QUANTITATIVE ANALYSIS OF LANDSCAPE CHANGE OBSERVED FROM FIRE LOOKOUTS IN GLACIER NATIONAL PARK, MONTANA: A REMOTE SENSING AND GIS APPROACH

THESIS

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This thesis is dedicated to my mom and dad, to whom I owe my love of science, learning, and an appreciation of the world around me; and to Maggie for her support throughout graduate school and especially for listening to my all too often incoherent ramblings and bringing me back to earth when my head was in the clouds.

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CHAPTER I

INTRODUCTION

This project was designed to repeat the panoramic photographs originally taken by the U.S. Forest Service (USFS) in Glacier National Park in 1935 and 1937. The U.S. Forest Service Region Six photographs documented areas visible from active forest fire lookouts in the mid 1930s to assist in locating forest fires. The original photographs were taken using a "photo-recording" transit developed by W.B. Osbourne of the USFS. The transit was a modified swing lens panoramic camera that recorded three 120° panoramic images (Figure 1) matched end to end to create a 360° panorama from each lookout (Arnst 1985, Klasner 2007).

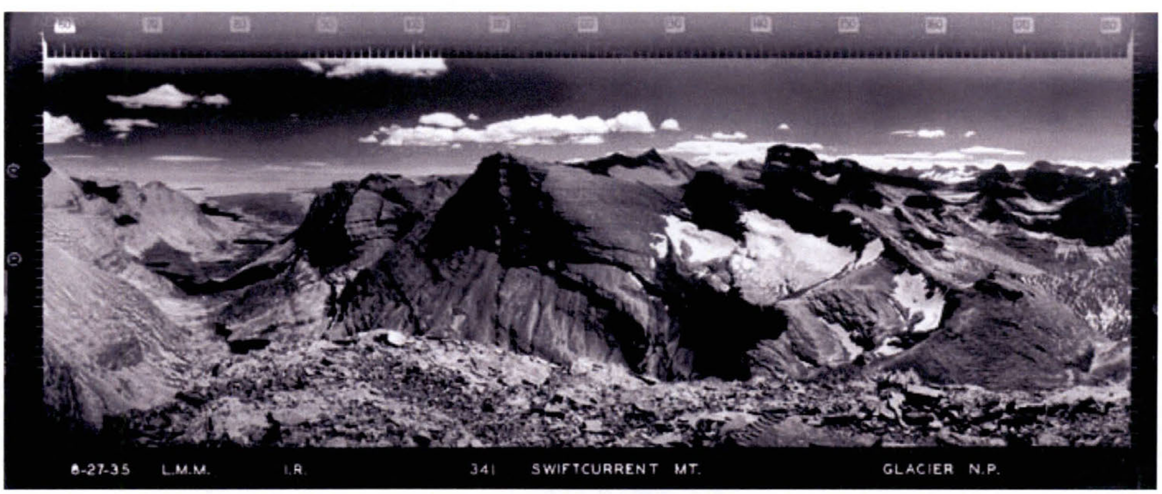


Figure 1: 120 degree photograph, Swiftcurrent Mountain, Glacier National Park.

The primary objective of this research was to repeat seven of the original lookout panoramic photograph sequences taken in Glacier National Park by Lester M. Moe during the summer of 1935 and 1937. The repeat photographs taken are compared to those taken by Moe to determine how the landscape of the areas surrounding the lookouts has changed in the 72 -74 years since Moe's photographs. The primary goals of the research were to quantify the magnitude and rates of landscape change in Glacier National Park with repeat photography as the primary data source. This study also acts as a test bed for a new methodology using GIS and remote sensing techniques to sample landscape change in the photographs.

This research is scientifically significant because it will provide more accurate estimates of landscape change than those of Butler and DeChano (2001) and will provide a new method of measuring several aspects of landscape change within Glacier National Park. By developing a new method to analyze repeat photographs, more quantitative measurements of landscape change will be produced, which will also lead to more research into the use of terrestrial photography in landscape change studies in geography and other disciplines.

CHAPTER II

LITERATURE REVIEW

Landscape and landscape change

The concept of landscape is important in geography and is often defined as the dynamic relationship between humans and the physical environment (Forman and Godron 1986). For this study, the definition of landscape is taken from the field of landscape ecology, which focuses more on the natural environment and less on human interactions, although humans still play a role. Forman and Godron (1986) define landscapes as a cluster of ecosystems that interact, occupy a similar geomorphic and climatic setting, and have similar disturbance regimes. Three main themes are present in landscape ecology, structure, function and change. The structure of a landscape refers to the distribution of plants, animals, energy and materials in the clustered ecosystems. The function of a landscape is how species, energy, and materials move within the landscape. Landscape change, then, is the alteration of the structure and/or function of a landscape (Forman and Godron 1986, Forman 1995). This study focuses only on changes in the structure of the landscape and not the function, because of the nature of the photographs used in this study.

In Glacier National Park a number of studies have been done on different aspects of landscape change. Three areas that have received attention are alpine treeline, forest and meadow infilling, and snow avalanche paths.

Alpine treeline

In the alpine treeline ecotone, sub-alpine flora reaches its upper climatic limit and alpine vegetation reaches its lower climatic limit. This boundary is normally expressed clearly in the landscape as the transition from closed forest canopy to alpine ground level vegetation. Although treeline may be expressed as a clear boundary, many studies have found that treeline in Glacier National Park has several broad controls on its position and patterns, but many local variables play an important role (Walsh et al. 1994, Butler et al. 1994, Resler 2006). Walsh et al. (1994) found that elevation, slope, and aspect were determining factors in the spatial pattern present at treeline. Several studies have found that sheltered areas, e.g. boulders or solifluction terraces, provide favorable sites for seedling establishment needed to advance treeline (Butler et al. 1994, Butler et al. 2004, Resler 2006). Other controlling factors include debris flows (Butler and Walsh 1994), varied spatial characteristics of soil (Butler et al. 2004), geologic substrate (Allen and Walsh 1996), as well as direct human-induced changes (Klasner and Fagre 2002).

Another area of research is the upward migration of treeline in response to changing climatic conditions. Malanson (2001) modeled the response of treeline to changing climatic conditions and found non-linear relationships between the climate variables and the spatial patterns expressed, stating that "surprises are more likely than precise prediction" (Malasnon 2001, 333). Butler et al. (1994) applied repeat photography at several sites in Glacier National Park to monitor treeline positions over roughly 20 years and found that at their sites there was little change in the position of treeline. Butler and DeChano's (2001) repeat photography study showed over the approximately 70 years between photographs results contrary to Butler et al. (1994); in some areas there has been significant upward migration of treeline. Klasner and Fagre (2002) found some increases in the areas of forest patches at treeline as well as forest patches becoming denser, leading to a more abrupt transition to tundra. Fagre (2003) observed changes in the spatial patterns and spatial distributions, but found no overall upward migration of the treeline. The varied results of these studies seem to confirm Malanson's findings from 2001.

Forest and meadow infilling

Forest and meadow infilling have gained attention as an indicator of climate change but could also be a result of fire suppression and management (Butler and DeChano 2001). Recent work with infilling has included Butler and DeChano (2001), Butler et al. (2003a), Butler et al. (2003b), and Cerney and Butler (2004).

Butler and DeChano (2001) observed extensive infilling in Glacier National Park from data taken from repeat photographs from 1935 to 1998. Cerney and Butler (2004), using repeat photography in Waterton Lakes National Park, documented crown closure and aspen encroachment in their sub-alpine study area. Butler et al. (2003a) described the phenomenon of the ribbon forests in Glacier National Park. As part of their observations, the authors noted that the interlaced forest and meadow system overall appeared to be stable, although they did observe some minor establishment of seedlings along the margins of the meadows. Butler et al. (2003b) also found evidence that some encroachment was taking place within the ribbon forests supporting the observations of

Butler et al. (2003a). Butler et al. (2003b) also observed that meadows throughout Glacier National Park as well as Waterton Lakes National Park have been experiencing encroachment since the early 20th century.

Avalanche Paths

Approximately 2,000 snow avalanche paths occupy the mountainsides in Glacier National Park (Butler 1979, Butler and Walsh 1990, Walsh et al. 2004). The spatial position and distribution of avalanche paths is controlled by the 'avalanche climatology' of the area as well as the lithologic and geologic structure of hillslopes (Butler and Walsh 1990). Because avalanche paths are prevalent within the park, they can be indicators of environmental change as Butler and DeChano (2001) illustrated by showing that many of the catchment areas of avalanches were experiencing conifer growth. The authors speculated that this could be a result of change in the 'avalanche climatology' of Glacier National Park.

Repeat photography

Repeat photography, or rephotography, is the process of reoccupying the site of a previous photograph and retaking the same scene (Rogers, Malde, and Turner 1984). One of the main uses of repeat photography is to detect changes in the landscape over a defined time interval (Munroe 2003). One of the first uses of repeat photography is credited to Sebastian Finsterwalder who measured glacial changes with a phototheodolite at Vernagtferner, Austria in 1888 and 1889 (Hattersley-Smith 1966).

A number of authors, including Malde (1975), Harrison (1974), Rogers et al. (1984), Veblen and Lorenz (1991), Butler (1994), Pickard (2002), Munroe (2003), and Kull (2005) have described the methodology of repeat photography. All of these authors listed above make note of several important steps when retaking photographs. The first step is relocating the site at which the original photograph was taken, second is matching the composition of the original photograph and third is "ensuring the comparability of camera equipment" (Butler 1994). All of these steps must be taken in order to produce high quality repeat photographs that can provide direct comparisons or measurements of change.

Panoramic photography

Panoramic photography consists of creating an image or series of images that provide a wider field of view than an ordinary single image. While panoramic photographs provide a wider field of view, they also have unique geometry that a single photograph does not possess (Malde 1983, Meehan 1996). Various methods exist for taking panoramic photographs; most common is the rotation of a standard camera on a tripod to create "segmented panoramas" (Meehan 1996). Meehan (1996) also discusses another method of panoramic photography using a "swing-lens" or "slit-scan shutter". The swing lens method, used in taking the original fire lookout panoramas, works by rotating the lens while the camera body remains stationary, exposing a narrow section of the film as the lens travels around. Both methods have their advantages; a swing lens camera produces a single uninterrupted image, while the lower cost of an ordinary camera and tripod make segmented panoramas the practical option for many.

Quantitative measurements taken from photographs

Several techniques exist to take measurements from terrestrial photographs including photogrammetry, rectifying images to a local datum, rectifying the images to a geographic location (georeferencing), and sampling specific areas of interest.

Photogrammetry is the "science of dimensional analysis from photographs" (Atkinson and Newton 1968) or "the process of making quantitative measurements from photograph-like images" (Graf 1985). The science of photogrammetry has been widely applied in the fields of aerial and satellite remote sensing but was first developed for use with terrestrial images (Atkinson and Newton 1968). By using basic trigonometric functions, real-world measurements can be calculated from a photograph. Terrestrial photogrammetry and the calculations necessary have been discussed by Hallert (1960), Atkinson and Newton (1968), Wolf (1974), and Graf (1985).

Rectification to a local datum is the process by which local control points are established within the study area so that time lapse or repeat photographs can be overlaid or compared using computer software to quantify change. Dexter and Cluer (1999) used this method to measure the erosion of sandbars in the Colorado River below Glen Canyon Dam in Arizona to demonstrate the downstream effects of the dam.

Georeferencing is the process by which an image is related to a specific geographic location in two- or three-dimensional space (Bernhardsen 2002). Georeferencing is traditionally done using surveyed ground-control points that can be seen in the image. In the context of aerial and satellite imagery, georeferencing can be accomplished quite easily because of the nadir or near-nadir perspectives of much of the imagery. Within the realm of terrestrial imagery, georeferencing is a more difficult process because of the oblique nature of the imagery. Georeferencing, while difficult, has been attempted by Aschenwald et al. (2001), Corripio (2004), and Corripio et al. (2004). Aschenwald et al. (2001) developed a methodology to georeference time-lapse photographs of a relatively small area using a digital elevation model and ground control points surveyed using a high-resolution GPS system. This method was applied to measuring landscape analysis of a single mountain slope. Corripio (2004) also developed a method to georeference terrestrial images to a digital elevation model. This method was designed to obtain high temporal resolution measurements of surface albedo on the Mar de Glace glacier, France. Out of this research a stand-alone computer application to georeference terrestrial imagery was developed. Corripio et al. (2004) used a similar method to measure snow drifting in the French Alps.

Several methods, both analog and digital, have been presented in the literature that use sampling to determine change in repeat photography. One method involves transferring the approximate locations of features of interest to a topographic map where measurements of change can be taken. This method was used by Butler and DeChano (2001) in Glacier National Park and Munroe (2003) in the Uinta Mountains. Munroe (2003) also employed two other techniques: a randomly placed grid on top of vegetation to determine differences in density, and digitized meadow areas to discern changes in the relative sizes of the meadows. Clark and Hardegree (2005) employed a purely digital approach by registering images together and randomly sampling pixels from the repeat photographs. Each randomly sampled pixel was assigned a land cover class and, if the class changed between photographs, change was recorded. Another digital approach published by Roush, Munroe, and Fagre (2007), used registered images and square polygon grids to sample treeline. Each polygon grid cell was assigned a land cover class and change was recorded if the grid cells changed classes between the repeat photographs.

CHAPTER III

STUDY AREA

Overview

Glacier National Park is located in northwestern Montana, straddling the Continental Divide and abutting the Canadian border at 49° North latitude. Glacier National Park also forms part of the Waterton-Glacier International Peace Park, formed in 1932, that combines Glacier with its Canadian counterpart, Waterton Lakes National Park. Waterton-Glacier International Peace Park is also designated as a Biosphere Reserve and a World Heritage Site.

Glacier National Park was chosen for this study because there have been limited anthropogenic impacts on the park. Another reason Glacier was used was the availability of the large number of photographs taken by L.M. Moe during the summers of 1935 and 1937.

Geology/Geomorphology

The geology of the park is dominated by Precambrian (Proterozoic) sedimentary rocks of the Belt Series that extend throughout northwestern Montana. Uplifted during the Larimide Orogeny, the shallow water sedimentary deposits of the Belt Series formations, limestones, dolomites, argillites, and sandstones, create the bedrock of the park. The major structural feature of the park is the Lewis Overthrust Fault, exposed along the eastern and southern flanks of the park. This thrust fault has resulted in Precambrian Belt Series rocks being superposed on younger and softer Cretaceous strata (Ross 1959).

The present geomorphology of the area has been dominated by the Pleistocene glaciations, which have carved the dramatic features for which the park is named. Glaciers from all four of the Pleistocene advances are thought to have played a role in denuding the landscape; however, the current landscape was carved primarily by valley glaciers of Wisconsin age. With the retreat of the glaciers, Holocene geomorphic activity has continued to modify the landscape (Ross 1959).

Climate

Glacier National Park is comprised of three distinct climatic zones, the wetter western slope, the dryer eastern slope and the high alpine environment. The western slope is characterized by influence of Pacific Maritime air masses that produce orographic precipitation. The eastern slope lies in the rain shadow of the western slope and is dominated by dryer Continental air masses. The alpine environment of Glacier National Park is typical of other alpine regions, with very short summers and heavy winter snows that persist well into spring (Finklin 1986).

Vegetation

Four main zones; the aspen parklands, the montane, the subalpine, and the alpine characterize the vegetation of Glacier National Park. The parklands can be found at the lower elevations on the dryer eastern side of the park at the transition from the prairie into the mountains. The dominant vegetation here is a patchy mix of aspen, grasses, and scattered low elevation needleleaf trees. The montane vegetation of the park is a mosaic of Douglas fir, ponderosa pine, western larch, and lodgepole pine. The lower subalpine zone shares many of the same species with the montane zone intermixed with Engelmann spruce, subalpine fir, whitebark pine, and alpine larch. Moving into the upper subalpine zone the climax vegetation is dominated by subalpine fir intermixed with Engelmann spruce and whitebark pine. In the harsh alpine zone, vegetation is very limited and reduced to ground cover, grasses, flowers, and lichens (Carrara 1989).

Site descriptions

The seven study sites for this study are defined by the field of view of the original 1935 and 1937 photographs from four forest fire lookouts at Apgar, Looking Glass, Hudson Bay Divide, and Many Glacier, and three other sites at Goat Haunt Overlook, Lake Sherburne, and Cut Bank Creek (Figure 2).

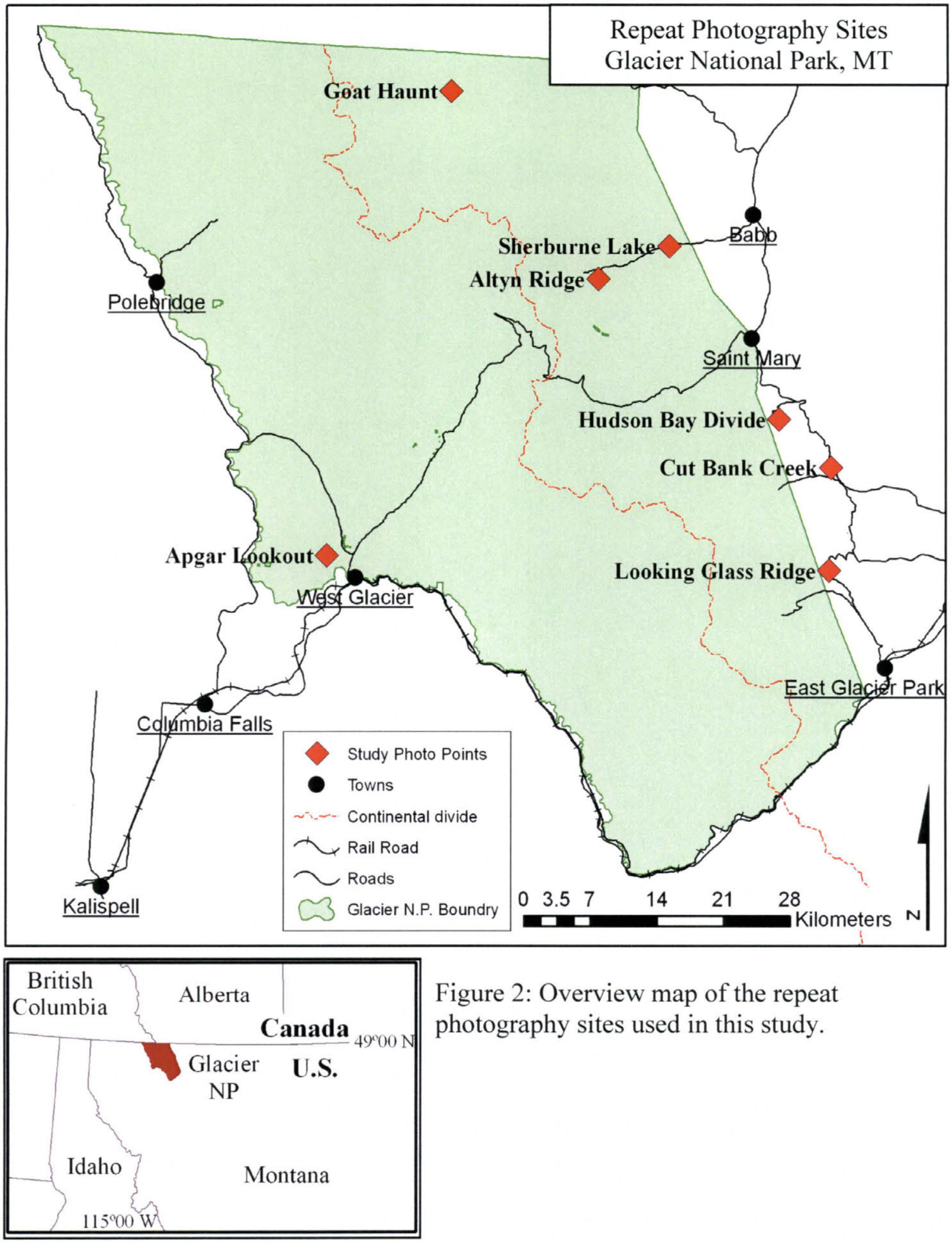


Figure 2: Overview map of the repeat photography sites used in this study.

Apgar Lookout

Location: 48.51818° N, 113.55495° W

Original Taken 23 July 1935. Repeated 20 July 2007.

The main field of view from the Apgar Lookout (Figs. 3 and 4) spans from West Glacier village to the south across Lake McDonald into McGee Meadow to the north. The repeat photographs were taken from the catwalk surrounding the upper level of the lookout structure in three segments, one each from the south, east and north sides of the structure.

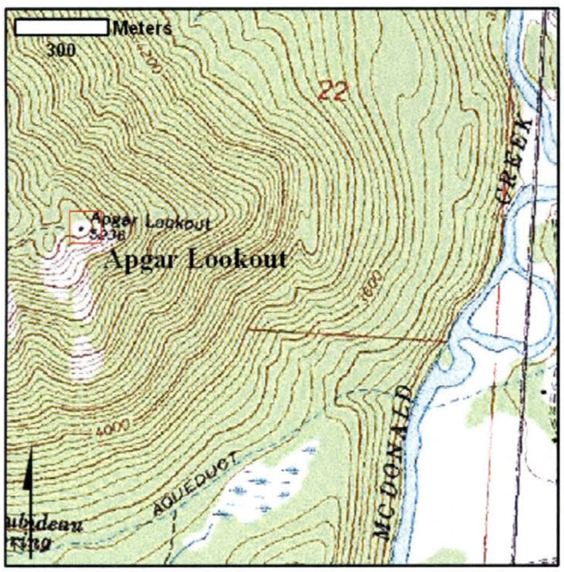


Figure 3: Topographic map (USGS) of the Apgar Lookout site.

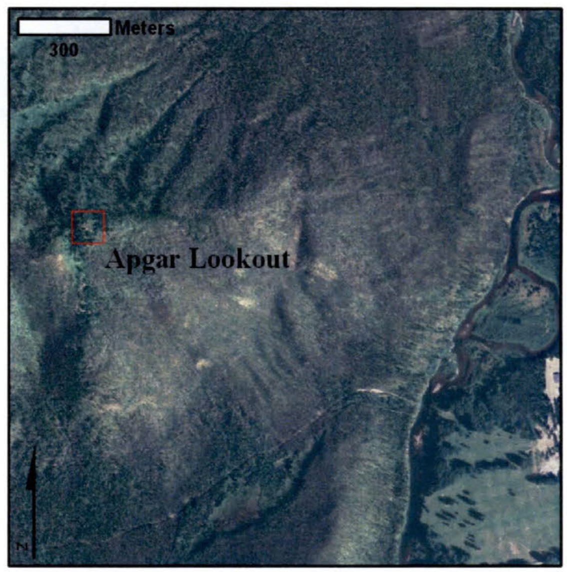


Figure 4: Aerial photograph (USDA) of the Apgar Lookout site.

Looking Glass Ridge

Location: 48.52922° N, 113.3041° W

Original Taken 25 June 1937. Repeated 24 July 2007.

The primary view from Looking Glass (Figs. 5, 6 and 7) is west into the Two Medicine valley, north to Divide Mountain and south across Lower Two Medicine Lake to Bison Mountain. The photographs were taken from the west side of the remaining structure.

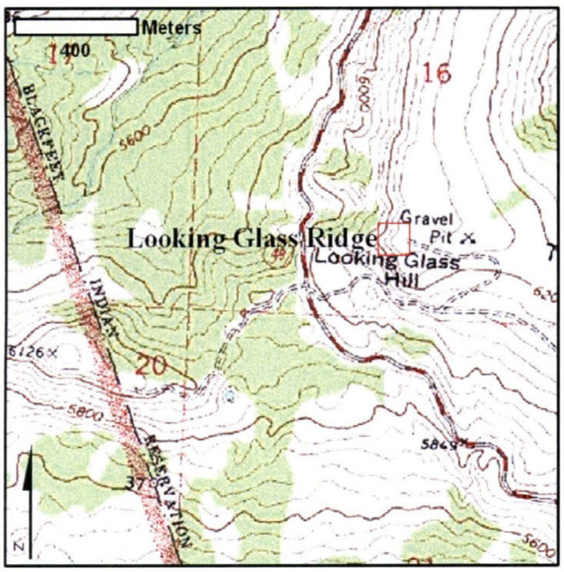


Figure 6: Topographic map (USGS) of the Looking Glass Ridge site.

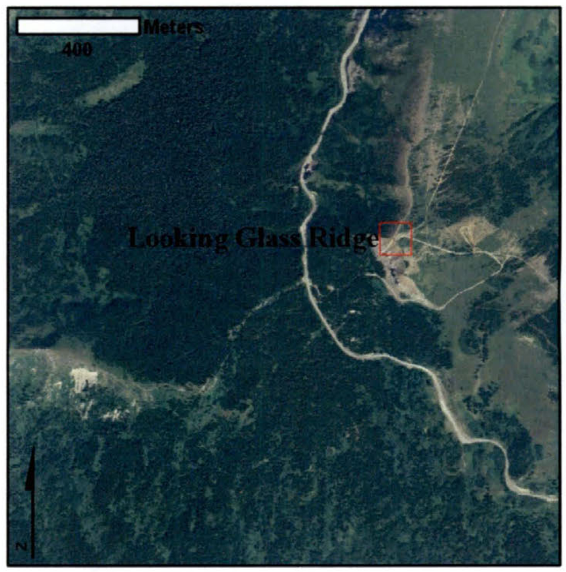


Figure 5: Aerial photograph (USDA) of the Looking Glass Ridge site.

Figure 7: The remaining structure of the Looking Glass Ridge fire lookout. The photographs for this site were on the far side of the structure.

Hudson Bay Divide Lookout

Location: 48.66879° N, 113.38601° W

Original Taken 25 June 1937. Repeated 24 July 2007.

This site encompasses a 360 degree view (Figs. 8 and 9) from the base of Divide Mountain north across Saint Mary Lake, east into the Blackfeet Indian Reservation, and south to the Cut Bank Creek valley. No fire lookout structure exists at this location; it has been replaced by an array of communication antennas. To not obstruct the views, one photograph was taken on the west side of the antenna arrays; the other was taken on the east side of the antenna arrays.

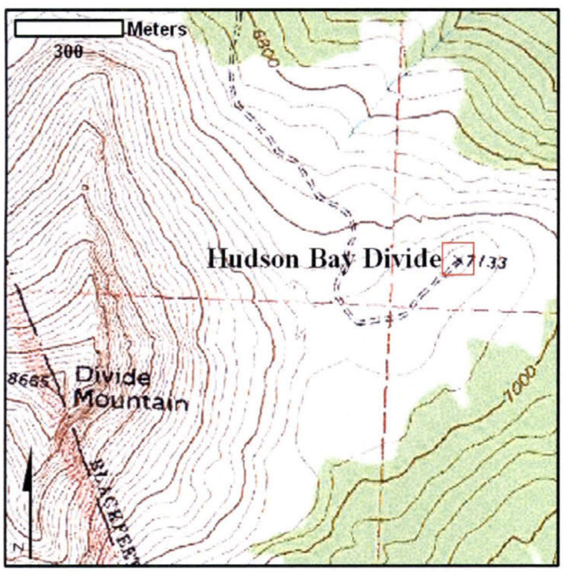


Figure 8: Topographic map (USGS) of the Hudson Bay Divide site.

Figure 9: Aerial photograph (USDA) of the Hudson Bay Divide site.

Altyn Ridge Lookout

Location: 48.79193° N, 113.65408° W

Original Taken 21 August 1935. Repeated 29 July 2007.

Located just above the Many Glacier Lodge, this site overlooks the Many Glacier valley (Figs. 10 and 11). The field of view from the former lookout site is east over Lake Sherburne, north to Altyn Ridge, and west to Grinnell Glacier. The photographs from this site were not from the original fire lookout site, because no remaining structure exists at this site, and trees tall enough to preclude taking photographs have encircled the area where the lookout was located. The alternate site was located immediately to the north atop a limestone ridge visible from the Many Glacier Lodge parking area.

NOTE: The original lookout is thought to have been at 48.7912° N, 113.6528° W (crosshairs Figs. 10 and 11, blue arrow Fig. 12).

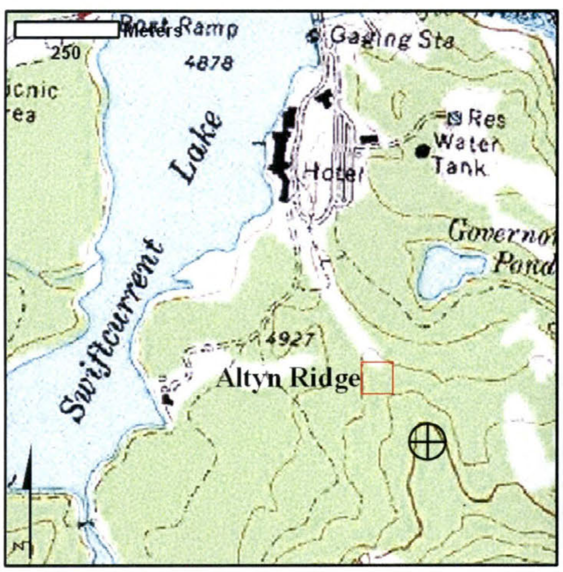


Figure 10: Topographic map (USGS) of the Altyn Ridge site.

Figure 11: Aerial photograph (USDA) of the Altyn Ridge site.

* The red boxes indicate the position of the repeat photographs and the crosshairs mark the location of the original photographs.

Figure 12: Approximate locations of the original and repeat photo points. The red arrow indicates the repeat photo point at the end of the limestone ridge leading up the right side of this photograph. The blue arrow indicates the site of the original photo point. (This photo was taken looking south atop the ridge between the Many Glacier Hotel parking lot and the Many Glacier Hotel)

Goat Haunt Overlook

Location: 48.96013° N, 113.87641° W

Original Taken 12 August 1935. Repeated 25 July 2007.

This site at the south end of Waterton Lake (Figs. 13 and 14) overlooks Waterton Valley to the south, Campbell Mountain to the west, and Waterton Lake to the north across the Canadian border into Waterton Lakes National Park. No structure exists at this location; the photographs were taken at the terminus of the Goat Haunt Overlook Trail, accessible from the Goat Haunt Ranger Station.

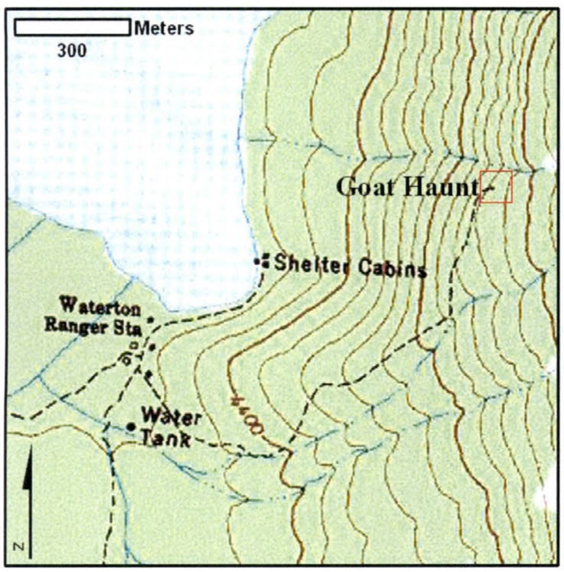


Figure 13: Topographic map (USGS) of the Goat Haunt Overlook site.

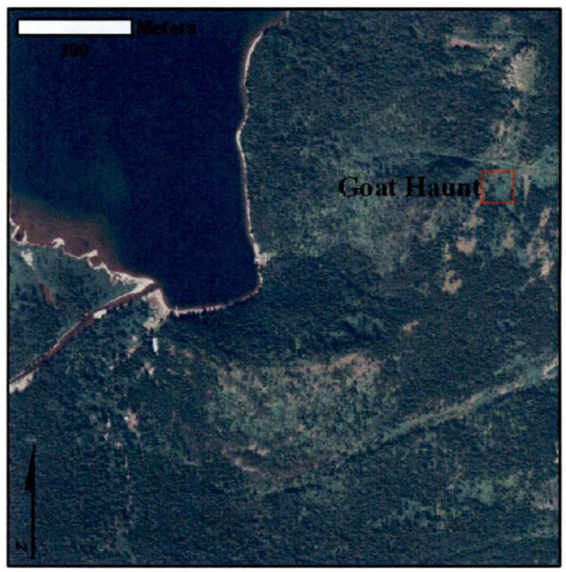


Figure 14: Aerial photograph (USDA) of the Goat Haunt Overlook site.

Figure 15: Sign indicating the end of the Goat Haunt Overlook trail. The photographs for this site were taken on the wooden bench to the west of this sign.

Lake Sherburne Roadside

Location: 48.82677° N, 113.55495° W

Original Taken 20 August 1935. Repeated 29 July 2007.

This site is located inside the GNP boundary on Glacier Route 3 before reaching the Many Glacier Entrance Station, labeled on some maps as Cassidy Curve. The view (Figs. 16 and 17) is comprised of Boulder Ridge to the south and west into the Grinnell and Swiftcurrent Valleys. The photographs were taken in the middle of the vehicle pullout.

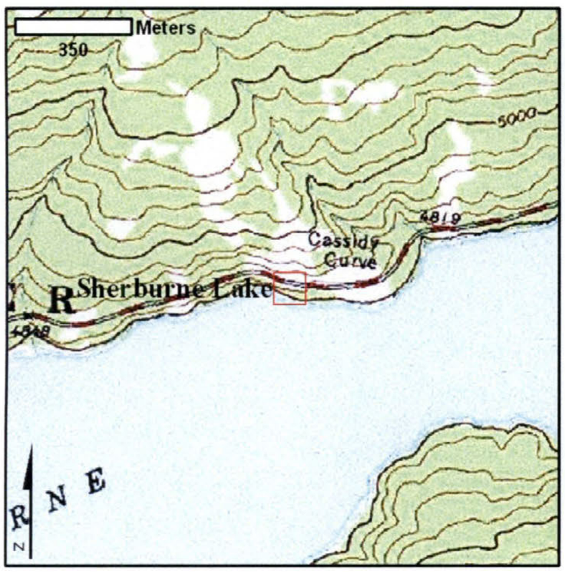


Figure 16: Topographic map (USGS) of the Lake Sherburne site.

Figure 17: Aerial photograph (USDA) of the Lake Sherburne site.

Cut Bank Creek Roadside (Milk Ridge)

Location: 48.62584° N, 113.30811° W

Original Taken 20 August 1935. Repeated 30 July 2007.

Located along Highway 89, 2.6 km north of the intersection with Starr School Road; this site looks south to Cut Bank Ridge, west into the Cut Bank Creek Valley and north toward White Calf Mountain (Figs. 18, 19 and 20)

NOTE: The above coordinates are not the original 1935 photo point. The 1935 photograph was taken ~200 meters further north along the Highway 89 at 48.6274° N, 113.3098° W.

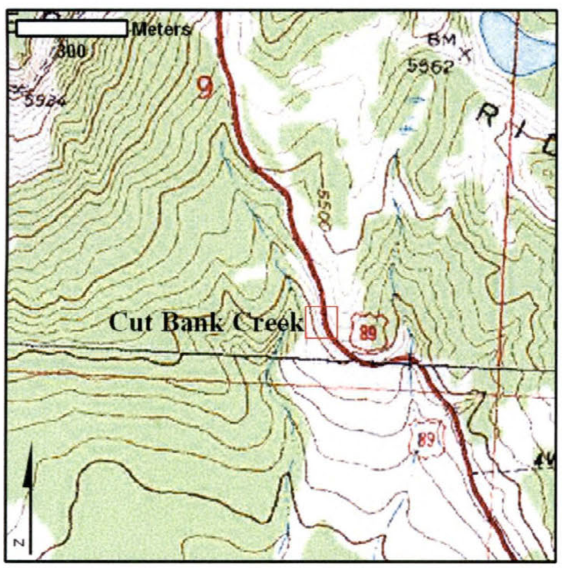


Figure 18: Topographic map (USGS) of the Cut Bank Creek site.

Figure 19: Aerial photograph (USDA) of the Cut Bank Creek site.

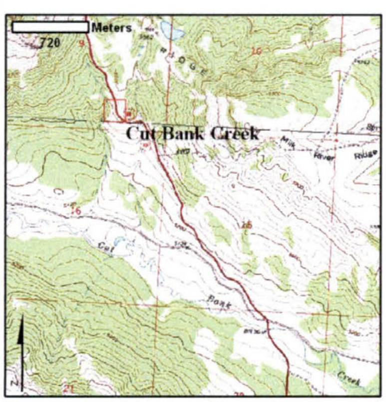


Figure 20: Overview map of the Cut Bank Creek site.

CHAPTER IV

METHODS

Site selection

The original (T_1) photographs had been scanned between 1998 and 1999 by the United States Geological Survey's Northern Rocky Mountain Science Center. The images were in a TIFF format at 4065 by 1680 pixel resolution. These images were studied to become familiar with the areas to be rephotographed and determine the position that each photo needed to be taken.

Sites were chosen based on original photograph quality and ease of access. These criteria were used because of the compressed schedule for research due to an active fire season in northwestern Montana. Seven sites were chosen as primary sites based on the parameters above and an additional four sites were chosen as back up sites. At three sites (Altyn, Lake Sherburne, Hudson Bay Divide) the original photo point was unknown and had to be determined by resection. Using back azimuths of prominent land features determined from the azimuth scales printed on each of the original photographs, resection lines were plotted on the corresponding USGS topographic quadrangle. All of the photo points were programmed into a Garmin eTrex Vista GPS receiver to help in locating and occupying the original locations.

Data collection

The fieldwork for this research was preformed from July 19 – July 30, 2007. Table 1 shows the dates and conditions on the day photographs were taken. Apgar, Altyn Ridge, and Goat Haunt required short hikes; Lake Sherburne, Hudson Bay Divide, Cut Bank, and Looking Glass were accessible by car. Altyn Ridge was the only site that was not accessible, so that an alternative photo point was chosen (see site descriptions). At each site, latitude and longitude were recorded using a Garmin eTrex Vista GPS receiver.

Table 1: Dates and conditions of repeat photographs.

Date	Photographs	Conditions
20 July 2007	Apgar Lookout	Extremely hazy from forest fires to the south and west.
24 July 2007	Looking Glass Hudson Day Divide	Generally clear, some residual haze after storms on 23 July significantly reduce haze.
25 July 2007	Goat Haunt	Clear after early morning fog.
29 July 2007	Altyn Ridge Lake Sherburne	Clear despite Skyland fire to the south along U.S. 2.
30 July 2007	Cut Bank Creek	Clear despite Skyland fire to the south along U.S. 2.

Panoramic photosets for each site were taken with an Olympus SP-500UZ digital camera with individual photographs taken at 7.2 megapixel resolution and 2816 by 2112 pixel size. The photographs were taken with the aid of a monopod to stabilize the camera and provide a rotation point for the panoramic sets. Each panoramic set was taken using an arbitrary starting point and rotated clockwise using the camera mounting screw as the rotation point. Each photograph was taken overlapping at least ¼ of the preceding image.

All photographs were checked in the field for overall quality, level horizon, and proper overlap using the digital camera's LCD screen. If a portion of the panoramic set was not to quality standards, then that photograph was retaken. At most sites, multiple sets of photographs were taken at different points to ensure as close a match as possible to the original photographs. The best matching panoramic sets were then used in the analysis.

Image preprocessing

Because the T_1 photographs were already in a moderate resolution, digital format, very little had to be done to prepare them for analysis. The first step in preprocessing T_1 images was to assign each 120^o segment an arbitrary coordinate system using the 'Define Coordinate System' function in ArcGIS. The custom coordinate system was defined with the origin in the upper left corner of the image. The custom coordinate system was necessary to streamline T_2 image registration and later classification of T_1 and T_2 images.

The second step of preprocessing was to combine the T_2 images into 120^o segments matching the T_1 image segments. The T_2 photographs were 'stitched' with ArcSoft® Panorama Maker Pro software to match the T_1 panorama segments. ArcSoft® Panorama Maker Pro was used because it automatically aligns and blends each of the T_2 image segments into a seamless panoramic image. The software also allowed for manual editing of the registration points in the event the software misaligned any portion of the images.

Image registration

After stitching, the T_2 photographs were registered to the corresponding T_1 photographs using the georeferencing tools in ESRI® ArcMap. Registration points were chosen based on features that could be easily distinguished and matched in both T_1 and T_2 images, mainly objects with distinct shapes or color, ridgelines, peaks, prominent outcrops, or sedimentary layers (Fig. 21). After the registration points were selected a spline transformation was selected to provide the best match the between the T_1 and T_2

images. The T_2 images were rectified to finalize the registrations process using a nearest neighbor resampling to export the warped image.

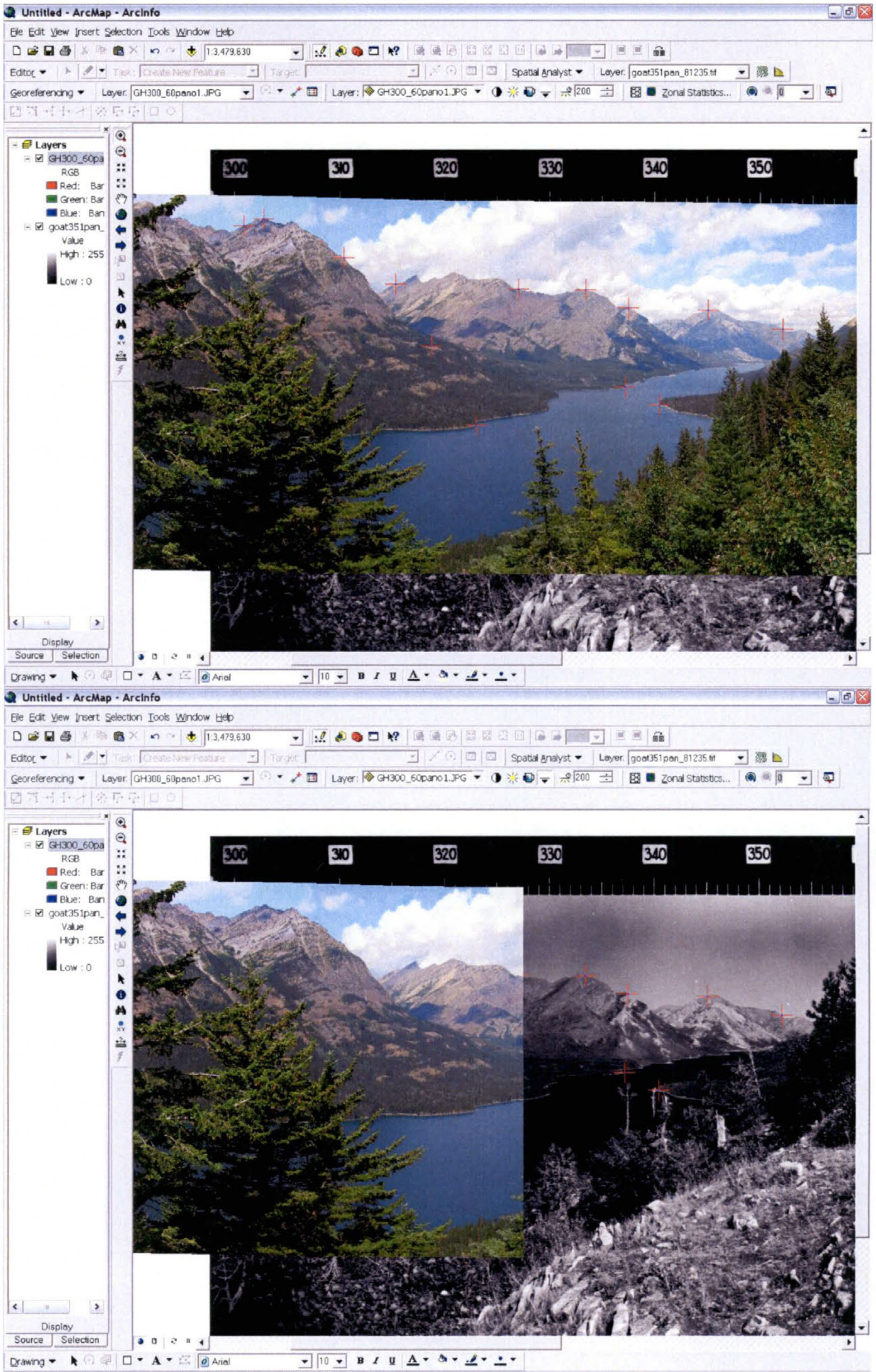


Figure 21: Overlaid and registered images from the Goat Haunt Overlook site. Registration points are red crosses. The top screenshot shows the T_2 image (color) over the T_1 image (monochrome). The bottom screenshot shows a good registration between T_1 and T_2.

Qualitative change assessments

Using the registered 120° panoramic segments, qualitative assessment of landscape change was performed through direct observation of the photo pairs. The qualitative observations were conducted on large-scale prints (9" by 52") of the full 360° views for T_1 and T_2 at each site. Areas of change were noted and the nature of the change recorded. These areas of change were then reexamined in ArcGIS aided by the use of the Effects toolbar in ArcMap that allows for adjustments in transparency of layers, allows one layer to be swiped across one another, and can flicker one layer on and off. Areas of change were outlined with polygons in ArcMap, numbered, and descriptions of the nature of the change were recorded in the polygon attribute table.

Quantitative change assessment

The quantitative assessment was performed on the areas of change identified in the qualitative assessment portion of this study using a combination of remote sensing and GIS tools. Subsets of the larger images were processed to provide a relative measure of landscape change between T_1 and T_2. Change in images was assessed using a random point sampling technique. This method was developed as an alternative to other digital methods of repeat photography analysis, e.g. Clark (2005) and Roush, Munroe, and Fagre (2007). Clark's method requires that images are exactly matched pixel for pixel, which is very difficult to accomplish. Roush, Munroe and Fagre's method is useful for photographs taken at close range where individual trees can be seen.

In order to speed up processing and reduce the noise that surrounding areas introduce, sites identified for quantitative assessment were cropped from the larger T_1 and T_2 images using the Raster Clip function in ArcMap. The clipped T_1 and T_2 images were run classified using the ISODATA unsupervised spectral classification algorithm, performed in the Erdas Imagine remote sensing software package. In order to maximize the differences between classes in the panchromatic T_1 images, the unsupervised classification was performed to include fifteen classes. The layered RGB T_2 images were also classified to fifteen classes to achieve a similar result to the panchromatic T_1 images. After the unsupervised classifications were run, each classification image was overlaid onto the original image in order to combine classes into one of three land cover classes shown in Table 2. This allowed finer resolution classes to be combined, simplifying the classification. All classified images were then exported in a GeoTIFF format for use in ArcMap.

Table 2: Land cover classes used in quantitative analysis.

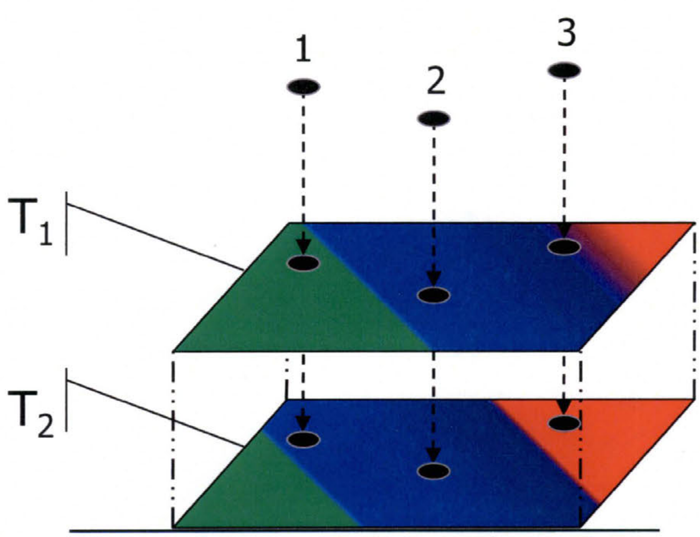
Class Value	Classes
1	Ground Cover Vegetation/Bare Ground
2	Transition Zone
3	Dense Vegetation

Each pair, T_1 and T_2, of classified images was loaded into ArcMap and checked for the proper overlay. Random points were added using a random point generator utility and were confined to the extent of the polygons surrounding each quantitative site. The total number of T_1 image pixels inside the polygon defining each site determined the number of random points added to each image set. This ensured that the images were sampled relative to their overall size. The function for determining the number of random points was T_1 total pixels divided by 500. The random points were assigned an attribute for the ground cover class in which they were situated, in both T_1 and T_2 images, using an extension that extracted the raster values at each point.

Landscape change was calculated by taking the differences in the sample points from T_1 to T_2, resulting in a scale of change from -2 to + 2 (Table 3). Percent change was calculated for each quantitative site and then aggregated to calculate percent change across all of the sites.

Table 3: Change scale and descriptions used in the quantitative portion of this study.

Change Scale	Type of Change
-2	Dense Vegetation to Ground Cover/Bare Ground
-1	Dense Vegetation to Transition
-1	Transition to Ground Cover/Bare Ground
0	No Change
+1	Ground Cover/Bare Ground to Transition
+1	Transition to Dense Vegetation
+2	Ground Cover/Bare Ground to Dense Vegetation



Point	T_1 Class	T_2 Class	Change (T_2-T_1)
1	Green (1)	Blue (2)	-1
2	Blue (2)	Blue (2)	0
3	Blue (2)	Red (3)	1

Figure 22: Illustration of the raster value extraction and change detection methods used in this study.

CHAPTER V

RESULTS

Qualitative analysis

All seven photo sites underwent qualitative analysis as described in Chapter 4. Three of the original seven photo sites were chosen for inclusion in the quantitative portion of this study based on quality of registration and the ability to successfully classify the images. Table 4 lists the sites that were not used and the reasons that some or all of the images from each site were excluded from quantitative analysis. The original images used for the qualitative analysis for all sites are included in Appendix A.

Table 4: Images segments excluded from the quantitative portion of this study.

Site	Images Excluded	Reason for Exclusion
Altyn Ridge	All	Parallax caused by different photo points.
Apgar	All	Poor air quality in T_2 images and extensive fire damage in both T_1 and T_2 (Half Moon Fire, 1929 and Robert Fire, 2003).
Goat Haunt	60°-180°	Not used for either qualitative or quantitative because of the lack of suitable registration points.
Hudson Bay Divide	All	Difficulty getting usable classified images from the T_1 infrared images, combined with extensive fire damage in the T_2 images (Red Eagle Fire, 2006).
Lake Sherburne	All	Parallax caused by different photo points and difficulty getting usable classified images from the Panchromatic and Infrared images.
Looking Glass Ridge	60°-180° / 300°-60°	Difficulty getting usable classified images from the T_1 infrared images.

Even though not all of the sites were included in the quantitative analysis, the qualitative observations of changes are still important in interpreting landscape change. These changes are described briefly here and discussed in Chapter 6.

Altyn Ridge had mostly smaller areas of change throughout the image. In the 180^{o}-300^{o} segment, two areas of change were noticeable: an area of infilling on the talus slope below Angel Wing and a large area of infilling (possible fire recovery) on the eastern flank of Grinnell Point adjacent to Swiftcurrent Lake. All of the changes in the 300^{o}-60^{o} segment were located on the south face of Altyn Peak. These areas included two avalanche chutes that removed trees along the shoreline of Swiftcurrent Lake, an area on talus infilling on the left side of the image and vegetation loss within the talus slope in the middle of the image.

In the Apgar photos the effects of two large forest fires can be seen in the T_1 and T_2 images. The Half Moon Fire in 1929 and the Robert Fire in 2003 burned almost the same area in this portion of the park. One striking area, visible in the 300^{o}-60^{o} segment, is the unburned area along Fish Creek in both T_1 and T_2 photos.

Hudson Bay Divide had a number of areas that changed, but also a number of areas that did not. The 180^{o}-300^{o} segment, showing the eastern face of Divide Mountain, most likely had changes in the abundance and position of vegetation. However, because of problems with the infrared film, vegetation is difficult to interpret and separate from the talus slope. The largest change in the 300^{o}-60^{o} segment was the effects of the Red Eagle Fire in 2006. One area of change was visible, despite the fire damage, was the area along U.S. Hwy. 89 on the left side of the image. In this area a number of new trees have become established outside of the denser tree patches.

Scenic Point in the 60°-180° segment of Looking Glass Ridge experienced a large amount of change between T_1 and T_2. The lower portion of the slope recovered from a fire seen in the T_1 images, and there has been a distinct expansion of upper treeline patches in the upper right of the image. In the 300°-60° segment of Looking Glass Ridge the largest changes occurred in the immediate foreground of the photographs. Infilling in the valley bottom could be recovery from the fire seen in the other two segments. The other area of significant change is the establishment and uphill migration of trees along the slope below the photo point.

Three areas of change were identified at Lake Sherburne. The first was located on Boulder Ridge on the south side of the lake. In the T_1 photo a large area along the lake shore appears to have been damaged by fire and had recovered in the T_2 image. The second area of change was along the north lake shore adjacent to Glacier Route 3 where aspen have matured.

<u>Quantitative analysis</u>

The final set of images used for this portion of the study was comprised of seven 120° image segments, all three from Cut Bank Creek, two from Goat Haunt, and two from Looking Glass Ridge. From the seven image segments, nine quantitative sample sites were extracted and classified as outlined in the methods. Table 4 shows each qualitative sample site with the size of the area sampled and the number of random sample points used in each.

Table 5: Qualitative sample site size and number of random sample points.

Qualitative Sample Sites	Size (pixels)	Random Sample Points Used
Cut Bank Creek 60°-180°	164,160	328
Cut Bank Creek 180°-300°	393,240	786
Cut Bank Creek 180°-300° (2)	36,800	74
Cut Bank Creek 300°-60°	68,790	138
Goat Haunt 180°-300°	37,200	74
Goat Haunt 180°-300° (2)	15,000	30
Goat Haunt 300°-60°	73,390	147
Looking Glass Ridge 180°-300°	250,730	501
Looking Glass Ridge 180°-300° (2)	612,680	1,225
TOTAL		3,303

Cut Bank Creek 60°-180°

The hillslope in this segment was observed in the qualitative analysis to have undergone infilling on the left of the image and a mix of infilling and losses along the riparian corridor of Cut Bank Creek on the right. In the T_1 image the left portion of this site was observed to have been disturbed, by fire or disease, leaving an open area in the forest canopy. In the T_2 image the same area had a closed canopy suggesting infilling and recovery form the disturbance present in the T_1 image. The quantitative data support these observations; 11 sample points in this area show an increase in vegetation from the Transition class in T_1 to the Dense Vegetation class in T_2. The riparian corridor of Cut Bank Creek on the right side of the site was thought to have experienced both gains and losses in equal amounts. However, the quantitative analysis showed that the change in this area was almost exclusively negative changes in vegetation. Eighteen sample points showed a negative (-1) change from dense vegetation to transition and four sample points showed positive changes (three +1 and one +2).

Figure 23: Results of the random point sample overlaid on the 2007 image, Cut Bank Creek 60°-180°.

Table 6: Results of the random point sample, Cut Bank Creek 60°-180°.

Change	Sample Points	Percent Change
Dense Vegetation to Ground Cover/Bare Ground (-2)	1	0.3%
Transition to Ground Cover/Bare Ground (-1)	2	0.6%
Dense Vegetation to Transition (-1)	17	5.2%
No Change (0)	282	86.0%
Ground Cover/Bare Ground to Transition (+1)	1	0.3%
Transition to Dense Vegetation (+1)	22	6.7%
Ground Cover/Bare Ground to Dense Vegetation (+2)	3	0.9%
TOTALS	328	100%

Cut Bank Creek 180°-300°

This segment had two quantitative sites, one larger site contiguous with the 60°-180° segment and one smaller site on the opposite side of the Cut Bank Creek valley. The larger site was observed to have undergone a large amount of change throughout the site. The upper left underwent the same T_1 disturbance, fire or disease, as the upper right portion of the 60°-180° site. Quantitative analysis confirmed the observations and recorded positive changes in the vegetation mainly in the +2 category (24 sample points) but also in the +1 category (14 sample points). The largest change at this site was a large area of loss along the bottom of the hill, a result of the logging activities of the Blackfeet Nation. Sixty-seven sample points showed negative change in the -2 category and twenty-nine additional points fell into the -1 category. The qualitative analysis of the second quantitative site identified large areas of infilling. The results from the quantitative analysis show that 17 of the seventy-four sample points (23%) recorded a positive (+2) change in vegetation.

Figure 23: Results of the random point sample overlaid on the 2007 image, Quantitative Site 1, Cut Bank Creek 180°-300°.

Table 7: Results of the random point sample. Quantitative Site 1, Cut Bank Creek 180°-300°.

Change	Sample Points	Percent Change
Dense Vegetation to Ground Cover/Bare Ground (-2)	73	9.3%
Transition to Ground Cover/Bare Ground (-1)	3	0.4%
Dense Vegetation to Transition (-1)	60	7.6%
No Change (0)	564	71.8%
Ground Cover/Bare Ground to Transition (+1)	1	0.1%
Transition to Dense Vegetation (+1)	51	6.5%
Ground Cover/Bare Ground to Dense Vegetation (+2)	34	4.3%
TOTALS	786	100%

Figure 25: Results of the random point sample overlaid on the 2007 image. Quantitative Site 2, Cut Bank Creek 180°-300°.

Table 8: Results of the random point sample, Quantitative Site 2, Cut Bank Creek 180°-300°.

Change	Sample Points	Percent Change
Dense Vegetation to Ground Cover/Bare Ground (-2)	0	0%
Transition to Ground Cover/Bare Ground (-1)	0	0%
Dense Vegetation to Transition (-1)	2	2.7%
No Change (0)	48	64.9%
Ground Cover/Bare Ground to Transition (+1)	1	1.4%
Transition to Dense Vegetation (+1)	6	8.1%
Ground Cover/Bare Ground to Dense Vegetation (+2)	17	23.0%
TOTALS	74	100%

Cut Bank Creek 300°-60°

The hilltop in this segment was identified as the only area of change in this segment. The areas of change within this site were the upslope migration of trees and the thinning of vegetation at the top of the hill. The quantitative analysis illustrated the changes observed, however more positive change and less negative change were recorded than expected. Thirty-five sample points (25.4%) recorded +2 changes whereas a total of forty-two points recorded +1, twenty-one each, of Ground Cover/Bare Ground to Transition and Transition to Dense Vegetation (30.4%). Negative changes of -1 were recorded at eight sample points (5.8%), seven points were Dense Vegetation to Transition and one point was Transition to Ground Cover/Bare Ground. The negative changes of -2 were limited to two sample points (1.4%).

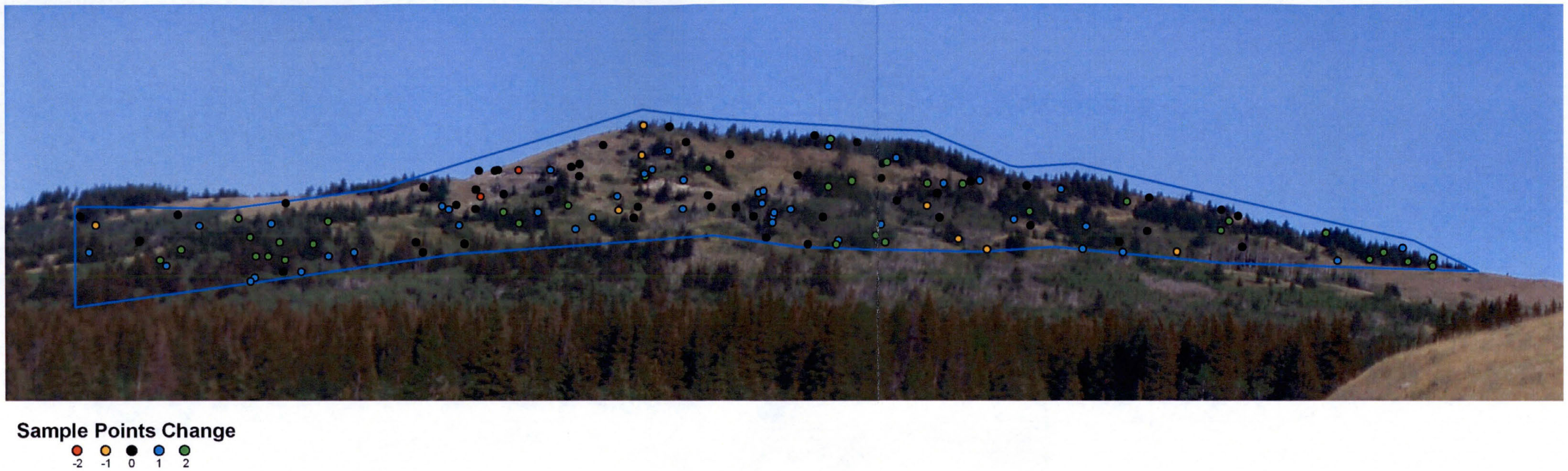


Figure 26: Results of the random point sample overlaid on the 2007 image, Quantitative Site 1, Cut Bank Creek 300°-60 °.

Table 9: Results of the random point sample. Quantitative Site 2, Cut Bank Creek 300°-60°.

Change	Sample Points	Percent Change
Dense Vegetation to Ground Cover/Bare Ground (-2)	2	1.4%
Transition to Ground Cover/Bare Ground (-1)	1	0.7%
Dense Vegetation to Transition (-1)	7	5.1%
No Change (0)	51	37.0%
Ground Cover/Bare Ground to Transition (+1)	21	15.2%
Transition to Dense Vegetation (+1)	21	15.2%
Ground Cover/Bare Ground to Dense Vegetation (+2)	35	25.4%
TOTALS	138	100%

Goat Haunt 180°-300°

This segment had two smaller areas of change indentified in the qualitative analysis. Both areas centered on bedrock outcrops and the loss of vegetation on the edges of these outcrops. Quantitative Site 1 contained 74 sample points, 28 of which changed based on data from the classified images. Twenty-five points (33.7%) indicated a negative change in vegetation. Most of these points of negative change were located adjacent to the bedrock outcrops, which is where the qualitative analysis suggested that change was going to be found. Quantitative Site 2 was expected to have similar results to Site 1 with changes around the edges of the bedrock outcrops. At this site only five of the thirty sample points (16.7%) showed negative changes and of the 12 points adjacent to the bedrock outcrops, only two showed negative change and one showed a positive change.

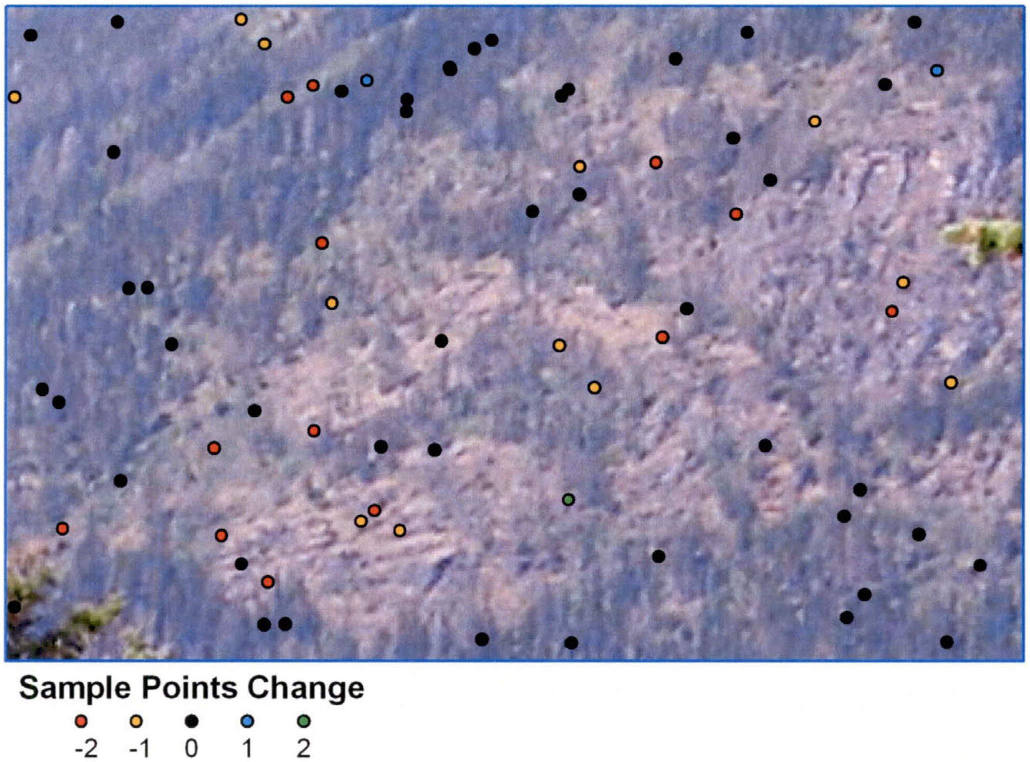


Figure 27: Results of the random point sample overlaid on the 2007 image, Goat Haunt 180°-300° Quantitative Site 1.

Table 10: Results of the random point sample, Goat Haunt 180°-300° Quantitative Site 1.

Change	Sample Points	Percent Change
Dense Vegetation to Ground Cover/Bare Ground (-2)	13	17.6%
Transition to Ground Cover/Bare Ground (-1)	8	10.8%
Dense Vegetation to Transition (-1)	4	5.4%
No Change (0)	46	62.2%
Ground Cover/Bare Ground to Transition (+1)	1	1.4%
Transition to Dense Vegetation (+1)	1	1.4%
Ground Cover/Bare Ground to Dense Vegetation (+2)	1	1.4%
TOTALS	74	100%

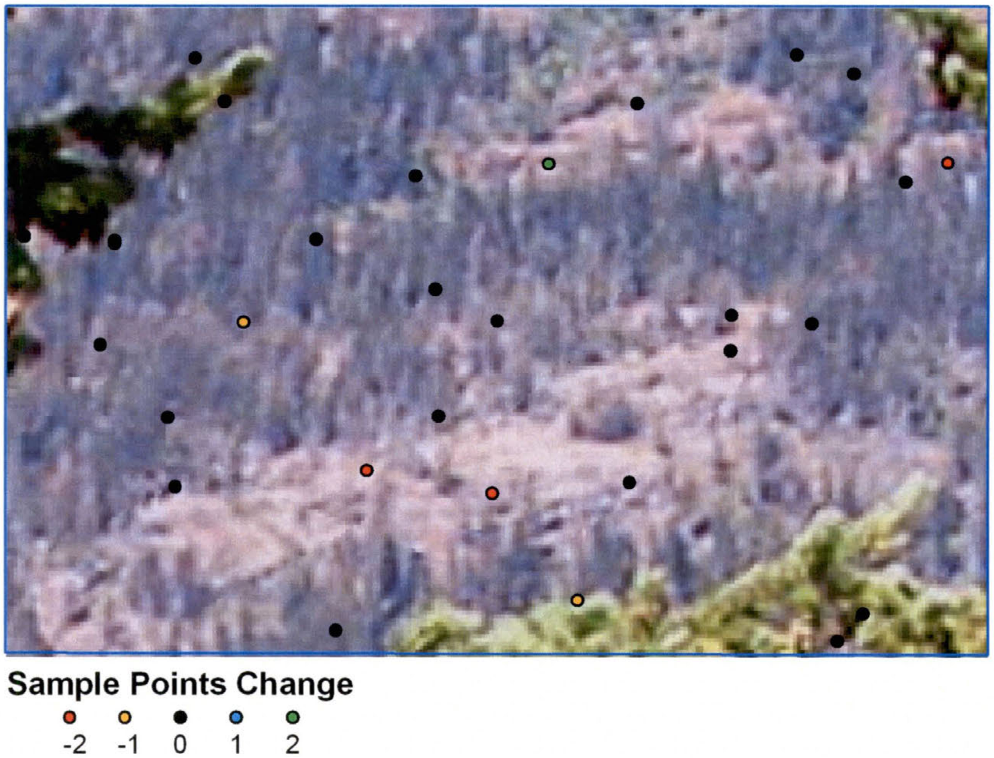


Figure 28: Result of the random point sample overlaid on the 2007 image, Goat Haunt 180°-300° Quantitative Site 2.

Table 11: Result of random point sample, Goat Haunt 180°-300° Quantitative Site 2.

Change	Sample Points	Percent Change
Dense Vegetation to Ground Cover/Bare Ground (-2)	3	10.0%
Transition to Ground Cover/Bare Ground (-1)	0	0.0%
Dense Vegetation to Transition (-1)	2	6.7%
No Change (0)	24	80.0%
Ground Cover/Bare Ground to Transition (+1)	0	0.0%
Transition to Dense Vegetation (+1)	0	0.0%
Ground Cover/Bare Ground to Dense Vegetation (+2)	1	3.3%
TOTALS	30	100%

Goat Haunt 300°-60°

This image segment experienced similar vegetation losses to the Goat Haunt 180°-300° segment. The qualitative analysis identified several smaller sites that all had vegetation losses at the margins of the bedrock outcrops. These small sites were grouped into one larger quantitative site. The change at this site followed what was observed in the qualitative analysis as vegetation loss at the margins of the bedrock outcrops, 31 (21.1%) sample points showed a negative change. An unexpected result was the 38 sample points (25.8%) that showed positive change. These areas were reexamined and it was observed that the areas of positive change were due to the canopy becoming denser, through infilling or maturation, between 1935 and 2007.

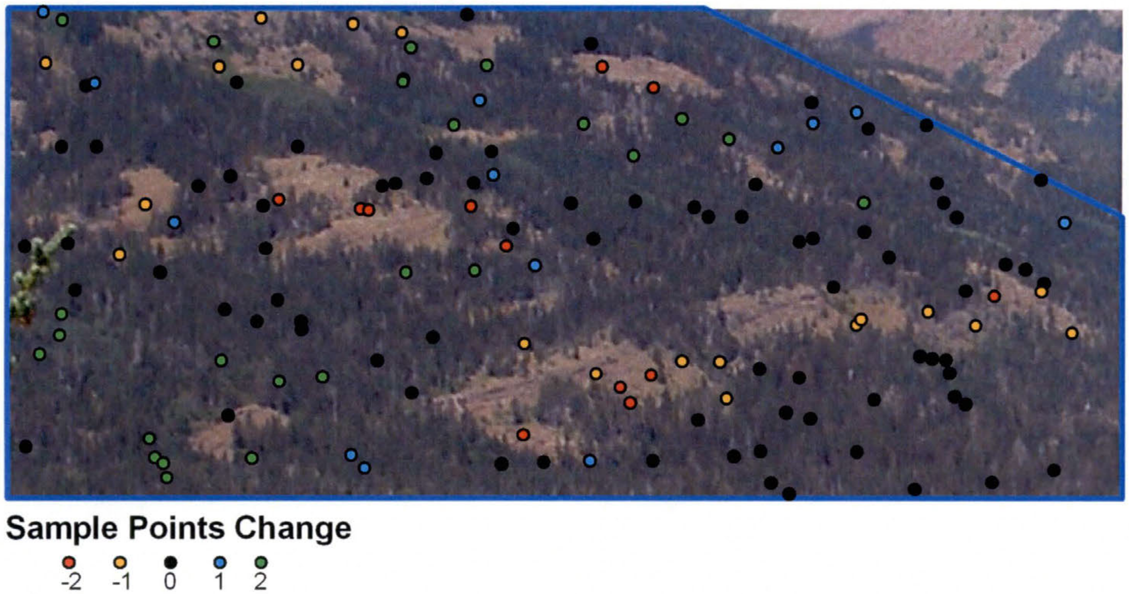


Figure 29: Results of the random point sample overlaid on the 2007 image, Goat Haunt 300°-60° Quantitative Site.

Table 12: Results of the random point sample, Goat Haunt 300°-60° Quantitative Site.

Change	Sample Points	Percent Change
Dense Vegetation to Ground Cover/Bare Ground (-2)	12	8.2%
Transition to Ground Cover/Bare Ground (-1)	6	4.1%
Dense Vegetation to Transition (-1)	13	8.8%
No Change (0)	78	53.1%
Ground Cover/Bare Ground to Transition (+1)	3	2.0
Transition to Dense Vegetation (+1)	10	6.8%
Ground Cover/Bare Ground to Dense Vegetation (+2)	25	17.0%
TOTALS	147	100%

Looking Glass Ridge 180°-300°

This segment contained two sites; one site occupying the north-facing slope of Scenic Point adjacent to Lower Two Medicine Lake, the second site was located on the east-facing slope of Spot Mountain. The two main areas of change in the first site were an area of forest fire recovery on the left side and the infilling in the riparian zone along Two Medicine Creek. The fire recovery was recorded in the quantitative analysis by the large number of sample points that recorded +1 and +2 change on the left side of the image. The riparian can also be seen clearly in the quantitative analysis by the +2 sample points extending upstream from Lower Two Medicine Lake. The negative changes at this site were not expected and, after reviewing the images, all of the negative sample sites are thought to be the result of classification errors.

The second site in this segment was characterized by change throughout the site. Most of the changes happened within the bottom half of this site; mainly infilling and the upslope migration of vegetation. The two meadow areas in the lower right showed the most dramatic infilling, illustrated by the large number of sites that recorded +2 change. Two other areas of change stand out in this site, the areas of negative change in both the upper left and upper right corners. These areas recorded a large amount of negative change at the upper boundary of the forest, which is not what was expected given the amount of positive change below these areas.

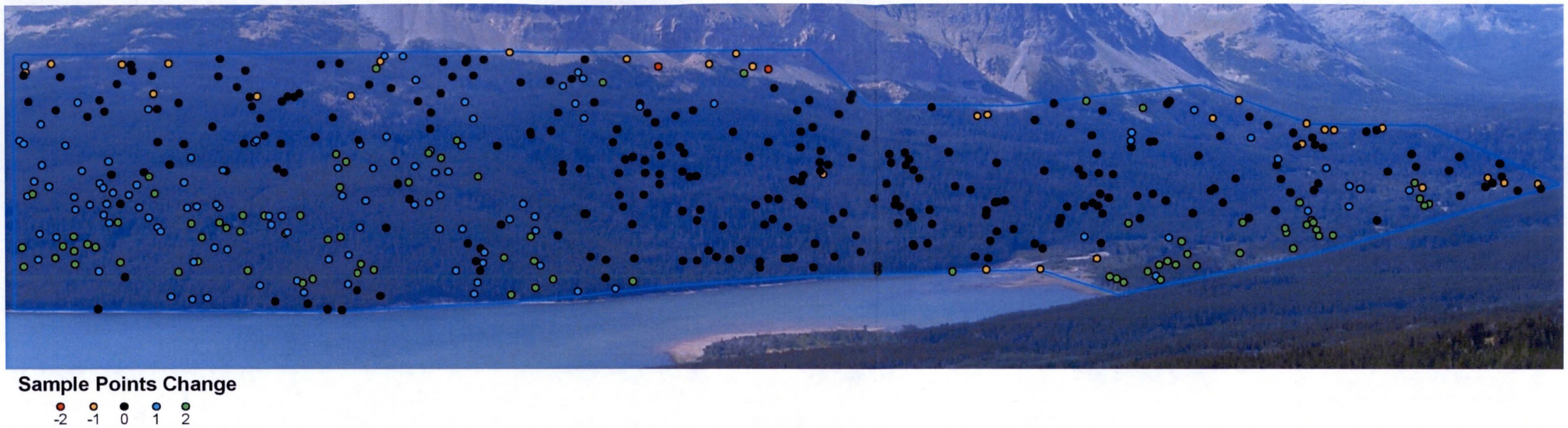


Figure 30: Results of the random point sample overlaid on the 2007 image, Looking Glass Ridge 180°-300° Quantitative Site 1.

Table 13: Results of the random point sample, Looking Glass Ridge 180°-300° Quantitative Site 1.

Change	Sample Points	Percent Change
Dense Vegetation to Ground Cover/Bare Ground (-2)	2	0.4%
Transition to Ground Cover/Bare Ground (-1)	7	1.4%
Dense Vegetation to Transition (-1)	23	4.6%
No Change (0)	274	54.7%
Ground Cover/Bare Ground to Transition (+1)	4	0.8%
Transition to Dense Vegetation (+1)	109	21.8%
Ground Cover/Bare Ground to Dense Vegetation (+2)	82	16.4%
TOTALS	501	100%

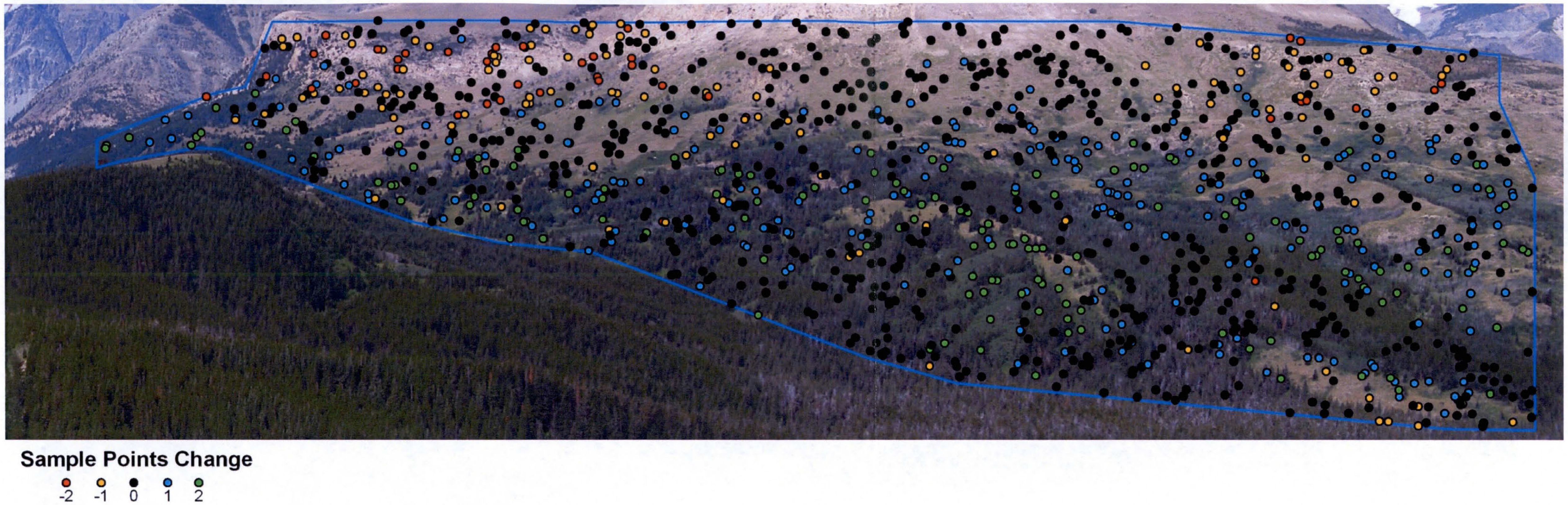


Figure 31: Results of the random point sample overlaid on the 2007 image, Looking Glass Ridge 180°-300° Quantitative Site 2.

Table 14: Results of the random point sample, Looking Glass Ridge 180°-300° Quantitative Site 2.

Change	Sample Points	Percent Change
Dense Vegetation to Ground Cover/Bare Ground (-2)	42	3.4%
Transition to Ground Cover/Bare Ground (-1)	80	6.5%
Dense Vegetation to Transition (-1)	33	2.7%
No Change (0)	699	57.1%
Ground Cover/Bare Ground to Transition (+1)	148	12.1%
Transition to Dense Vegetation (+1)	79	6.4%
Ground Cover/Bare Ground to Dense Vegetation (+2)	144	11.8%
TOTALS	1225	100%

CHAPTER VI

DISCUSSION AND CONCLUSIONS

Landscape change in Glacier National Park

From the 3,303 sample points distributed through the seven quantitative analysis sites, these data illustrate general stability in the environment but also a trend toward increasing vegetation. Table 15 shows that the majority (62.55%) of the sample points recorded no change. Positive changes accounted for 10.35% (+2) and 14.50% (+1) of the sample points, and negative changes for a total of 4.48% (-2) and 8.11% (-1).

Table 15: Total sampled changes for the quantitative portion of this study.

Total Change	Total Sample Points	Percent Change
Dense Vegetation to Ground Cover/Bare Ground (-2)	148	4.48%
Transition to Ground Cover/Bare Ground (-1)	107	3.24%
Dense Vegetation to Transition (-1)	161	4.87%
No Change (0)	2066	62.55%
Ground Cover/Bare Ground to Transition (+1)	180	5.45%
Transition to Dense Vegetation (+1)	299	9.05%
Ground Cover/Bare Ground to Dense Vegetation (+2)	342	10.35%
TOTALS	3,303	100%

Although the above data do illustrate an overall trend toward increasing vegetation they do not show the large variations in recorded changes both within and between sites. Table 16 shows the range of values that were recorded for each category of change. These variations in the dataset suggest that there are other factors at work than just gains or losses of vegetation throughout the study area. Many of the areas of change seen in this study seem to be related to local disturbances (e.g. fire, disease, geomorphic activity); many of the areas of large positive changes were recovered from disturbances visible in the T_1 images and many of the negative changes were related to disturbances seen in the T_2 images. In addition to the disturbance-related changes, a small number of sample points fell into another category of change. These areas, both positive and negative, are most likely the result of factors like mortality, maturation, infilling and migration through seed dispersal.

Table 16: Minimum, maximum, and average values for each category of change.

Change	Minimum	Maximum	Average
Dense Veg. to GC/BG (-2)	0.0%	17.6%	5.6%
Trans. to GC/BG (-1)	0.0%	10.8%	2.7%
Dense Veg. to Trans. (-1)	2.7%	8.8%	5.4%
No Change (0)	37.0%	86.0%	62.9%
GC/BG to Trans. (+1)	0.0%	15.2%	3.7%
Trans. to Dense Veg. (+1)	0.0%	21.8%	8.1%
GC/BG to Dense Veg. (+2)	0.9%	25.4%	11.5%

The disturbances that were observed in both the qualitative and quantitative portions of this study fall into four broad categories: anthropogenic, fire, geomorphic/climatic, and disease. All of these disturbances can occur at small and large scales; from the small scale affecting individual plants or groups of plants to the large scale affecting thousands of acres. Anthropogenic disturbances can be seen throughout the park in conjunction with road and building construction. The most widespread anthropogenic impacts are those of the commercial logging operations of the Blackfeet Nation along the eastern border of the park. These effects can be seen at Cut Bank Creek and Hudson Bay Divide. Fire is one of the largest single disturbances observed in this study as it affected large areas at three of the seven sets of repeat photographs, Apgar T_1 and T_2, Looking Glass T_1, and Hudson Bay Divide T_2. Through burning, fire creates a new and diverse landscape by recycling nutrients and promoting biodiversity.

Geomorphic disturbances cover a wide range including: rock falls and talus slopes, snow avalanches and floods. The effect rock falls have on vegetation varies with the size of the event; even small events can kill trees and large events can disturb large areas of forest. Rock falls kill trees and other vegetation through impact trauma and uprooting. Talus slopes are the result of rock falls and act in their own way to disturb vegetation. With continued input, talus slope sediments migrate downhill, displacing vegetation as they progress. These two geomorphic processes are common throughout the park and can be seen in the photographs from Altyn Ridge, Cut Bank Creek, Goat Haunt, Hudson Bay Divide, Looking Glass Ridge and Lake Sherburne. Snow avalanches paths are a prominent feature in Glacier National Park (Butler 1979), and snow avalanches can cause a large amount of disturbance as they flow downhill by uprooting the surrounding vegetation. The effects of snow avalanches can be seen in the Altyn Ridge and Goat Haunt photographs. Flooding in this environment can come from two sources, either heavy rainfall or rapid snow melt. The primary effects of flooding on vegetation are impact trauma from flood debris and uprooting through erosion and impact. The effects of flooding are visible in the T_1 image at Looking Glass 180°-300° along Two Medicine Creek.

Two of the primary diseases affecting vegetation in Glacier National Park are blister rust *(Cronartium ribicola)* and the Mountain Pine Beetle *(Dendrotonus ponderosae)*. Blister rust is a fungal infection affecting whitebark pine trees throughout the American West. Blister rust spores enter trees through the needles and grow, eventually producing cankers that can girdle branches or the trunk of the tree, killing the tree (Hunt 1997). Mountain Pine Beetle affects trees, primarily ponderosa, lodgepole, and limber pine, by boring into the outer layers of the trees disrupting nutrient and water transport through the phloem (Cole and Amman 1980). The effects of both blister rust and Mountain Pine Beetle produce trees that are red or orange in color. Without a close up examination, it is difficult to discriminate between the two in the photographs from this study. Areas of disease were seen at Goat Haunt, Cut Bank, Altyn Ridge, and Lake Sherburne.

Table 17: Summary of disturbances recorded in the qualitative and quantitative sections of this study.

Site	**Qualitative Analysis**	**Quantitative Analysis**
Altyn Ridge	Geomorphic (rock fall, talus slopes) Fire Disease	N/A
Apgar	Fire	N/A
Cut Bank Creek	Anthropogenic	Anthropogenic
Goat Haunt	Disease Geomorphic (avalanche, rock fall, talus slopes)	Disease
Hudson Bay Divide	Fire Anthropogenic	N/A
Looking Glass Ridge	Fire Geomorphic (flooding, rock fall, talus slopes)	Fire Geomorphic (flooding, rock fall, talus slopes)
Lake Sherburne	Fire	N/A

Qualitative methodology

The methods developed for this study proved effective for the purpose of analyzing change in repeat photography. The overall process was straightforward and the automated nature of many of the intermediate steps helped the process progress smoothly. Each step in the process presented unique challenges; by utilizing multiple computer programs (ArcGIS and Erdas Imagine) tailored to the specific tasks, the effort required to overcome challenges was reduced.

Registration of the images was an important step in the analysis process because precisely matched photographs are necessary for meaningful results. The georeferencing tool in ArcGIS was efficient and accurate in matching up the photo pairs, and the transformations provided were able to mimic the distortions present in the T_1 photographs. Identifying sites for quantitative analysis was aided by the use of the Effects toolbar in ArcGIS. The tools provided in this toolbar allow the user to adjust the transparency of layers, and wipe one layer on and off another without having to turn those layers on and off. The process of classifying each image into fifteen classes was very efficient with the help of the batch processing tool in Erdas Imagine. By using the batch processor, each set of photographs could be processed all at once. The process of combining classes and assigning labels was the most time consuming step, each class in each photograph had to be identified and grouped to produce the final classified images. Random point samples and raster value extraction were performed quickly with the two ArcGIS macros chosen to perform each task.

As with any GIS or remote sensing tool, a certain amount of error is to be expected. The two main sources of error in this method were registration and classification errors. Registration errors were the result of the T_1 and T_2 images being misaligned by the computer as the result of misplaced control points or the inability of the transformation to manipulate the images to match each other. This type of error was reduced by placing many control points throughout images and revising control points that had an adverse affect on the registration. Classification errors were the result of the computer being unable to differentiate features in the photographs because of the similar spectral signatures. This was especially a problem when classifying the panchromatic T_1 images that only had 256 colors; many of the features in these photographs were the same color and therefore grouped into the same class.

Overall this technique is an effective tool to analyze a wide range of repeat photographs for biogeographic and geomorphic change. Several areas for improvement exist for this technique and are good candidates for future research. The major areas for improvement focus on the classification and sampling of the images. Improving the classification of the T_1 and T_2 photos may provide for better data and more clearly defined classes. This could be accomplished through traditional supervised classification methods or newer methods like object oriented classification.

Future research and applications

Several future directions exist for this research, many relating to the study area of Glacier National Park. The first step in future research would be to compare the methods used in this study to those used by Roush et al. (2007), to validate both techniques and test how scale affects both methods. Another important area of research would be to use areas of change identified in this research as the study areas for future projects in order to establish the ages and/or periodicity of the disturbances and recovery periods for the areas where changes were measured.

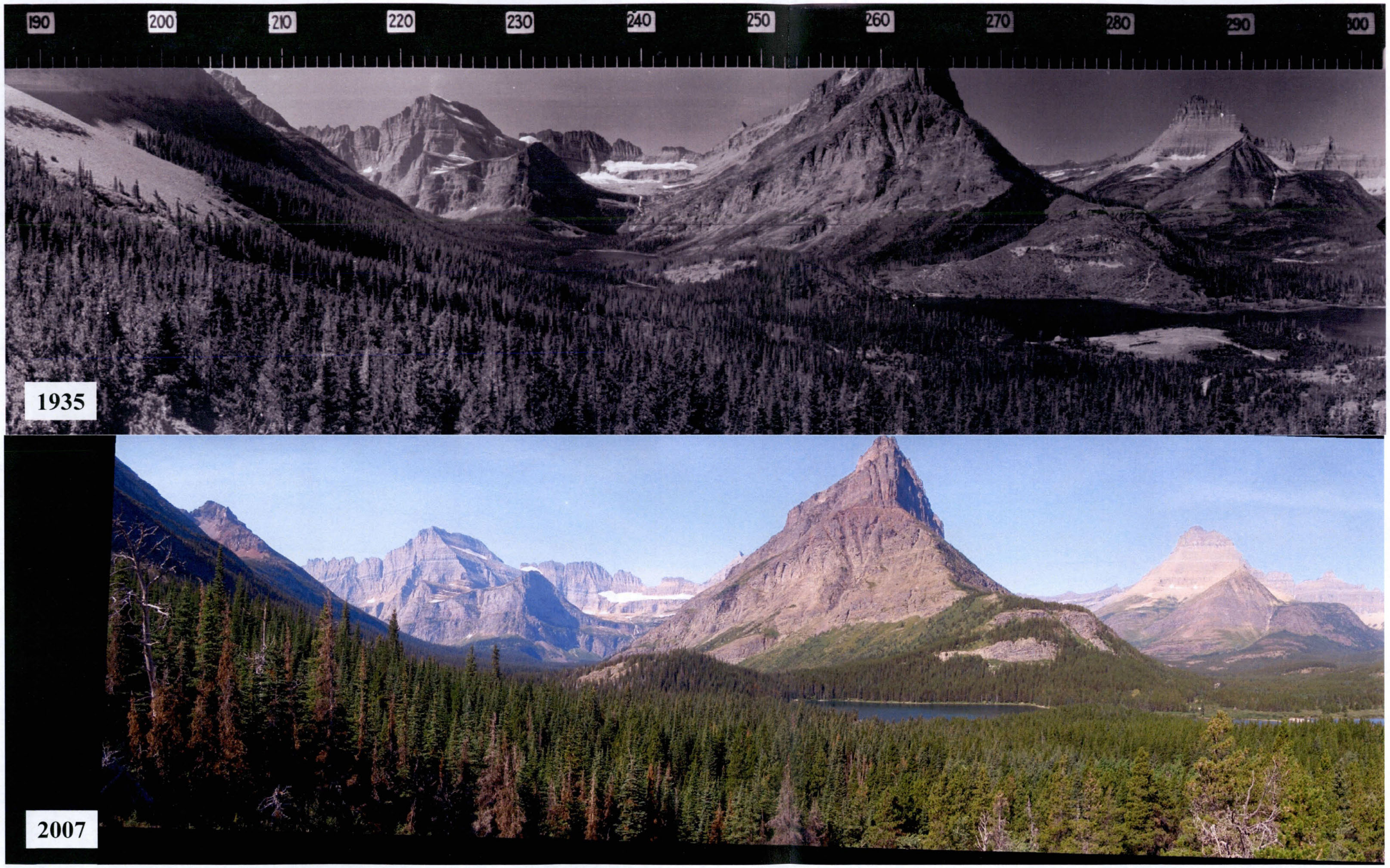
With the repeat photo pairs from this study, a number of other studies could be undertaken. Examples include a study of the shrinking of semi-permanent snow patches and how the disappearance of the snow patches would affect the hydrology of Glacier National Park; or a study of how the patterned ground at Divide Mountain has changed in 70 years.

APPENDIX A

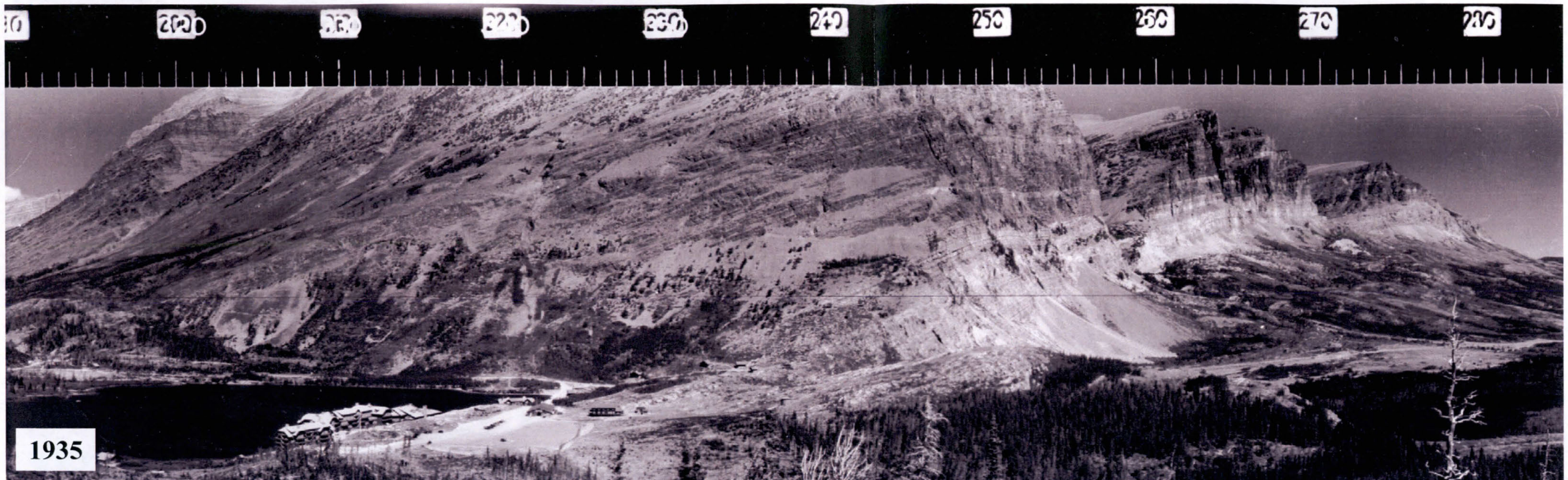
REPEAT PHOTO PAIRS

This appendix contains the original repeat photo pairs for each 120^{o} segment for all seven of the original sites. The photographs are paired, T_1 on top and T_2 on bottom, in alphabetical order. Three segments were not included in this appendix, Altyn 60^{o}-180^{o}, Goat Haunt 60^{o}-180^{o} and Lake Sherburne 300^{o}-60^{o}. These segments were photographs of the hillslopes immediately adjacent to the photo points and were not included because they were not repeated in the field.

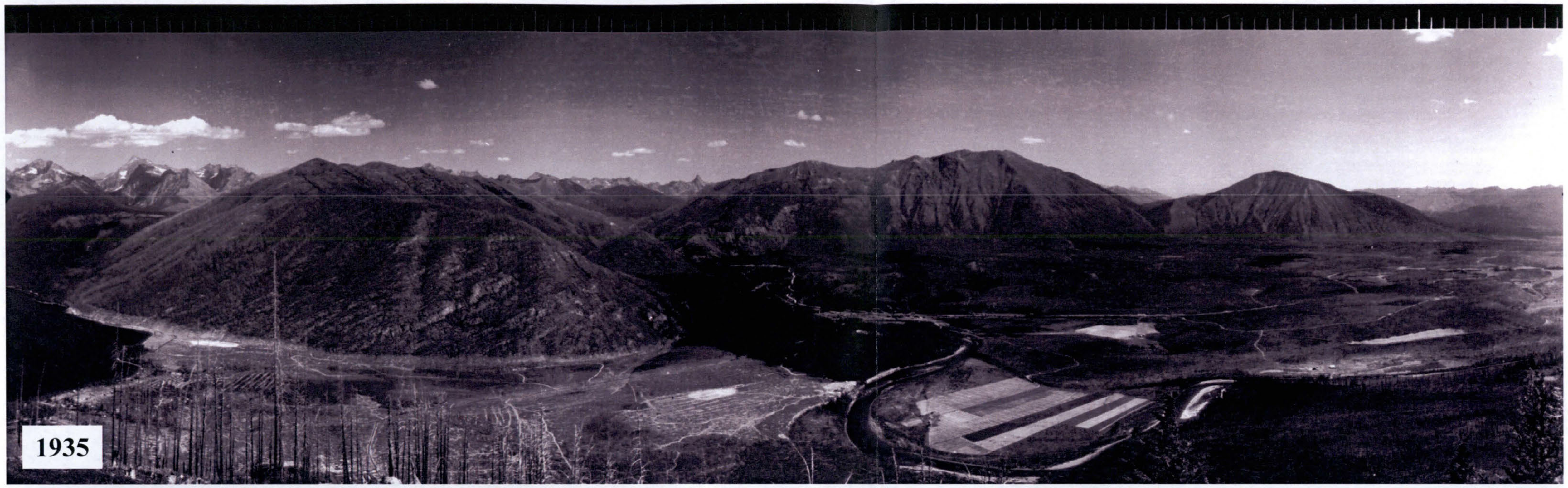
Altyn Ridge 180°-300°



Altyn Ridge 300°-60°



Apgar 60°-180°

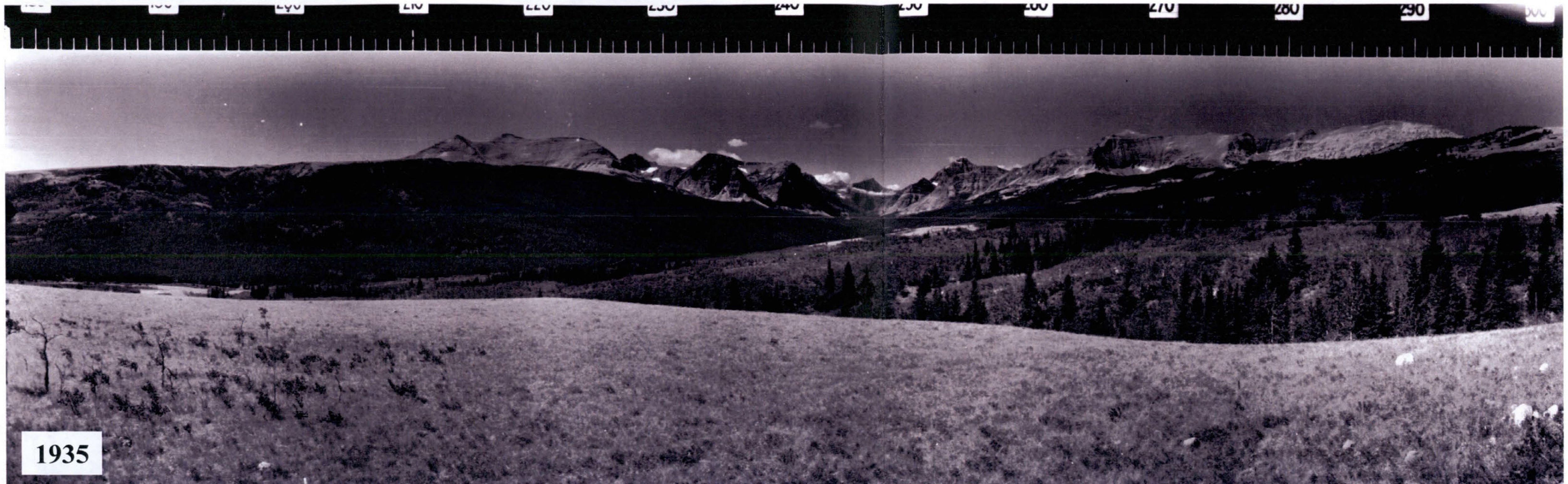


Apgar 180°-300°

Apgar 300°-60°

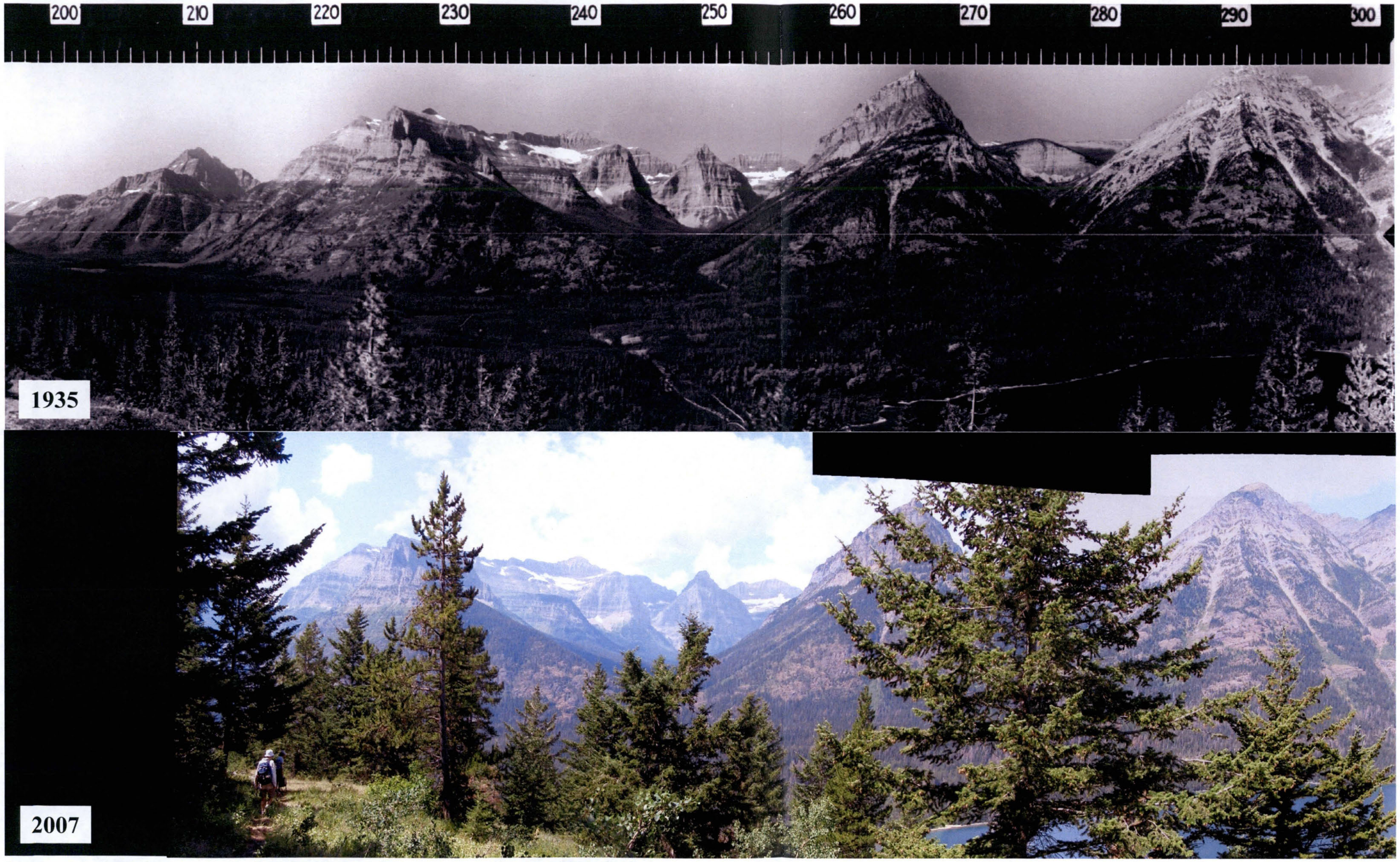
Cut Bank Creek 60°-180°

Cut Bank Creek 180°-300°



Cut Bank Creek 300°-60°

Goat Haunt 180°-300°



Goat Haunt 300°-60°

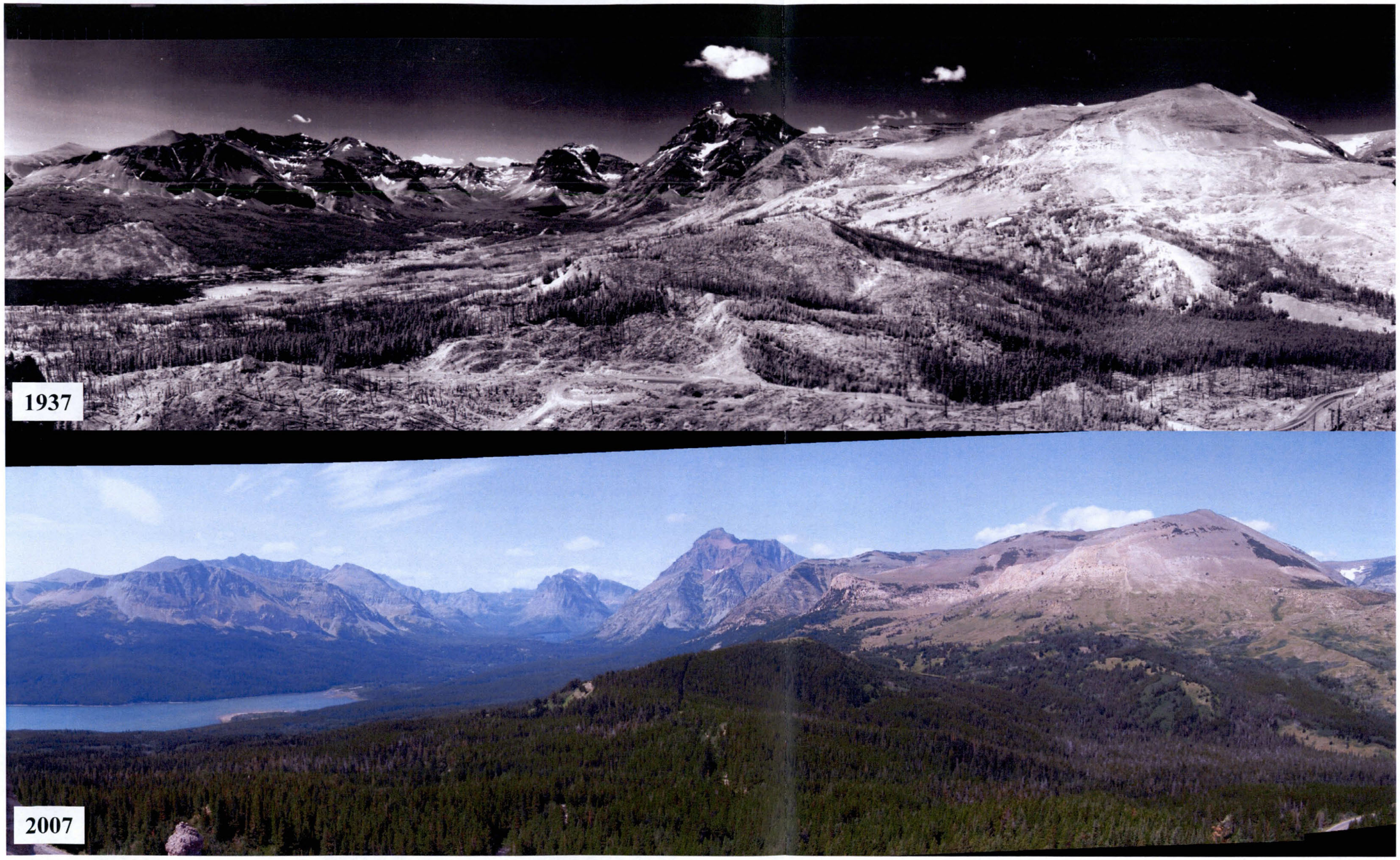
Hudson Bay Divide 60°-180°

Hudson Bay Divide 180°-300°

Hudson Bay Divide 300°-60°

Looking Glass Ridge 60°-180°

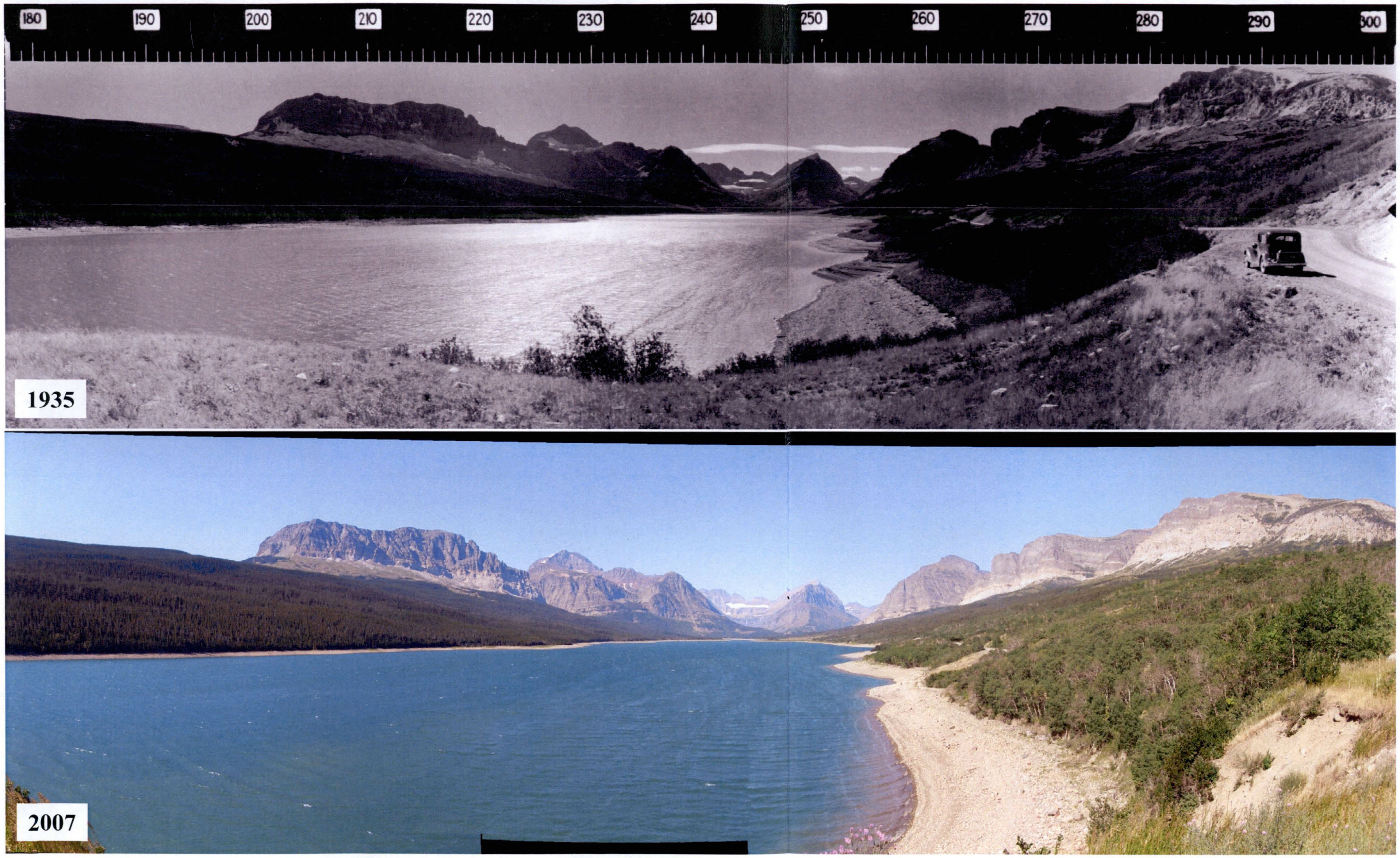
Looking Glass Ridge 180°-300°



Looking Glass Ridge 300°-60°

Lake Sherburne 60°-180°

Lake Sherburne 180°-300°

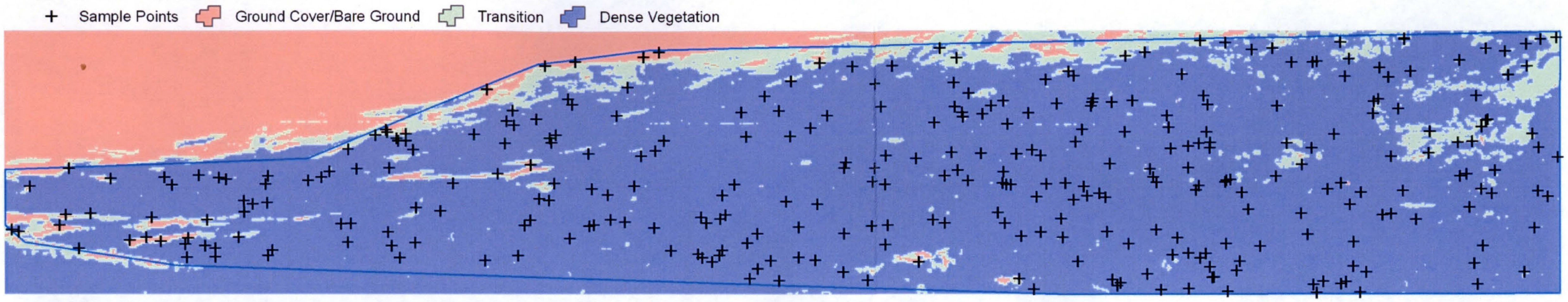


APPENDIX B

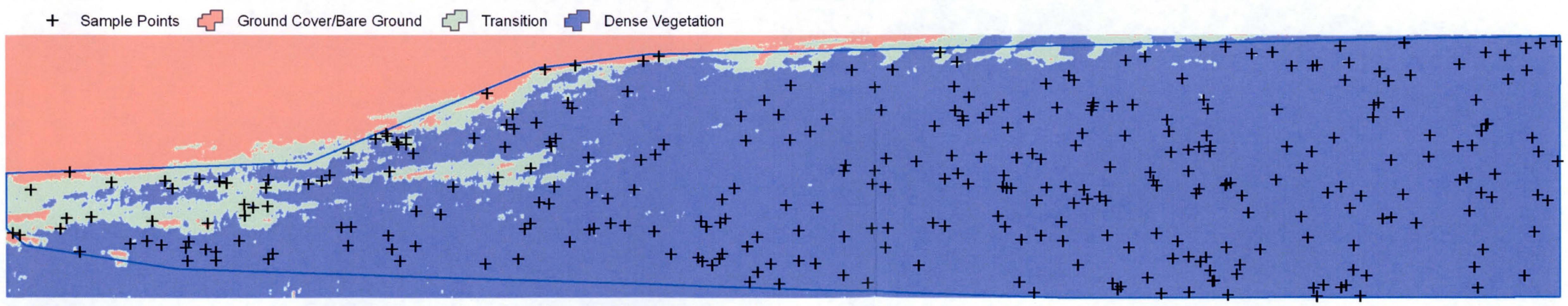
CLASSIFIED IMAGES OF QUANTITATIVE ANALYSIS SITES

The images included in this appendix are the three-class results of the unsupervised classification. These images are paired, T_1 on the top and T_2 on the bottom and are presented in the same order as the Quantitative Results section. The random sample points are also provided for reference.

Cut Bank Creek 60°-180°

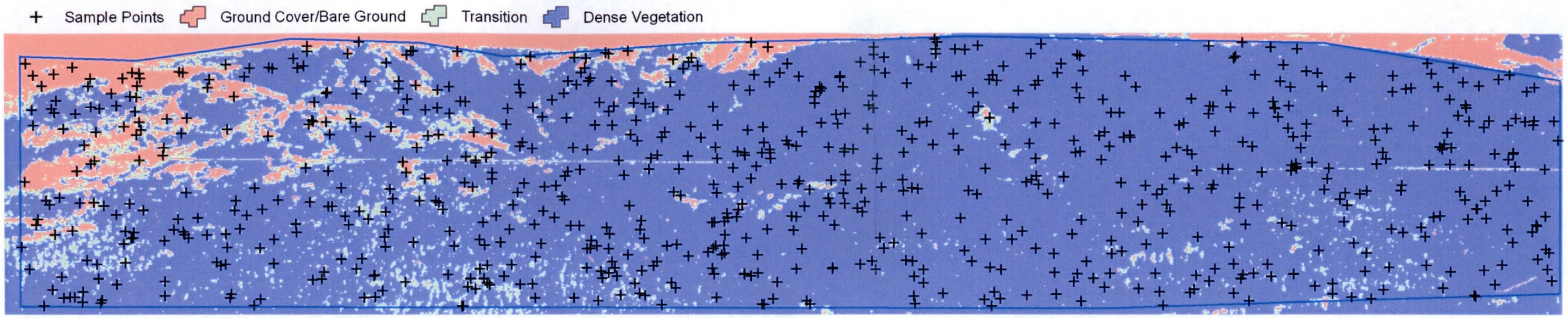


1935

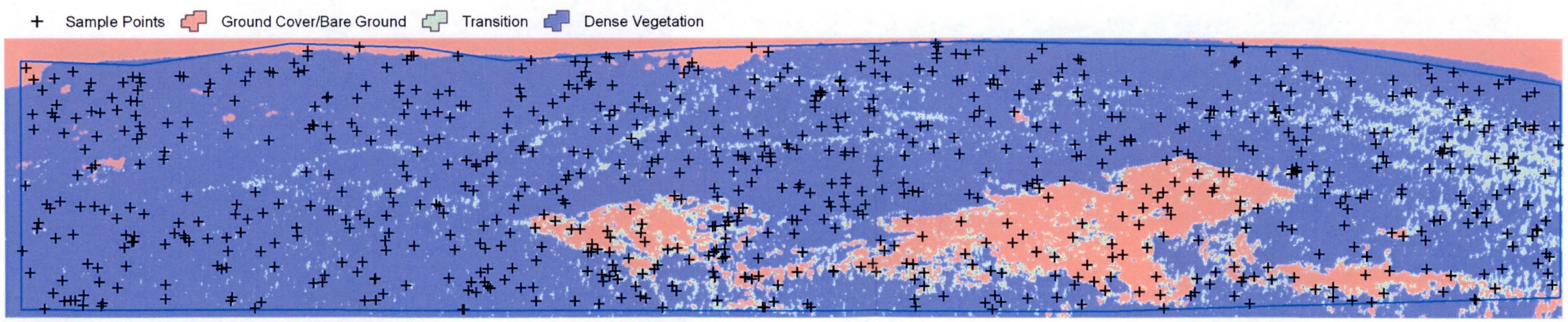


2007

Cut Bank Creek 180°-300° Site 1

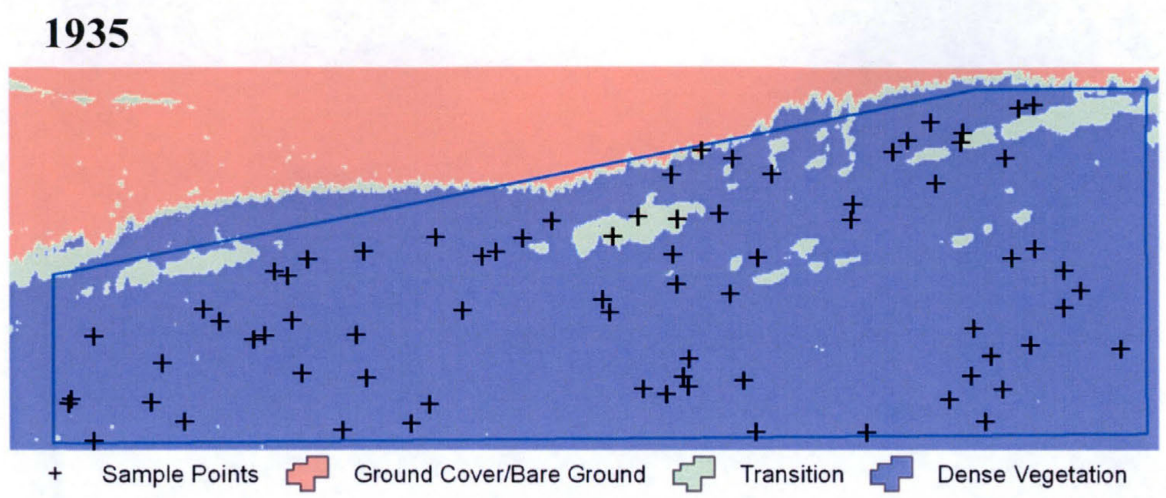


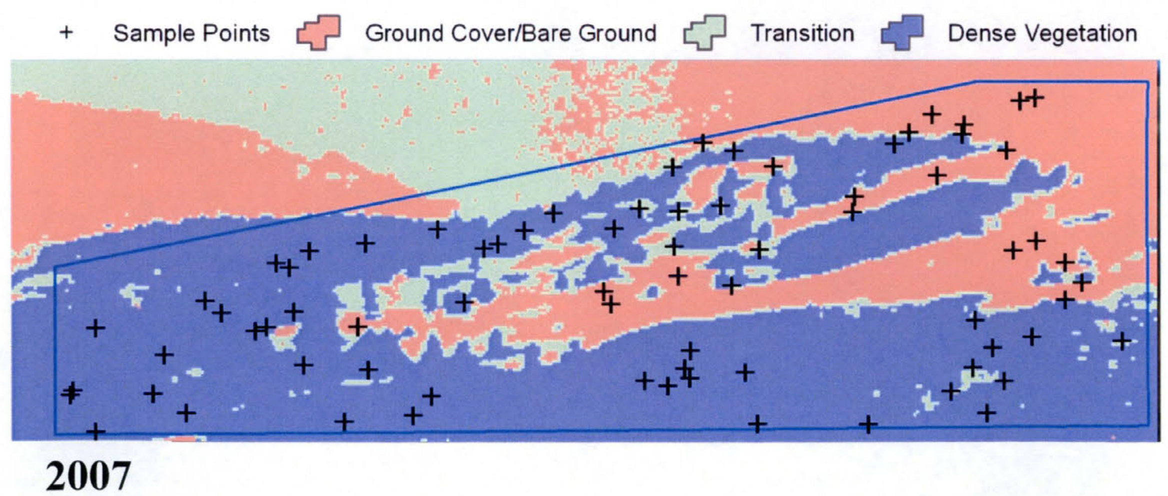
1935



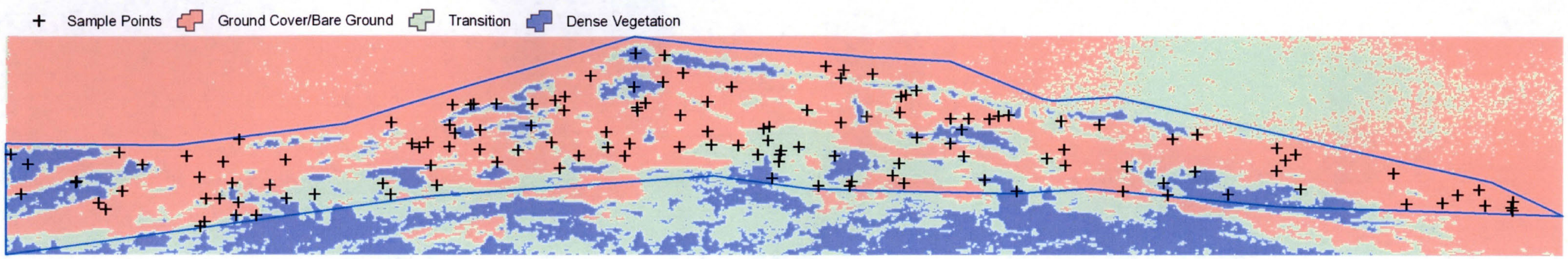
2007

Cut Bank Creek 180°-300° Site 2



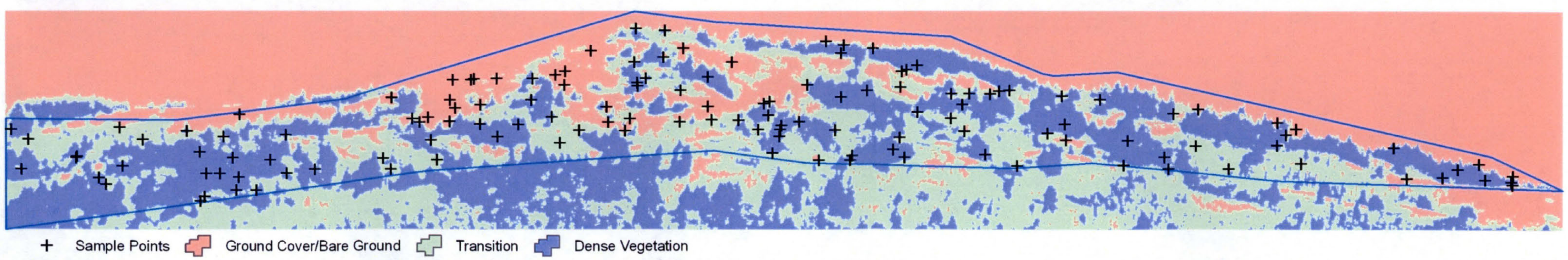


Cut Bank Creek 300°-60°

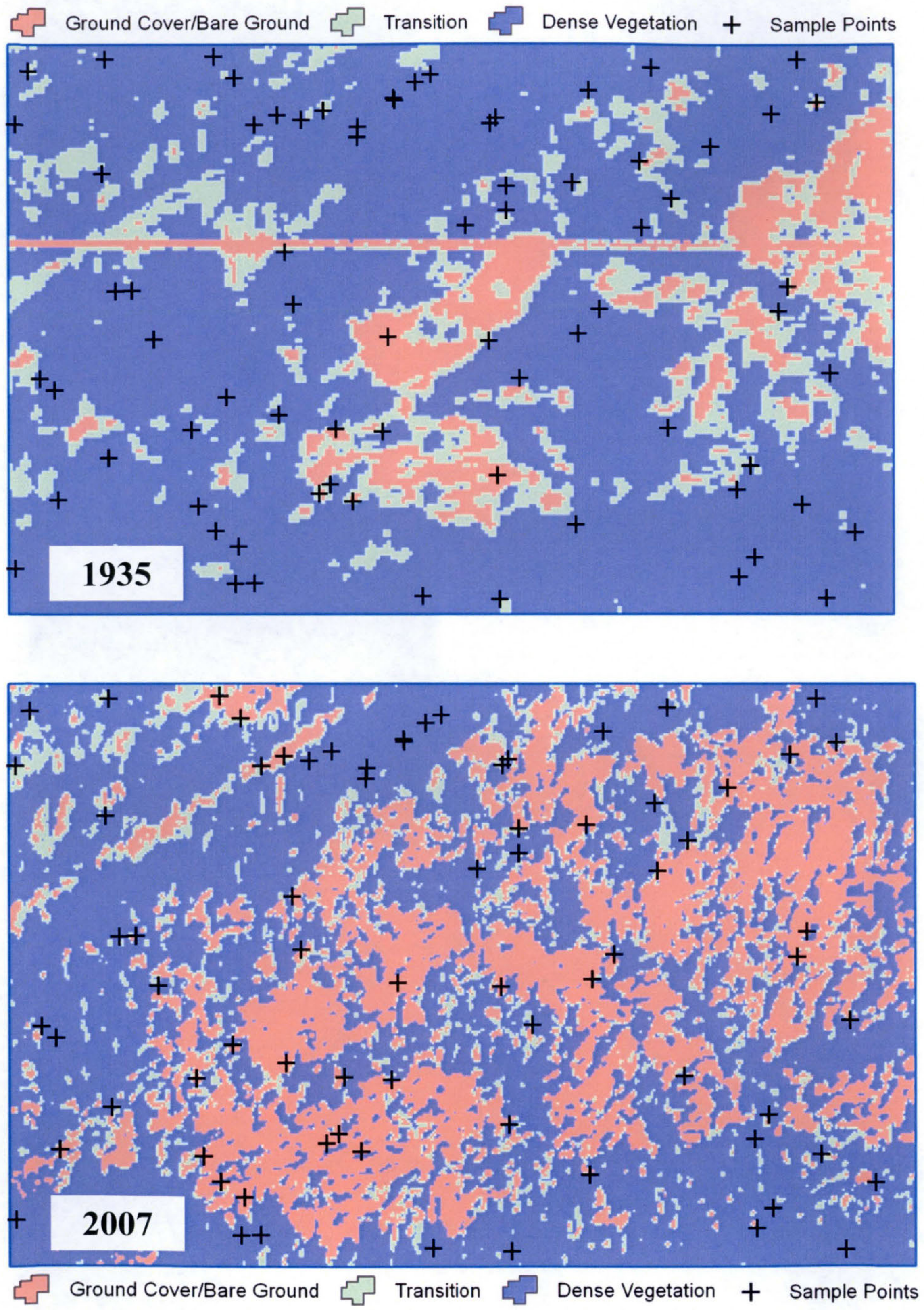


1935

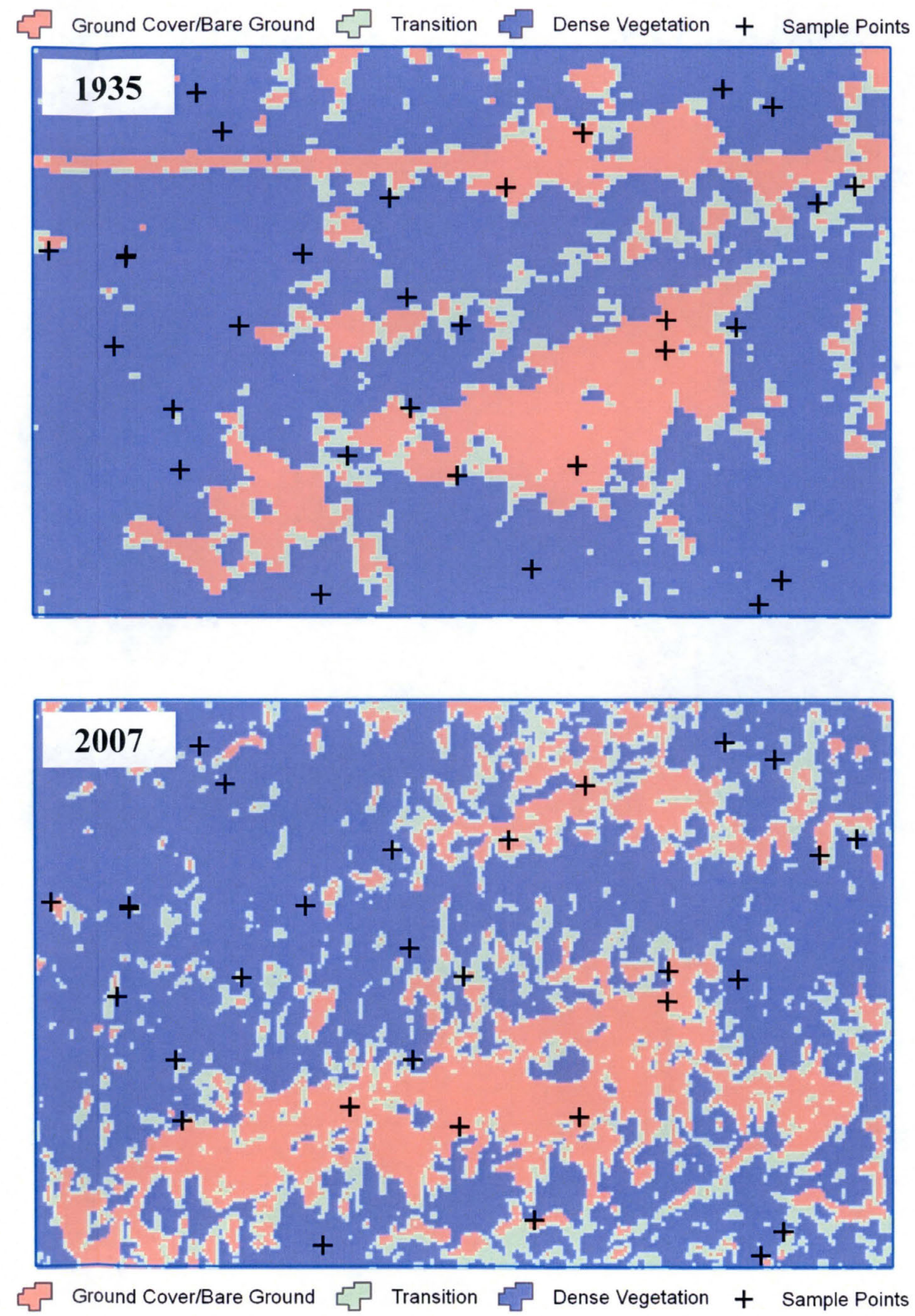
2007



Goat Haunt 180°-300° Site 1

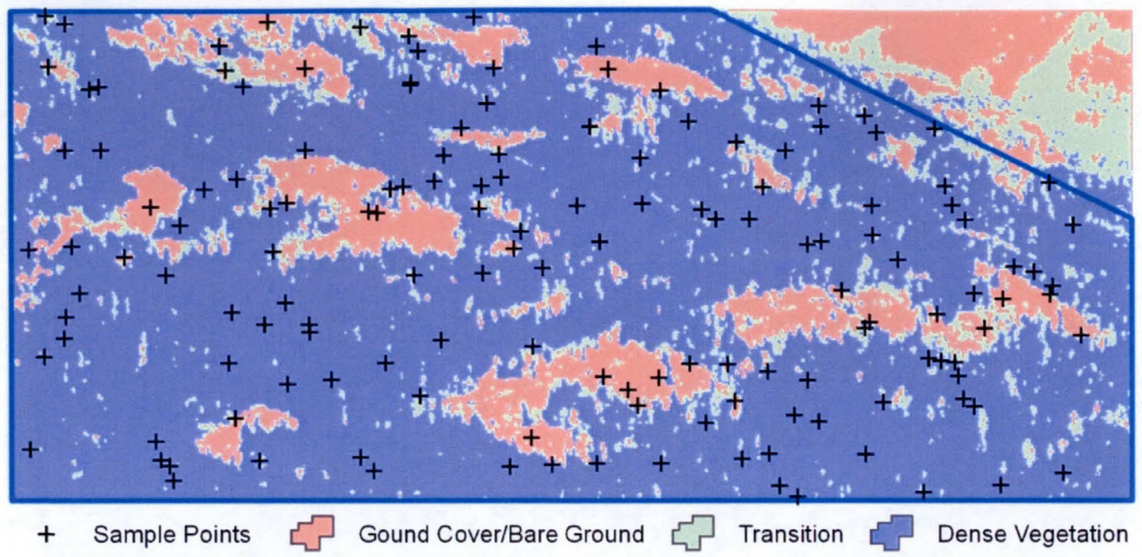


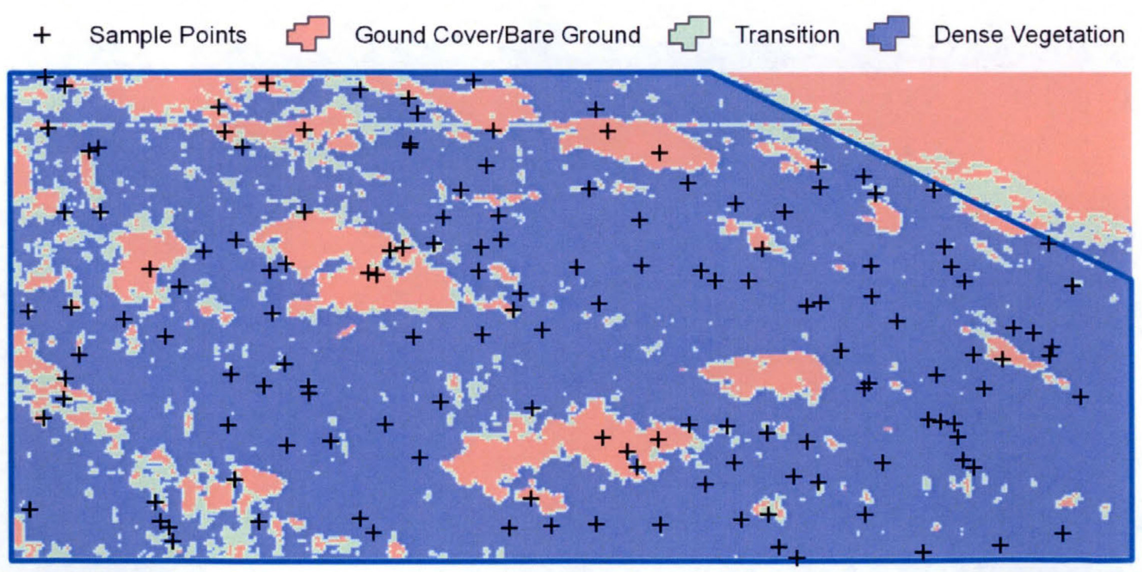
Goat Haunt 180°-300° Site 2



Goat Haunt 300°-60°

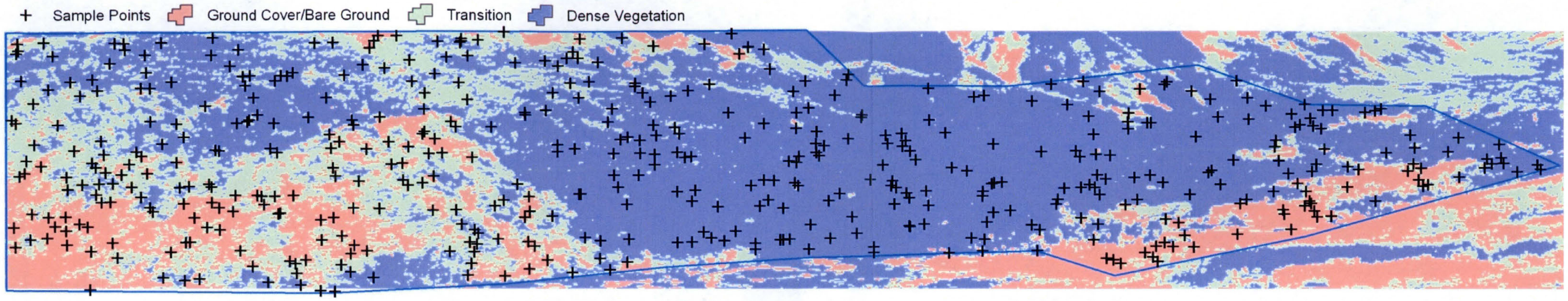
1935



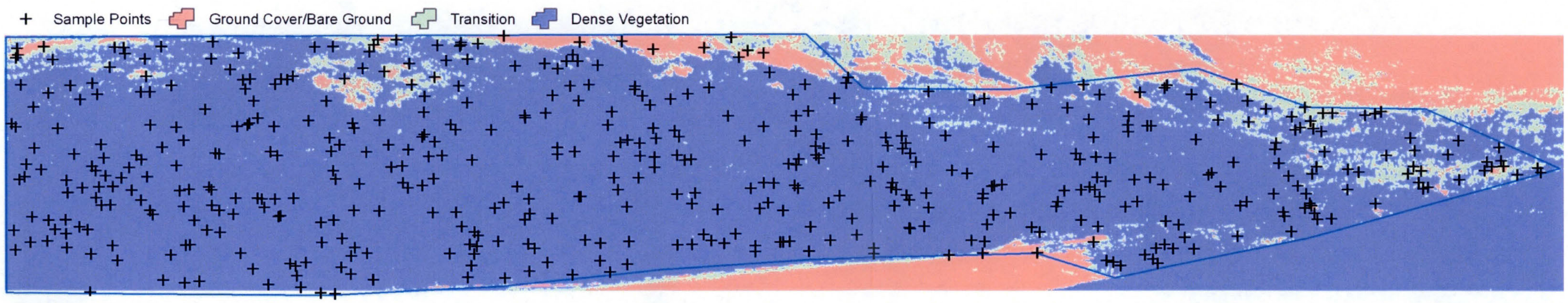


2007

Looking Glass 180°-300° Site 1



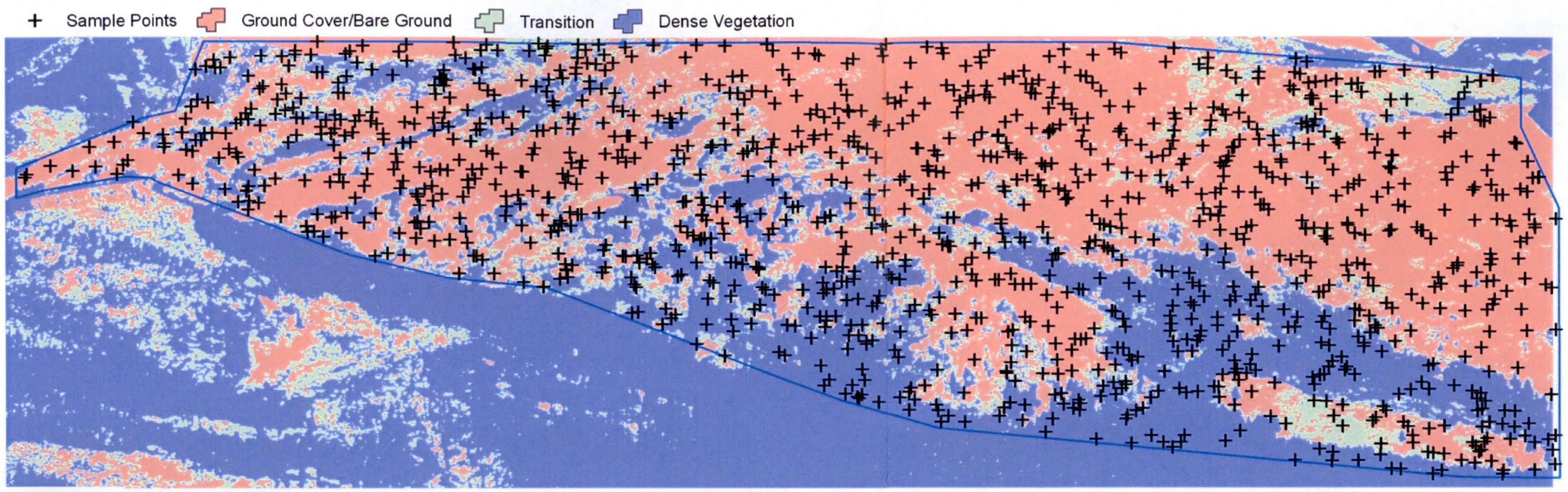
1935



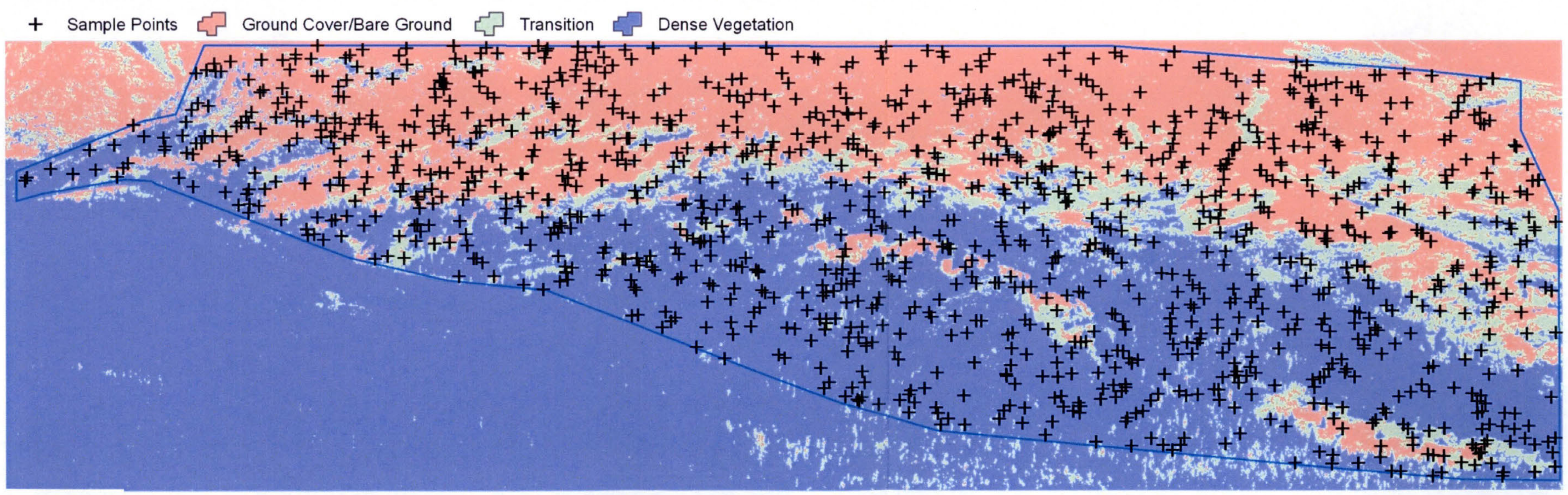
2007

82

Looking Glass 180°-300° Site 2



1937



2007

REFERENCES

Allen, T. R., and S. J. Walsh. 1996. Spatial and compositional pattern of alpine treeline, Glacier National Park, Montana. *Photogrammetric Engineering and Remote Sensing* 62:1261-1268.

Arnst, A. 1985. *We Climbed the Highest Mountains.* Portland, OR: Fernhopper Publishers.

Aschenwald, J., K. Leichter, E. Tasser, and U. Tappeiner. 2001. Spatio-temporal landscape analysis in mountainous terrain by means of small format photography: A methodological approach. *IEEE Transactions on Geoscience and Remote Sensing* 39:885-893.

Atkinson, K. B., and I. Newton. 1968. Photogrammetry. In *Photography for the Scientist,* ed. C. Engel, New York: Academic Press.

Bernhardsen, T. 2002. *Geographic Information Systems: An Introduction.* New York: John Wiley and Sons.

Butler, D. R. 1979. Snow avalanche path terrain and vegetation, Glacier National Park, Montana. *Arctic and Alpine Research* 11:17-32.

———1994. Repeat photography as a tool for emphasizing movement in physical geography. *Journal of Geography* 93:141-151.

Butler, D. R., and L. M. DeChano. 2001. Environmental change in Glacier National Park, Montana: An assessment through repeat photography from fire lookouts. *Physical Geography* 22:291-304.

Butler, D. R., G. P. Malanson, M. F. Bekker, and L. M. Resler. 2003a. Lithologic, structural, and geomorphic controls on ribbon forest patterns in a glaciated mountain environment. *Geomorphology* 55:203-217.

Butler, D. R., G. P. Malanson, and D. M. Cairns. 1994. Stability of alpine treeline in Glacier National Park, Montana. *Phytocoenologia* 22:485-500.

Butler, D. R., G. P. Malanson, and L. M. Resler. 2004. Turf-banked terrace treads and risers, turf exfoliation and possible relationships with advancing treeline. *CATENA,* 58:259-274.

Butler, D. R., L. M. Resler, D. A. Gielstra, and D. L. Cerney. 2003b. Ecotones in mountain environments: Illustrating sensitive biogeographical boundaries with remotely sensed imagery in the geography classroom. *Geocarto International* 18:63-72.

Butler, D. R., and S. J. Walsh. 1990. Lithologic, structural, and topographic influences on snow avalanche path location, eastern Glacier National Park, Montana. *Annals of the Association of American Geographers* 80:362-378.

Butler, D. R., and S. J. Walsh. 1994. Site characteristics of debris flows and their relationship to alpine treeline. *Physical Geography* 15:181-199.

Carrara, P. E. 1989. *Late Quaternary glacial and vegetative history of the Glacier National Park region, Montana.* Washington, D.C.: U.S. Government Printing Office, USGS Bulletin 1902.

Cerney, D. L., and D. R. Butler. 2004. Examining montane ecotone change with repeat photography. *Papers of the Applied Geography Conferences* 27:111-121.

Clark, P. E., and S. P. Hardegree. 2005. Quantifying vegetation change by point sampling landscape photography time series. *Rangeland Ecology and Management* 58:588-597.

Cole, W.E., and G.D. Amman. 1980. *Mountain pine beetle dynamics in lodgepole pine forests*. Ogden, UT: U.S. Department of Agriculture, USFS General Technical Report INT-89.

Corripio, J. G. 2004. Snow surface albedo estimation using terrestrial photography. *International Journal of Remote Sensing* 25:5705-5729.

Corripio, J. G., Y. Durand, G. Guyomarch, L. Merindol, D. Lecorps, and P. Pugliese. 2004. Land-based remote sensing of snow for validation of a snow transport model. *Cold Regions Science and Technology* 39:93-104.

Dexter, L. R., and B. L. Cluer. 1999. Cyclic erosional instability of sandbars along the Colorado River, Grand Canyon, Arizona. *Annals of the Association of American Geographers* 89:238-266.

Fagre, D. B. 2003. Spatial changes in alpine treeline vegetation patterns, Glacier National Park, Montana. Available from http://nrmsc.usgs.gov/research/treeline_rsrch.htm (last accessed 02/10 2007).

Finklin, A. I., 1986. A climatic handbook for Glacier National Park with data for Waterton Lakes National Park. US Department of the Interior, US Forest Service General Technical Report INT-204, Ogden, UT. 124 pp.

Forman, R. T. T. 1995. *Land Mosaics: The Ecology of Landscapes and Regions.* New York: Cambridge University Press.

Forman, R. T. T., and M. Godron. 1986. *Landscape Ecology.* New York: John Wiley and Sons.

Graf, W. L. 1985. Geomorphic measurements from ground-based photographs. In *Geomorphology: Trends and Themes,* ed. A. Pitty, 211-225. Totowa, N.J.: Barnes and Noble Books.

Hallert, B. 1960. *Photogrammetry: Basic Principles and General Survey*. New York: McGraw-Hill.

Harrison, A. E. 1974. Reoccupying unmarked camera stations for geological observations: *Geology* 2:469-471.

Hattersley-Smith, G. 1966. The symposium on glacier mapping. *Canadian Journal of Earth Science* 3:737-743.

Hunt, R. 1997. White pine blister rust. In *Compendium of Conifer Diseases*, ed. E. M. Hansen and K. J. Lewis. St. Paul, MN: American Phytopathological Society.

Klasner, F. L. 2007. Panoramic photographs of Glacier National Park and surrounding area. Available from http://www.nrmsc.usgs.gov/research/panphoto.htm.

Klasner, F. L., and D. B. Fagre. 2002. A half century of change in alpine treeline patterns at Glacier National Park, Montana. *Arctic, Antarctic, and Alpine Research* 34:49-56.

Kull, C. 2005. Historical landscape repeat photography as a tool for land use change research. *Norsk Geografisk Tidsskrift* 59:253-268.

Malanson, G. P. 2001. Complex responses to global change at alpine treeline. *Physical Geography* 22:333-342.

Malde, H. E. 1975. Geologic benchmarks by repeat photography. *Journal of Research of the U.S. Geological Survey* 1:192-206.

———1983. Panoramic Photographs. *American Scientist* 71:132-140.

Meehan, J. 1996. *Panoramic Photography.* New York: AMPHOTO Books.

Munroe, J. S. 2003. Estimates of Little Ice Age climate inferred through historical rephotography, Northern Uinta Mountains, U.S.A. *Arctic, Antarctic, and Alpine Research* 35:489-498.

Pickard, J. 2002. Assessing vegetation change over a century using repeat photography. *Australian Journal of Botany* 50:409-414.

Resler, L. M. 2006. Geomorphic controls of spatial pattern and process at alpine treeline. *The Professional Geographer* 58:124-138.

Rogers, G. F., H. E. Malde, and R. M. Turner. 1984. *Bibliography of Repeat Photography Evaluating Landscape Change.* Salt Lake City, UT: University of Utah Press.

Ross, C. P. 1959. *Geology of Glacier National Park and the Flathead region, northwest Montana.* Washington, D.C.: U.S. Government Printing Office, USGS Professional Paper 296.

Roush, W., J. S. Munroe, and D. B. Fagre. 2007. Development of a spatial analysis method using ground-based repeat photography to detect changes in the alpine treeline ecotone, Glacier National Park, Montana, U.S.A. *Arctic, Antarctic, and Alpine Research* 39:297-308.

Veblen, T. T., and D. C. Lorenz. 1991. *The Colorado Front Range: A Century of Ecological Change.* Salt Lake City, UT: University of Utah Press.

Walsh, S. J., D. R. Butler, T. R. Allen, and G. P. Malanson. 1994. Influence of snow patterns and snow avalanches on the alpine treeline ecotone. *Journal of Vegetation Science* 5:657-672.

Walsh, S. J., D. J. Weiss, D. R. Butler, and G. P. Malanson. 2004. An assessment of snow avalanche paths and forest dynamics using Ikonos satellite data. *Geocarto International* 19:85-93.

Wolf, P. R. 1974. *Elements of Photogrammetry (with air photo interpretation and Remote Sensing)*. New York: McGraw-Hill.

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