

Moving at a Glacial Pace: A Biogeomorphological Analysis of Ecological Succession in
Recently Deglaciaded Terrain in the Selkirk Range, BC

by

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B.A., Willamette University, 2014

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We acknowledge and respect the lək'wəŋən peoples on whose traditional territory the university stands and the Songhees, Esquimalt and WSÁNEĆ peoples whose historical relationships with the land continue to this day.

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Abstract

This research developed a novel workflow for combining different types and scales of data to understand the development of small, steep, and sheltered glacial forefields across space and time using the Avalanche glacier of the Selkirk Range, BC as a case study. As glaciers recede, symbiotic geomorphological and ecological feedback loops determine the ecological succession in recently deglaciated terrain, which can in turn effect landform stability and water quality downstream. In order to describe emergent land cover patterns in the forefield, this research uses Corenbilt's (2007) fluvial biogeomorphic succession (FBS) framework to interpret a century of land cover changes. To do so, an experimental protocol was developed that combined remotely sensed data – repeat photographs, historic air photographs, satellite imagery, and digital elevation models – and data collected in-situ using a photo transect method. Analysis of more than a century of photographs determined that the Avalanche glacier is receding at a slower rate than has been observed in the region's larger glaciers, subsequently leading to a slower rate of forefield habitat expansion. Still, all four stages of fluvial biogeomorphological succession were found across the Avalanche glacier's forefield. It was found that in the Avalanche forefield, terrain age seems to place a limit on which successional stage is possible at any given location within the forefield, but topographic features like slope angle seemed to influence succession patterns within areas that had the same terrain age. Further research is needed to see whether these findings are consistent for similar steep, small, and sheltered glaciers in the region.

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This work was also inspired by the places I have had the immense pleasure of recreating in, working on, and learning from. First and foremost are the mountain meadows in the lands of the Tübatulatal, Tule River, Mono, Newe, Numu, and Paiute peoples in what is now known as the Sierra Nevada (or, *pamidu toiyabe* in Paiute) in California. The tremendous capacity for change and renewal exhibited by the meadows that I saw being restored by California Trout were the original impetus for this project. At every step of the way, I returned to the wisdom I learned among those sedges. In a meadow that had been nearly desertified for half a century, we saw a fish return to the pools. It had swum 4,000 vertical feet upstream, even as it had likely been several generations since doing so had been possible. What a gift to get to witness the memory of the earth in that way. Later, in 2020, during my first weeks in Victoria, the Kern Plateau burnt down. It was such a tremendous fire that ash from those lands settled on the shores of my new home on Vancouver Island, thousands of miles away. Studying fire maps, I saw that our restoration had worked: the recently rewatered meadow sites didn't burn, even as the forests all around them did.

Of course, this project was inspired by relationships with people as much as with relationships with place. First, with Eric Higgs, who accepted me as his student against what seemed to me at the time to be tremendous odds. Eric and I first met when I was some 5,000 km into a bicycle ride-gone-wrong. I showed up on his doorstep during the first downpour of fall. He let me in; in his foyer, I shook rain off my back like a dog. I remember thinking as I did, "There goes my last chance." Instead, we drank several pots of tea and talked about literature for hours, and for some reason Eric decided to bring me onto his team. I'm still not sure why. But his decision to do so has changed my life. Later, Michele Koppes took a similar chance on me (me, without any experience taking scientific coursework and an allergic aversion to anything resembling statistics, now trying to develop novel methods in geomorphology) when she became my committee member. She is intimidatingly smart, but I always assumed in ways that were beyond me. She proved me wrong here when she picked up a subtle Donna Haraway reference in this work, increasing the degree to which I feel intimidated. It has been terrific to have my work – my meanderings, my tendency to philosophize – so deeply engaged with by these two brilliant thinkers.

So many others deserve mention here. I feel deeply indebted to the people in Victoria who offered me a safe place to land. 2020 was a hell of a year to leave America. Arriving in Victoria, I was working on a team in California doing data analysis on Covid deaths in the community I had left. During my spare hours between meetings and classes, I would log onto this database from my desk in UH4 and frequently be surprised by what I found: medical records that revealed the suffering, sometimes fatal, of my friends and their families. This tremendous, unspeakable loss was backlit by the looming election, and then all of the chaos that happened in this wake.

What all of this meant, in practice, is that I arrived in most meetings ready to pontificate about the news. In hindsight, it strikes me as incredibly generous that my new colleagues let me take up the space in our work meetings to make sense of the world. I have often felt that academia fails in its inability to be affected by, and reflexive to, “the times.” Here, in these relationships, I was proven wrong.

Speaking of affect: Dr. Sarah Hunt’s course changed me most deeply. On the first day of that course, Sarah asked each of us to whom we were accountable while we did our work. (Obviously, that question has continued to color mine.) No scholar has ever impacted my thinking as much as Sarah has. What gives work meaning? How do we know if what we’re doing matters? How do we know that what we’re doing won’t accidentally cause harm? How can scholarship subvert, remain undisciplined, remain sneaky? How do we let it change us? The answers to each of those questions I learned during the vibrant discussions held in Sarah’s course. This work – and indeed, my intellectual orientation towards the world as it stands – could not have been possible without it.

Another way relationships buoyed me while I was undertaking this work: by letting me change along with it. Learning about forefields, it became abundantly clear that a central task for living in the future will be an expanded capacity to love things as they change, even as they become unrecognizable, even if they become risky or ugly or totally beyond what we expect. This research found me at a moment that I, too, was undergoing tremendous and irreversible change. So many people stuck with me through this. So many people helped me remember into being parts of myself I thought I had forgotten. To everyone who encouraged me to re-learn how to climb, how to ski, how to bike, how to *live*: thank you. This feels most true of my intrepid field team. When we embarked on our trip to the Avalanche glacier, I was not yet fully well. My three team members trusted me fully to guide them into raucous and potentially dangerous terrain. Their trust not only made this work possible – it made something vital in *me* become possible again, too.

Living in *these times* often feels very hard. This work has taught me that continuing to find ways to delight, to care, to find beauty – it’s worth it. What an unexpected gift to receive at the end of this project, when all I thought I’d get was a piece of embossed, heavyweight paper with my name on it.

Introduction

Around the world, anthropogenic climate warming is causing rapid glacial melt. Unprecedented rates of greenhouse gas emissions have led to rising air temperatures and increased radiative forcing (Painter et al., 2012). Alpine areas are especially impacted by a warming climate: Compared with other terrestrial ecosystems, high mountain landscapes have experienced a more pronounced increase in air temperature in recent decades (Auer et al., 2007; Gobiet et al., 2014). This means that glaciers are becoming smaller and will, in many places, disappear (Huss et al., 2017). Today, glaciers cover 10% of the earth's land, but most are predicted to melt out entirely by 2100 or sooner (Marzeion et al., 2018). This poses tremendous threat to the human and non-human communities downstream who rely on the ecosystem services glaciers provide – freshwater for drinking, freshet for fish, and so forth (Cook et al., 2021).

The recession of these rivers of ice leaves broad areas of land, known as *glacier forefields*, ice-free. Since the Little Ice Age (LIA) ended in the 19th century, glaciers have been receding. When they do, the surrounding landscapes are modified through the processes of floral colonization and pedogenesis (Matthews, 1992). Lands exposed via glacial recession have different successional processes than other landforms undergoing primary succession due to the influences of altitude or latitude, the influence of periglacial geomorphology, and the landform instability caused by glacial recession. In alpine environments, the intensified effects of global warming also play a role. For example, glacier forefields are understood to be prime landscapes for the upward expansion of alpine vegetation (Dullinger et al., 2003; Dullinger et al., 2004; Fischer et al., 2019). In short, glacier melt allows for the birth of new ecosystems – and, in some cases, the creation of new viable habitat for surrounding flora and fauna. Globally, the next

century of rapid, anthropogenic warming will leave some 104,000km² of new land available for colonization (Arendt et al., 2012).

In the Canadian provinces of Alberta and British Columbia, rapid climate warming during the 21st century will cause thousands of square kilometers of new land to become exposed from beneath the melting ice. Between the two provinces, glaciers currently cover a total area of 26,700 km². By 2100, the volume of glacier ice in western Canada will shrink by 70 ±10% relative to 2005, with the highest melt rates anticipated in the Interior ranges (Clarke et al., 2015). The Columbia and Rocky Mountains are experiencing some of the most rapid deglaciation anywhere in the world (Huss et al., 2017). Models indicate that 80-90% of glaciers in those ranges will vanish by 2100 (Marshall et al., 2011). Between 16,00km² and 24,030km² of glaciated terrain will become available for habitat expansion in AB and BC in the next several decades.

Despite this tremendous expansion of paraglacial terrain – unstable, transient landscapes that are transitioning from glacial to post-glacial landscapes – the processes by which bedrock is transformed into functioning habitat are not yet fully understood. Less still is understood about how these processes play out in the forefields of remote, steep, small, and sheltered glaciers, even as these glaciers are particularly abundant in mountainous areas. Research indicates that cirque glaciers are melting much less quickly than the more-frequently-studied large icefields; it is, then, possible that forefield dynamics also have modified successional processes than those that have been described in the forefields of larger, less-steep, and more rapidly melting glacial forefields (Glaussen and Tanner, 2019; Eichel et al., 2013; Franzén et al., 2019). In response to this gap, this research project sought to develop a proof-of-concept methodology that could describe spatio-temporal patterns of land cover composition in this type of terrain, using the Avalanche glacier (Figure 2) as a case study. To do so, it was first necessary to develop a data

collection protocol that would account for the remoteness and inaccessibility of this type of forefield environment, which largely prevents frequent visitation to collect data in situ.

To this end, I have sought in this thesis to answer two questions:

1. *How can remotely-sensed and in-situ data be combined in order to describe ecological patterns in a forefield environment?* and
2. *What patterns of emergent land cover composition are present in the Avalanche glacier forefield?*

For more than a century, these paraglacial systems have functioned as living labs for myriad developments in ecological thinking. Changes to forefield landscapes around the world have been well-documented, with some glacier forefield research beginning as early as at the end of the Little Ice Age (Coaz, 1887; Butters, 1914; Cooper, 1916, 1931; Lüdi, 1921, 1958; Negri, 1934; Fægri, 1933; Friedel, 1934, 1937, 1938). For nearly 150 years, glacial forefields have been used for studying the processes of primary succession. Indeed, the study of plant communities that develop in deglaciated areas provided a major basis for the development of ecological succession theory in the beginning of the twentieth century (Clements, 1916; Gleason, 1927; Cooper, 1916). Receding glaciers deposit sediment across a forefield; these sediments, combined with warming temperatures and abundant water from glacial melt, spur new life. Across all latitudes and altitudes, the expansion of ice-free areas opens up substantial quantities of substrate for ecosystem development.

Newly deglaciated areas are increasingly important components of mountain and high-latitude ecosystems because of their potential to act as refugia -- for temperature-dependent plants, insects, and the larger fauna that feed on them -- under conditions of anthropogenic climate change (Hock et al., 2019; Ficetola et al., 2021). Indeed, some research has shown that over the last two centuries, alpine environments have experienced up to a 62% decline in

unvegetated debris/rock outcrop, as the same landscapes experienced more than 300% increase to forests and nearly 200% increases to alpine grasslands (Hohensinner et al., 2021). And, glacial melt can have locally beneficial impacts for biodiversity. A 2019 meta-analysis of 2100 papers about the effects of glaciers on biodiversity found that there is strong scientific consensus that glacial retreat will lead to local increases in biodiversity (Cauny-Fauvrié and Dangles, 2019). Glacial retreat is also predicted to establish tremendous expanses of new aquatic habitat – a study published in Nature Communications in 2021 found that the retreat of western North America’s glaciers will create 6,000km of new river habitat for Pacific salmon (Pitman et al., 2021).

These ecological developments come in the wake of substantial impacts to human and non-human communities who have relied on the cryosphere for time immemorial (Huss et al., 2017). Deglaciation leads to failed slope stability and glacial outburst floods (Haeberli et al., 2016). The timing and magnitude of seasonal streamflow will be altered; erosion rate, nutrient flux, and sediment transfer processes in rivers and proglacial lakes will all change (Bolatti et al., 2021), all of which will influence water quality and aquatic habitat. Millions of people will be affected – approximately 1/6th of the Earth’s population relies on water from mountain glaciers for drinking water, irrigation, mining, hydropower, agriculture, and recreation (IPCC, 2013). In addition to deglaciation, these systems are also undergoing habitat loss and species migration, erosion and other changes related to a warming earth. Models indicate that, in previously snow-dominated regimes, precipitation will increasingly fall as rain, rather than snow (Mudryk et al., 2020); when precipitation does fall as snow, it melts at unprecedented speed due to warmer springtime temperatures. Currently, 9% of total streamflow comes from the contributions of glacial melt -- but in the critical late summer months, when snowmelt typically stops, that amount rises to 25-47% (Jost et al, 2012; Naz et al, 2014). Glacier-fed river systems are

forecasted to rise precipitously until the 2050s through the peak melt period, at which point these contributions will dramatically taper (Huss et al., 2017).

The Columbia Basin has 2,100 glaciers; the Avalanche glacier is but one tiny mass of ice among thousands more. But the lessons that are revealed in its forefield extrapolate out to broader inquiries about rapid change – how life might insist on the cracks, and how that regrowth might play a role in stabilizing erosional processes or increasing water quality are indicative of what might be possible in these waters. This is a land defined by water, and yet on the day of this writing (April 22, 2022), there are 376 active drinking water advisories along the banks of the Canadian portion of the Columbia. There is water here; not everyone gets it. This work was taken up in the increasingly transparent context that so much 21st century science operates under: that the practitioners of science need to ask questions that might help us learn how to live – not only how to overcome these inequities, but also what it means to be a person under the conditions of rapid climate change. How might we stay firmly rooted in this place and continue to be in relationship with it as it changes? These questions circle the real impetus for undertaking this scientific research: the warrant of the project is that what happens next in these landscapes matters because it implicates how we imagine the future, who gets to live in it, and how. For this reason, this work will rely more heavily on history and social science than might otherwise be expected in a work that tests a scientific hypothesis.

In the context of increasingly urgent concerns about risk, resilience, and adaptation, the study of glacial forefields is an essential component to broader questions of downstream water quality, erosional hazards, habitat shifts, and more. Even as deglaciation has well-documented risk factors, emerging changes in ecosystem composition can potentially exert controls on some of the adverse effects associated with deglaciation. Proglacial areas have been shown to provide regulating services, including natural hazard regulation and the development of new soils and

provision of expanded habitat (Bollati et al., 2021). But, to know the extent to which these ecosystem services might be present, one must first have a means to understand the glaciological and subsequent ecological responses to rapid, anthropogenic warming. The questions driving this thesis research are grounded in this context. As such, this research attempts to describe a possible workflow for understanding ecological responses to anthropological deglaciation, and test the methods using the Avalanche glacier as a case study.

Study Area

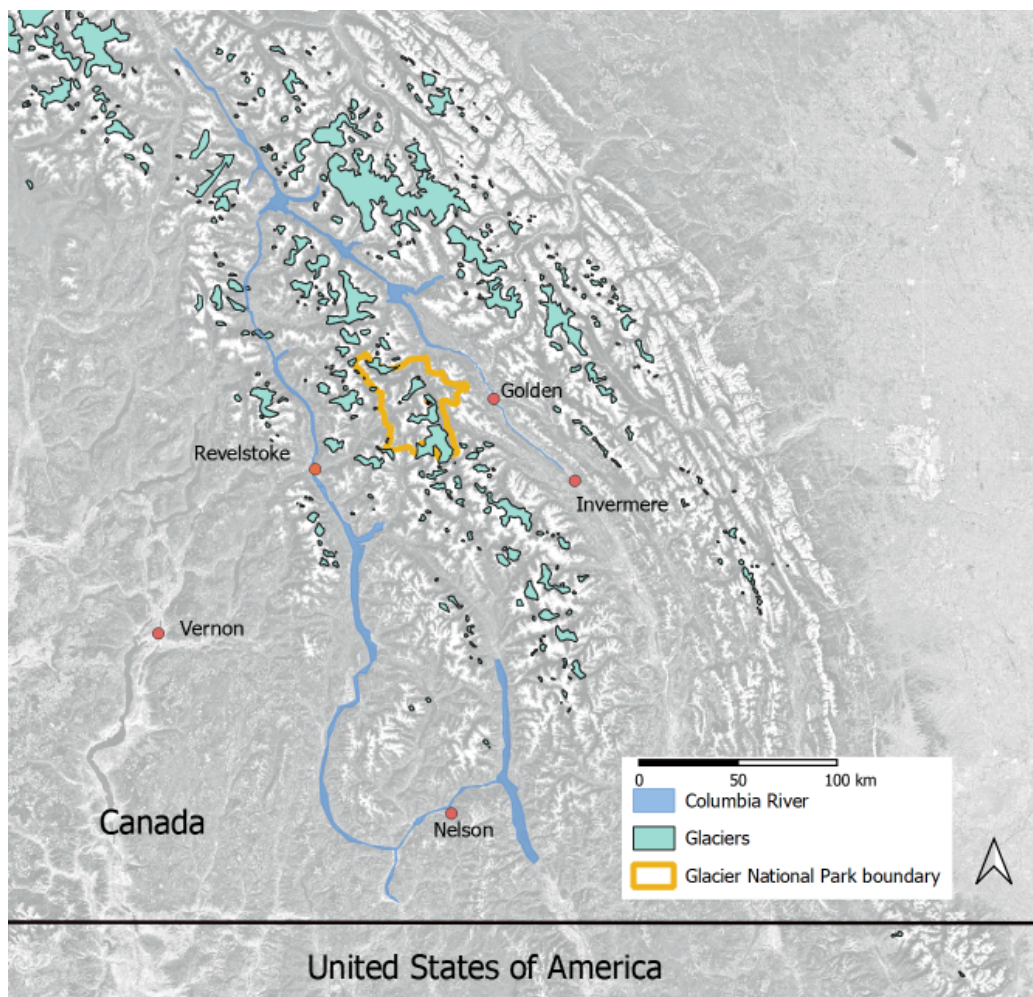


Figure 1: The Canadian portion of the Columbia River Basin and its glaciers.

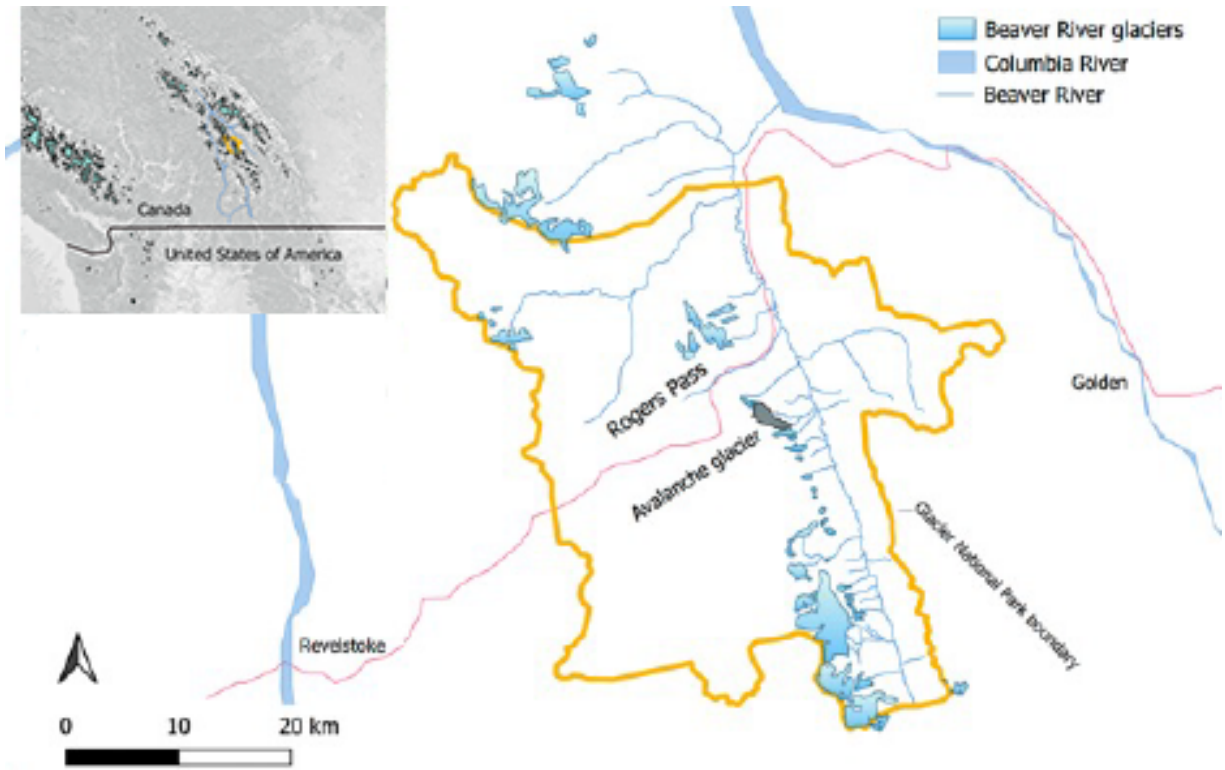


Figure 2: A map of the study area. The insert uses the OpenBaseMap QGIS plugin as a base layer. The map shows the boundary of Glacier National Park, with the Avalanche glacier in grey near the middle of the park.

The study area for this research is the Avalanche glacier forefield located in the Selkirk Range of the Columbia Mountains in interior British Columbia's Glacier National Park (Figure 3). The Canadian portion of the Columbia River Basin has an estimated 2100 glaciers and icefields (Figure 2) (Ommanney, 2002). BC's Interior mountains contain the fastest declining glaciers of any mountain region in the province. The Columbia Mountains (comprised of the Purcells, Selkirks, Monashees, and Cariboos) are declining fastest, having lost approximately 24% of their mass between 1985-2005 alone (Bolch et al., 2010). These rates put the region among the most rapid deglaciation of any place on Earth (Tennant et al., 2012). Glacier mass balance models indicate that 80-90% of glaciers in Western Canada will vanish by 2100 (Naz et al., 2014) – although in the Columbia Basin (Figure 1), total deglaciation is predicted to occur as

early as 2085 (Pelto et al., 2020). The most rapid melt is predicted to occur between 2020-2040 (Clarke et al., 2015).

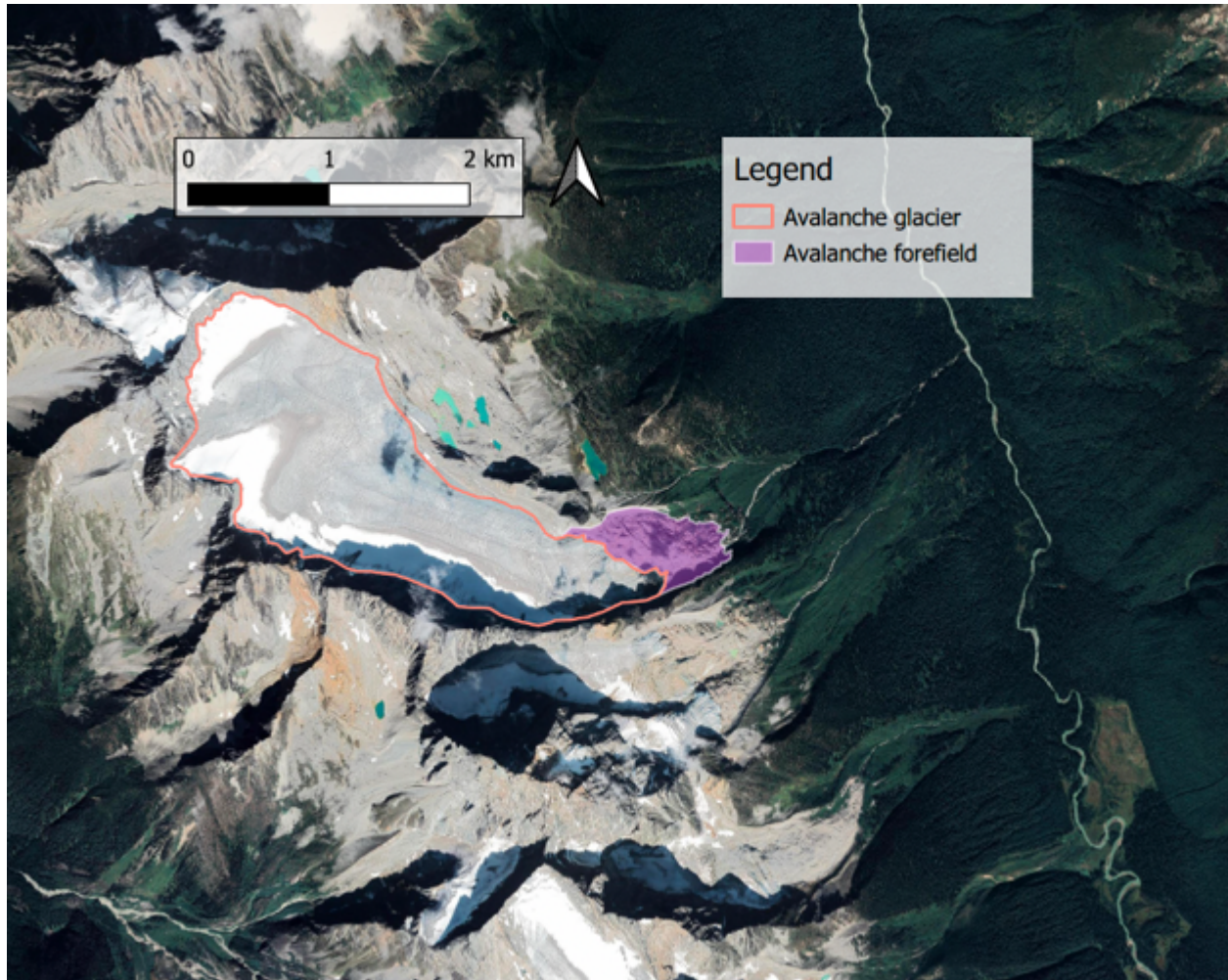


Figure 3: Areal extent of glacial retreat since 1902 shown in purple. Satellite imagery taken from Google Earth.

The Avalanche glacier is an east-facing glacier in the northern Selkirks. (Figure 3). It is located 3km to the northeast of Mount Sir Donald in Mt. Revelstoke/Glacier National Park. The glacier drains into the Beaver River. The Beaver River Valley below hosts one of the last pockets of old growth, inland cedar anywhere on the planet. The Avalanche glacier is the most accessible glacier of the Beaver River Valley – closest to the road, and closest to established routes and trails. Of the small, steep, cirque glaciers of the Beaver River Valley, the Avalanche is the glacier

with the clearest historic photographs – historical imagery looks straight on, without significant distortions like what’s seen in the photographs pointing farther south down valley. And, because of its proximity to Roger’s Pass, there were more, and earlier, air photo flight paths that travelled directly overhead. This relatively rich data made it a prime candidate for studying the glaciers of the Columbia River’s headwater tributaries.

The Columbia River headwater’s eight tributary streams have offered “regional coherence” (Kennedy and Bouchard, 2000) for time immemorial; indeed, before settlement disrupted and restructured habitation in the region, the original Sinixt, Secwepemc Ktunaxa, and Syilx peoples each organized their winter homes around a separate tributary. This legacy of water as the defining aspect of place extends into contemporary culture: whereas the Indigenous peoples lifeways once revolved around landscape, sociopolitical structures today revolve around controlling the river. This is most plainly evident via the ongoing Columbia River Treaty renegotiations between regional and international actors (and in which, key Indigenous actors have been conspicuously left out). These negotiations bear international significance: The Columbia River ranks fourth in annual discharge among all North American rivers (Carver, 2017). It provides water for 6 million people, and power for 44 million (Tsurutu and Schnorbus, 2021). For the entire watershed, the Upper Basin (which includes the region from the headwaters near Invermere, BC, just SE of the Selkirks, around Roger’s Pass, and to the Revelstoke valley to the west – see Figure 1) provides 40% of total runoff, despite only comprising 15% of the total watershed area. The region surrounding the Canadian section of the Columbia is also home to over 700 species of birds, mammals, fish and reptiles.

Structure of the document:

In this thesis I first present an introductory history of human influence in the Columbia Basin. The rest of the **literature review** covers the development of several relevant fields of inquiry: proglacial studies, fluvial geomorphology, repeat and transect photographic methods, and image analysis methodologies. I also provide a brief summary of the Mountain Legacy Project, under whose purview this thesis was completed.

Next, the **methods** used in this research are presented, including: (1) archival data collection; (2) repeat photography; (3) photographic line transect; (4) manual and artificial intelligence methods for producing land cover classifications of repeat photographs; (5) georeferencing oblique repeat and semi-oblique air photographs; (6) mapping viewsheds captured in photographs from the transect; (7) manual classification of land cover types using satellite photos; and, (8) manual classification of land cover types using transect photographs.

A **results** section provides a summary the findings produced by the research methods. It will summarize the data produced via land cover classification techniques, describe the terrain age of different areas of the forefield, explain how terrain features in the forefield were classified, and finally describe the spatial arrangement of the four fluvial biogeomorphic stages (FBS) throughout the forefield.

In my **discussion** chapter I dive further into the findings, referring back to the existing body of research to interpret the collected data. It revisits the roles of terrain age and terrain complexity as competing factors in forefield environments, reflecting on the how these factors appear to shape the emergent ecological patterns of the Avalanche forefield. It will describe the process of designing, and the limitations encountered while performing, the transect method. And, this section will explain how lived experiences of climate change – unprecedented heat domes and raging wildfires – acted as limitations upon the research process.

Finally, my **conclusion** chapter will provide a summary of the thesis, and offer suggestions for further research. Finally, it will open into a discussion of the limitations of drawing conclusions from quantitative analyses alone. This final discussion section offers reflections on criticisms from adjacent field of relying on data as fact, and ponder whether more narrative-driven approaches could better represent ephemeral forefield landscapes.

Positionality statement

In 2014, when I began doing ecological restoration work, my first project was contracted by the Idaho Kootenai tribe. Alongside members of the tribe, I built rock reinforcements along a degraded river bank to help restore salmon spawning habitat on a tributary to the Columbia River. Since then, I have worked, played, and learned from the river in every jurisdiction it runs through. I have also had the immense pleasure of spending significant time in the river's headwaters in British Columbia, first on a summer-long cycling and mountaineering trip in 2019, and again during the 2021 field season. Spending time with these lands and waters feels intimately tied to my identity, and has directly informed my decisions to pursue academic research. Despite the myriad benefits I have gained from my time in this land, I have only ever visited it as a settler; therefore, my ability to enter into relationship with the land, and come to understand it, is inherently limited. My enduring hope for this research has been that it may serve towards grounding any future community I may enter into with the original stewards of the mountains and waters of the Columbia.

It is also my hope that, in my application of novel analyses of historical images, I have worked to undermine the legacies of colonialism perpetuated by the very photographs I relied upon. Much of this thesis was based on the use of early 19th century survey photographs taken by

the Dominion Land Survey. The photographs by A. O. Wheeler that were the genesis of this project were originally taken as part of a widespread colonial mapping process by which early settlers asserted their power over the landscape (Macgregor, 1981). The maps they produced from these photographs helped transformed vast areas into private property that could be settled. Indeed, A. O. Wheeler's initial apprenticeship with the Survey was on a project whose primary mission was to survey newly-created Indian reserves (Patillo, 2007) – the etymological linkage to the word surveillance ought not be forgotten here. After his photo-topographical surveying career had been established, Wheeler joined the newly-formed colonial militia in order to fight against the Métis in the 1885 North-West Rebellion and was appointed to the Intelligence Corps branch of the Dominion Land Surveyors. While the landscape photographs that Wheeler and his contemporaries took have been lauded as art, archive, and critical in the establishment of ecological baselines for scholars today, they were necessarily intended for the genocidal ends of the early government. In the interim century, the photographic impulse has not been much transformed: the satellite images that this research relies on to supplement these repeated historical photographs relies on technologies developed and funded by the militaries of imperial states. The images they produce continue to enact the processes of surveillance, settlement, extraction, war, and death. These tools are not neutral, and my work is borne out of these brutal lineages. At every step of this research, I have remembered that the ecological monitoring techniques employed by this work were coeval with the tools of military imperialism. It would be folly to pretend that this research is neutral, but I have remained vigilant to ensure that this work does more to betray, rather than replicate, the structural, environmental and interpersonal harms caused by ongoing processes of colonialism.

Literature Review

To begin this literature review, I provide an introductory history of human influence in the Columbia Basin. Special attention is paid to issues of Indigenous stewardship and sovereignty in these lands, as well as to the ways that settler colonialism has left lasting landscape-level impacts in the Basin. European settlement began in the region concurrently with the end of the Little Ice Age. Glaciers began to retreat; simultaneously, the land was affected by the forced displacement of Indigenous peoples and lifeways. The landscape was subsequently reimagined via the extensive damming of the Columbia. The interwoven impacts of settlement and climate change are the backdrop to all of the scientific inquiries described in the rest of the Literature Review.

After the human geography has been established, a century of glacial forefield research developments will be presented, alongside the field's recent transition away from chronosequence methods in favor of geomorphic (and, especially, microtopographic) lenses for reading the landscape. Corenbilt et al.'s (2007) and, subsequently, Eichel et al.'s (2013) development of a biogeomorphological succession schema in particular will be highlighted. The successional stages used in the analysis of this thesis' data will be defined. I introduce the Mountain Legacy Project (under whose purview this thesis was completed); the Project's work will be put in conversation with other recent developments in glacial studies that employ repeat photography, including a section that will review how other glacial research has defined land cover classification masks, when such a system was used to analyze repeat photographs.

People in place

While this thesis is first and foremost a work of ecological and spatial inquiry, the study takes place in a geography that has long been materially affected by human influence. The landscape is defined by the river; the river is defined by human use. The Columbia Valley is situated between the Rocky and Columbia Mountains in the interior of what is now called British Columbia. In it, the Columbia River begins. On the valley bottom, the largest continuous wetlands anywhere in North America stretch for so long, they cross two longitudes. Just down river from these wetlands, much of the valley has been flooded by a reservoir, called Lake Kinbasket, which was constructed in 1961 by the American utility company, Bonneville Power Authority. The river passes through dozens of subsequent dams before ultimately draining into the Pacific.

The Columbia Valley's economic development has been marked by controversies and human displacements, mostly focused on gaining control of, and developing hydropower from, the river (Carver, 2017). The development of dams – including some of the world's largest and most complex – along with treaty provisions with the US that incentivize the storage of water at sites upstream of the US-Canada border were, throughout the latter 20th century, the backbone of the region's economy (Britannica), and spurred the development of the headwater region's major towns: Invermere, Golden, and Revelstoke. Several unincorporated towns dot the river's banks, along with Syilx Okanagan, Secwepemc, and Ktunaxa reserves. Today, the Columbia Valley hosts an economy primarily based on ranching, logging, mining, and tourism (Water in the Columbia). The valley borders Mount Revelstoke/Glacier National Park to the west and Yoho National Park to the east, and also acts as the western gateway to Banff and Jasper National Parks. The Rocky and Columbia Mountains draw skiers, climbers, and hunters; the valley floor

offers opportunities to hike, fish, or tour natural hot springs. Despite the abundance of work opportunities, the region is also one of infrastructural inequities. The distribution of water resources in Canada is in a globally-recognized state of crisis: Human Rights Watch reported in 2016 (Human Rights Watch, 2016) that the manufactured mismanagement of Canada's water resource and its systematic negligence in providing safe drinking water to First Nations was so severe it constituted a human rights violation according to at least six international treaties of which Canada is signatory. The Columbia Basin, whose population is less than 100,000, consistently has more than 100 active water quality advisories (Drinking Water for Everyone, 2022).

Despite the ongoing issues of water insecurity, which are most prevalent in First Nations reserves, the people of the Columbia headwaters have always been people whose lifeways center the river. In the Sinixt creation story, Rain and Coyote fall in love and decide to exchange gifts. Rain tore her heart out of her chest and threw it onto the ground; where the blood seeped across the land became the headwaters of the Columbia (Armstrong, 2007). The story ends by insisting that the Sinixt people live forever in accordance with those waters (Wood, 2020). Pre-contact, the Sinixt peoples would visit the headwaters in ceremony annually, as a way of assuring good health (Wood, 2020). The Ktunaxa also have cosmologies that mirror the structure of the river's early tributaries across the Columbia Basin (Kennedy and Bouchard, 2020). It is said that connection to the river is the best way to stay in relation with *kikum* (the Human Spirit/deity), who travels its waters by canoe doling out wisdom and healing (Our History, n.d.). The primacy of water holds true for the Syilx, too: in the Okanagan language, the first bit of the word knowledge, *naw'qinwixw*, refers to a slow-moving current or dripping water (Armstrong, 2007; Okanagan Nation, 2018). Even inter-tribal relations were grounded in these hydrologic systems: Each group may have had a permanent camp designated to a discrete tributary, but all of the

groups traveled the rivers together, visiting each other's camps while searching for fish (Lozar, 2018).

By the 1840s, preceding settlement by some decades, smallpox had already decimated the Indigenous population. The Oregon Treaty of 1846 established the U.S.-Canada border between the Rocky Mountains and the Pacific, effectively bifurcating the homelands of the Indigenous peoples. Soon thereafter, the Syilx peoples remaining on the Canadian side of this new border began to organize a military confederacy to resist the new colonial governments' attempts to keep the groups from traveling freely along the waterways as they had always done (Lozar, 2018). Throughout this time, the border was a cursory idea with little to no material dimension. Indeed, it was only created to divide up financial resources that comprised a system having little or no relevance to the lifeways of Indigenous peoples; even as border discourses subsequently shape shifted and emerged as a tool to displace and control tribal members, these conversations had little immediate effect on the many Indigenous people who continued to move freely across their territory. As reservations proliferated on both sides of the border, many Ktunaxa people especially were known alternately to visit reservations on either side of the illusory border in order to collect food rations from both sides (Lozar, 2018). After years of disruptive resistance to mining on the one hand, and manipulation of rationing systems on the other, the Ktunaxa peoples were finally told to cut all ties from the U.S. side of the border.

The Sinixt ultimately faced a similar boiling point. An 1890s-era mining boom in the Slocan Valley forced Sinixt to migrate south at risk of violent confrontation with aggressive settlers, who described the Sinixt as "dangerous" (Lozar, 2018) and demanded that their emerging settler-state government have them removed. A small reservation was formed. While some Sinixt remained scattered throughout the territory, after a decade plus of requests by two Sinixt bands to have a reserve designated at *kp'itl'els* (confluence of Kootenay and Columbia),

their requests were finally rejected when the land was instead given to a group of Russian religious dissenters fleeing persecution. In 1900, the simultaneous advents of a near-total eradication of bison herds and the creation of the first residential schools effectively enforced the border, ending the ancestral practice of free movement along the waterways. When the last member of the Oatscott Sinixt died in 1956, the Crown declared the Sinixt extinct.

These forms of erasure had irreversible and material consequences through permanent alterations to the landscape, perhaps most notably by way of the flooding of tens of thousands of hectares of lands across the Arrow Lakes and Big Bend regions of the Columbia River. Where there had once been the last remains of village sites and other traces that this valley is sacred land, there was now only rising water. In 1956, research published by the U.S. Army Corps of Engineers described the influence of seasonal snowpack on the Columbia River; it was the first of its kind in the region to indicate future snowpack instability (U.S. Army Corps of Engineers, 1956). Five years later, the first series of hydroelectric dams were built in Canada by U.S. corporate actors, as per the newly-signed Columbia River Treaty (CRT). No Indigenous peoples *or* newly-landed settlers were consulted, although tens of thousands of ancestral villages and burial sites were flooded (Swainson, 1979). The settlers whose farms were flooded were only consulted after the fact, for compensation and relocation assistance.

In 1987, Sinixt peoples from the Colville Reservation migrated North and established a re-occupation camp near Vallican, B.C., where they remain, 35 years later. It is the longest-standing reoccupation site anywhere in Canada (Wood, 2020). Of the many ways various Indigenous peoples and alliances have made themselves comprehensible to the Crown, perhaps most reflective of the recent calls for reconciliation was the case of Rick Desautel. A Sinixt member and U.S. citizen, Desautel harvested an elk on Crown land in B.C. and immediately called RCMP so that he could be arrested for hunting as a “foreigner” (Rowlands and Wildman,

2018) in order to initiate a court case in the Canadian legal system. The case was heard before the Supreme Court of Canada in October, 2020. In 2021, the Court decided in favour of Desautel, effectively declaring that the Sinixt peoples are still here. This is a precedent-setting case for Indigenous peoples in Canada. The Sinixt hope that the decision will reinstate their right and title, allowing them to participate in salmon restoration, especially along the Grand Coulee dam where they have been releasing salmon for years. In the 1960s, there were “salmon as big as golden retrievers” (White, 1995) in this section of the river; salmon traveled from the Pacific, and there were unique inland varieties. The construction of several dozens of dams, starting in the 1960s (shortly after the Sinixt were declared extinct) cut off the lifeways of salmon and has had devastating ecological and cultural consequences.

These legacies of extraction, water, sovereignty and separation continued throughout the 20th century. Many scholars have written about the inscription of the river with the structures and injustices of settler colonialism. When the Columbia River Treaty (CRT) renegotiations began in 2020, some researchers claimed that this new treaty is merely an iteration of how future-oriented management practices designed to be reflexive to water scarcity are instead reflective of “state-centric discourses” (Baltutis and Moore, 2020).

In 2018, Dr. Matthew Evenden published a review of riverine historiographies (Evenden, 2018). Despite an unabated “stream of river histories,” Evenden noted the distinct need to re-locate these histories to the Anthropocene, and called upon environmental historians to increasingly draw upon critical theory to interpret the socio-hydrological significance of these systems. “Looking forward,” he wrote in conclusion, “we must remain open to new comparisons, theorizations, and methodologies that will allow us to tackle emerging problems and situate the history of rivers in a range of spatial scales as well as larger planetary narratives” (Evenden, 2018). The anthropogenic influence that is causing forefields to emerge en masse is the same

“planetary narrative” that enabled a century of mining, logging, damming, displacement, dispossession, encampment, resistance, and novelty in the headwaters of the Columbia. While the primary methods employed in this thesis did not directly engage the sorts of social science methods that might measure the social significance of the ecological or hydrologic changes in the Columbia, it remains essential to pay proper attention to the myriad ways that human influence can shape ecology – and to the ways that ecological transitions always occur in the context of the communities that live downstream. These contexts will be revisited in the Discussion.

Glaciological history in the Columbia Basin

Tree ring data indicate that the Upper Columbia’s Little Ice Age maximum occurred between 1830 and 1862 (Walker and Pellatt, 2008). As in much of the globe’s cryosphere, the cause of deglaciation has shifted since ~1980 from being predominantly caused by natural, Holocene-era climate variability (~75% of total forcing) to being primarily influenced by anthropogenic causes (i.e., solar variability, land-use change, anthropogenic aerosols, and greenhouse gas emissions) (Marzeiron et al., 2014, Hock et al., 2019). From 1991-2010, anthropogenic heating was responsible for $69 \pm 24\%$ of glacial recession globally, with particularly high confidence levels in North America. Today, glacier reduction is up to 300% faster than it was merely 20 years ago (Sommer et al., 2020; Ficetola et al., 2021). Pelto et al. (2020) suggests glaciers may be entirely absent from the Columbia River Basin as early as 2085.

Many of the larger glaciers in the Upper Columbia Basin have had traits like their mass-balances or projected rates of retreat extensively researched. For example, the Illecillewaet glacier, just 3km southwest of the Avalanche glacier, has been the subject of more than a century of systematic observations (Wood, 2012). While other glaciers in the Selkirks have been missed

by these century-long observations, remote sensing techniques have enabled decades of research into the rates of recessions of the area's larger glaciers in particular. Pelto (2017) describes the rate of retreat of 16 major glaciers of the Southern Interior mountains of BC using Landsat imagery from 1985-2015. The majority of these glaciers lost 15% or more of their area in the 30-year period, sometimes retreating more than a kilometer. Nearly all of these glaciers were either associated with icefields, or were described as having low-slopes. Studies in Iceland shown that active, temperate glaciers have locally distinct responses to climate change (Evans, et al., 2016; Chandler et al., 2020). Such studies have shown that process changes (i.e., sediment transport, moraine activity; etc.) cause topographically-controlled changes to the architecture of a glacier's terminus, in addition to climatically-driven glaciological changes. These observations of diversity in process-form responses highlight the need for continued monitoring of individual temperate glaciers to assess the impact of ongoing climate change (Nakawo and Raymond, 2000; Magnusson et al., 2012; Evans et al., 2016 and 2016; Chandler et al., 2020).

Glacier chronosequence studies

To early researchers, succession following deglaciation seemed a marvel. In 1887 Johann Coaz—a Swiss alpinist, topographer and scholar—was on his second trip up the Rhonegletscher when he found waxy yellow saxifrages growing where there had been ice only three years earlier (Coaz, 1887). Downslope, where the glacier's recession had occurred one decade prior, Coaz counted thirty-nine species of plants. “Serious thoughts took hold of us,” he wrote in an expedition journal. “Amazed and awe-struck we gazed across this magnificent mountain world” (Anker, 1999). When glaciers shrink, what remains is like a contour map whose lines are time. As years pass, lichen turns mineral dust into dark, carbon-carrying soil. Early arrival species

such as fireweed (*Chamaenerion angustifolium*) grows in cracked granite. The cracks widen, and in them, trees seed. For Coaz, it took 30 distinct alpine first ascents, and a lifetime of repeated visits, to notice the waxy yellow saxifrages at the toe of the Rhonegletscher (Coaz, 1887). Before this discovery, ecologists studying primary succession -- whereby a newly-formed land surface devoid of life transforms into an ecosystem -- had always used space as the constraining variable. But, as the Little Ice Age (LIA) ended, Coaz saw life renew. In ecological terms, that discovery is what enabled researchers to substitute space for time. Still, it took more than half a century before anyone thought to name the vacant space where glaciers have retreated. It came from the German *gletschervorfeld* (Matthews, 1992). *Vorfeld*: like an apron, like the paved area in front of an airport's landing zone.

The procession of development, by which space becomes substituted for time as a control factor for observing primary succession, is called a chronosequence. For more than a century, researchers have noted that an increase in distance from the margin of a retreating glacier could be interpreted as representing a temporal sequence (Matthews, 1992). The geography of a forefield contains multiple terrain ages, all visible within a single space. The development of life, from the creation of soils to the creation of ecosystems, happens in these landscapes (Matthews, 1992). As such, forefields have long been used as sites for the study of primary succession.

Chronosequences endure as a common method of study in glacial forefields precisely because the front of a retreating glacier acts as an observable, temporal control on spatial land cover patterns. Immediately after deglaciation, the terrain is devoid of any living organisms, save, perhaps, some remnant bacteria left over by the ice. As time passes, living organisms spread in these spaces. New ecological patterns emerge. Chronosequences, then, have been used in the context of soil development (Jenny, 1941, 1946), the establishment of lichen communities (D'amico et al., 2014), vegetation succession (Perring, 1958; Jenik, 1986), ecosystem

development (Olson, 1958; Jenny, 1961, 1980), and, even, landscape succession (Troll, 1963, 1971). Indeed, the theory of ecological succession was first developed in deglaciated areas, where researchers were able to watch communities develop from bare rock (Clements 1916, Cooper 1931, Connell and Slatyer 1977). Early theories proposed three distinct models to describe the processes of primary succession (Connell and Slatyer, 1977). Early theories suggested that pioneering species modify the environment, thus making it primed for later inhabitants. This model is grounded in the primacy of biotic interactions. A second model, the tolerance model, suggests that subsequent successional stages succeed because early pioneers have traits that limit their early success (i.e., slow growth rates); or, alternately, have tolerance to environmental factors (i.e., shade-tolerant plants). The inhibition model, meanwhile, suggests that later successional stages are only possible via the early die off and release of resources from pioneers (Matthews, 1992; Ficetola et al., 2021).

With this in mind, Matthews (1992) proposed the first geo-ecological model for understanding the ecology of recently deglaciated terrain. The stages he described are:

1. Pioneer Stage. Terrain age ~ 0-15 years. Characterized by substrate sorting; seedling germination; and establishment of lichen, algae, and moss populations.
2. Early Successional Stage. Terrain age ~ 15-40 years. Characterized by die-back of short-lived pioneers; establishment of rhizomatic and clonal plant species; cryptogamic crust formation stabilizes slopes.
3. Intermediate Successional Stage. Terrain age ~ 40-80 years. Characterized by high vegetation cover (typically 60-70% of total area); plant community diversification; grassland and shrub community establishment.

4. Late Successional Stage. Terrain age > 80-100 years. Characterized by occurrence of tree species and shade plants and/or mature and diverse grasslands.

Of course, this model still places an emphasis on time as the primary controlling factor on development. While it is true that terrain age places limits on what level of succession may have been attained -- certainly a mature conifer cannot spring up to full height mere years after ice has receded -- recent research is shifting away from length of time in favor of analyses that instead focus on the intricate complexities of space and substrate. In the years following Matthews' description of forefield ecology in his seminal text on the subject, glacier recession rates around the world have accelerated. And there have been rapid developments in the understanding and appreciation of abiotic feedback cycles (Eichel et al, 2013; Levy et. al, 2015; Eichel, 2016; Miller et al., 2020).

It took decades of research before an awareness of the biotic richness of glaciers themselves was integrated into the study of forefields. Only recently has the research begun to incorporate microscopic ecological communities. Forefields' initial bacteria content is more similar to communities found in glacial sediment than what is found in atmospheric deposition (Ficetola et al., 2021), indicating that these bacteria inform early communities in deglaciated surfaces (Rime et al., 2016) -- and signaling that there are likely feedback loops between communities existing in the near-glacier areas of the forefield and on the glacier itself (Anesio et al., 2017; Kim et al., 2017).

As the field has evolved, the chronosequence technique (and, indeed, the concept of primary succession itself (Hagvar & Ohlson, 2013)) have come under scrutiny. As early as the mid-20th century, forefield researchers began to observe that many of the conclusions drawn by chronosequence methods were isolated from objective grounding in biotic or abiotic principles

(Matthews, 1992). This has led to some researchers combining data sources, for example via the use of chronosequences paired with species transects (Glausen and Tanner, 2019) in order to show variations in species density and richness. More recent studies (Synan et al., 2021) use modified chronosequence techniques alongside random sampling to show that approximate terrain age and distance from the toe of a glacier have different statistical relationships with species densities in a forefield, indicating that space may not always be a fair substitute for time. However, this assumption is complicated by planetary atmospheric inputs like oceanic decadal oscillations. Many mid-latitude glaciers in North America, for example, were found to have either stopped receding, or to have advanced, during the Pacific Decadal Oscillation that lasted from the mid 1940s through the 1970s.

While long appreciated as a favoured forefield analysis technique, chronosequence methods have come under scrutiny (Johnson and Miyanishi, 2008; Buma et al., 2017) for inflating the significance of time in lieu of more rigorous analysis of local context and empirical data. Others have shown that geomorphic processes may indeed be more consequential to colonization than time (Moreau et al., 2008). Maps of land cover nearly never show zonation that perfectly correspond to terrain age. Rather, it has been well-established that land cover composition more often emerges in complex mosaics, which are a function of geomorphic and hydrologic processes (Coaz, 1887; Friedel, 1938; Richard, 1968; Jochimsen, 1970; Matthews, 1979). As such, the emergent ecosystem composition at sites of recent deglaciation have been found to be diverse and, often, not controlled by terrain age. The question of time as a constraining factor becomes further complicated by the irregularity of historically time-controlled functions of climate such as weather, seasonality, or temperature. This is important, because the trajectories and outcomes of vegetation change are associated with a variety of processes on global, regional, and local scales; these include microclimatic feedback loops that

affect, for example, surface energy balance, ground thermal characteristics, spatial patterns of snow, and evapotranspiration (Lambert et al., 2020). These processes determine primary succession patterns, and implicate local hydrology, such as by the accumulation of groundwater resources (Eichel, 2016).

The role of microtopography

That landscape dynamics following deglaciation might have synergetic biotic and abiotic dimensions was first proposed in Matthews' 1992 geo-ecological model of vegetation succession. Because of the longstanding emphasis on time as the primary controlling factor, few investigations have sought to clarify fine-scale land cover patterns in the world's glacial forefields; even fewer exist that seek to make biogeomorphological analyses, as is increasingly called upon to reflect the dynamism of these landscapes (Matthews, 1992; Corenbilt, 2007; Eichel, 2018). When subjected to disturbances such as flooding, geomorphological instability, cryoturbation, and grazing (Kaufmann et al., 2002; Garibotti et al., 2011; Chapin et al., 2016), ecological processes in forefields may be slowed, altered, or reversed. The frequency of these disruptions highlights the importance of microtopographic data to understand the nonlinear trajectories of community development in deglaciated terrain. It is well-documented that heterogeneous microtopography influences the spatial distribution and trajectory of plant colonization (Raffi et al., 2016, Garibotti et al., 2011). Increasingly, it is also being found that topographic heterogeneity also correlates to an ecosystems' resistance and resiliency to climate change – especially in arctic and alpine environments (Graae et al., 2018; Mesquita et al., 2018). And, in forefields, microhabitat diversity has been shown to modulate ecological responses to geomorphologic and climatic disturbances (Gentili et al., 2015). In any alpine environment,

exposed sites are more subject to katabatic winds, frequent freezing air, and active periglacial processes (e.g., sorting of sedimentation due to freeze-thaw cycles, cold air pooling, etc.). These unfavorable conditions lead to high seedling mortality rate and a stagnation of pioneer succession (Alsos et al., 2007).

Lag times in primary succession are typical in high mountain landscapes. Even under Holocene warming patterns, alpine zones experience a time lag between climatic fluctuations and primary succession via upward migration into higher alpine zones. Some recent analysis (Zimmer et al., 2018) of primary succession in alpine habitats indicate alterations to community assemblages in areas that have undergone primary succession under more rapid conditions of warming. This indicates a need for research that investigates potential migration lags in the most recently exposed portions of glacial forefields. Along these lines, some research has found that community composition in forefields differs substantially from surrounding sites, even when abundant seed stock is present (Franzén, et al., 2020) due to extreme environmental stressors. Franzen et al.'s 2020 study of a Swedish Lapland glacier found that higher temperatures, such as those seen during the latter half of the 20th century, correspond with more successful primary succession, perhaps due to a longer growing season -- although only regional temperature trends were used. As the authors of that study note, this presents a serious limitation in the data, given the high variability of temperatures in a site with incredibly diverse microclimates. More research is needed to understand whether or how emergent forefield successional patterns differs under contemporary, anthropogenic climate conditions.

For the last decade, a growing body of research has therefore focused on microtopography as a driving control on community development in forefields. For example, Temme and Lange (2014) research in European glacier forefields found that the combined influences of landform, slope, curvature, and aspect likely explained more than half of soil

characteristic variation. More recent work in the Swiss and New Zealand Alps has concluded that the same topographic variables combined with geomorphic activity can account for species richness (Wojcik et al., 2021). In the Himalaya, it was found that even the rate of retreat was likely equally controlled by a glacier's size as it was by the topography beneath it (Sigdel et al., 2020). Still others identified microclimate (as a factor of local topography) as frequently having a comparable or, sometimes, stronger effect than that of time (Ficetola et al., 2021; Raffl et al., 2006), as demonstrated by research that found that wet microhabitats can reach high plant diversity 20 years earlier than drier areas of the same forefield. At later stages of succession, soil characteristics and similar geomorphological traits likely outweigh time (Rydgren et al., 2014).

Ecological transect methods can, in some settings, be used to generate finer resolution data, such as what would be needed to understand migration lags, microhabitat variety, or anthropogenic increases to colonization success rates. For example, transect quadrants can show variations in slope, aspect, local climate, altitude, and solar irradiance which together generate different micrometeorological conditions (Garibotti et al, 2011). Transects seem to be used alongside other data collection techniques. In very few instances, line transect methods are employed in lieu of random sampling. For example, Franzén et al. (2020) instead use altitude as the control with which site selection was made, collecting data every ~1000m of rise along an approximated midline that stretched from the present to the historic edge of a glacier. In situ records were supplemented by historic data gathered via visual observation of historic photographs. These data were subsequently cross-referenced to terrain age using classic chronosequence techniques in order to draw conclusions about "successful colonization" at various terrain ages according to plant richness metrics. Typically, fine-scale data are used to make fine-scale conclusions. In a review of more than 700 studies, Ficetola et al., (2021)

concluded that generalizations remain so difficult that time since deglaciation is likely still the best indicator for community structure over large spatial scales.

Biogeomorphological succession

One identified gap in the existing data is a lack of appropriate appreciation for biogeomorphic interactions in forefield landscapes specifically. Biogeomorphology, which was first coined in 1988 (Viles, 1988), refers to an “approach to geomorphology that considers the role of organisms” and has been used to describe the reciprocal relationships between abiotic and biotic features (Resler et al., 2010, Corenbilt et al., 2011, Eichel et al., 2013). In its early application to forefields, it was applied as a framework to describe the heretofore under-researched interactions, mechanisms, influencing factors, and resulting patterns between ecological and geomorphic dynamics (Eichel et al., 2013). Miller et al.’s 2019 work summarized the status of the literature on the interaction between abiotic and biotic factors creating a potential for a window of biogeomorphic feedbacks in glacial forefields. They found that the following factors constituted the geomorphic dynamics consistent in forefields during the paraglacial period (immediately following glacier recession):

- Disturbance. This includes barriers to pioneer uptake due to rock slope stability, sediment-mantled slope erosion, mass movement, fluvial erosion, etc., but also some benefits, such as via fine material deposition and subsequent increases to moisture retention and soil development.
- Water dynamics. Precipitation, snowmelt, glacier melt, groundwater seeps, and moraine ice core melt can alternately act destructively and as resource. Glacial sediments are well-draining in nature, and so geo-ecological processes are often water-limited. Hydrological

flow can disperse microbes, stimulate sediments weathering and soil development. Fast flows can foster mass movements, freeze soils, or otherwise act as disruption.

- Microbes. Microbe communities are essential for the conversion of paraglacial substrate into a habitat that can support ecosystem succession by providing carbon, fixing nitrogen, and reducing pH.
- Lichen. Lichens can weather rock masses 200-300 times faster than chemical weathering alone, converting rock to sediment in as little as three years.

With these factors in mind, it has been found that primary succession of glacier forelands can control geomorphological processes such as glaciofluvial floodplain and moraine slope development (Eichel, 2018; Gentili et al., 2015). Fluvial biogeomorphic work has primarily focused on river channels that have undergone disturbance (more than 400 out of the total 450+ studies that cite Corenbilt's 2007 introduction of the term focus on riparian systems). But, for the past 15 years since it was first introduced, it has frequently been applied in forefield contexts, too. In both riverine and glacial forefield settings, geomorphological, hydrological, and ecological processes work symbiotically. For example, Corenbilt's 2020 article on the colonization of a channelized river found a 95% statistical association between geomorphological and vegetation variables. The fluvial biogeomorphic model has been adopted by many in proglacial research: Corenbilt's original 2007 article has been cited in at least 48 peer-reviewed studies in deglaciated terrain.

The fluvial biogeomorphological succession (FBS) phases are as follows (Corenbilt, et al. 2007; Eichel, 2018):

- Geomorphic phase. Characterized by terrain distance -- this class is most proximal to the glacier's edge. Braided streams and shifting sediment constrain pioneer colonization.
- Pioneer phase. Characterized by coinciding terrain age *and* distance from glacier. Pioneer species begin near channel banks.
- Biogeomorphic phase. Characterized by the proliferation of woody roots, acting as ecosystem engineers. Below-ground biomass stabilizes glaciofluvial slopes; channel width is thereby reduced. Above-ground biomass increases surface roughness, reduces flow velocity, etc., by which floodplains are aggradated. Riverways are consolidated into single streams.
- Ecological phase. Vegetation communities stabilize and exert significant control on fluvial systems. Biogeomorphic determinants lessen; biotic processes (e.g., competition) become the primary driver of landscape change.

Jana Eichel's 2013 study of the Turtmann glacier forefield in the Swiss Alps was likely the first published study that employed the biogeomorphic succession phases proposed by Corenbilt et al. (2007). The application of biogeomorphic concepts has since shown huge potential in expanding the complexity of forefield environments, where extreme physical conditions lead to especially close linkages between geomorphic and biotic processes (Eichel et al., 2013). That survey combined 74 existing plots of geomorphic and vegetation data alongside 35 plots that had a consistent terrain age and could therefore be used to disaggregate time from geomorphic controls. They found that areas of high geomorphic activity were correlated to primarily pioneer vegetation; moderate activity areas were correlated to predominantly dwarf

shrubs; and species richness was highest at areas of low geomorphic activity. Eichel and Corenbilt subsequently coauthored a 2015 study of the same glacier which confirmed the role of alpine ecosystem engineer species on the structure and function of lateral moraines, and additionally showed that such feedbacks could only begin once geomorphic activity had already decreased to such an extent that the ecosystem engineers in question could reach a threshold of total surface cover area (Eichel et al., 2015). In that work, they developed the “biogeomorphic feedback window” which describes the “specific envelope of conditions” that include geomorphic disturbance magnitude, severity, and frequency, as well as plant species resilience and resistance to disruptive events (i.e., can either return to equilibrium, or absorb the impact without disturbance) (Eichel et al., 2015). The authors explain:

The ‘biogeomorphic feedback window’ on lateral moraines, depending on the geomorphic disturbance regime (process magnitude, ecologic severity, process frequency) and plant species traits (resilience and resistance). Thresholds preconditioning (establishment threshold) and confining the biogeomorphic feedback window (engineering and competition threshold) are shown.

Subsequent research has validated the importance of this window, finding that it triggers the transition from a primarily geomorphic system to one that has the potential to become primarily driven by ecological processes. Once a community crosses a critical above or below-ground biomass threshold, erosional processes begin to be constrained. Fine sediments are trapped and retained until eventually, the substrate solidifies. The processes continue until a competition threshold is met, at which time the environment has become so stabilized that no major geomorphic disturbances (rockfall, avalanche, landslide) are likely to occur because of the prevalence of late successional shrub and tree species domination (Eichel et al., 2015).

Mountain Legacy Project & photographic methods

Historic information is necessary for establishing reference conditions of changing landscape composition overtime. Once established, these baselines are used to understand emergent ecologies, set management and restoration targets, and generate ecological legacies (Higgs et al., 2014; Schweiger et al., 2018). The predominant source for these data is via orthogonal imagery, taken perpendicular to the Earth's surface, via drone, aircraft, or satellite. These image sources only became available in the mid-20th century -- in the 1940s for aircraft, and the 1970s for satellites (Belward and Skøien, 2015). Terrestrial oblique photographs, on the other hand, proliferated simultaneous to the development of the earliest photographic technologies in the 1860s (Webb, 2010). In British Columbia, systematic land surveys began to be conducted in the 1880s. Repeat photography -- the process in which historic photographs are meticulously repeated in order to be interpreted and analysed for change over time -- is used in order to a) predate the availability of orthogonal data, extending the historic baseline by several decades, and b) provide an oblique perspective that can capture details of a landscape that would be absent or foreshortened in nadir imagery. Historical photographs used for repeat photography often predate conventional remote sensing data (i.e., aerial and satellite imagery) by decades. Repeat photography began as a methodology to study glaciers in the late 1800s (Webb, 2010; Hattersley-Smith, 2011). Sebastian Finsterwaler's early work in the Alps was followed by glaciologists working across the United States (Gilbert, 1904) and the Canadian Rockies (Cavell, 1983) -- including of the nearby Illecillewaet glacier (Champoux and Ommanney, 1986). These methods have been used extensively and globally to track glacier retreat, including tremendous, decades-long efforts in the U.S. Glacier National Park and Denali National Park in particular. Even beyond the empirical knowledge produced in a repeat photograph, image pairs are often

highly evocative and therefore have useful applications within engaged research for their ability to communicate scientific knowledge to “lay audiences” (Curtis et al., 2012).

Since 1996, the Mountain Legacy Project (MLP) has been conducting systematic repeat photography to collect data about landscape change (Sanseverino et al., 2016). The basis for this work is access to more than 120,000 glass plate photographic negatives, a majority of which are held by Library and Archives Canada (LAC), taken by Dominion Land Surveyors and the Geological Survey from 1888-1958. Over the last several decades, upwards of 10,000 historic photographs have been repeated from the exact same location, resulting in sequential images that represent a century or more of landscape change. When paired (Figure 4), these photographs can provide data for studying change at several scales from community to landscape. Despite a vast archive of glacier photos, and the primacy of repeat photography as a method in the study of glacial recession, only a handful of MLP researchers have undertaken prolonged research on changes to mountain glaciers, and none have taken on proglacial mountain landscapes.



Figure 4: A repeat photo pair documenting the Robson Glacier, taken from the MLP Explorer website. The historic photo, above, was taken by A. O. Wheeler in 1911 with a group of scientists from the Smithsonian Institution. A team of MLP researchers repeated the survey in 2011. Other MLP research teams have also documented the recession of the Kaskawulsh (Yukon), Athabasca (Alberta), and Mt. Sir Donald and Illecillewaet (BC) glaciers. More about this work can be found at mountainlegacy.ca/project/ice/.

A variety of data extraction and analysis tools have been developed by MLP. An HTML- and JavaScript-based application called the Image Analysis Toolkit (IAT) can align image pairs and analyze land cover change over time; a Python-based machine learning tool (PyLC) classifies images at a pixel-scale for different land cover categories. Both tools' primary function

is to generate land cover classification masks. In an image classification mask, each pixel in a photograph is analyzed using automated and semi-automated algorithms to determine land cover type (e.g., shrub, or ice, or bare rock). Different colors represent different land cover classifications. The end result is a series of polygons superimposed over a photograph; all polygons together are referred to as a mask. Once land cover types are represented by color, statistical analysis of the number of pixels in any given classification relative to the total number of pixels in an image can explain land cover patterns across a landscape.

Once appropriate masks are selected, a comparison of masks from a historic photograph and a repeated photograph can document how a landscape has changed over time. Historically, MLP has had consistent success in the generation of such masks, and the subsequent description of linear relationships between percent cover and surface area (Fortin et al., 2018). The work of Fortin (2018) and others have found that, compared to Landsat aerial imagery, oblique photographs are more frequently able to detect narrow landscape features, possibly due to the higher spatial resolution of the oblique photographs, and to their angle of incidence against steep slopes. More information about these tools, and the archival material gathered by MLP, can be found at mountainlegacy.ca.

While these tools have not previously been tested in forefield environments, they are consistent with the classification tools occasionally used in forefield studies: Several recent forefield studies have used an image classification method to quantify landcover composition. These studies were referenced when choosing my own classifications in PyLC during image analysis. Four studies (Lambert, 2019; Mesquita et al., 2018; Lambert et al., 2020; Smittenberg et al., 2012) used bare rock as a classification. Water was used in three; glacier/ice was used in three; exposed soil/bare ground was used in two; snow was used in one; poorly-sorted debris was used in one; boulders/talus was used in one. The most popular classification for vegetated

landcover was “shrubs/bushes”, present in four studies. Three studies included grassy/herbaceous and pines/trees classifications. One study (Klaar et al., 2015) disambiguated species-level landcover types relevant to the study area: “‘alder’; ‘cottonwood’; ‘spruce’; ‘mature’ (spruce–hemlock dominated forest); ‘open vegetation’ (includes both muskeg and small, scrubby vegetation dominated by blueberry, crowberry and small willows) and ‘mountain vegetation’ (typically higher elevation, open vegetation dominated by *Epilobium latifolium*, *Dryas* and scattered blueberry and crowberry)”; the rest of the landcover was referred to as “non-vegetated”. Other studies used vegetated classifications including mature forest, open vegetation, scrubby vegetation, tundra, open forest, and closed canopy. One study clumped all of these possible classifications together as “vegetation”. None of the studies described how their classification types were chosen. From the options presented in these previous studies, the following seven classifications were selected for use in this research (verbiage was adapted to match those used in the BC Land Cover Classification Scheme): rock/rubble, exposed land, herb, low shrub, upland forest; water; and snow/ice.

Typically, the MLP repeat photography work flow relies primarily on repeat photographs. However, for this project, it felt important to visit the forefield site and develop a method to derive finer-scale detail of the microtopographic features on site than what would be visible from the repeat photographs, taken from a distance of four kilometers. Based on previous work (Glaussen and Tanner, 2011, among others), I determined that a photo transect would be the best method. A photographic transect is a method in which a transect line is followed, and photographic points (quadrats) are taken as data (Cagney et al., 2011). While transect methods are widely employed in forefield studies, especially in the context of chronosequences (as described above), photo transects are used less frequently. This technique was preferred for this study because a variety of different data types were needed. Other sampling methods are used

when detailed information about plant species, or bacterial community growth, or substrate chemical composition is desired. While photo transects do not allow for the same specificity that other sampling methods offer, they do allow coarse-grain information about plant growth, topographic features, and above-ground hydrologic features to be described. While a greater level of detail would allow for better statistical analyses to be drawn, these other methods are more time consuming and more expensive. And, in the context of traveling amidst environmental hazards common to forefield environments, photo transects allow researchers to quickly move through dangerous terrain.

Methods

For this thesis, I wanted to map the recession of the Avalanche glacier over the last century, and to describe land cover composition of its forefield using Corenbilt's fluvial biogeomorphic stages (FBS) framework (2011). An experimental protocol was developed that combined remotely sensed data -- using repeat photography, historic air photos, satellite photos, and digital elevation models (DEM) -- and data collected in-situ using a photo transect method. Repeat photography refers to the process in which historic photographs (in this case, glass plates taken in the late 19th century) are meticulously repeated in order to be analysed for landscape change over time. Historical photographs used for repeat photography often predate conventional remote sensing data (i.e., aerial and satellite imagery) by decades, offering a century-long view of change -- and, the oblique perspective of survey photographs can capture details of the landscape absent in nadir imagery. As discussed in the preceding literature review, these methods have been used extensively in research conducted around the world to track glacier retreat -- including tremendous, decades-long efforts in the U.S. Glacier National Park and Denali National Park in particular. Other forms of remotely-sensed data can provide information across wide spatial and temporal scales. Historic air photos (taken during annual fly-overs for cartographic and other geographical ends) can be analyzed for change at annual or decadal scales. Automated analysis tools have been developed to interpret these data and can reduce human error. Conversely, data collected in-situ -- such as that gathered during a photo transect that traverses a forefield -- can provide significantly higher-resolution data. And, metadata collected on site can validate lower-resolution, remotely-sensed data, or even provide new insights absent from coarse resolutions. For example, in the absence of very high-resolution geospatial data, in-situ measurements taken for geomorphic qualities such as slope angle and the

existence of sheltered sites can provide microtopographic detail that is sorely missed when only low-resolution data exists. E.g., for the mountains of interior B.C., only 25m DEMs exist; similarly, the closest-range satellite images have a 5m pixel resolution. In forefield contexts specifically, data of this resolution cannot be used alone to describe emergent patterns of land cover composition in forefield environments specifically.

This chapter will begin by discussing historic and remote data collection (via repeat historic and air/satellite imagery) and analysis, before turning to a description of the photographic transect's development as a method, and the parameters that were built in order to analyze those photographs.

Archival data collection

To understand the historical changes to the Avalanche glacier's extent, and the primary succession processes that have historically occurred across the forefield, archival imagery was needed. Repeat photography methods – such as those used in this project to establish a post-Little Ice Age baseline for the Avalanche glacier and surrounding landscape – employ historic survey photographs, maps, and survey logs. For almost twenty years, Mountain Legacy Project has had a formal Memorandum of Understanding for joint research and collections management with Bibliothèque et Archives Canada-Library and Archives Canada (BAC-LAC), where some 70,000 glass plate negatives from the late 19th- and early 20th-century Canadian federal topographic and geological surveys are stored. The British Columbia Archives is home to several tens of thousands of glass plate survey negatives from the British Columbia Land Survey. The focus of my work in Glacier-Mt. Revelstoke National Park focused primarily on federal surveys associated with the railway belt surveys. The primary dataset available in Glacier National Park

is from A. O. Wheeler’s 1901 and 1902 land surveys, conducted with the Dominion Land Surveyors Intelligence Corps. Taking panoramic photographs from across the Columbia Mountains, Wheeler subsequently drew maps and, in 1905, published his maps and trip notes in the book “The Selkirk Range.” As of 2021, eight from his 36 1901 stations had been repeated by MLP in 2011, and none of the 13 stations taken in the 1902 survey. While the 1901 survey documented the west, north, and south quadrants of the Columbia Mountains, the 1902 survey documented the eastern quadrant, with stations on either side of the Beaver River Valley. Of the 13 latter stations, six were taken from the Bald Hills, located east of the Beaver River (Figure 5). Three of these stations point west towards to eastern aspect of the Sir Donald subgroup: Grizzly Creek West, Bald Mountain North No. 1, and Bald Mountain West.



Figure 5: On the right, the locations of Wheeler’s 1902 Bald Mountain survey stations. The locations of these stations is determined by referencing Wheeler’s 1911 text, *The Selkirk Range*, which has notes and crude maps. The locations are subsequently confirmed in Google Earth Pro by aligning the panoramic survey photographs with the 3D-rendered landscape visualization in Google Earth. The 2021 Google Satellite map, sourced via the QGIS Google plug-in, is the background.

The vast majority of the plates from this survey have not yet been digitized. Typically, a researcher would identify a study area, research which surveyors traveled through the region in

question, and travel to BAC-LAC to look for relevant images. These images would be digitized at high resolution, catalogued by BAC-LAC, and uploaded to MLP servers for research and wider availability (explore.mountainlegacy.ca). This process was made practically impossible during the ongoing Covid-19 pandemic, when travel to the archives was discouraged. Therefore, only previously-identified and digitized photographs were available to choose from approximately 10,000 images in the MLP collection. A collection of particular interest, A.O. Wheeler's 1901-02 survey had been digitized as rapid appraisals, but not yet processed via a high-resolution scanner. When collections are rapidly appraised by MLP teams, hundreds of glass plates are re-photographed using digital cameras. This allows for a large number of images to be digitized quickly and at low costs, but the resulting images have relatively low resolutions. Due to a variety of factors (a quick project turnaround, permitting delays, COVID-19 staffing shortages, etc.), I was unable to get high-resolution digitizations until after the field season was completed; thus, all of the preliminary research, and repeat photography, proceeded from less-than-ideal historic scans. The resultant loss of detail makes pre-processing tasks like locating survey sites, and field work tasks like aligning the camera properly to take a repeat, more difficult. After archival images were selected to be repeated, I worked with MLP collaborators, including Rob Watt and Mary Sanseverino, as well as Wheeler's hand-drawn maps and Google Earth Pro to determine the survey location of each of the historic images. There were some high resolution digitizations completed by BAC-LAC circa 2011 to support repeat photography at six survey stations adjacent to Roger's Pass, but many of these had been repeated from incorrect station locations, which made finding the correct location during pre-processing difficult. After the 2021 field season, an order for high-resolution digitization was submitted to LAC. Archive staff have been working with MLP for decades and have developed standardized best-practices

for the digitization of MLP requests. When the historic maps were digitized, they were georeferenced in order to establish the boundaries of the forefield in 1902. (described later in this chapter).

In addition to oblique survey photographs, historic aerial imagery was also used in this research. Whereas the survey photographs were repeated in order to study land cover change over time, aerial photos were used to map the recession of the glacier's terminus at decadal time scales. To find the highest resolution images, a systematic review of the available data was undertaken. Aerial photographic data coverage over British Columbia is held in two primary catalogues: provincial and federal. Provincial data are housed on the website GeoBC, beginning as early as 1936. These data are organized by film rolls, drawn onto stenographic maps. A manual search of every map from 1950-2005 found five flyover paths that covered the study area (1950 being the first year that any flyover surveys were conducted in the Roger's Pass region. Beginning in the 21st century the resolution of satellite imagery available to the public surpassed the quality of flyover survey photos; 2005 was the last year that the areal resolution of pixels was finer-grained in air photos than in satellite imagery available for this region). Of these, two film rolls are held at the University of Victoria Air Photos Collections, and three were held at the University of British Columbia's Geographic Information Centre's Air Photo Collections. To find federal photographs, I conducted a systematic review of Natural Resources Canada's National Air Photo Library's website, Earth Observation Data Management System (EODMS). EODMS houses more than 6 million air photos, dating back as early as the 1920s. I searched every flight path from 1920-2020 over a manually-drawn polygon that covered the study area in the National Air Photo Library, up to an 80,000 square-meter resolution. Even lower resolution images exist, but were omitted from this search because the data would have been too coarse to be usable in this research. This search identified 10 potential flight paths, which I retrieved three film rolls from libraries at the University of British Columbia, two rolls from the University of

Calgary, and three rolls from the University of Alberta. At each library, the photos are stored as 10x10in silver gelatin prints. The prints from University of Calgary were scanned at 1200 dpi using a ColorTrac SmartLF SC42 by the library's staff. The prints from U of A were scanned at 1200 dpi using a Colortrac SmartLF SCi. The air photos held by UBC were ordered to the UVic library via interlibrary loan. The UBC and UVic-held photos were scanned using an Epson Expression 10000 XL scanner at 1200 dpi.

Satellite imagery was also requisitioned for this research. Satellite imagery can provide finer-scale data than air photos, and is available from more frequent time intervals – annually or even daily, rather than just once every several years. Satellite imagery was used to classify two FBS stages – ecological and geomorphic (more on this later). The primary source of satellite data was from Planet Labs (planet.com). Since 2009, Planet Labs has operated a fleet of nearly 200 satellites in order to collect daily, high-resolution imagery of the Earth. Their imagery has a 3.7m pixel resolution. Before image data becomes useable, it undergoes an in-house georectification process that removes pointing error and terrain variability distortions. Planet Labs also directly integrates with ArcGIS Pro software, allowing for the creation of base maps using satellite imagery that are automatically updated every time new satellite data becomes available.

Repeat Photography

I used methods developed by the Mountain Legacy Project for accurate repeating of historical images. Since 1996, the Mountain Legacy Project (MLP) has been conducting systematic repeat photography to collect data about landscape change (Sanseverino et al., 2016). Repeat photography, and the subsequent analysis of repeated image pairs, can be used to

document changes across large areas. For this project, historic photographs were used to determine the historic, baseline conditions for land cover composition at the end of the Little Ice Age. Repeated photographs were taken in order to document the land cover composition of the landscape today.

As explained in the Literature Review, the dataset used in this project was A. O. Wheeler's 1901 and 1902 land survey photographs. Of these, two priority stations were selected, each which had direct sightlines across the Beaver River Valley to the Avalanche glacier. The approximate location of these historic photo stations was found by using hand-drawn maps and expedition notes compiled by Wheeler's team in his 1905 book. Once approximate station locations were identified, these coordinates were input into Google Earth Pro (GE). Using the tilt and drag functions in GE, the satellite imagery was manipulated to represent the viewshed from the approximate station coordinates. The virtual GE viewshed was explored until notable features like foreground ridges and rocky promontories were aligned similarly to the waypoint alignment in the historic photographs. These techniques are used in preparation for departing for the field to refine the station location.

A field team consisting of myself, James Tricker, Claire Wright, and Suzanna Zak (henceforth referred to as "the field team") embarked on a trip to the Bald Hills on July 18, 2021. In the original survey, A. O. Wheeler took photographs from seven stations in the Bald Hills, a lower elevation range that is situated across the Beaver River Valley to the east of the Selkirks. Of these, three stations have several photographs, taken looking west, that capture the glaciers of the Sir Donald subgroup from different perspectives. We repeated two of the three stations between July 18 and 19, named (by Wheeler) Grizzly Creek West and Grizzly Creek West 2. Station location is determined on site using visual triangulation techniques: foreground features such as large boulders or remnant cairns left by the original surveying team are used as primary

clues. Using printed copies of the historic photographs, and zoomed-in digital versions stored on team member digital devices (smart phones), the tripod location and height is adjusted centimeter by centimeter until the foreground and background landscape features overlap consistently between the camera viewshed and the historic photograph (Figure 6). Photographs were taken using a Fuji GFX50S camera (32-64mm lens; set to 32 mm for photographs). The photos were recorded in RAW file format. Surveyors typically use one or two tripod locations; each photo corresponds to a different azimuth direction while the camera is rotated usually without significant adjustment the tripod. In some cases, minor adjustments are needed between photographs to accommodate for the different focal length of historic cameras. On site, additional data are collected: azimuth of each photo using a custom-fabricated system adapted to Novoflex rail and graduated tripod head, GPS coordinates taken by a Garmin inReach Explorer+, weather information with a Kestrel handheld instrument, and time of day. All of these data as well as field narratives were recorded manually on custom field sheets and later transcribed for the database supporting explore.mountainlegacy.ca.

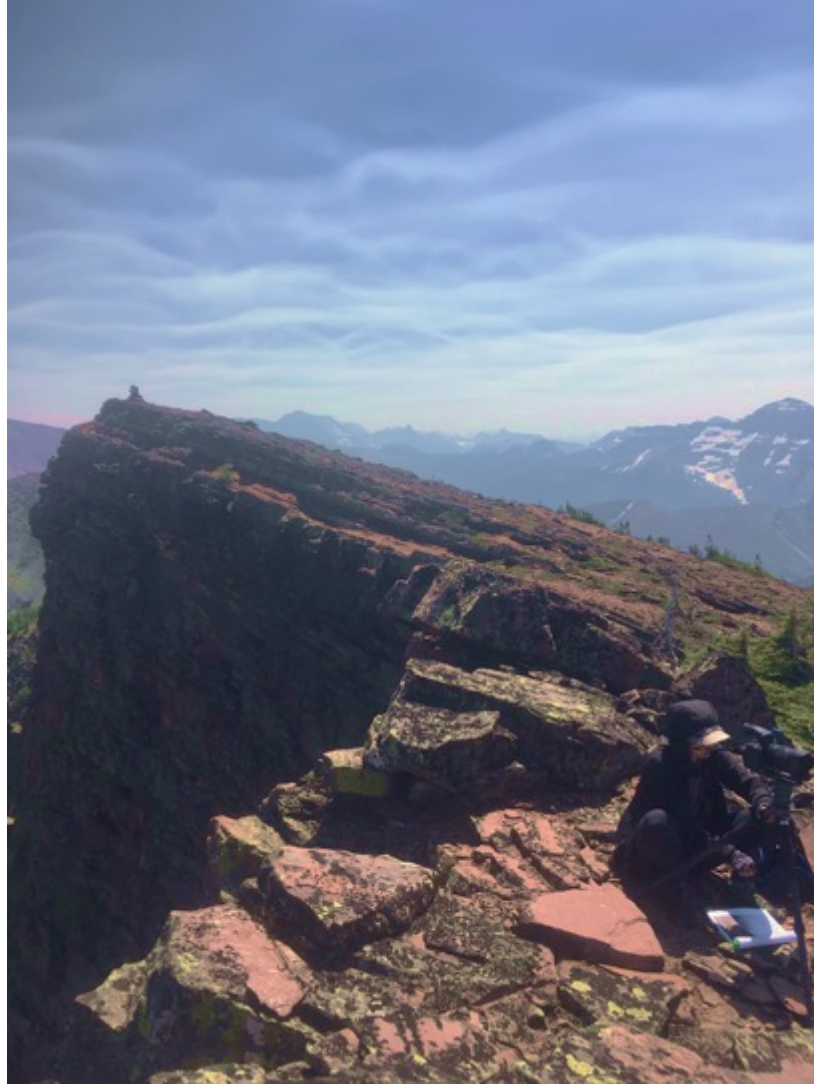


Figure 6: S. Zak aligning the camera using print outs of the historic photographs for reference. This photograph was taken at a station in a different research area that MLP worked in before traveling to the Bald Hills, but was selected because it highlights the frequently precipitous nature of the photograph stations that were visited.

Upon arriving at the first Grizzly Creek station significant new tree growth had occurred at the site of the historic photographs. A series of images was taken, but it was determined that not much useful information would be produced. Therefore, it was determined that “alternate” photographs would be taken (see: Figure 7). Each photograph was taken from a distinct alternate location. Locations were determined using the following considerations: proximity to original site; visibility of prominent features; comparable elevation; obstruction of foreground features.

This resulted in six unique locations within the Grizzly Creek Station. A side-by-side comparison of the historic, the “true” repeat, and the “alternate” repeats, can be seen in Appendix A. Repeat photographs were download and backed up. Upon completion of the fieldwork season, the photographs and associated field and metadata were uploaded to the MLP online database and made freely available to the public (explore.mountainlegacy.com).



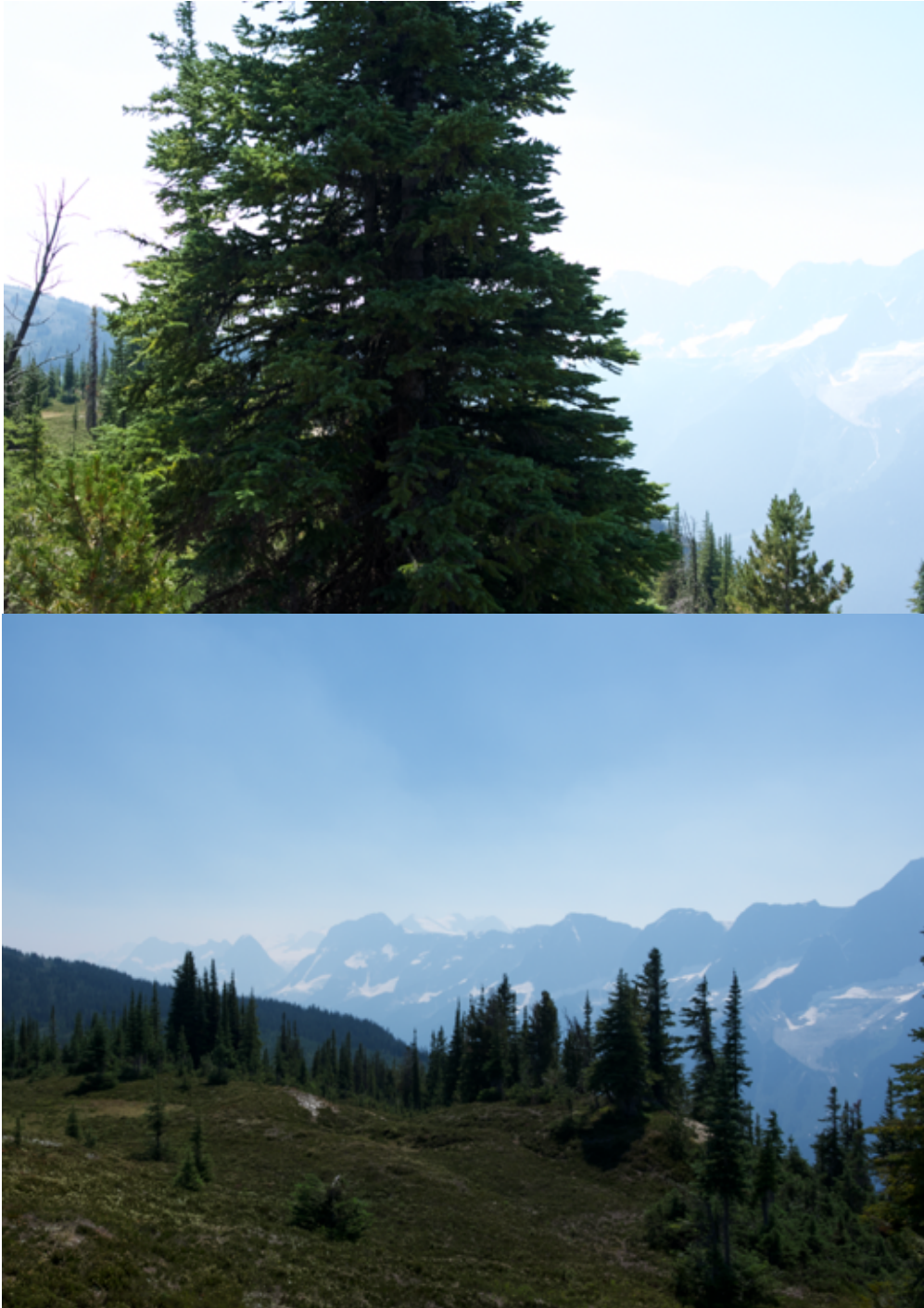


Figure 7: A 1901 historic photograph, followed by a repeated photograph taken from the approximate location of the original survey; tree growth blocks most of the background. Below, an alternate photograph taken from a nearby location where more of the background was visible.

During post-processing analysis of the repeat photography data, land cover masks were generated. Several MLP-designed tools were used, including the Python Landscape Classifier

(PyLC), a trainable, machine learning land cover classification tool for Python developed in 2020 by graduate student Spencer Rose (Rose, 2020). It uses deep convolutional neural networks that have been trained using manually classified high-resolution photographs from the MLP collection. For this project, oblique historic and repeat photographs were analyzed with the PyLC algorithm in Python 3.9. Images were analysed using a 1.0 scale, meaning that the resolution of the masks is generated at the same pixel resolution as the original, input photograph. The resulting masks are described in the Results, or can be found in Appendix B. To determine the consistency of these automated classifications with the patterns visible in the photographs, land cover masks were copied over the original images in photographs in Adobe Photoshop; the opacity of the mask layer was augmented until it was transparent enough to interpret the photograph and verify whether or not masks were correctly aligned.

The manually-corrected land cover classification masks generated in PyLC were not able to distinguish between all categories derived from the BC Land Cover Classification scheme and previous research that has used classification masks to describe land cover patterns (Figure 8). Rock/rubble and exposed land were classified in the same mask, as were herb and low shrub, and water and snow/ice. When the original eight land cover classes were input, several land cover classification types were absent (rock/rubble, herb, low shrub). Having a higher number of categories also appeared to result in a higher level of misclassification: e.g., the category masks were inconsistent with land cover types represented in the photographs. To try to reduce these errors, some categories were joined. The highest level of accuracy was found with the following categorizations:

- Exposed land (representing “exposed land” and “rock/rubble” from the BC Land Cover Classification Scheme)
- Low vegetation (representing “herb” and “low shrub”)

- Upland forest
- Water/snow/ice (representing “water” and “snow/ice”)

Limiting the number of categories was found to have a much lower level of error.

PyLC is not a perfect tool; in many images, uniform land cover was misread by the classifier and incorrectly classified as bare ground, likely because of the high levels of haze. Using Photoshop, masks were manually modified. To do so, the photograph was zoomed in to 100%. The outlines of polygons were drawn using a brush with a <10 pixel-radius. In any situation of doubt, the pixel classification masks were either defaulted to the AI, or deleted.

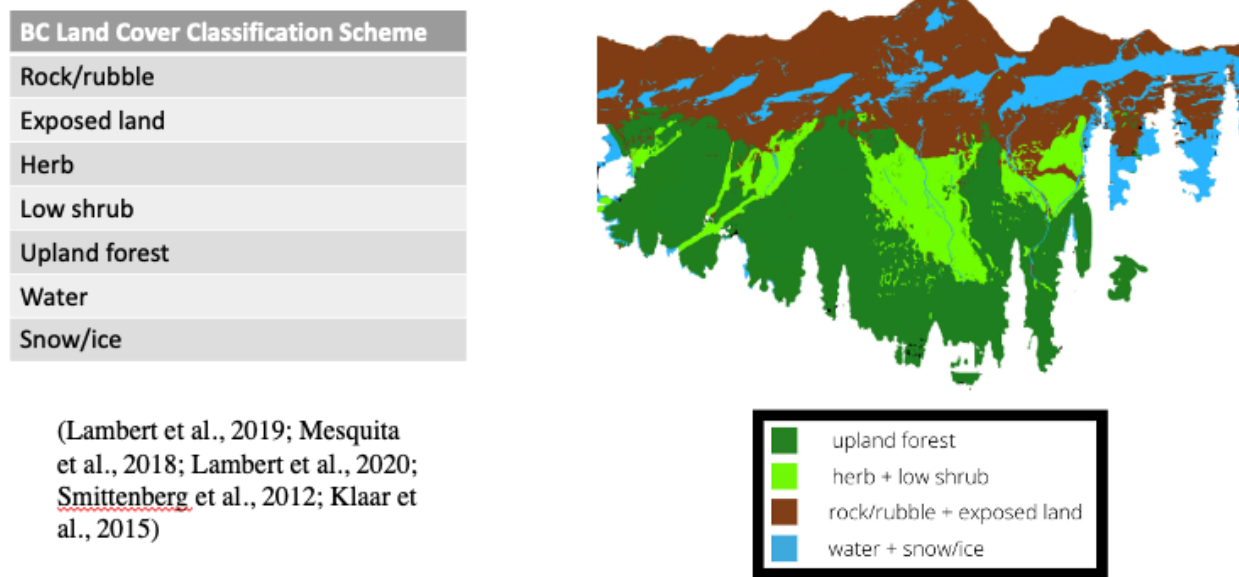


Figure 8: On the left, the eight land cover classifications that were determined via a literature review are represented in a table, alongside the corresponding citations. On the right, a manually-corrected land cover classification mask from a repeat photograph is shown; in the end, only four categories were represented using both PyLC and purely manual classification methods.

These masks indicate three primary land cover type in the forefield: upland forest, herb and shrub, and bare rock. This method could be useful for analyzing changes to shifting treelines in areas experiencing deglaciation, for example (see the section in the Literature Review about

Repeat Photography for more on this). However, the entirety of the forefield being classified under a single mask meant that this method was inadequate for providing any useful information with regards to this thesis. Therefore, historic photographs were not classified (by definition, the forefield was covered in ice in 1902; no need, then, to classify automatically) and this method was abandoned early into the data analysis process.

While land cover masks did not prove fruitful, the images were still georeferenced in order to map the historic and contemporary boundaries of the Avalanche glacier and its forefield. This process allows classification masks from an oblique photograph are given spatial extents. I used the MLP Image Analysis Toolkit (IAT), a web-based platform that was introduced in 2015 that combines digital elevation model (DEM) data, images, and classification masks to georeference oblique images and their classified land cover masks. MLP researchers have developed a workflow for using DEMs data to georectify oblique images – my work specifically relied on guidance from Mike Whitney and Maya Frederickson, who each have made tremendous progress in refining these methods. Every non-sky pixel has a known location in space, as accurate as the underlying digital elevation model. I relied on the Province of British Columbia 25m Digital Elevation Models (DEM) and Digital Terrain Models (DTM) publicly available for use. In QGIS, these DEM and DTM data were used to create hillshaded terrain models. The hillshade files were then imported to IAT, and combined with GPS coordinates (X, Y, and Z), azimuth and camera field-of-view to create a virtual photograph (VP). Discrepancies between the VP and the original image were address by adjusting virtual camera position as close as possible to the real photo (Figure 9).

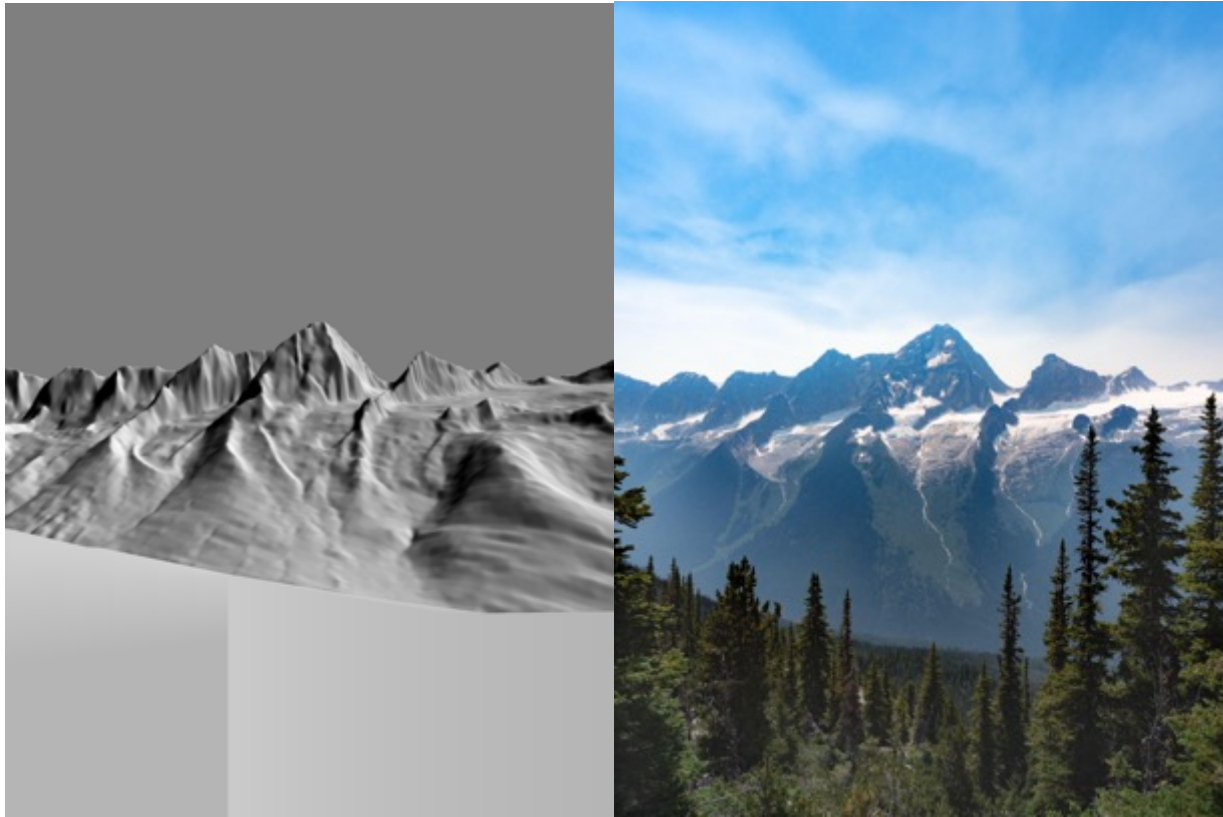


Figure 9: Virtual photo on the left, repeat photo on the right.

Next, a companion tool within the IAT suite is used to align digitally the VP and the real photo. Once four or more points have been chosen in common between the two files, the tool adjusts the image for alignment. Then, the file showing the classification masks is uploaded, and similarly adjusted until aligned with the virtual photo. When the alignment was completed, the aligned masks were uploaded to the georeferencing tool within the IAT. This generates a viewshed, in which the masks are mapped in a .tif file that has the same pixel resolution as the DEM file. Finally, the viewshed .tif is converted into a raster file in QGIS.

Georeferencing air photographs to determine glacial extent

From the archival material available, eight aerial photo survey sets were georeferenced. Georeferenced images allow the land cover analyses gleaned from image analysis to become

mapped. For this project, georeferenced images were used primarily to map the glacial extent over time. However, more recent images were also used to describe land cover classifications of the forefield. This section will focus on the former; a description of how land cover classifications were derived can be found in the subsection of the Methods, “Determining fluvial biogeomorphic stages.”

Georeferenced historic oblique, repeated oblique, air photo, and satellite photos from 1902-2021 were used to determine the extent of the Avalanche glacier and, thereby, to estimate the terrain age of the forefield. The table below shows the data source of each year that has been mapped.

Year	Data Source
1902	Historic photograph (A.O. Wheeler)
1952	Air photo
1966	Air photo
1970	Air photo
1978	Air photo
1995	Air photo
2005	Satellite
2011	Satellite
2021	Satellite

Table 1: The glacial extents at different years over the last century were derived from georeferenced oblique, air, and satellite images. The satellite images have a near-perfect accuracy, whereas the manual georeferencing techniques for air photos and oblique images have a greater margin of error.

Aerial photos were prepared in Adobe Photoshop. They were rotated until true north was estimated at the top of the image. Once pre-processing was complete, the photographs were georeferenced using QGIS Desktop 3.20.3, using the Georeferencer GDAL plugin. The QGIS Georeferencer tool allows the user to manually select ground control points (GCPs) by clicking

on a map in lieu of pre-existing GPCs whose GPS coordinates have been taken onsite. A minimum of six tie points is required. Photographs were georeferenced against already-georeferenced, 2m satellite images from Planet Labs. The QGIS Georeferencer shows residual values in the number of pixels. If the georeferenced image resulted in GCP residual values higher than 2 pixels, the process was started over with new GCPs. A manual alignment check was also performed by changing the transparency of the air photo raster in QGIS. If GCPs tied to lakes, ridgelines, and peaks in the cirque surrounding the Avalanche glacier were aligned, the georeferenced image was determined to be usable even if the air photo coverage elsewhere in the image (i.e., north of Rogers Pass, across the Beaver River Valley, etc.) was geometrically distorted; those areas are outside of the study area. Georeferenced air photos and Planet Labs' georeferenced satellite imagery used in this project can be found in Appendix C. Once the photographs had all been georeferenced, these rasters were used to make shapefiles representing the terminus of the Avalanche at different stages of melt over the last 70 years, since air photo surveys began. The 1902 extent was determined by classifying the historic photograph in PyLC, and then georectifying the image classifications using the process described above; the eastern boundary of the "snow/ice" mask was determined to represent the 1902 glacier terminus.

Photographic Transect Data Collection

I deployed a photographic transect methods to document and characterize the glacier forefield. Transect photographs were used to capture fine scale topographic and ecological information that was absent from remotely-sensed data; it was later classified in order to plot the Pioneer and Biogeomorphic stages from the FBS framework. The photo transect method is based on common transect field methods, but adapted in a distinctive, possibly original, way for this

research. This method was created after several preliminary trials at the University of Victoria campus and, subsequently, at the Research House in Waterton Lakes National Park. The team that troubleshooted the method included PhD candidate Alina Fischer, Dr. Eric Higgs, as well as all members of the field team. Early trials found that a tripod with a horizontal tilt tripod head would be necessary.

In preparation for the transect, I had to map the historic terminus of the glacier, which represents the lowest boundary of the forefield. Because high-resolution historic images were not available before I departed for field work, I developed an adapted method for georeferencing the historic image. To do so, I used the “tilt” function in Google Earth Pro until the virtual landscape was aligned with the historic image. I then traced the terminus of the glacier using the “route” function. A horizontal line was drawn across the width of the terminus; the midway point of that line, where it intersected with the glacier terminus, would become the starting point for the transect. A line drawn between this point and the contemporary toe would function as the transect line (see: Figure 10).

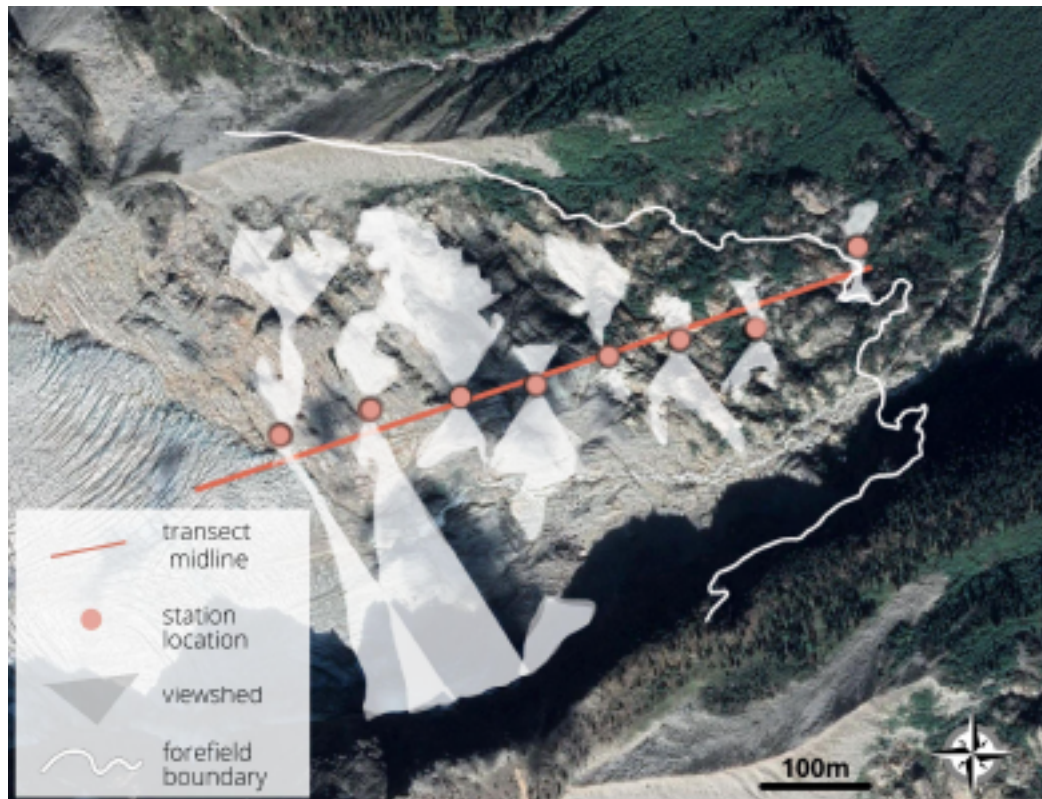


Figure 10: Line transect, over satellite imagery sourced from the Google Earth plugin in QGIS. The orange line is the transect; pink circles represent the eight transect stations, and the viewsheds approximated in post-processing. The white line on the right side of the image represents the 1902 forefield boundary, as calculated by georeferencing a 1902 historic photograph.

After one day of reconnaissance onsite at the glacier's forefield, it became evident that using conventional methods for establishing transect points (e.g., distance, random waypoints, etc.) would be infeasible: a significant portion of the terrain was unnavigable due to cliffs, overhead hazards like glacial erratics and seracs. Therefore, to adapt the protocol to be field-ready, two protocols were implemented: first, distance between transect points was determined along an altitudinal gradient (i.e., would use 50m of change to *altitude*, rather than horizontal distance over terrain); and, second, rather than strictly adhering to the transect line, the data would be collected as close as possible to the transect line. It was determined that any stations that could not safely be situated within 5m of the line would be dismissed; however, there were no obstructions encountered in the field that prevented a station location from being within this

distance. These protocols made collecting data in vertical and off-vertical cliff terrain possible while prioritizing the safety of the team. The first station was recorded on the transect line at an elevation of 1650m. Starting at a 50m contour line was determined to be the most field-ready starting point. From there, we used the altimeters on an iPhone 10R and a Garmin Etrex 22 GPS device; the average between the two, which consistently differed by 6m, was used to find the next station's 50m elevation. Photographs were taken in RAW using a Fujifilm X-Pro2 with a Fujinon Aspherical Super EBC XF 35mm lens.

At each 50m location we determined the photograph location by traveling as closely as possible to the transect line and the correct 50m elevation interval. Upon arriving at the closest, accessible location a 1m x 1m marker was set on the ground. A tripod was set up, facing the direction of the transect line. At each station, the tripod legs were set to the first leg width extension, and each leg was fully extended in order to maintain a consistent camera height (roughly 1.3m) above the ground. With the legs all fully extended, the tripod was consistently perpendicular to the slope angle of the ground. The tilting extension bar of the tripod head was locked at a 90-degree angle so that the camera was parallel to the ground (Figure 11). The inclination of the bar was taken as an average slope angle at the station location; the bar was also used to take the bearing. Bearing and slope angle were recorded using the native compass and inclinometer apps on the iPhone 10R. At each station, coordinates recorded using an inReach Explorer+. One photo was taken of the ground (Figure 12), showing the 1-by-1 meter square outlined by the ruler. Then, the camera was rotated 90 degrees to the left, and then 180 degrees, and leveled using the camera's internal level. These landscape photographs taken from the transect location recorded ground cover. The process was repeated until the team was <50m in elevation from glacial ice. All 24 transect photos from the eight locations can be found in Appendix E.



Figure 11: The field team setting up the tripod at Station 6. Only two people were needed to take the transect photo and collect GPS data. To maximize efficiency and minimize our time in this exposed terrain, the other two field members would look for the safest path uphill to the next station while the others were collecting data. It still took more than a half hour to complete each station and travel to the next.



Figure 12: An example of one of the orthogonal photos taken during the transect of the Avalanche glacier forefield, taken at Station 7. The orange ruler is 1m x 1m.

The viewsheds from the transect images were mapped using Google Earth's viewshed tool so that subsequent analysis of the land cover composition patterns identified in each photo could be plotted. For each oblique transect image, the satellite image is tilted until it corresponds to the azimuth recorded in the station metadata. A line is drawn straight up from the station (where a line straight up represents the angle of the azimuth relative to North). Then, the angle of the field of view (FOV) from the camera used in the field is entered. The image is tilted to $\frac{1}{2}$ of the FOV; another line is drawn straight up. Then the image is tilted to the number of degrees of the FOV in the other direction, and a line is drawn straight up. The latter two of the lines drawn represent the FOV from the station. A pin is positioned digitally in Google Earth, and the "Show viewshed" option is selected. This generates a polygon of all possible viewable land from the station from 2m above the ground. Everything within the FOV triangle is within the FOV of the

image. Then, I accounted for obstruction by objects in the foreground. To do so, I compared the 3D rendering in Google Earth of the landscape to the actual landscape represented in the images. Because Google Earth's renderings rely on DEM, they miss features like boulders, trees, and small cliffs that would have obstructed the real viewsheds captured in the transect photographs. When large features on the edge of the visible landscape were present in the Google Earth landscape, those features were marked as waypoints. The waypoints were then used to refine boundaries of the automatically-generated viewsheds in order to have a more accurate representation of the photographic viewshed. This process was repeated for each of the 16 oblique transect photos, until all VSs were mapped (Figure 9). They were then exported as KMLs and input to QGIS as polygons.

Two software applications (QGIS and CalTopo) were used to extract topographic data from the resulting viewshed polygons, to allow me to capture how features like slope angle, aspect, and elevation might affect the successional processes visible in each transect photograph's viewshed. The data from these applications supplemented metadata for terrain attributes were collected at each of the transect station locations. A suite of analysis tools exist within QGIS to characterize topography: terrain roughness indices, slope analysis, etc. However, because the data source for these tools was a 25m DEM, none were able to provide meaningful analyses of microtopography in particular. I turned to CalTopo, which has powerful visualization tools. Using 10m data derived from Sentinel weekly satellites, it automatically calculates slope angle, aspect, and elevation. The viewshed polygons created in Google Earth were uploaded to CalTopo, and the combined N and S facing oblique images' corresponding VSs were used to generate a topographic profile for each station (available as maps and figures in my Results).

Determining fluvial biogeomorphic successional stage

One of the two questions this project seeks to answer is how the Avalanche glacier's forefield can be characterized using Corenbilt's fluvial biogeomorphic succession (FBS) framework. Some of these classifications were derived from transect photographs; others were found by analyzing satellite imagery.

Before classifying the transect data, I first had to select 'indicator species' that would signal an FBS stage. The following ecological land cover types were identified in the collected literature (see: Literature Review: Fluvial geomorphology) as having import over successional processes:

- Mature conifers
 - Isolated indicates terrain age
 - Continuous indicates ecological succession stage
- Established woody vegetation
 - Isolated through continuous indicates biogeomorphic succession stage
- Grass
 - Isolated indicates biogeomorphic succession stage
 - Continuous indicates ecological succession stage
- Vascular plants
 - Isolated indicates pioneer succession stage
 - Continuous indicates biogeomorphic phase
- Small shrubs
 - Isolated through continuous indicates biogeomorphic succession stage
- Saplings
 - Isolated through continuous indicates biogeomorphic succession stage
- Pioneers (lichens and mosses)
 - Isolated through continuous indicates pioneer succession stage

The biogeomorphic succession scheme also identifies the following significant geomorphic attributes:

- Slab (sheer)

- Growth is severely limited, indicating the geomorphic succession stage
- Slab (textured)
 - Textured slab with cracks, sheltered sites, gullies, etc., offer good protection from wind and good water pooling, allowing for seedlings to root and grow. Textured slabs indicate the pioneer successional stage
- Till
 - Till totally absent of visible fauna represents the geomorphic successional stage
 - Till with isolated visible plant growth represents the pioneer successional stage

In order to interpret patterns across space, a classification schema was developed to categorize the density of these features. Of the ten features listed above, eight categories were derived. Because grass was almost entirely nonexistent in the transect data, and because it shares a signal with vascular plants, the two were joined into one classification. And, “small shrub” was omitted, as size is a function of above ground and below ground mass, and krummholz shrubs may have significant but invisible biogeomorphic control over a landscape. Or, alternately, small shrubs may signal that an area has just begun to emerge from the pioneer stage. Within the FBS framework, whether or not a species indicates a stage – especially when considering the biogeomorphological window – depends on whether or not the critical mass of a community has arrived at a threshold.

Using these species types, transect photographs were classified using manual classification techniques developed specifically for this project. Eight land cover features (five ecological and three geomorphic) were considered. Each of the four FBS stages had two relevant features. Looking at each of the transect photographs, the presence and density were assigned a numeric value.

<u>Assigned integer</u>	<u>Description</u>
0	Absent
1	Isolated (i.e., a single plant or a very small area of a geomorphic feature)
2	Discontinuous (i.e., a few plant individuals were present; or a limited spatial area (<1/2 total) was geomorphic)
3	Continuous (the feature represented the dominant land cover type)

Table 2. Integer values were assigned to each of the 8 features that signal an FBS stage; each transect photo had an integer value assigned to each feature.

These classified images are in Appendix E. Once all of the photos were classified, the quadrats (downward-facing photographs) and the oblique photograph's viewsheds for each station were assigned an FBS stage. To do so, the values given to the eight features under consideration were summed within each image based on the FBS stages (two features per stage). Finally, each photograph was classified according to the FBS stage with the highest additive score (Figure 13).



Figure 13: The quadrat photo from Station 1, with the classification table below. The biogeomorphic stage had the highest value; so, this image would have been classified as that stage, even though some indications from other stages (i.e., talus, symbolizing the Geomorphic stage) were also present.

Ecological	Mature Conifers	0
	Established woody vegetation	0
Biogeomorphic	Vascular plants/grass	2
	Conifer saplings	2
Pioneer	Moss	0
	Lichen	1
Geomorphic	Talus/till	1
	Bedrock	0

Table 3: Classification table for the photograph in Figure 13.

For example, the Station 1 quadrat had no mature conifers or established woody vegetation, the two features associated with the ecological stage, so it had a score of 0 for that phase. Meanwhile, vascular plants/grass and conifer saplings were both given ratings of 2 (discontinuous), meaning that the score for the Biogeomorphic stage's score in that quadrat was

4. The summed scores for the pioneer and geomorphological stages were both 1. Taken altogether, the quadrat was classified as belonging to the Biogeomorphic stage since this stage received the highest score. The scores for each transect photo can be found in Appendix D, alongside a table representing the summed scores that show which FBS stage each photo was assigned. The original transect photos are in Appendix D.

In addition to using transect viewsheds, it was also determined that air photos and satellite imagery could be used to classify the terrain. Some features of significance within the FBS framework take up significant enough space above ground to be visible from the satellite images made available in the Google Maps base maps plug-in in QGIS. For example, the 2021 satellite imagery available from the GoogleEarth plugin in QGIS has fine enough resolutions to be able to distinguish ecological (i.e., dense, dark green patches from continuous forest cover) from geomorphic land cover. Additionally, the following geomorphic categorizations were visible in the orthogonal imagery (Figure 14):

- Exposed bedrock (slabs and cliffs)
- Till (talus, exposed ground, and unsorted mixtures)
- Water

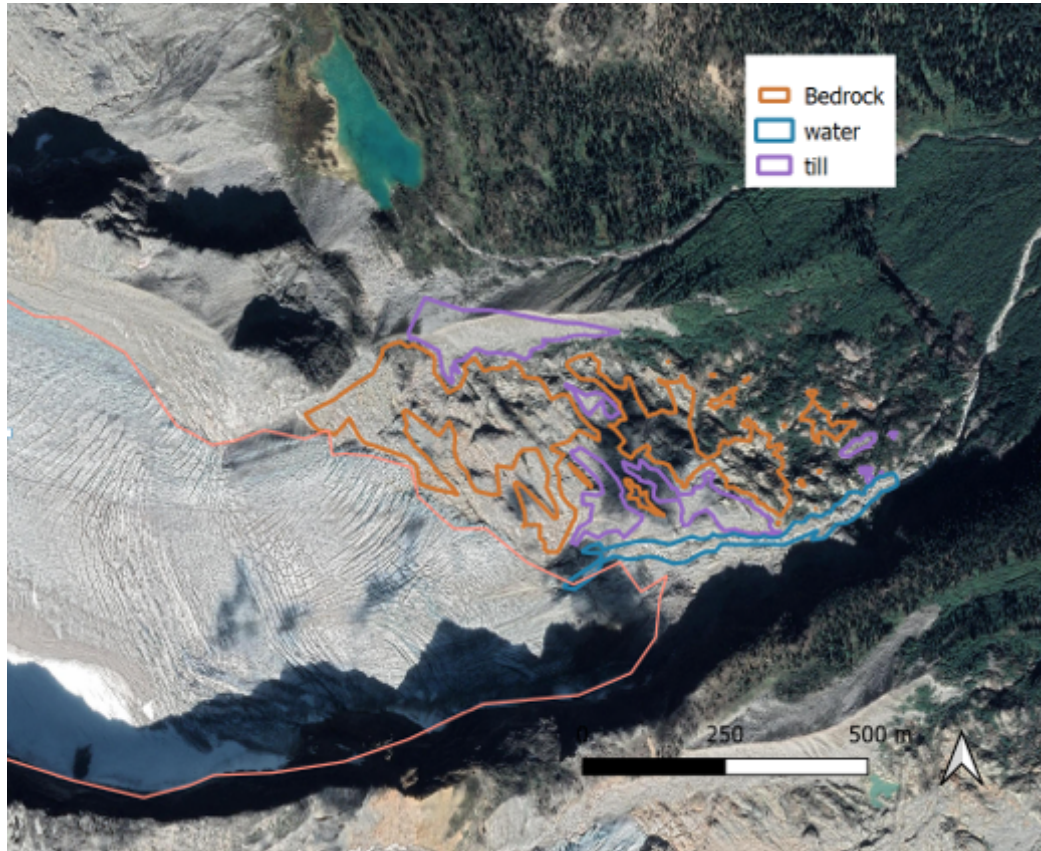


Figure 14: The polygons represent different manually-classified plots: areas outlined in orange correspond to exposed slab, purple represents till, and blue represents water. The base imagery is a georectified satellite image provided by the Google Earth plugin in QGIS.

Where it was clear in the fully zoomed-in most recent satellite imagery that one of those features was the dominant land cover in an area, a polygon was drawn in QGIS outlining that area. Wherever there was uncertainty, no polygon was drawn. Using this manual classification technique with satellite data allowed me to plot polygons in the forefield that were beyond the boundaries of the transect photographs' viewsheds. Figures that show the fully classified forefield can be found in Results.

After vectors for each stage were created, I subsequently combined slope angle data with successional stage maps. To do so, I overlaid the vectors representing each successional stage over a shaded slope angle map that was produced in QGIS using 25m DEM. Then I extracted slope angle data so that within each successional stage, I could tally the total number of 25m

quadrants at each slope angle range, between 1-10, 11-20, and so forth, and calculate whether certain slope angle ranges were more likely to have a certain successional stage, and vice versa.

Results

The methods described in the previous chapter sought to determine a functional workflow for combining in situ, remote, and archival data in order to describe changes across space and time, such as those briefly mentioned above (and which will be further elaborated in the Discussion). In this chapter, the results of the experimental protocol described in my Methods are presented. First, I introduce a series of maps documenting the terrain age across the Avalanche glacier forefield, using historical glacial extents as indicators of terrain age. Next, I describe topographic classifications of the forefield. Then, I describe the results of combining terrain age, topography, and land cover classifications (derived from transect photographs as well as satellite imagery) in order to map the fluvial biogeomorphic successional stages across the forefield.

Terrain Age

Terrain age can be extrapolated from the mapped historic extents. These mapped extents (Figure 15) can also be used to study the distance that the Avalanche glacier has receded over time. The Avalanche glacier retreated 0.469km^2 between 1902 and 2021, or an average of 3900m^2 each year. Between 1952 and 1995, when the Avalanche glacier had mostly stabilized, its areal extent gained 0.028km^2 , or 651m^2 annually. Since 1995, the rate of recession has been slightly lower than it was before 1952, retreating only 6230m^2 per year; in the last decade, that rate has further slowed to only 2700m^2 per year.

Station 1	120 years
Station 2	110 years
Station 3	100 years
Station 4	90 years
Station 5	50 years
Station 6	25 years
Station 7	16 years
Station 8	10 years

Table 4: The approximate terrain age at each transect station.

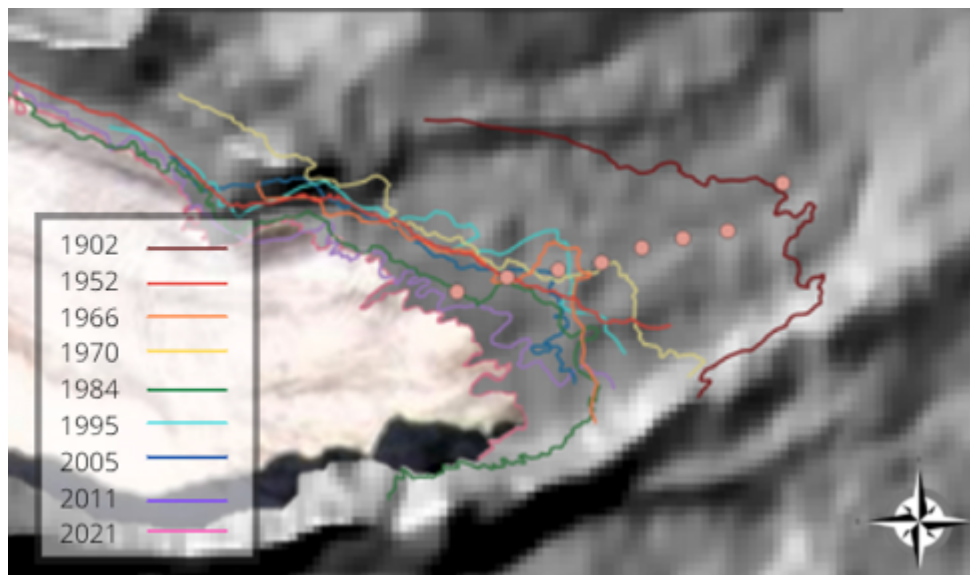
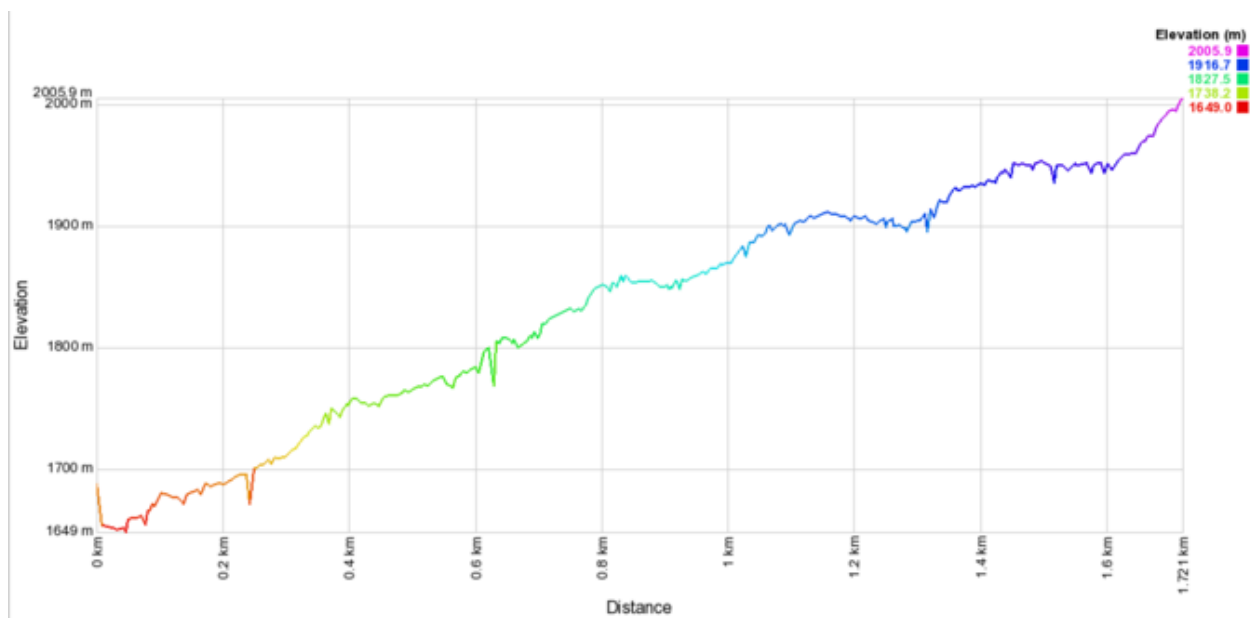


Figure 15: Historic extents (colored lines) paired with the transect stations shows the terrain age of the Avalanche glacier forefield. The map indicates steady recession from 1902-1952, and 1995-present, with little/no recession between 1952-1995. A hillshade made using 25m DEM is the base map, with the image of the glacier on the left taken from a 2021 Google Earth satellite.

Topography

As discussed in the Literature Review, recent research suggests that terrain age may not be the primary control on ecological succession in forefield environments -- topography also exerts a control. The Avalanche forefield has diverse topographic features; in the field, I observed that slopes shifted between nearly-flat to nearly-vertical rapidly as we traveled upslope, often at less than one meter squared spatial scales (Figure 16)





Figures 16-17: To crudely represent slope angle across the forefield, this map shows the elevation profile of the “track” that was recorded in the application GaiaGPS while conducting the transect – the track is shown in the image below. By syncing with my Garmin Instinct Solar GPS watch, this track was able to document more subtle changes to the elevation than, say, a line plotted on a map (which would refer to 25m, 30m, or 60m DEM). This is because the watch technology is designed using an altimeter to measure elevation, rather than referring back to GPS information. Because our track was nowhere near straight – we were traversing cliffs, navigating overhead hazards – the graph is not a perfectly accurate description of the microtopography of the forefield’s transect line. However, it does feel the most representative of the vast variations that were encountered in the terrain. Figure 16 shows the track over satellite imagery from Google Earth.

Figure 17 shows the changing elevation across the path the field team took, and is useful for thinking about the topographic diversity across the mid-section of the forefield. More information is needed to portray microtopography in each of the transect viewsheds. To reflect this, I used the CalTopo website. The viewshed polygons created in Google Earth were uploaded to CalTopo, and used to generate a topographic profile for each transect station. The base map in

each image represents shaded slope angles. Automatically generated charts and graphs represent the range of slope angle, elevation, and aspect across the entire viewshed polygon at each station (Figures 18-25).

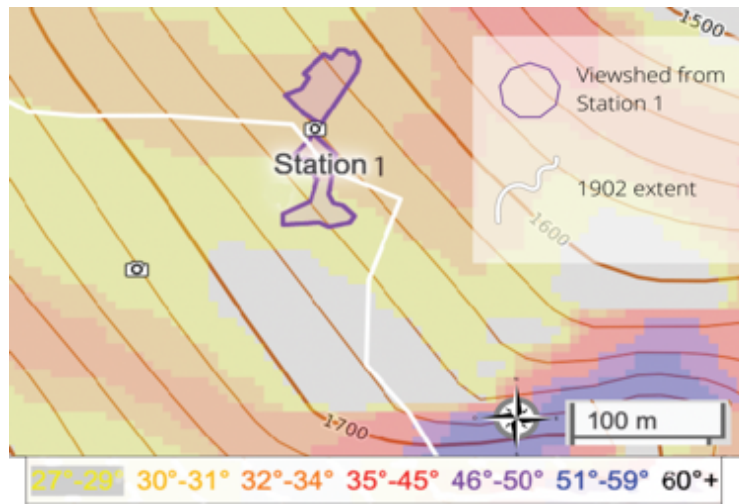


Figure 18: Topographic features for Station 1 showing 1902 extent of the glacier, and terrain stats for the viewshed area, as calculated by CalTopo. The viewshed spans 63 vertical meters; the average slope angle is 30 degrees; and 100% of the area contained within the polygon faces due NE. The base map for the map, made in CalTopo, has topographic contour lines as well as colors that represent average slope angle across the area, calculated using 10m DEM taken from satellite data. The average elevation of the visible terrain is 5400 feet, or 1645m. In the field, the elevation recorded at the station was 1643.5m. Slope angle recorded at the site of the tripod was 14 degrees. This discrepancy can be explained by local microtopographic variations to slope angle in areas smaller than 10m being too fine-scale to be captured by the 10m satellite data.

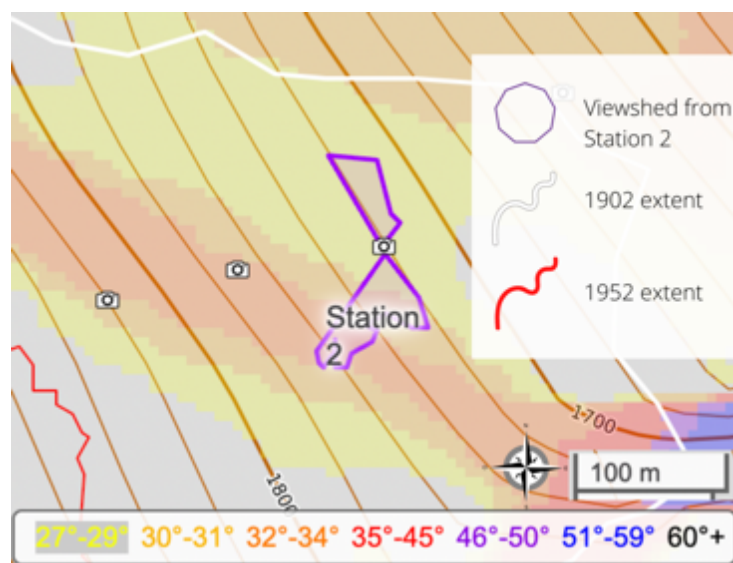


Figure 19: Topographic features for Station 2 showing 1902 and 1952 extents of the glacier and inclination of the surrounding terrain, as calculated by CalTopo.

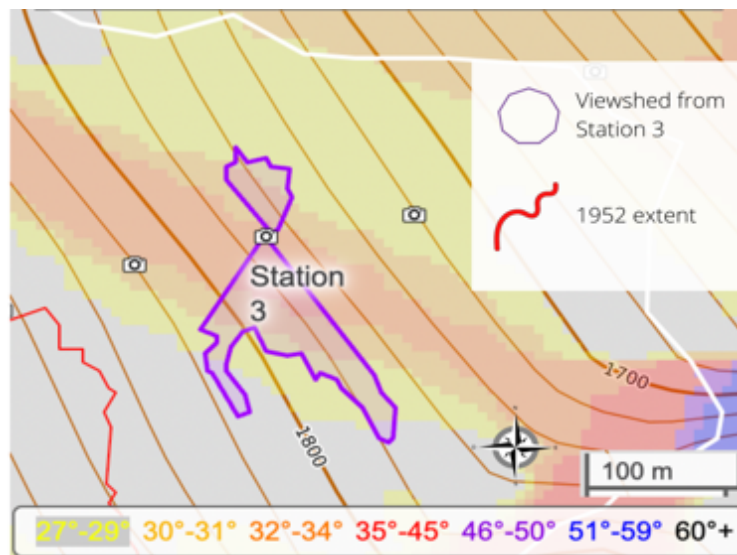


Figure 20: Topographic features for Station 3 showing 1902 and 1952 extents of the glacier and inclination of the surrounding terrain, as calculated by CalTopo.

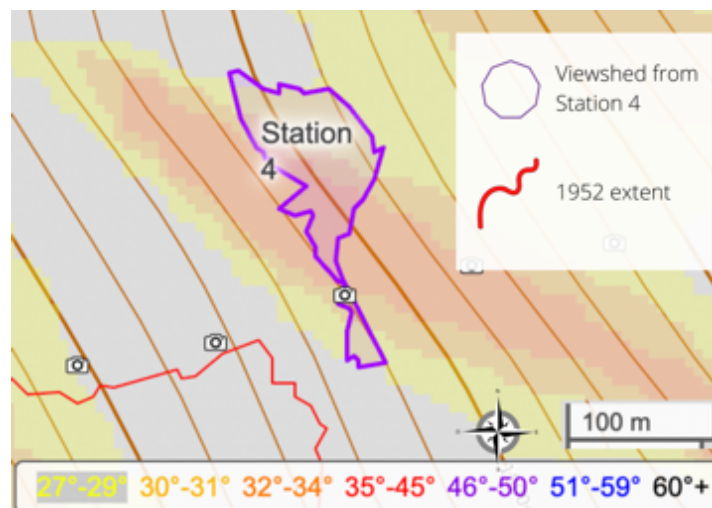


Figure 21: Topographic features for Station 4 showing the 1952 extent of the glacier, and inclination of the surrounding terrain, as calculated by CalTopo.

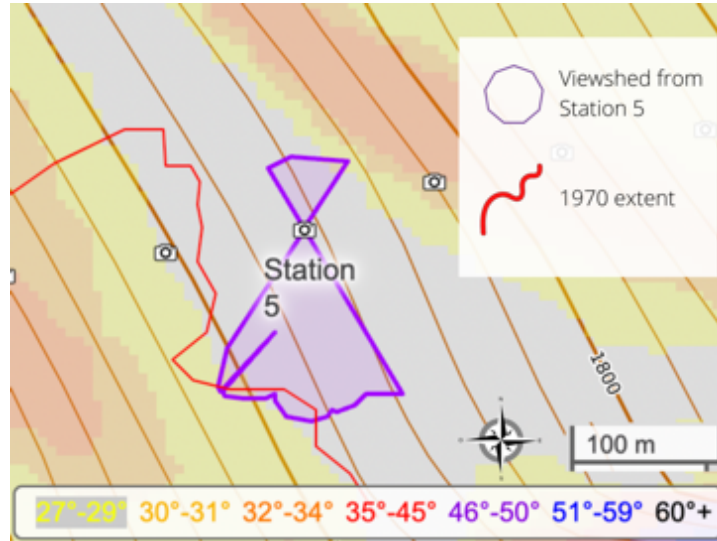


Figure 22: Topographic features for Station 5 showing the 1970 extent of the glacier and inclination of the surrounding terrain, as calculated by CalTopo.

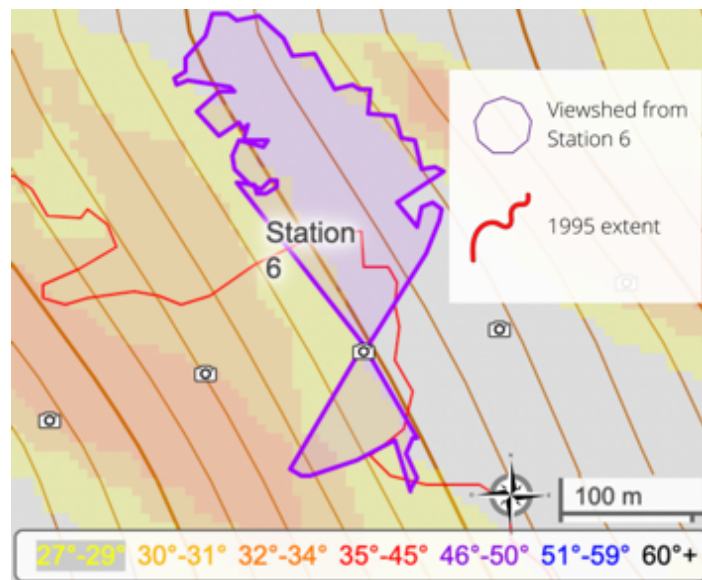


Figure 23: Topographic features for Station 6 showing the 1995 extent of the glacier, and inclination of the surrounding terrain as calculated by CalTopo.

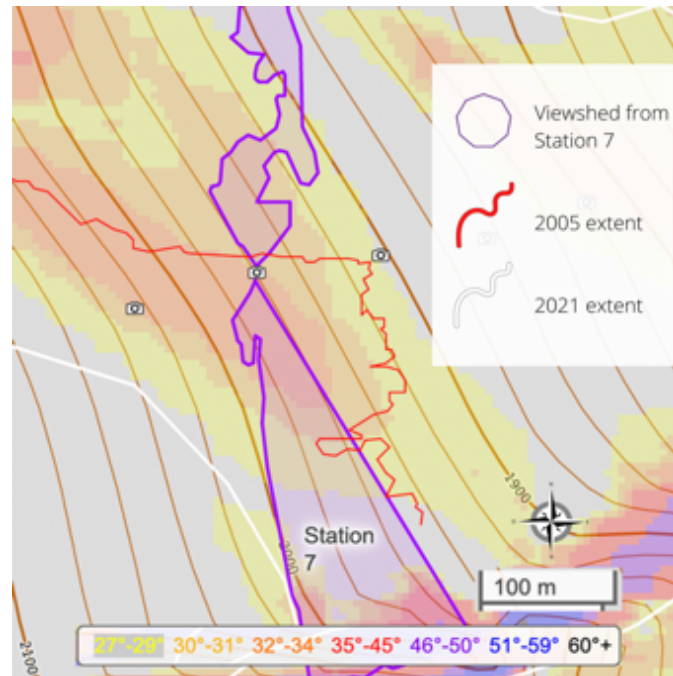


Figure 24: Topographic features for Station 7 showing 2005 and 2021 extents of the glacier and inclination of the surrounding terrain, as calculated by CalTopo.

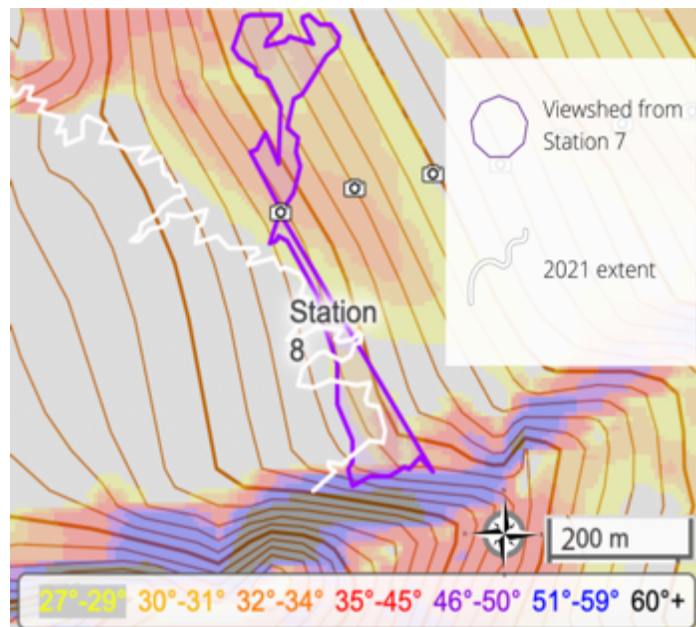


Figure 25: Topographic features for Station 8 showing the 2021 extent of the glacier, and inclination of the surrounding terrain as calculated by CalTopo.

These visualizations show that, while there were significant deviations in the area represented in the viewsheds across the eight transect stations, there were not major topographic

variations when coarse-grained elevation data was employed. There were not dramatic deviations to average aspect (all predominantly NE), or slope angle. The average elevation did rise at fairly even steps -- 50m in all cases, except between Stations 6 and 7, likely due to a lack of microtopographic variation at that elevation and a subsequent lack of obstruction to the line of site (Figure 26). Again, these data were at a coarser scale than the scale at which variations were found to exist in the field. And so, while the forefield can be categorized generally as having consistent slope angles and aspect across elevational zones, not enough data exists to infer how these topographic features might influence succession.

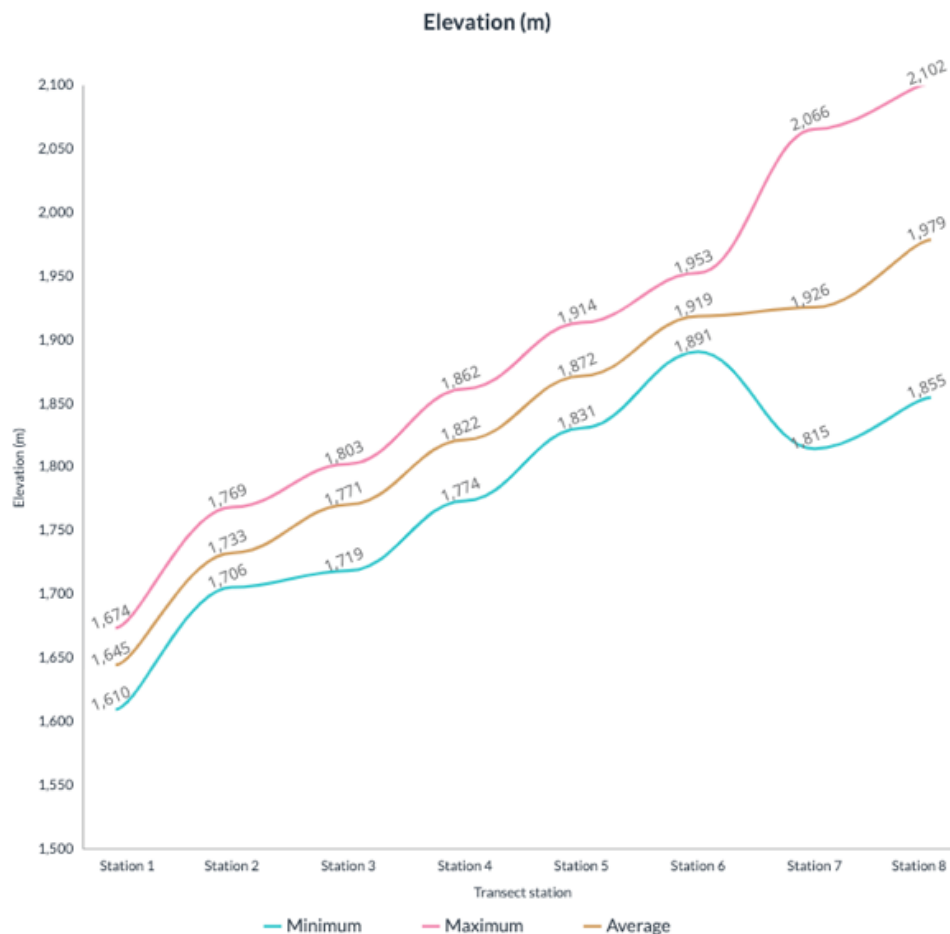


Figure 26: The minimum, maximum, and average elevation (in meters) of the area captured in the viewshed of each transect photograph, using data from CalTopo. The final 3 stations have a wider range because, as elevation increased, there were fewer variations in microtopography and flora. The low-lying and mostly uniform talus fields had few obstructions, which resulted in a larger photographic viewshed.

Biogeomorphic succession stages

Terrain features and the classifications generated using satellite and transect imagery can be combined to understand the spatial distribution of different biogeomorphic successional stages. As explained in the Methods, the maps showing distribution of successional stages that were produced used different data sources for different successional stages.

These maps were also produced without the inclusion of any of the masks generated using the repeat photography. As explained in the Methods, the tools that generate land cover masks of oblique photography only produced a few land cover classifications, including bare rock, shrub, forest, and ice/water. In the context of the fluvial biogeomorphological schema, all of this means that only geomorphic (bare rock) and ecological (forest and shrub) signals were classified; the rest was absent from the automated classifications. Even then, the nuances within these stages -- the existence of mature grasslands, the establishment of shade crops -- disappear. More importantly, any attempt to understand forefields as biogeomorphological spaces -- in which terrain roughness or microtopography are coeval with plant community establishment -- is impossible with the scale of the imagery I worked with. Manual editing could not rectify this problem (Figure 27); regardless of method, the entire forefield was classified under a single mask.

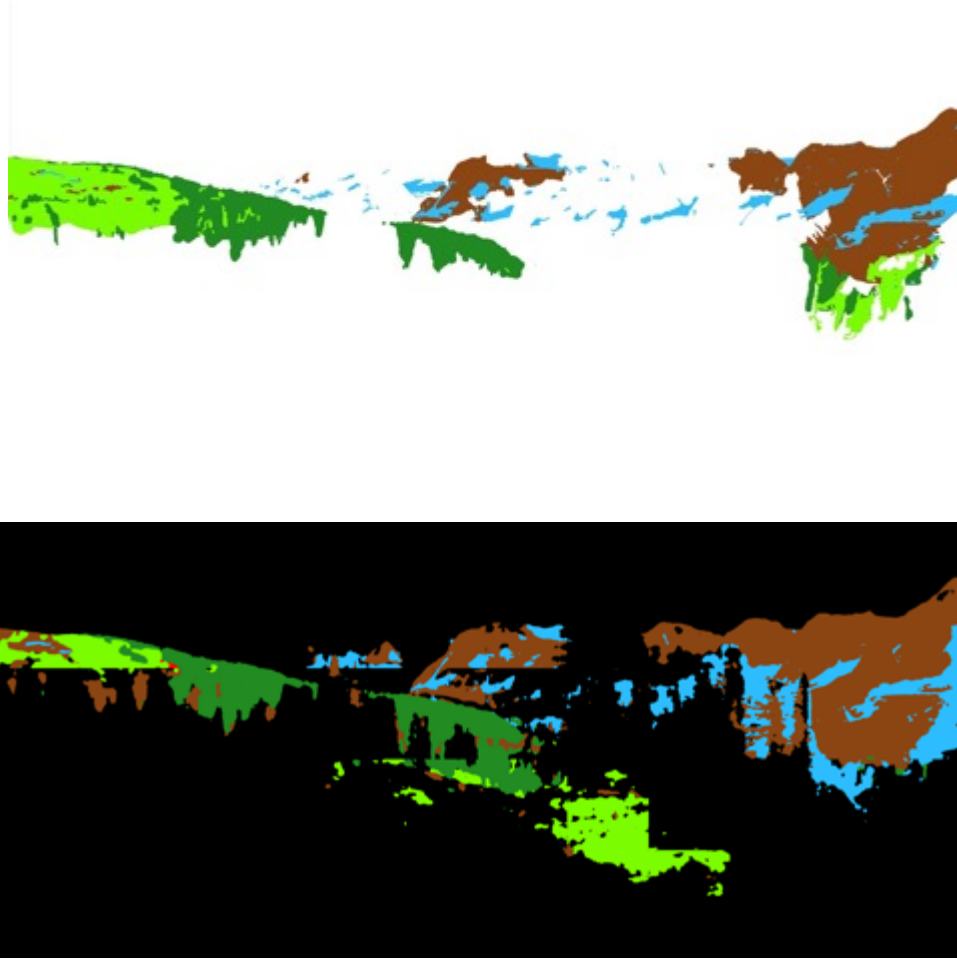


Figure 27: A manually-corrected mask is on the top, with the automated masks from PyLC below.

These observations were codified by a side-by-side analysis of a photograph taken during the 2021 repeat photography effort, alongside a transect photo documenting the same area of the forefield (Figure 28).



Figure 28. On the left, the repeat photograph is zoomed in to 100% to the approximate location of transect station #8. On the right, a photograph taken on the ground while the field team visited the forefield. The photo on the left was classified in PyLC as “rock.” The image on the right, however, shows porous dirt, talus, sheer rock cliffs, established woody plants, vascular plants, and conifers.

As such, the resulting maps showing FBS stages in the forefield relied exclusively on other data sources and analysis techniques: transect photos were used for all four stages but were especially useful in identifying pioneer and biogeomorphological stages; satellite imagery was used to determine which forefield areas outside of the boundaries of the transect photographs’ viewshed boundaries were in the ecological or geomorphological stages. The following map was produced using these classifications (Figure 29).

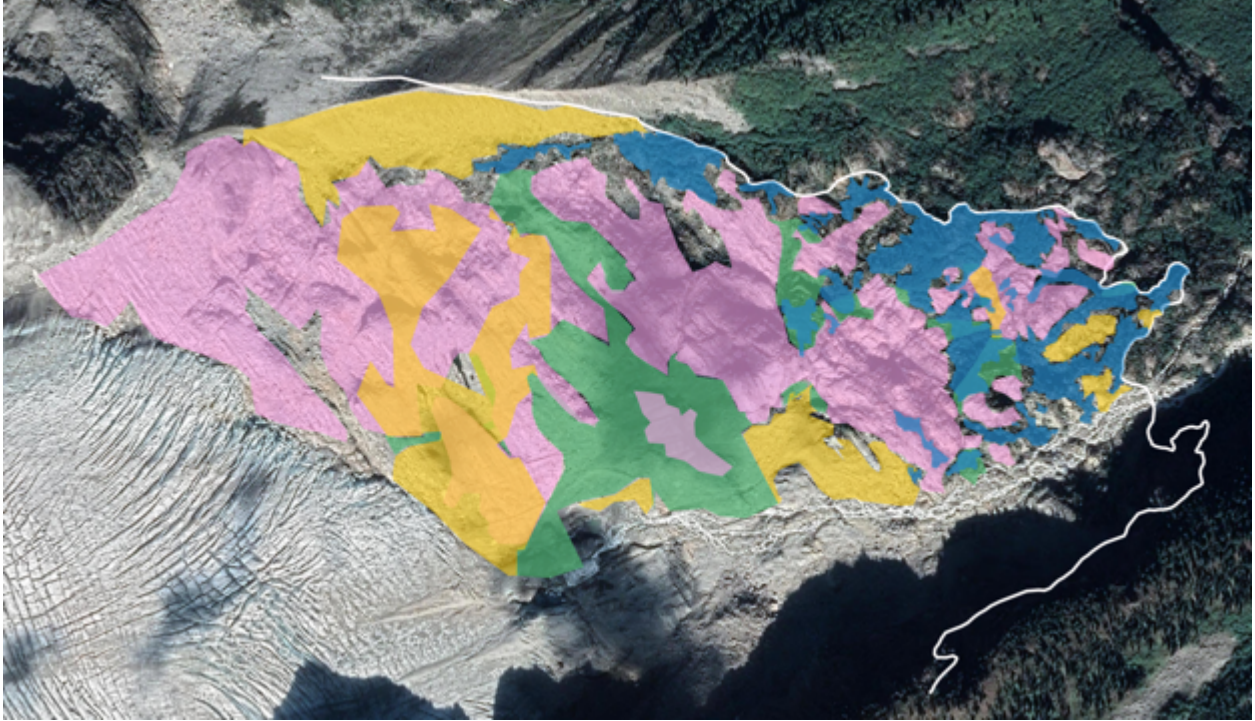


Figure 29: The blue areas represent the part of the extent that has been classified as being within the ecological succession stage; green is biogeomorphological; yellow is pioneer; pink is geomorphological. The resolution of these stages is likely closer to a 1m x 1m pixel scale; therefore, this map is not intended to have perfect spatial accuracy but instead to show the emergent patterns across a large spatial area. The base imagery is a georectified satellite image provided by the Google Earth plugin in QGIS.

All four stages of fluvial biogeomorphic succession are present across the forefield. The ecological stage is visible in the lowest elevation and oldest terrain region of the forefield (55-120 years). It is the dominant land cover pattern for the terrain that melted out before 1966. The biogeomorphological stage is present in the lower section of the forefield, including in some overlapping areas of the ecological stage. Areas classified as biogeomorphological have a terrain age of between 50-110 years. The biogeomorphological zone covers a larger total area than the zone classified as ecological, although this may be due to higher-altitude viewsheds having a larger total area than the lower elevation's viewsheds which were predominantly ecological. The pioneer stage is present in the region of the forefield that has a terrain age of 25-50 years. However, indicators of pioneer succession are present throughout the forefield. At older/lower

elevation areas within the forefield, there are strong indicators of pioneer succession at areas of exposed bedrock, i.e., on textured slabs. The area nearest the glacier is classified as geomorphic. Terrain as old as 50 years was showing evidence of widespread geomorphic classification, especially as much of that terrain remains exposed bedrock. All terrain younger than 25 years was classified as geomorphic. Additionally, isolated lichen and mosses (indicating pioneer succession) were present on terrain <10 years since melt; at Station 8 (terrain age <10 years), a single vascular plant was visible in a photograph. However, these species were all very isolated, and did not become discontinuous until >25 years after the melt.

Comparing Slope Angle and Succession

When it became evident that terrain age was not the only factor influencing successional stage, I turned back to topography to see if slope angle exerted a control. As discussed in the Methods, I overlaid the stage vectors on a shaded slope angle map (Figures 30-33) in order to extract the total number of quadrants within an area at different slope angles, ranging from 1-10 to 60-70. Each quadrant represents a 25m pixel in the DEM.

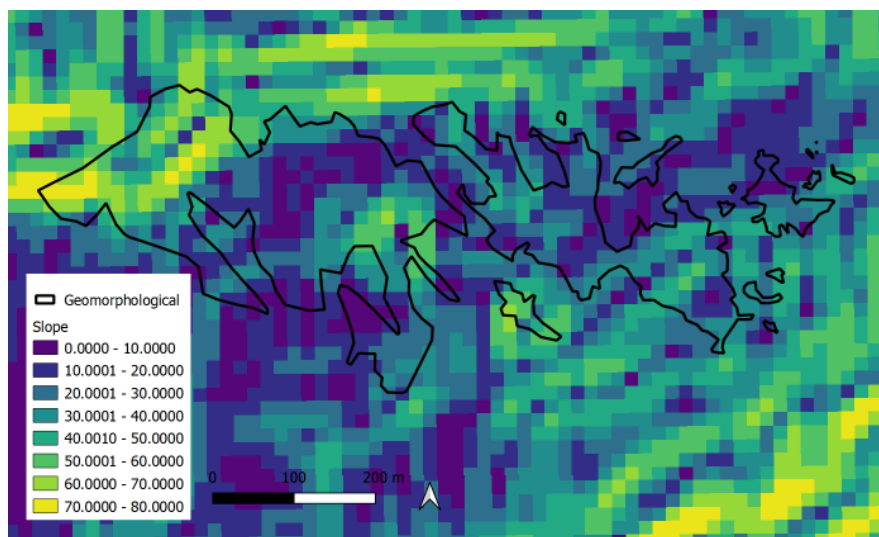


Figure 30: A vector plotting all areas classified as geomorphic is superimposed on a shaded slope angle raster, produced in QGIS using 25m DEM. All slope angles are present within the geomorphological succession vector.

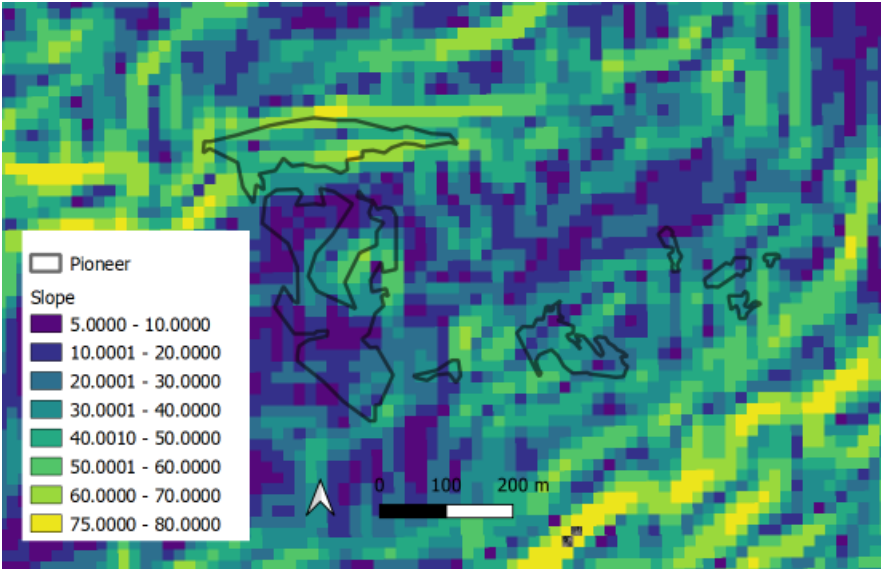


Figure 31: The slope angle of areas in the Pioneer stage. While the distribution of slope angles in this stage is consistent with other stages, the majority of low-angle areas are in the higher elevation region of the forefield, which runs downhill from west to east. Downslope, the pioneer stage appears more likely to be present in the middling slope angles (20-40 degrees), whereas upslope it appears to be more likely to be in the 0–20-degree range.

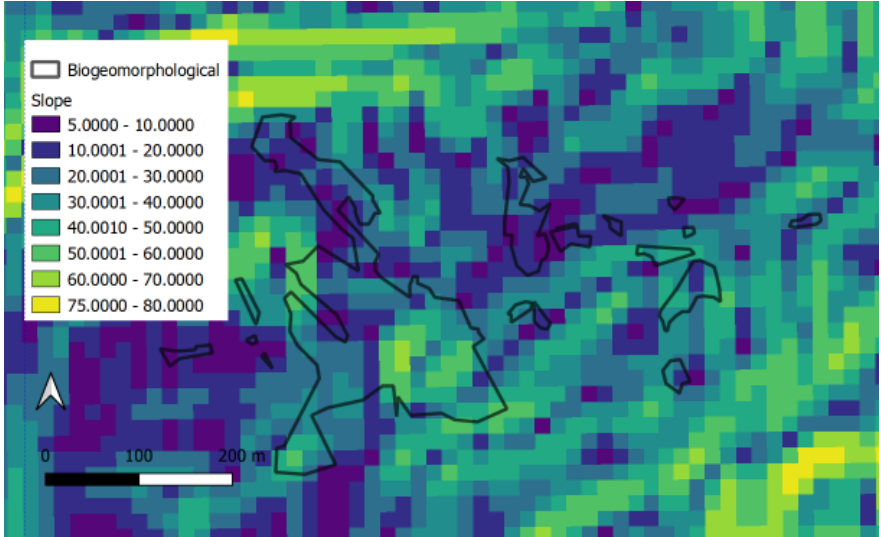


Figure 32: The slope angle of the biogeomorphological stage. This stage is the least present in 0–10-degree slopes relative to the other three stages.

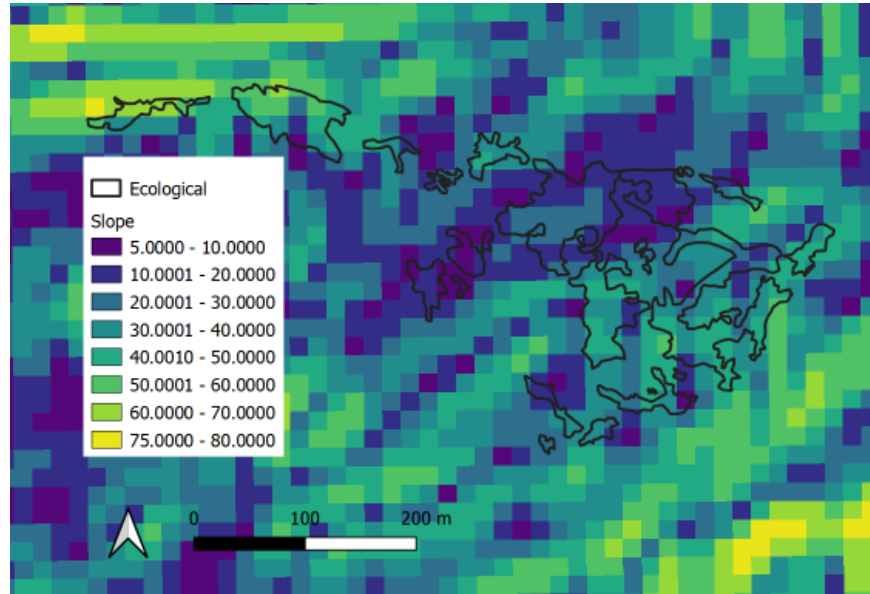


Figure 33: The ecological stage. A lower percentage of quadrants classified as ecological were in the 10–20-degree quadrants than in any other stage; conversely, this stage had the highest percentage of quadrants in the 40–50-degree range.

The tables below show the total number of quadrants in each stage at different slope angles, as well as the percentage of each successional stage within each slope gradient. The area classified as geomorphic was twice as large as any other classification. Therefore, a second table was produced to show the percentage of total area within each successional stage (Table 5).

	Geo.	Pioneer	Biogeo.	Ecol.	Total # of quadrants
0-10	53	34	9	14	110
10-20	106	44	38	34	222
20-30	57	1	33	29	121
30-40	64	30	24	28	146
40-50	27	27	19	28	101
50-60	30	23	18	8	79
60-70	8	1	2	5	15
Total # of quadrants	345	160	143	146	794

Table 5: The number of quadrants present within each slope angle gradient in the four different FBS stages.

	Geo.	Pioneer	Biogeo.	Ecol.	% of total quadrants
0-10	15%	21%	6%	10%	13%
10-20	31%	27%	27%	23%	28%
20-30	17%	1%	23%	20%	16%
30-40	19%	19%	17%	19%	18%
40-50	8%	17%	13%	19%	13%
50-60	9%	14%	13%	5%	10%
60-70	2%	1%	1%	3%	2%

Table 6: The percentage of quadrants by slope angle, relative to the total number of quadrants in each FBS stage.

When the entire forefield is considered, regardless of terrain age, FBS stages are fairly evenly viable regardless of slope angle when that is the only factor being considered (Figure 34). This remained true at younger terrain ages, where the primary difference was that there were no ecological areas in the more recently deglaciated terrain.



Figure 34: Donut charts represent the percentage of quadrants in each slope angle, respective to the total area of quadrants classified per FBS stage. Charts on the left are for the total forefield area; charts on the right only refer to quadrants that have been deglaciated since 1995. For example, 10% of the total area classified as ecological was between 0-10 degrees; 6% of the total area classified as biogeomorphological was at that inclination; so forth. The extent of the forefield did not undergo significant change between 1950 and 1970 due to glacial stabilization; and, in the area that has become exposed since 2011, there are only 17 25m quadrants (less than 5% of the number used to generate the charts on the right of the figure), so no further analysis of slope angle relative to FBS stage and terrain age was possible.

When terrain ages were added to the map (Figure 35) it was found older areas of the forefield were more likely to have moderately steep slope angles (40 to 50 degrees). In the terrain under the area of the forefield where the terminus oscillated during the glacier's period of

stabilization between ~1950-1990, there is a higher proportion of very steep terrain (>60 degrees), and of very flat terrain. (<10 degrees).

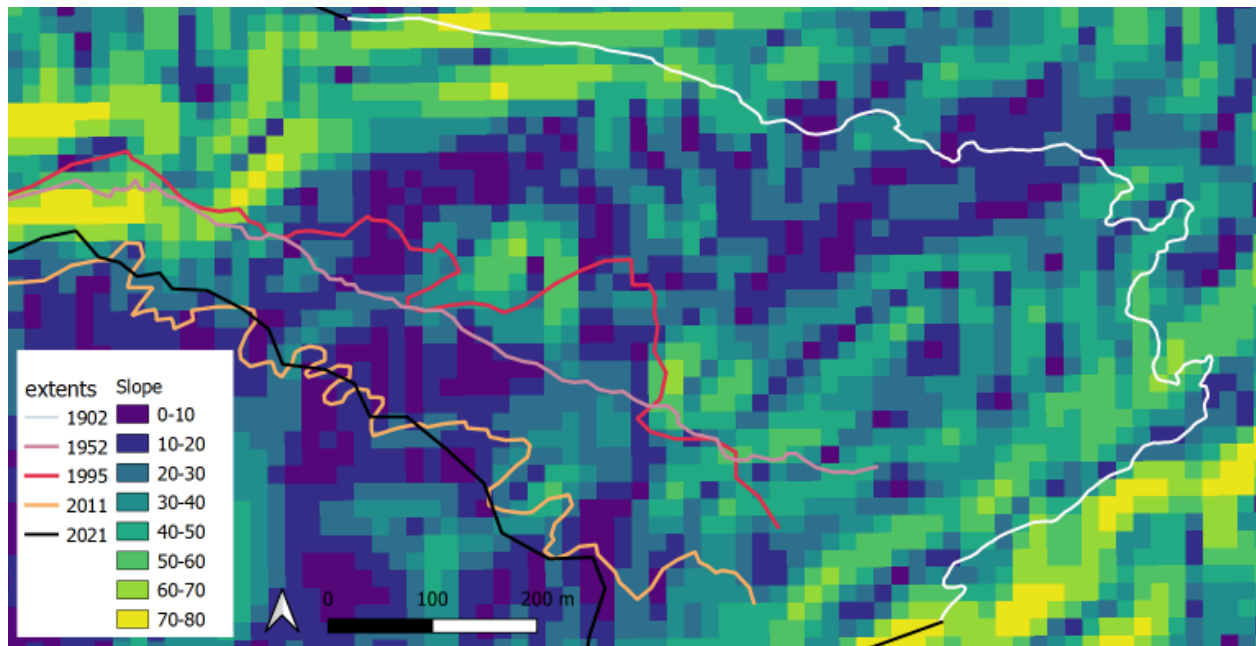


Figure 35: Glacier extents from 1902, 1952, 1995, 2011, and 2021 are shown over a slope angle map.

From ~1950-1990, the glacier's extent was relatively stable. Since 2011, there has been so little recession that only 17 25m² quadrants exist in the area that has receded since 2011. The area that has become exposed since 1995 has topographic heterogeneity; however, difference appears to be relative to distance to the midline, rather than terrain age. Near the middle of the forefield, there is a greater area of low-angle terrain. Near the northern and southern edges of the forefield, slope angle increases. This trend is visible throughout the forefield, but is most pronounced in the area that has receded more recently. While not immediately apparent when slope angle is considered alone, there is a significant glacial outflow river in the southernmost portion of the forefield. The ecological, pioneer, and geomorphological stages are well distributed across the forefield; the latter two stages are present at all terrain ages. The biogeomorphic stage does, however, appear to be influenced by slope angle – but *only* when terrain age and proximity to the glacial outflow are also considered.

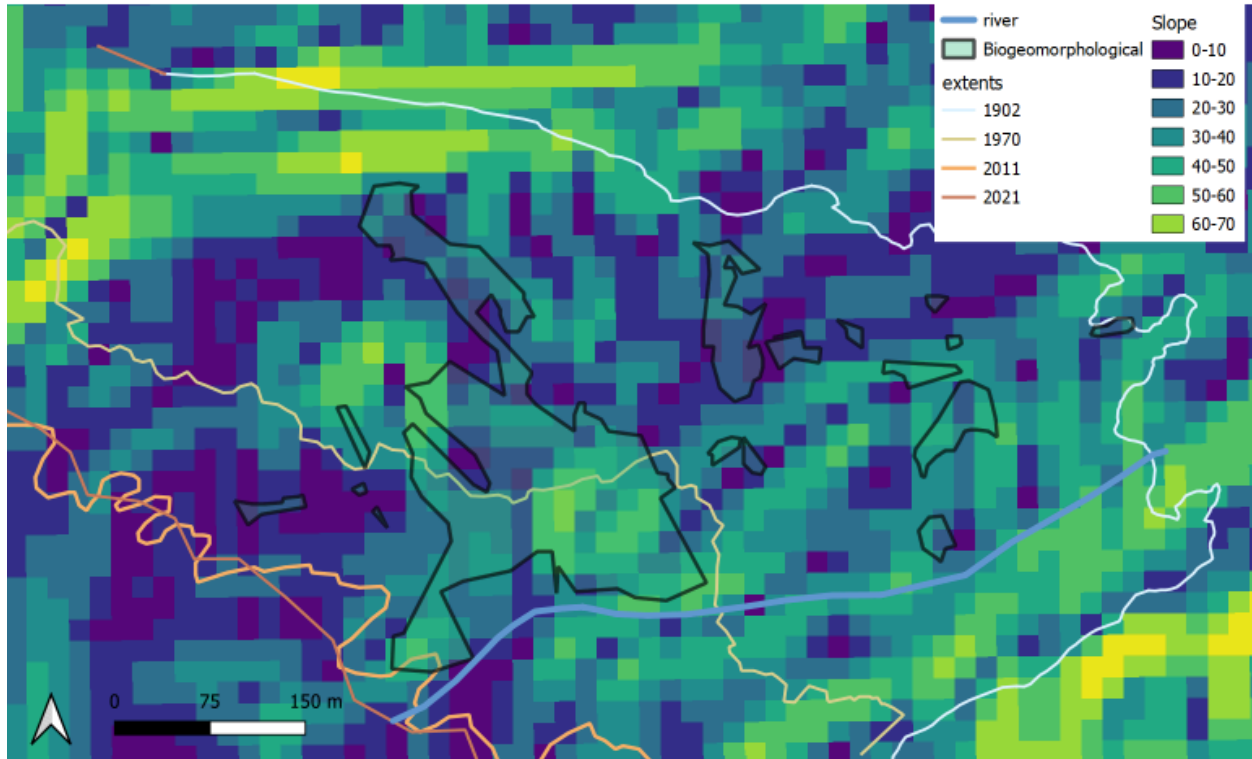


Figure 36: The river system in the forefield is shown alongside glacial extents at various years above a slope angle gradient. In the space between the yellow line representing the 1970 extent and the pale orange line representing the 2011 extent, a large area on the southern portion of the forefield has been classified as biogeomorphic. In that zone, the lower-slope angles were not classified as biogeomorphic; only areas with steeper inclines had evidence of achieving the biogeomorphic window.

When all three features are plotted alongside the areas classified as biogeomorphic (Figure 36); the following trends become visible:

- Most of the forefield's biogeomorphic areas are in areas with a terrain age of 50 years or less; in areas with a terrain age greater than 50 years, the land is either fully transitioned to ecological, bedrock, or bedrock with encroaching pioneer species like moss and lichen;
- In areas of the forefield that have deglaciated since 1970, biogeomorphological succession almost exclusively occurs in areas with a mean slope angle between 20-30 degrees (in areas that, in the satellite imagery, show mixed bedrock and

till), *or* in areas whose mean slope is between 30-60 degrees *and* which are very proximal to running water.

- Very near the contemporary extent, in areas with a terrain age less than one decade, biogeomorphic succession is present but only at sites with a mean slope angle between 30 and 50, and within 50 meters distance to the outflow river.

Discussion

This research found that, while there is a first-order relationship between terrain age and successional stage, successional stages vary widely at each terrain age. The findings also suggest a second-order relationship between substrate, topography – especially slope angle – and successional stage. That is, terrain age seems to *limit* the range of stages that is possible in a given space. But other geomorphic controls were found to frequently override terrain age in determining which successional stage a given region of the forefield was experiencing. The forefield contains a mosaic of different, sometimes overlapping successional stages – with much of the landscape still teetering on the brink of ecological potential, yet to be fully transformed into a functioning ecosystem. These findings were grounded in biogeomorphological ecological succession framework that has been developed over the last 15 years (Corenbilt et al., 2007, 2017; Eichel et al., 2011, 2013). These studies, and others, show consistent findings: myriad and difficult-to-capture factors allow some spaces within a forefield to arrive at the biogeomorphological window, in which unwieldy landscapes can shift into stable, plant-controlled regimes. Other research has concluded that when, or whether, any zone within a forefield makes this transition is difficult to predict. Such classifications are usually only possible to capture once the transition has already occurred.

Nevertheless, one key takeaway of this report is that there are areas within the forefield that may yet arrive at the biogeomorphological window. Even in parts of the forefield that had a 100-year terrain age, there was evidence that the biogeomorphological stage had either been achieved (Figure 37), or that the window of transition might be arriving – which, with further

research, could allow researchers to infer the potential for continued ecological changes in the decades to come.

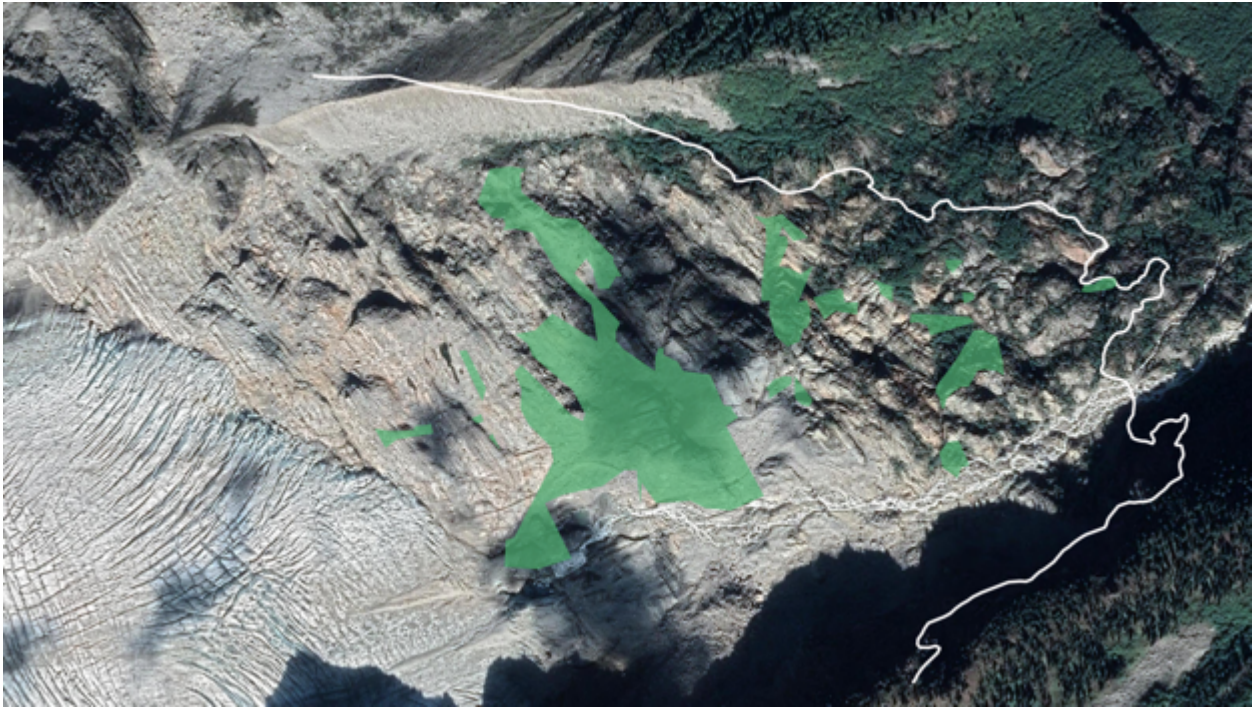


Figure 37: The green areas represent the part of the extent that has been classified as being within the biogeomorphological stage. These areas were selected using classified viewsheds from the transect imagery; where satellite imagery contradicted the viewshed classifications, the satellite classification was favored. The base imagery is a georectified satellite image provided by the Google Earth plugin in QGIS.

The most startling finding in this report was that the biogeomorphic window can be achieved even within a decade of glacial melt, but only when a specific set of conditions are met: when mean slope angles are between 30 and 50 degrees, till is heterogenous and well-sorted, exposed bedrock is absent; and abundant water exists within fifty feet.

This thesis research represents one of only a handful of studies taken over 150 years of forefield research that employs repeat photography, air and satellite photography, and in-situ data in tandem. Used together, a successful workflow was developed that was able to describe the development of fluvial biogeomorphological succession stages in this type of remote, difficult-

to-access, alpine forefield environment. The workflow developed was successful, even as hazards were encountered: Moving between transect stations entailed traveling over scree slopes, exposed granite and quartzite slabs, steep cliffs, dense alder and other brush, water crossings, wet meadows, and snowfields. Melting glaciers are incredibly complex structures: the ice melts, shifts, and groans, is capable of releasing large slabs of ice due to serac fall, and huge fields of boulders and loose rock often cover sections atop the ice field, which are also subject to be released as the glacier moves.

It is precisely this dynamism that makes the study of glacial forefields so critical. As the landscape transitions from pioneer to latest successional ecological communities, specific ecosystem functions and services are soon to follow: for example, successful colonization stabilizes glacial sediments, which would otherwise wash and slide across slopes, filling glacial reservoirs and contaminating watershed resources (Bogen 1988; Hauenstein 2005; Raymond Pralong et al. 2011). This plant-controlled development of forefield geomorphology underscores the importance of “geomorphologic-engineer species” (Corenbilt et al., 2011). Engineer species can “modify sediment and landform dynamics” (Corenbilt et al., 2011): lichens and moss convert rock into sediment; and, as Corenbilt shows, subsequent species like willows, alders, or other woody vegetation which control geomorphology. Succession may therefore “have consequences for the physical components of ecosystems and particularly Earth surface processes and landforms” (Corenbilt et al., 2011). These modifications then feed back to the structure and function of the developing ecosystem. This has micro- and macro-scale significance: biogeomorphic systems control the function of ecology and land surfaces over windows of time as short as a year, extending to “evolutionary timescales” (Corenbilt et al., 2011).

The findings of this study also suggest that more research is needed into the dynamics of small glaciers in and around the Columbia Basin. The Avalanche glacier was found to have

receded steadily after the end of the Little Ice Age through the 1950s. It then stabilized for several decades. Since then, recession has been slow – only a few meters per year – vastly slower than the rates observed from the region’s larger glaciers. Whereas a 2013 paper showed that the mean retreat rate of 22 Columbia Basin glaciers from 1919-2009 was 12.8 meters per year (Tennant and Menounos, 2013), the Avalanche retreat at 25% that rate. In a hundred-year period, Tennant and Menounos (2013) observed that the nearby Columbia Icefield retreated 2.4km²; in the same period (1921-2011), the Avalanche glacier only lost 0.336km². Interestingly, the mean slope for the 25 glaciers studied by Tennant and Menounos (2013) was 21 degrees; the Avalanche glaciers, meanwhile, is 39.7, almost twice as steep (more on the potential of slope angle below to influence succession follows this section). As discussed in the literature review, other inventories of the Southern Interior mountains (DeBeer et al., 2007) have found that local conditions likely impact the rate of recession, particularly on smaller glaciers that are “in sheltered sites, such as below steep valley walls or in deep cirque basins, where conditions are favorable for their preservation (i.e. they receive enhanced mass input by avalanching from adjacent slopes and are protected from direct solar radiation throughout a large part of the year).” Less is known about the historical retreat rates of other glaciers in the Columbia Mountains, especially predating the 1980s. Much of the recent research has used tree-ring data for mass balance observations (Watson et al, 2008; Wood et al., 2012); beyond what has been described in this thesis, little is known about the rate of recession or the forefield composition of the hundreds of smaller glaciers in the range. This research gap includes rate of recession, as well as inquiries into whether forefield dynamics are distinct across glacial size, rate of retreat, aspect, and so forth. Such research would be necessary in order to accurately model, predict, and plan for landscape-scale hazards – as well as (potentially hazard-reducing) landscape-scale modifications to ecological and hydrologic regimes at this critical headwater site.

A note on the selection of methods

The driving question for this project was to determine what land cover patterns have emerged at sites of rapid deglaciation; a necessary second question, then, was to select a combination of methods to make sense of the different data sources available. In beginning this project, I initially intended to use a suite of tools developed by MLP that have elsewhere been shown to create high-resolution, accurate data about land cover classification categories using oblique photography. The typical workflow using these methods entails generating repeat photography pairs, aligning historic and repeated photographs, classifying images according to land cover type, comparing the historic and repeated masks to analyze change over time and, when relevant, georeferencing these masks to create maps of land cover types. Despite previous successes in the MLP lab, a standard repeat photography workflow was found to be inadequate for answering the questions this project asks. Here, a narrative overview will describe the realizations that were made along each step of the way. The purpose of this write-up is to illuminate for the reader the limitations encountered using conventional analysis methods, and to expand on how these limitations led the initial research question to evolve symbiotically along with the experimental protocol that was followed.

As mentioned in the methods, analysis of repeated oblique photographs using conventional methods was found insufficient; these difficulties were preceded by difficulties encountered during the repeat photography process itself. The net result of these two difficulties meant that the project had to be largely reimagined *after* the data collection concluded. The first encumbrance was the smoke: the field team was taking photographs across a long distance (about 3km) at the height of a historic wildfire season. Significant efforts were taken to reduce noise and haze in post-processing using Adobe Photoshop and CaptureOne. Even so, as

described in the Results, the edited photographs could not generate more than four land cover classifications in the Python algorithm PyLC.

The limitations of this classification schema felt especially apparent when compared to the human-scale experience of being present in the landscape. It took hours to scramble from the marshy helicopter landing pad where a Parks Canada had deposited the field team to the 1902 terminus location: down a steep moraine, over newborn bedrock, and across silty, braided streams. Even for Coaz (1887), the first known researcher of the forefields, appreciated the specificity of this nuance: the realization that initiated the entire field of study was inspired by the appearance of a single saxifrage's bloom.

The challenge of working with oblique images led me to ask: What resolution of data *is* needed to make meaningful conclusions about a forefield – and especially about its arrival in the transitory biogeomorphological succession stage -- given that the emerging body of research emphasizes slope angle over nearly every other factor (and which has, indeed, been attributed to as much as 50% of forefield succession)? As evidenced in the literature discussed in the preceding section introducing glacial forefield research, there is no consensus within the field about what resolution is necessary. Moreover, my own analyses indicated that relying on remotely sensed data alone may would lead to significant oversimplifications of classification. It may well be the case that in forefield environments, it is impossible to know what resolution of data is necessary without first spending time onsite, where the nuances of microtopography become clearer. Or, perhaps, under which atmospheric conditions and focal lengths permit repeat photography to be a meaningful method. A clear day and a station at near-range may have led to different conclusions.

These limitations also constrained the types of analyses that were possible. As the transect photographs' viewsheds were plotted, a margin of error was introduced. When they were

classified, that error was compounded: areas close to the camera were over-emphasized; ecological features were omitted from the orthogonal photographs but overemphasized in oblique images due to their relative sizes compared to, say, lichen, which were only really evident in orthogonal photographs. Additionally, once satellite imagery were used to add expansive areas of bedrock to the geomorphic classification, all other areas were subsequently de-emphasized by comparison. This means that when I use raw data to make any calculations, the geomorphic class is always inflated -- it's more than twice as abundant than the others.

Additionally, slope angle analysis revealed that the middle of the forefield – where the transect's midline was located – had a higher proportion of low-angle terrain than its north and south edges did, which were much steeper. This – combined with the reality that our stations were necessarily on terrain less than 30 degrees, lest the tripod become unworkable – adds further skew to the data, and limits the amount of meaningful numerical analyses that can occur.

Transect adaptations like taking more data points at each elevation or selecting transect stations at a diversity of slope angles could help overcome this bias. This work has been a practice in comparing observations to conceptual level trends using limited data. I have hesitated to make claims about correlation or causality; too much is absent from the data I was able to collect. As such, while a linear regression model could have been employed to better assess, for example, the correlation between slope angle, proximity to water features, terrain age, and successional stage, it was determined that the data was not robust enough to draw reliable *statistical* conclusions. Further work might consider combining higher resolution DEM, more transect photo samples across each terrain age, re-adapting the transect method to have samples at terrain age intervals rather than vertical distance, or focusing just on one successional stage that is well-captured using these techniques (e.g., the biogeomorphological stage) to have robust enough data to apply a multivariable linear regression model to interpret and predict forefield development.

Terrain Age, Topographic Complexity, and Glacier Change

The Avalanche glacier is melting, leaving behind hundreds of hectares of new ice-free terrain (Figure 38). However, For the last few decades, glacial retreat has been slow relative to the post-LIA rate: between 2005-2019, the glacier extent retreated vertically by 39 metres at the point of the toe that receded the most; in other areas, the termini was as much as 54 meters lower than it had been 14 years previously. That the Avalanche glacier appears to be melting slower now that it has historically is consistent with other research from the area. For example, in 2020, Pelto et al. published research that found that the Columbia Basin's glaciers were 38% thicker than previous climate models had predicted (Pelto et al., 2017).

By using analysis tools in Google Earth Pro while designing this research project, I observed that the Avalanche glacier has slope angles, elevation profiles, and surrounding topography that is more consistent with the other glaciers of the Beaver River Valley than with the Illecillewaet, or the other large icefields studied by Pelto (2017) and others. The Avalanche Glacier stretches laterally across the eastern flank of the range under the steep crests of Avalanche, Uto, and Eagle peaks, before bending downslope to the east. The entire top and southernmost sides of the glacier are flanked by cliffs, 300-400m tall. Like the large icefields in Pelto's survey, the wide upper section of the Avalanche glacier has a relatively low slope angle (10.1 degrees average); however, the lower section, where recession has been observed, is much steeper (39.7 degrees average). It has long been understood that slope angle is an important factor in glacial dynamics (e.g., Reid, 1896, Clarke, 1991). For example, a steeper subsurface slope angle causes increased glacial stress as the mass of ice strains under the gravitational pull down the mountain's slopes. That is, an increasing slope increases a glacier's velocity. In general, larger glaciers have gentler slope angles (Wu et al., 2016; Junfeng et al., 2014); smaller

glaciers are more able to withstand steeper slope angles because of the lessened pull of gravity on smaller masses. However, steeper glaciers are also less subject than glaciers at gentler angles to direct solar radiation, which decreases the rate of melt. As such, it appears to be important, in the Columbia Basin and around the world, to devote more research to the melt rates of smaller, sheltered glaciers (Naz et al., 2017; Pelto et al., 2017, 2020). For the Avalanche glacier, the relatively steep slope angle is consistent with the steeper slopes of these smaller, eastern-facing, and cliff-walled glaciers, which have an average slope angle of 38.7 degrees – but significantly steeper than the nearly flat slope angles of the dozens of icefields Pelto et al. (2017) surveyed in the Basin and which it was found, three years later, were not indicative of total glacial loss in the region (Pelto et al., 2020).

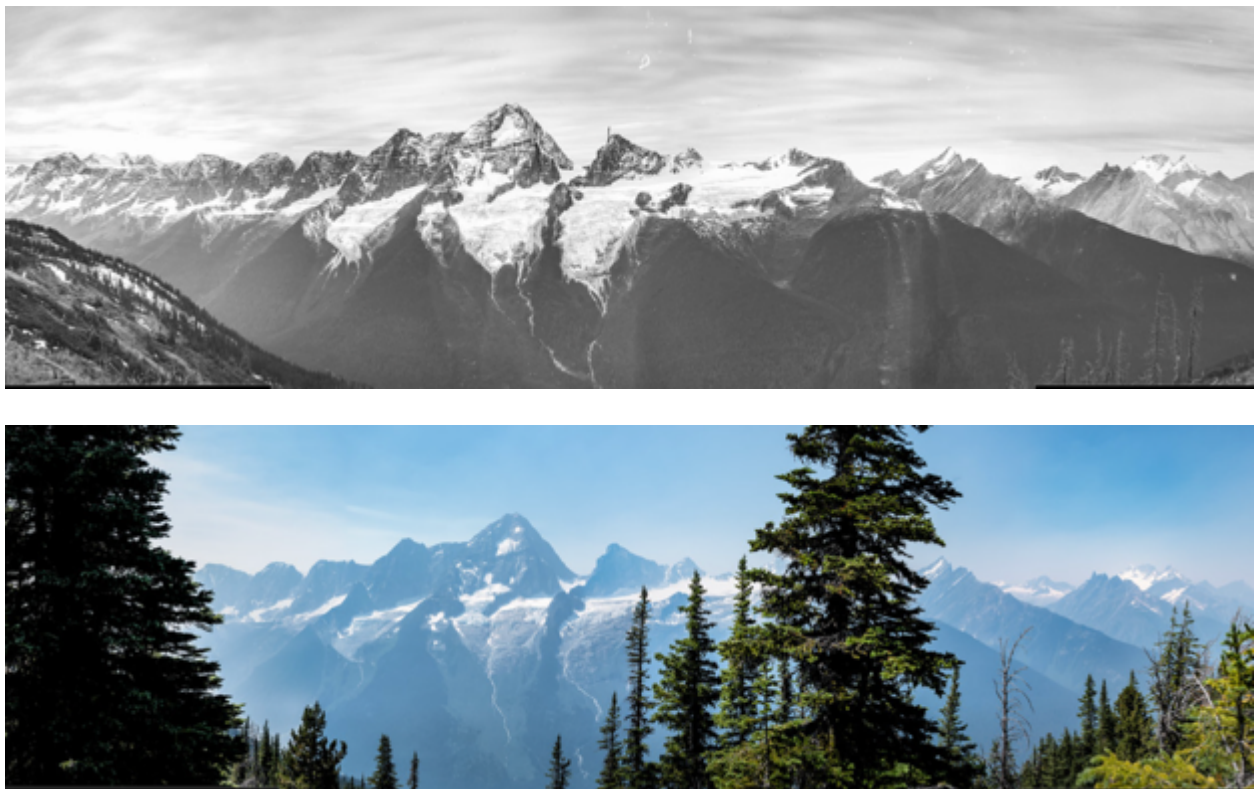


Figure 38: Above, a composite of the historic photographs taken in 1902 showing significant deglaciation across the Beaver River Valley. The Avalanche glacier is the large glacier in the center of the image, and the last glacier on looker's right. Below, the same view repeated in 2021. To the south (left), only glacial remnants remain.

The Avalanche glacier has been receding slowly for the last few decades. It also appears to be the case that the Avalanche glacier has not melted at a consistent rate over the last 120 years. For example, for a nearly 40-year period in the mid-20th century, the Avalanche glacier advanced, retreated, and advanced again; its 1950 and 1990 extents were mere meters apart according to the georectified air photos. This indicates that following an initial 50-year period of significant recession following the end of the Little Ice Age, the Avalanche Glacier mostly stabilized (likely due to the North Pacific Decadal Oscillations cold trends from the 1950s through the 1980s). When it began to recede again around 1995 it did so about one-third the rate experienced during long-term Holocene-type, post-LIA warming. Of course, the extent of the boundary does not paint a full picture of a glacier's stability: glacier mass balance is a more precise measurement of a glacier's total size and therefore a more meaningful indicator of melt. Recession could, for example, be offset by the downward gravitational pull of a glacier, meaning that observable recession would actually be occurring at the top of the glacier, not at its lower extent. That said, the mostly-stable retreat of the glacier indicates that it may be subject to less radiative forcing and, therefore, less at risk due to the effects of climate change. Furthermore, higher up on the glacier, where the upper icefield-type section that lies roughly on a north-south axis, the glacier does not appear to be demonstrating significant retreat: that boundary has only retreated 25.01m since 1952.

While reviewing the literature, I came across no studies that indicated how rate of melt impacts forefield succession in and of itself. That is, if a plot of land becomes vacated quickly, it has not been found to be inherently more or less prone to colonization. However, it has been well documented that the abundance of water that comes from more rapid melt does impact the success of ecological succession in forefields. This is especially true when taken in tandem with topographic information such as slope angle. When subjected to disturbances such as flooding

(Garibotti et al., 2011; Chapin et al., 2016), ecological processes in forefields may be slowed, altered, or reversed. The outcome depends largely on microtopography. Early colonizers depend on the availability of beneficial seed dispersal attributes (Chappin et al., 1994; Stöcklin, 1996; Franzen, 2020), as well as “safe sites” for seedlings (Jumpponen et al., 2004), such as shallow depressions or nearby boulders, both of which facilitate “microwatersheds” that block downstream transportation of seeds due to runoff, and supply adequate hydration for germination.

An analysis of the role of microwatersheds was not possible in the Avalanche glacier, or was any fine-scale understanding of the role of slope angle in this environment. This is because no high-quality DEM was available. An absence of high-resolution air photos also constricted the potential to make watershed analyses – if such data had been available, a comparison of sites that routinely have late-lasting seasonal snowpack and their late summer vegetative growth, or the growth of sites nearby and downslope, could have been made.

However, the presence (or absence) of the main glacial outflow in the forefield did seem to have tremendous impact on the speed at which a biogeomorphic window might be achieved. Figure 35 showed a map that combined slope angle, terrain age, and primary outflow alongside a vector outlining areas classified as biogeomorphic. That data shows that – outside of a few isolated examples of rooted flowers captured in the transect data (and only ever isolated; never discontinuous or continuous) – pockets of the forefield can discontinuously achieve the biogeomorphic feedback window less than ten years after glacier melt if slope angle, till homogeneity, and hydrologic features line up.

Previous work into fluvial biogeomorphic dynamics in forefields identify two possible explanations. First, Miller et al.’s 2019 work describing paraglacial geomorphic disturbances found that, while water dynamics can alternately act destructively and as a resource, geo-

ecological processes in forefields are also water-limited due to the well-draining nature of glacial sediments. Where hydrologic features are abundant, flows can disperse microbes and stimulate soil development by weathering sediments (Miller et al., 2019) – both which could explain why the biogeomorphic window’s presence in >10-year terrain age areas is limited to zones within 50m of the forefield’s river system. Conversely, Eichel et al. found in a 2015 study that low geomorphic activity predates the establishment of any biogeomorphic features. This suggests that the areas in the Avalanche forefield may be benefitted by near-river soil saturation, but simultaneously limited by the geomorphic disturbances common very near the glacial extent (Eichel et al., 2015), as well as by a dynamic, braided stream system that has yet to channelize or have ecosystem engineer species capable of stabilizing its banks. Moreover, steeper slopes are inherently less stable (and made even less so by saturation, which increases the possibility and process magnitude of geomorphic disturbances like landslides). Therefore, these areas classified as biogeomorphic because of discontinuous vegetation are more likely on the border of that stage and the pioneer stage – which is indeed characterized, in part, by species beginning near channel banks (Corenbilt et al., 2007; Eichel et al., 2018). Like Eichel et al.’s 2013 study, areas prone to high geomorphic activity are correlated to primarily pioneer vegetation.

The role of data resolution

Forefield research has long struggled with how to make meaningful analyses given limited data resolution is a frequent problem in forefield environments, and especially as biogeomorphic and microtopographic controls become better-understood (Gentili, 2015; Eichel, 2013; Eichel, 2020; Fiectola, 2021; Garibotti, 2011; Sigdel, 2020). Fine-scale data are critical for the emergent transitions, both in climate (due to global warming) and understanding (i.e., the establishment in the last few decades of biogeomorphology as a field of study). Fine-scale

mapping of alpine refugia is additionally needed in order to assess the impact of habitat change on geomorphologically active mammal communities who rely on these refugia (Gentili, 2015). Nevertheless, granular, low-resolution data such as that gathered by remote sensing still dominates. These data cannot capture microclimatic, microtopographic scales, even as these are the most well-understood factors in ecological infill. For example, Lambert et al. (2020)'s ongoing surveys of forefields in the U.S. Glacier National Park intended to use image classification to typify land cover types as either tree, shrub, or herbaceous. However, analysis of their 30m-resolution Landsat data revealed that the pixel-scale classifications could not distinguish between the three types. They were, ultimately, all classified as "vegetated" (Lambert et al., 2020).

This is a typical problem with remotely sensed data. Very few examples of the research use field-collected data to complement remotely sensed data. When field observations are collected, they are typically valued only as validation measures, e.g., by the establishment of ground control points like those needed for some orthorectification methods, or to provide field-based accuracy assessments of remotely sensed data analysis. Despite the growing awareness of microtopographic and biogeomorphic controls on emergent patterns of land cover composition in glacier forefields, few methods have been developed to overcome the gaps in more traditional transect and chronosequence methods for ground observations; fewer still describe the potential for remotely sensed data and field observations to be integrated.

The majority of geomorphological processes, especially those that define the geomorphic and pioneer succession periods, were missed by all data collected in this project. As discussed in the literature review, Miller et al.'s 2019 provided a meta-analysis of factors understood to potentiate a biogeomorphic feedback window; it concluded that disturbance, water, microbes, and lichen are all essential. Of these critical components, only lichen are visible in the transect

data (they were, of course, invisible in the air, satellite, and repeat photos). And, where they were visible, this was only the case in the very-near ranges. There were no examples in the literature surveyed for this research that showed photographic methods successfully being adapted to document the processes of microbial geomorphology – all instead relied on microscopy or other sampling techniques.

Similarly, the extent to which the transect photos could successfully classify a pioneer stage is also limited: because of the lack of soil sampling, hydrological data collection, or microscopy, none of the early pioneer processes dependent upon microbial communities were invisible using the methods. A more thorough field technique might have additionally collected all potentially covariate features: soil temperature, soil moisture content, concavity/convexity of the quadrat terrain, windspeed, air temperature, and more all fall under the category of potentially influential characteristics. Nevertheless, the presence of indicator flora like mosses and lichen, which participate in the conversion of bedrock into organic soil capable of supporting other life, were captured using the transect data – and these species would have been missed if only remote sensing techniques had been employed. By centering on transect data as the primarily data source, this project favored signals that indicate the Biogeomorphic phase, as those are the most noticeable in the dataset. In both the oblique and the orthogonal photographs taken during the transect, vegetation that is indicative of Biogeomorphic succession (conifer and woody shrub saplings, grasses, vascular plants) were observed.

Transect photos were also maladapted to accurately document the ecological stage. An orthogonal quadrat taken during the transect necessarily cannot capture a data point containing evidence of a mature conifer: the horizontal bar extending off of the tripod above of the quadrat would have been blocked had a tree been present in the quadrat. Indeed, the research team was biased towards selecting transect sites where it was possible to set up the tripod. As such, data

beyond what was visible in the transect photographs was needed to capture these phases. It was determined that satellite imagery could fill this gap. In the satellite imagery, continuous bedrock, continuous till, and continuous mature conifer forest tracts were all visible. This choice to include mixed data sources at vastly different spatial resolutions allowed all four FBS stages to be documented. As mentioned earlier, seldom few previous studies have combined remote and in situ data when documenting forefields. For any work relying primarily on photographic methods, or using the FBS framework, doing so has clear benefits.

Transect as method: limitations and potential

The original purpose of the transect research technique had been to establish ground control points (GCP)s. GPS waypoints from these points were intended to be mapped onto the viewshed; photos taken at the various stations would act as ground truths against the generated classifications from oblique repeat photographs linked to historical imagery. However, once data analysis was underway, it became apparent that these transect photographs might offer other options for analysis. At each transect station, three photos were taken. One pointed directly at the ground; the other two looked out at 90 degrees relative to the forefield's midline. Oblique photos cannot be extrapolated to show the percentage of any given land cover type outside (or even within) the viewshed. To make such extrapolations from the overhead photographs, three or more data points at each elevation would have been needed. While density cannot, then, be determined using these data, they were successful in documenting what types of land cover are present in a specific photographic viewshed. The downward-looking photographs show the differences between bare rock, scree, dirt, and lichen; the outward-looking ones show plant cover, terrain roughness, as well as providing some evidence for whether the phenomena

documented in the downward-looking photographs are isolated, discontinuous, or continuous. It became apparent that a new method for describing land cover types would be necessary, using a process of triangulation involving the transect photographs.

Transect methods such as the one applied in this study are subject to a range of errors. For example, when forefield transects have been repeated (i.e., Glaussen and Tanner 2019 and then Synan et al, 2021), it has been found that small quadrat sizes (1m²) falsely indicate high levels of variation in species counts between sample points, even at an interval distance of only 10m, because of the standard errors of measurement summed across each transect. Even once these errors are reduced and linear regression models are applied, some species were still found to display no variance when grouped by sample age (Synan et al., 2021). My data did not lend itself to this kind of error measurement, but what I observed in the field is consistent with other fine-scale forefield research.

While an array of problems can additionally be introduced when manual classifications are applied in lieu of more standard statistical analyses, there are also benefits to such a methodology. For example, Eichel et al.'s 2015 study used a process of ordination to classify samples within the FGS scheme and noted that such a conceptual classification is biased towards magnitude-frequency relationships. While the ordination process reduces the need to use time-consuming and labor-intensive field sampling techniques to describe magnitude and frequency of species or assemblages, making general conclusions in the absence of field data has been criticized as only being valid when the system being studied exists in a state of equilibrium (Crozier et al., 1999). This is necessarily not the case with a glacier forefield. Nevertheless, Eichel et al. concluded, “the advantages of our approach justify its use in our biogeomorphic study, as our classification allows to determine [sic] the direct relationship between geomorphic activity and vegetation development efficiently in a limited fieldwork time period” (2015).

Fieldwork challenges

This study design was constrained by the rigors of mountain travel. Indeed, under rapidly shifting climate conditions, my research was directly affected. Extreme weather seems to have become a staple of daily life in British Columbia over the course of this research effort. Reality has become a limiting factor on what remains possible. This research reflects the reality that the lived experience of climate change presents a significant barrier to one's ability to study the effects of climate change. In late June, 2021, the province of British Columbia experienced a once-in-a-millennium (Gardner, 2021) weather phenomena known as a "heat dome," in which a tremendous high-pressure front created intense heat. The abundance of energy produced by this high-pressure system sparked 710,117 lightning bolts in less than 15 hours on Wednesday, June 30 (Kahn, 2021), which in turn ignited lethal wildfires across the province. By late July, the Interior region of BC where this research took place was additionally under Level 4 drought conditions, the second highest in a six-class system. In short, by the time the field team arrived in the Bald Hills, BC was experiencing catastrophic and widespread wildfires. On the day we entered the Bald Hills, there were four active wildfires within Park boundaries. On the day after we hiked out, July 21, 2021, a dry lightning storm produced several hundred lightning strikes in the area surrounding the five repeat photography stations. Visibility conditions were rapidly shifting. While the field team waited until the clearest part of the day to take the repeat photographs, there was nevertheless a high level of smoke that day. Wildfire smoke fills the air with aerosols and particulate matter that presents a physical barrier between the lens of a camera and the landscape-subject. This is compounded by the distance between the lens and the landscape in this set of repeat photographs: at the nearest point, the field team was still imaging across a space of more than 5 km. Therefore, the photographs were hazy. Sharpness, contrast,

and color were all affected; these factors limited the quality of the image analysis that was possible.

Available field methods do exist to overcome wildfire smoke. One could, for example, come back on a better day. Our team chose to employ the “wait and see” method. Despite spending hours at Grizzly Creek, the smoke got denser, rather than lighter, as we waited (Figure 39). Over the next 24 hours, while we waited in a backcountry camp on-site, the smoke continued to get thicker. The original plan had been to take a third station (“Bald Hills South”), which would have documented the glaciers of Beaver Creek Valley’s south-eastern extent. However, due to the increasing impenetrability of the smoke, and even more significant tree cover than was present at Grizzly Creek, the third planned station was ultimately cut from the plan. A return to the field station was discussed; however, smoke continued to increase dramatically over the next several weeks. Indeed, conditions did not alleviate substantially until September, when short days and risk of wintry conditions made a return to the site (which entailed a three-day backpack, about half of which was off of established trails) outside of the scope of feasibility for this project. Further, as a Masters research project I was practically limited to a single field season.



Figure 39: Looking east across the broad top of the Bald Hills. Wildfire smoke obscures the mountains.

While repeat photographs taken for this project were limited by atmospheric conditions, the methods could successfully be applied, including for many other glaciers in the region. A. O. Wheeler's survey took place over the course of two long field seasons. They trekked deep into what is now called Glacier National Park, photographing from the summits of peaks that the staff at GNP told me I would be unwise to try to access without a helicopter – and without an expert mountain pilot at that. Unlike the photographs taken from the Bald Hills, which my team repeated, the majority of these photographs are from closer range. Shooting at close range, atmospheric conditions make less of an impact. Indeed, my team had additionally planned to visit many of these stations. I had hoped to photograph the Illecillewaet and Sir Donald glaciers just on the western side of the crest atop which the Avalanche sits. We anticipated shooting the Tupper glacier north of Roger's Pass, and inventorying a number of smaller glaciers visible from Asulkan Pass. In the end, our team decided to preserve our lung health – the rate of the pollutant

PM 2.5 hovered around 16x the rate deemed safe by the World Health Organization for the week we spent posted up in camp, hoping for clear skies. It is possible that such close-range photographs may have allowed for new developments of forefield research where only remote data was possible; my hope had been to use the transect data to ground-truth my findings from my repeat photographs, such that I might have been able to more confidently analyse forefield development across a range of repeated photographs.

Because of the density of wildfire smoke, the decision was made in the field to focus instead on the photo transect methods and abandon the six other repeat photograph stations that I had initially planned to take. The transect method had yet to be field tested. We skirted the outer edge of the glacial basin until we arrived at the base of the forefield. From there, we had to find a path up what would have been the middle of the glacier a century ago. Hazards abounded. We had seen from across the valley while taking the repeat photographs that the glacier above was cracked in places, making serac fall a possibility. These hazards were, of course, also inflated due to the heat dome. Unprecedented heat leads to unprecedented melt. Our team had been hearing from our local contacts – Park staff, mountaineering guides, and the employees of gear shops in Revelstoke – of glacier calving and ice fall all over the region, on snow routes that are typically safe in the summer. Three days before we departed for the transect, my friend, alpine guide Josh Majorossy, told me that he had gone to a snow climb he does most seasons, usually late in the summer, that week. When he got to the base of the route, it was bone-dry. All of this was in our minds as we traversed the forefield. As traveled up the glacier's midline, we saw massive boulders—glacial erratics—balanced at unlikely angles on the ledges above us. Field team members would later observe that the place had the eerie, electric feeling of still being unsettled. The forefield seemed an assemblage of discrete parts that had not yet found their final place of repose. This work was not done without risk.

Conducting research in mountainous zones is inherently risky. It will, perhaps, become ever riskier due to the compounding threats of climate change. Going into the field season, I was hard-pressed to find accessible safety protocols that had been designed for conducting research in proglacial mountain regions. Indeed, I spent weeks writing to colleagues that have worked in glaciated terrain in the Far North, in Antarctica, and in the Himalaya, asking if they could point me towards any standardized guidelines for conducting research in such conditions. No one had any. That the annals of science have historically excluded safety protocols from their published methods is a limitation. Our team could not surmount it; after our experiences in the Avalanche forefield, we decided to abandon plans to conduct a second transect in the nearby Illecillewaet forefield. Going forward, teams conducting similar work will additionally be confronted with the compounding hazards of a changing climate: not only the serac falls and loose rock and steep cliffs always encountered in steep forefield sites, but also dangerous levels of pollution, high temperatures, unseasonal storms and floods, nearby wildfires – and grief, underscoring all of it.

Conclusion

Summary

The world's glaciers are melting; most will vanish this century, and many will go much sooner. Since the end of the Little Ice Age, an exponential growth in the amount of greenhouse gas emissions -- for which imperialism and racial capitalism are overwhelmingly responsible -- has created atmospheric conditions that are incompatible to the Earth's cryosphere. Temperatures rise; ice melts. In western Canada, this means tens of thousands of hectares of new terrain that had previously been glaciated becomes exposed. Since the 1880s, researchers have been trying to make discernible the patterns through which these bedrock sites give way to functioning ecosystems. Historically, the bulk of these efforts have used a chronosequences technique that privileges terrain age as the determining factor. These techniques monitor recession over time, and have (often incorrectly) assumed that time since melt corresponds to successional stages. In this thesis project, I determined the terrain age of the Avalanche glacier's forefield at decadal scales. Then a biogeomorphological framework, developed over the last decade (Corenbilt et al., 2011; Eichel et al., 2013), was applied. Such a framework decentralizes terrain age to instead focus on the geomorphological and ecological processes that interact to determine whether, and how quickly, primary succession is possible in a forefield.

My findings in Glacier National Park's Avalanche glacier were consistent with other studies that have applied fluvial biogeomorphological succession (FBS). Very near the contemporary terminus of the glacier, a dynamic landscape of sheer rock, talus, and tiny braided streams dominated; no visible life had established. These characteristics were evident at various points much further downslope, too. There were areas that appeared to still be in the geomorphic stage across all terrain ages, especially at very steep, sheer sites. This is consistent with much of

the recent literature, that indicates microtopography exerts a strong control on the possibility of primary succession. Beginning 100m beneath the terminus, more evidence of the pioneer phase became evident; this, too, was not limited to the upper regions of the forefield, but appeared throughout the terrain – again, in pockets where the terrain was textured, but prevalingly exposed rock with few sites for till to accumulate or seeds to take root. The biogeomorphic phase – in which below-ground root biomass begins to stabilize the terrain – was evident throughout the forefield, including in discontinuous patches very near the contemporary glacier's terminus. Significant areas of the forefield showed evidence of being in this phase, which indicates that the forefield – especially in the oldest terrain – is likely transitioning from being primarily controlled by geomorphic mechanisms to being controlled primarily by ecological functions. Finally, only the very oldest and lowest parts of the forefield had reached the ecological phase, in which biotic processes like competition become the primary driver of landscape change.

In addition to studying successional phases, this project also advanced understanding of rates of recession in the small glaciers in the region. By analyzing historic air, satellite, and oblique landscape photographs, it was found that the Avalanche glacier has been melting at a relatively slow rate (<4m/year) compared to the other glaciers in the Upper Columbia Basin (Pelto et al., 2017). Combining repeat landscape photography and air photography was shown to significantly extend the baseline for studying terrain age and rates of recession. It is not a commonly used technique; most glacier studies rely on contemporary reference and repeat photography (e.g., in which a research team routinely visits a site to repeat their own photographs, rather than any historical imagery); or, researchers use air photographs alone. While higher resolution photographs would likely be needed to determine a site's FBS stages over time, this method proved useful for studying historic glacial extents and should be applied when a baseline preceding the advent of air photography circa the 1940s is needed.

Implications

This research undertook a systematic review of glacial forefield development in a region where few such studies have ever been conducted. Indeed, the biogeomorphological framework is relatively new within the literature of forefield ecology. The framework used in this thesis has not previously been applied in North American temperate glaciated regions; this is, as far as I know, the first study to take a biogeomorphic approach to describing forefield development in a Canadian context. Importantly, there is vanishingly little other scholarship on forefield environments using *any* analytical framework along the Upper Columbia (while conducting this research, I came across none), even as this area is both home to some of the most rapid deglaciation in North America, *and* acts as headwaters for the fourth largest river on the continent. At the time of this writing, there are no peer-reviewed studies documenting glacial change anywhere on the Eastern slopes of the Sir Donald subgroup, even as the Beaver River Valley's glaciers feed one of the last pockets of old growth, inland cedar anywhere on the planet. This research effort may have been the first. The research method employed in this project could be adopted for sites across the region; it could, for example, be used to compare forefield development across different aspects, sizes, elevations, or latitudes. A larger-scale inventory of forefield development could help local planners anticipate risks associated with paraglacial landform instability.

Other inventories of the Southern Interior mountains have found that local conditions likely impact the rate of recession, particularly on smaller glaciers that are “in sheltered sites, such as below steep valley walls or in deep cirque basins, where conditions are favorable for their preservation (i.e., they receive enhanced mass input by avalanching from adjacent slopes and are protected from direct solar radiation throughout a large part of the year)” (DeBeer et al.,

2007). Less is known about the historical retreat rates of other glaciers in the Columbia Mountains, especially predating the 1980s. This is among the first studies to show post-LIA retreat rates of any glacier in the upper Columbia, other than the Illecillewaet. It indicates that, as has been documented in other areas, high-elevation cirque glaciers likely have slower rates of recession, relative to the more frequently-studied large glaciers and icefields in the region. Whereas other small glaciers of the world have been shown to have slower rates of recession (Wood, 2013; DeBeer et al., 2007), such analyses have not been conducted in this region. These findings indicate that hydrological models (Pelto, 2017; Carver et al., 2017; Naz et al., 2014) for the Upper Columbia may be underestimating late season freshet and other glacial contributions – or, conversely, overestimating peak flow – in watersheds dominated by small glaciers. Further research into the region’s smaller, steeper glaciers –such as what has been undertaken in this thesis research project – is needed to determine whether previous findings are consistent with all glaciers within the region.

Both the analysis of FBS stages and a discussion of why smaller glaciers might have locally-distinct rates of recession would benefit from higher resolution data. There is evidence that both primary succession and deglaciation may be controlled by microtopography. However, seldom few analyses of forefields conducted anywhere in the world have used technologies like LiDAR to get sub-1m resolution microtopographic data. In the case of the Upper Columbia in particular, there is a dearth of useful data. This project encountered significant limitations due to the lack of any digital elevation model (DEM) data below 25m resolutions. In the absence of super-high resolution elevation data, other methodologies have been developed; including, for example, using repeat photographs themselves to create DEM. More research is needed here, both to understand how these technologies can be adapted to refine forefield research in general, and also to develop a better understanding of periglacial topography in the Upper Columbia

Basin in particular. Nevertheless, this research confirmed that even in the absence of high-resolution elevation data, both remote-sensing and in situ data collection techniques can provide meaningful analyses about geomorphological and ecological feedback loops in high alpine areas undergoing land cover change.

Postscript

Throughout this document, there has been a tension between the spatial resolution of available data, and the types of conclusions that this research initially hoped to draw. What is the best way to describe a pattern in a place? And more ephemerally: In the scope of irreplaceable loss occurring in every location on this planet, where does new life insist on taking root in the cracks? While reflecting on these questions, I frequently felt more drawn to the first-person experience traveling through the Avalanche glacier forefield than I did to the data. I think, for example, of my hesitancy to classify a sheer cliff as “geomorphological,” even as that may feel most immediately true. Where there were divots, tall pines towered overhead. Where there were shallow cracks, there were pillows of moss. Where there were little rivulets running with late-season melt, there were fireweeds and saxifrages in bloom. These meter-by-meter variations exist beyond what could be reasonably captured in the sorts of data that even high-tech LiDAR surveys could produce. An individual, unexpected pine may have little significance on the ecology of a landscape – nor on a landscape’s ability to weather landslides or avalanches, to retain water, to alter hydrological flows. It remains somehow remarkable that such variation might exist in a place.

In all of my surveys of forefield research, I did not come across any literature that sought to tie these emergent forefield landscapes to the context of settler colonialism and anthropogenic change that together have led to widespread deglaciation. Fields like critical ecology or abolition

geography¹ have yet to reach the scholarship of the cryosphere. Ecological research represents a material frontier of place-making. That is: ecological processes are necessarily coeval with sociopolitical processes; people and land always refer back to one another; these relationships leave visible marks on the land. Relationships with place change the substance of place. Ecological research is a discrete form of governance by which peoples and cultures are alternately subjugating, or subjugated. In the context of glacial forefields, further work is needed that works to “point out that politics has invaded the landscape, that the landscape is now a victim of history, that history is not only the history of human actions, of causes, but the history of effects, of ecological damage” (Solnit, 2014). Rather than live in new relationship with invasive, with novelty, or with damage, the impulse of ecologists is so often so measure and monitor. Power is transmuted; a more subtle way of exerting control is invented. I think of the weeks spent in the office’s front lawn, playing with the folding ruler, the bendable tripod head, as we imagined how we could read a pattern into the complexity of the forefield. I think of the subsequent months spent translating the photos I took in that space into spreadsheets, into integers, into categories with names. In effect, the extent to which instrumentation can collect meaningful data is a reflection of the discrete power it exerted over a landscape. A discursive turn away from such routine categorizations is needed. To do so, the sort of quantitative work that this paper has undertaken, could, for example, be reconsidered as a way of imagining a watershed beyond the moment that extractive networks “killed the river” (White, 1990).

¹ An emerging body of work seeks to delineate the role of colonialism in global warming; Dr. Sue Pierre of University of California, Berkeley, for example, has developed a framework that looks at primary, secondary, and tertiary causes. Using her framework, imperialism and war would both be considered tertiary causes, as the huge amount of emissions from these sources are to blame for the rising temperatures that are making glaciers melt. For more on this, see the work of Sue Pierre, Katherine Yusuff, or Sharad Chari.

These possible interpretive lenses are, of course, well beyond the scope of this particular research project. In the scientific approach taken in this project, the only possible conclusions are ones that follow from the data. And yet: the data alone do not capture the grandeur of the experience of traveling through the forefield. Nor do they adequately reflect the sociopolitical complexity that acts as context for all studies of ecological change. As such, these final reflections are intended to act as an invitation for future research to use an interdisciplinary approach to expand considerations of the limitations of work that takes data at face value. Scientific inquiry can be bettered when researchers attend to moments that data be pushed past modelling and into the realm of imagining the *poiesis* of possible futures – one that insists, for example, on futurity for the Sinixt, Ktunaxa, and Secwepemc people who have already stewarded this landscape through many iterations of world-ending.

Early in this document, the first-known forefield researcher (Matthews, 1992), Johann Coaz, was introduced. Over the course of his 30 distinct first ascents in the Swiss Alps, Johann Coaz began to notice flowers. The year was 1887. At the toe of the Rhone-gletscher, there were waxy yellow saxifrages growing where there had been ice only three years prior. Downslope, life abounded: where the glacier's retreat occurred one decade prior, Coaz counted 39 species of plants. Before Coaz, ecologists studying primary succession -- whereby a newly-formed land surface devoid of life transforms into an ecosystem -- had always used space as the constraining variable. As the Little Ice Age ended in the late 19th century and the world's glaciers began to recede, Coaz saw life beginning. In ecological terms, this discovery is what enabled researchers to substitute space for time. Here is what the land can become at ten years, and twenty years, at a hundred. Normally these inquiries are too time-consuming for a single research project, a single researcher's life. In glacier forefields, that is not so. As they recede incrementally, the edges of glaciers reveal bare rock. What is left downslope is like a contour map whose scale is time. Any

onlooker can see how boulders become dirt. Watch as lichen turns mineral dust into organic matter. Watch as fireweed grows through the cracks in the granite. Watch the cracks widen; watch trees seed, sprout, and tower. “Out of some persistent sense of large-scale ruin, we kept inventing hope,” (DeLillo, 1985). It is beyond the scope of the quantitative sciences to undertake such a task. Nevertheless, analysts may still frame research questions that might offer reasons to hope, if only so that we (as people living through what have been called the most critical years of the Anthropocene) may reconcile despair with the necessity of what we have to do (find a way to survive, like the tiny yellow-petaled flowers bursting through). Reading Coaz’s careful observations, I am reminded that mountaineering and mountain research have always been twin pursuits: both stem from an enduring relationship. Both insist on a meticulous attention. In mountaineering, and for the Mountain Legacy Project, the adage goes that the summit is just the beginning. It appears to be so, too, for the Columbia Basin’s vanishing cryosphere: the line where glaciers vanish is also the place where novel possibilities for continuation take root. For the 2021 field team, too. When our feet met the puddles at the terminus, fed by the metronome drip of the melting glacier, we were amazed. The overhang of the ice sent drips onto sparkling bands of quartz that had never before been seen. That had, until a few weeks ago, perhaps, never before been kissed by the wind.

What if the greatest legacy of forefield research is the invitation to be delighted? At one particularly notable cliff band that the field team had to navigate, a meter-high waterfall landed in a shallow basin of water. At its outflow, it drained into a patch of thick grass reminiscent of a meadow, complete with tiny yellow flowers of the variety I’ve before heard referred to as “belly flowers,” as one would have to lie down to get a proper identification. I remain an amateur plant-

IDER at best, but the site smelled just like the sedges that grew in meadows where I have collected data in in the past.



Figure 40: The photograph I keep.

“It’s seductive to assume that data is, indeed, wisdom. Or that knowledge can exist without data. And how easy, and how effortlessly, one can parade and disguise itself as another” (Morrison, 1998). After months of analyzing data, this memory (now evoked in a framed film still over my desk) still feels like the surest wisdom I have to take away. This is, perhaps, the dream of microtopographic-scale data: that we might reveal new ways to be in relation with the type of magic that one has to lie on your stomach in damp grass to understand.



Figure 41: Photos by S. Zak. On the left: belly-down in the last patch of watermelon snow. On the right, fireweed grows in the shadow of the Avalanche glacier.

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Appendix

Appendix A: Historic and Repeat Photographs

All photos from A. O. Wheeler's 1902 survey, Station 65, "Grizzly Creek West." Each number corresponds to one viewshed; the letters distinguish Historic (a), Original location repeat (b), and Alternate location repeat (c).



1a.



1b.



1c.



2a.



2b.



2c.



3a.



3b.



3c.



4a.



4b.



4c.



5a.



5b.



5c.



6a.



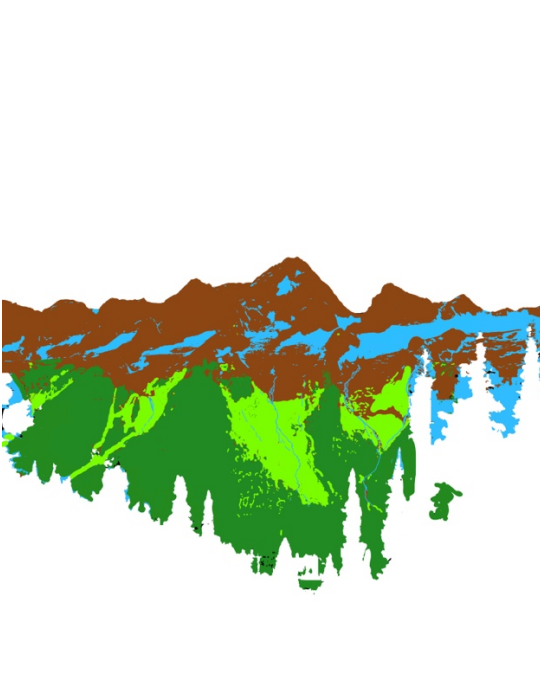
6b.



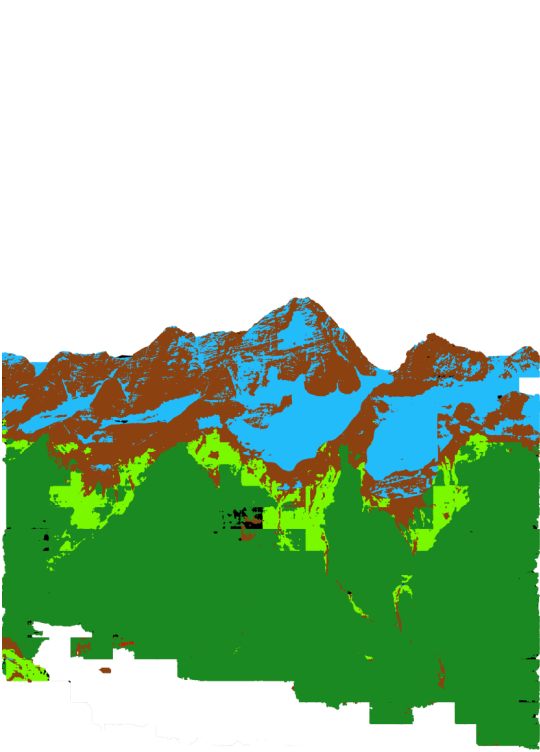
6c.

Appendix B: Image Classification Masks

Repeat:



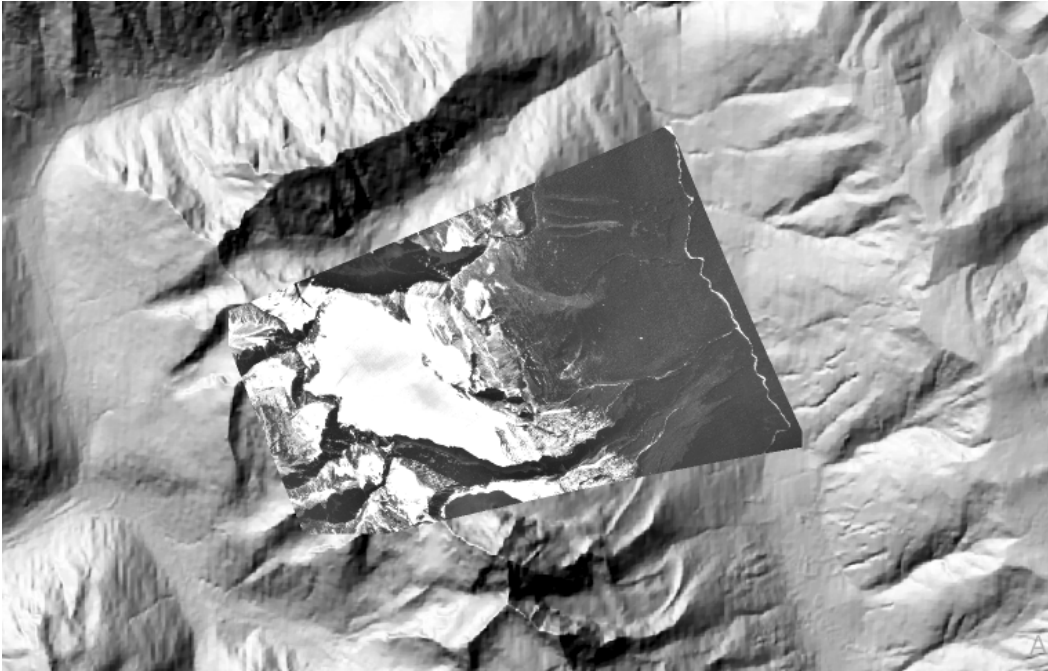
Historic:



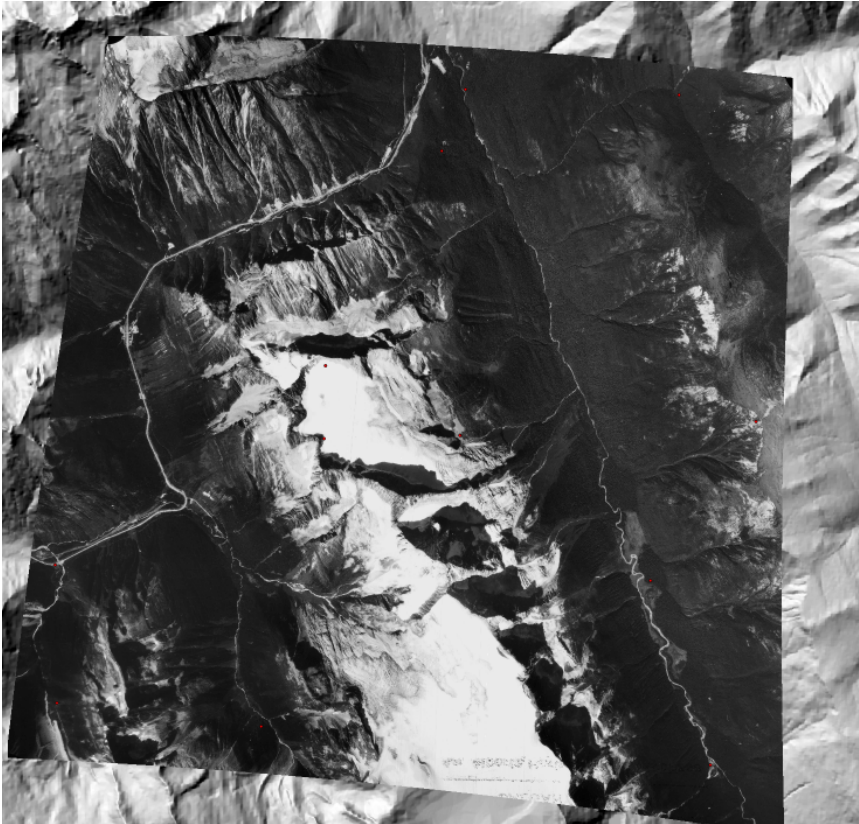
Appendix C: Georeferenced Air Photo Rasters



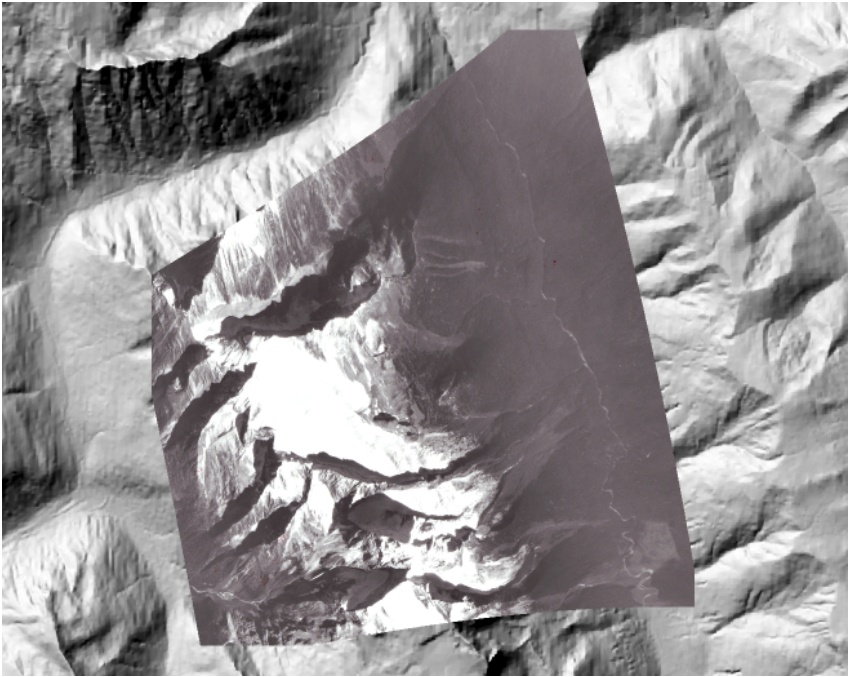
1955 (Film roll A13252)



1966 (Film roll A1 9430)



1970 (Film roll BC5391)



1978 (Film roll 22442)



1995 (Film roll BCB96506)

Appendix D: Transect Data

	Stn 1 ortho	Stn 1 N	Stn 1 S	Stn 2 ortho	Stn 2 N	Stn 2 S	Stn 3 ortho	Stn 3 N	Stn 3 S	Stn 4 ortho	Stn 4 N	Stn 4 S	Stn 5 ortho	Stn 5 N	Stn 5 S	Stn 6 ortho	Stn 6 N	Stn 6 S	Stn 7 ortho	Stn 7 N	Stn 7 S	Stn 8 ortho	Stn 8 N	Stn 8 S	
mature conifer	0	2	2	0	2	2	0	1	2	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	
established woody veg	0	3	2	0	3	2	0	3	2	3	3	3	0	1	2	0	0	0	0	0	1	0	0	0	
vascular plant+grass	2	0	1	0	0	2	0	0	1	2	1	2	2	2	2	0	1	2	0	2	2	2	0	1	0
conifer sapling	2	0	1	1	1	1	0	0	1	0	0	2	0	0	0	0	1	1	0	1	1	0	0	0	
hill	0	0	0	0	0	0	0	0	0	2	0	2	2	1	1	3	1	1	0	0	0	0	1	1	
pioneers (lichen/moss)	1	1	1	1	1	1	1	0	1	0	0	1	1	1	1	1	1	0	0	1	1	1	1	0	
slab (sheer)	0	2	0	1	1	2	2	3	3	0	1	1	0	1	1	0	1	0	3	2	2	2	1	2	
slab (textured)	1	2	3	1	2	2	2	2	2	0	1	2	0	1	1	0	2	0	2	2	2	3	1	2	
Ecological	0	5	4	0	5	4	0	4	4	3	4	5	0	1	2	0	0	0	0	1	0	0	0	0	
Biogeomorphological	4	0	2	1	1	3	0	0	2	2	1	4	2	2	2	0	2	3	0	3	3	0	1	0	
Pioneer	1	1	1	1	1	1	1	0	1	2	0	3	3	2	2	4	1	1	1	1	1	1	1	2	
Geomorphological	1	4	3	2	3	4	4	5	5	0	2	3	0	2	2	0	3	0	5	4	4	4	4	3	

Station 1.

North



Orthogonal



North



Station 2.

South



Orthogonal



North



Station 3.

South



Orthogonal



North



Station 4

North



Orthogonal



South



Station 5

South



Orthogonal



North



Station 6

South



Orthogonal



North



Station 7

South



Orthogonal



North



Station 8

South



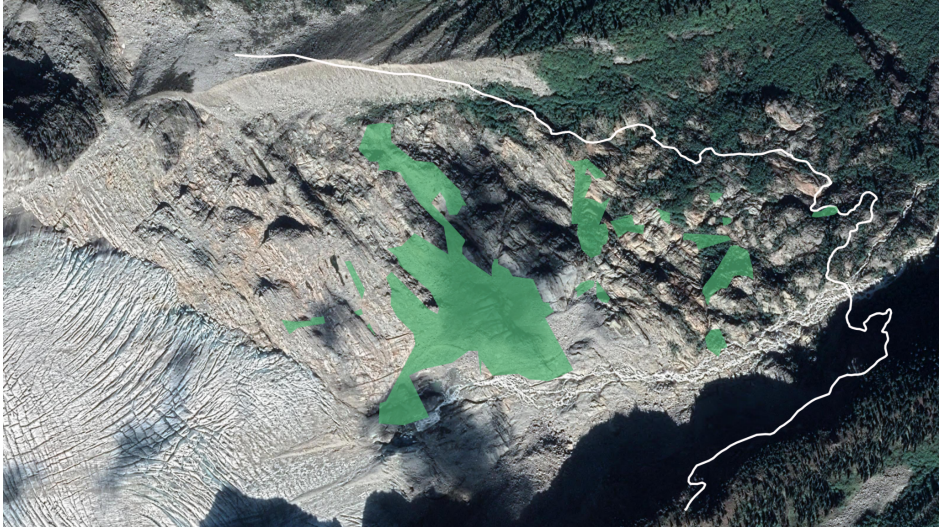
Orthogonal

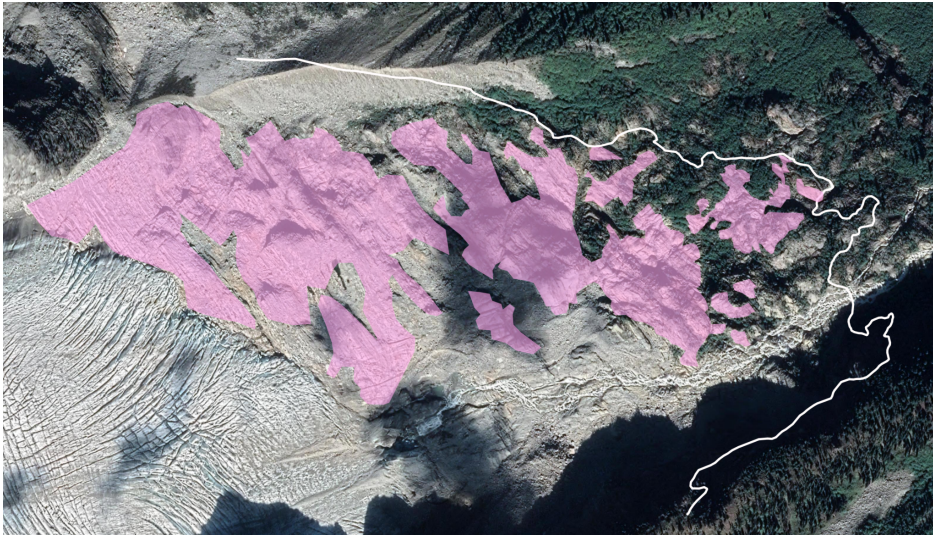
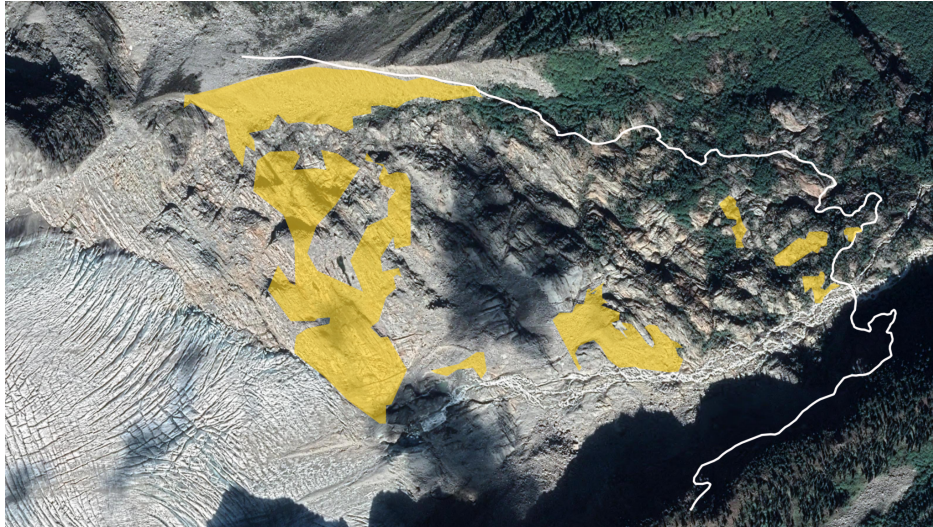


North



Appendix E: Mapped FBS stages





Appendix F: Slope quadrant data

Slope angle by stage

	Geomorphic	Pioneer	Biogeo.	Ecological
0-10	53	34	9	14
10 to 20	106	44	38	34
20-30	57	2	33	29
30-40	64	30	24	28
40-50	27	27	19	28
50-60	30	23	18	8
60-70	8	1	2	5

Terrain age by stage

	Geomorphic	Pioneer	Biogeo.	Ecological
All ages	345	161	143	146
Before1952	206	92	81	146
Since 1995	139	69	62	0
Since 2011	5	8	3	0

Biogeomorphic + age + proximity to water by slope angle

	1902-1970+>50m to water	1970-2011 + >50m to water	2011-2021 + >50m to water
0-10	11	1	0
10 to 20	29	5	0
20-30	21	12	0
30-40	11	9	0
40-50	6	12	0
50-60	0	2	0
60-70	0	0	0
	1902-1970 + <50m to water	1970-2011 + <50m to water	2011-2021 + <50m to water
	0	0	0
	1	1	0
	1	2	0
	1	4	0
	0	5	1
	0	2	1
	0	0	0