrate community observed at

Figure 3. Examples of aquatic invertebrates commonly found in streams. Clockwise starting in upper left: mountain midge (Deuterophlebiidae), flat-headed mayfly (Heptageniidae), giant stonefly or salmonfly (Pteronarcyidae), and tube-case caddisfly (Limnephilidae).
U.S. GEOLOGICAL SURVEY/JOE GIERSCH

the streams being evaluated for the effects of human disturbance is compared to the status observed at unimpaired stream sites (sites with no or minimal human activity), which are referred to as reference sites (Stoddard et al. 2006, Herlihy et al. 2008, Hawkins et al. 2010). The conditions observed at these reference sites are used to set expectations for sites to be assessed. Although in many parts of the world, identifying relatively pristine streams to be used as reference sites can be challenging, in Alaska it is relatively straightforward. Because macroinvertebrate assemblages naturally vary considerably among streams in response to local and regional environmental drivers, the reference sites must be properly classified so that the biological potential at each assessed site can be accurately determined by comparison to the appropriate subset of reference sites.

The first of these common bioassessment methods uses data about the environmental setting (for example, elevation, mean annual precipitation, basin area) and the invertebrate taxa observed at a large number of reference sites in a given area to develop predictions about the distribution of native invertebrates in response to environmental gradients (Wright et al. 2000, Clarke et al. 2003, Carlisle and Hawkins 2008). These predictions can then be used in combination with data on the environmental setting that describe a site we want to assess to predict the native invertebrate community that would be expected to be present at that site in the absence of human disturbance (i.e., if that site were, in fact, of reference site quality). Divergence away from those expected conditions, expressed as a percentage loss of predicted native taxa, indicates a loss of biological integrity and suggests that the site may be impaired by human disturbance. This divergence can be quantified using a simple index, O/E, which is the ratio of the number of expected native taxa actually observed at the site (O) to the number expected based on the predictions (E). O/E is a direct measure of how "complete" the native macroinvertebrate community is at that site, relative to what would be found at a similar unimpaired reference site. This method has several advantages. It is conceptually straightforward, in that an O/E value of 0.5 at an assessed site indicates that 50% of the native taxa have been lost. Similarly, an O/E value near 1.0 indicates that the native invertebrate community is largely intact. It is also site-specific, in that rather than making general predictions, for example at a regional level, about the native taxa to be expected, it makes specific predictions for each site based on that site's environmental setting. And it is standardized, in that an O/E index value of 0.5 means the same thing everywhere, even among streams that may vary widely in the number of expected taxa. This allows for comparisons of conditions among sites that differ ecologically.

In the second common approach, what's generally known as an *Index of Biological Integrity* (IBI), or in more recent years a *Multi-Metric Index* (MMI) is developed (Simon and Lyon 1995, Royer et al. 2001, Stoddard et al. 2008). Essentially, an IBI is constructed by examining various metrics that describe ecologically important aspects of the macroinvertebrate assemblage, and that are predicted to change in response to ecosystem degradation, for example overall taxa richness, the percentage of sensitive mayfly, stonefly and caddisfly taxa, the percentage of predatory taxa, and the percentage of pollution-tolerant taxa. These metrics are screened for their ability to discriminate between reference sites and a set of selected disturbed sites, based on the metric values calculated for each site. In this method, then, we are applying our knowledge of stream ecology and how we expect stream communities to respond to disturbance, to select the metrics. The metrics whose values best distinguish between reference sites and disturbed sites are then rescaled and combined into a single MMI, which can be used to assess ecological condition. In general, reference sites will have high IBI scores, whereas sites where ecological integrity has been impacted by disturbance will have low scores. The IBI approach is currently the most widely applied bioassessment methodology around the world.

Once developed, either index can be used to quantitatively assess ecological conditions at one or more sites that have been potentially impacted by human disturbance. These sites are often called *test sites*. Generally, sites with index scores (either O/E or IBI) statistically close to the range of index scores at reference sites are judged to be equivalent to reference and hence not impaired by disturbance (or, in other words, to have high ecological integrity), while sites with index scores statistically different from reference sites are deemed to be impaired; that is, to have lower ecological integrity. Typically, the range of index scores is divided into classes that reflect the degree to which ecological integrity has been impaired, ranging from no impairment to severe impairment. The U.S. Environmental Protection Agency (EPA) uses both of these methods in its national assessments of the ecological condition of streams (Paulsen et al. 2008), although Alaska has not yet been included in those assessments.

The National Park Service is currently collaborating with the Bureau of Land Management (BLM) and Utah State University to apply these index-based bioassessment methods to streams throughout eastern Alaska. Although there has been limited development of both IBI (Rinella et al. 2005, Rinella and Bogan 2007, Rinella and Bogan 2010) and O/E (Simmons and Ostermiller 2012) indices in Alaska in the past, they have been relatively limited in geographic scope and examined relatively small numbers of sites. Accordingly, our project will be the most comprehensive and large-scale bioassessment effort to date in Alaska. As noted above, O/E indices and IBIs use different approaches to determining ecological condition, and can perform differently depending on various factors; accordingly we are developing and applying both methods, which will provide two complementary assessments and thus increase the robustness of our conclusions about the ecological condition of assessed streams.

We are using macroinvertebrate and environmental data collected from 299 streams across a large swath of eastern Alaska (Figure 4) to develop the two indices. These data were collected by the Central Alaska Network for the NPS Inventory and Monitoring Program, by the Alaska Department of Environmental Conservation for an EPA-funded pilot study that was part of the EPA's National Rivers and Streams Assessment, by the BLM Assessment, Inventory and Monitoring Program for the BLM National Aquatic Monitoring Framework, and by the U.S. Geological Survey as part of two NPS-funded water quality studies. In addition, data were collected in 2018 at a small number of sites in the Kantishna Hills of Denali National Park and Preserve in collaboration with the BLM to provide additional data on historically mined streams in that area. Data collection methods were similar across all agencies, and are largely based on the field protocols for the EPA National Rivers and Streams Assessment (USEPA 2017). The majority of these streams are classified as reference sites, meaning they are largely unaffected by any human activity, while a subset have been classified as "test" sites due to varying degrees of human disturbance. Most of the disturbed streams have been affected by historic mining activity. Applying our indices to these disturbed sites will provide a quantitative assessment of the degree to which the disturbances have altered the ecological integrity of these streams. This in turn can help facilitate the prioritization of streams for restoration, by providing a defensible ranking system for comparing disturbed sites across interior Alaska using a common standard. Furthermore, these indices will be useful in determining the degree to which stream restoration efforts succeed in improving ecological integrity. Although this project is being developed with the primary goal of examining the effects of historical and current mining disturbance on streams, these indices will also allow agency managers and the state of Alaska to quantify the effects of other disturbances, for example roads and urbanization, on the integrity of stream ecosystems in Alaska.

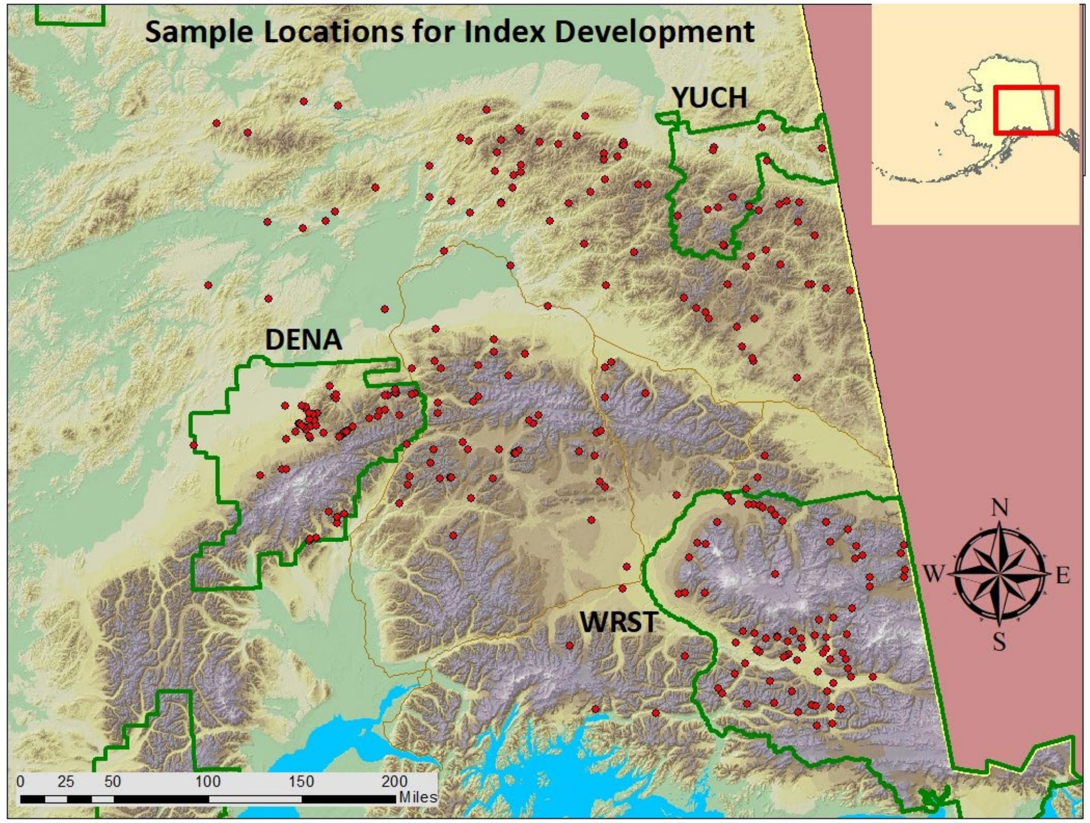

Figure 4. Locations of the stream sites where invertebrate and environmental data were collected for this project. DENA = Denali National Park and Preserve, WRST = Wrangell-St. Elias National Park and Preserve, YUCH = Yukon-Charley Rivers National Preserve.

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Setting up acoustic recording equipment at Katmai National Park and Preserve.
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