Evaluating the Feasibility of Repeat Photography as a Service to Monitor the Effects of Climate Change

An Interactive Qualifying Project
submitted to the Faculty of
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degree of Bachelor of Science

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Report Submitted to:

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Rich Schrader (Sponsor)	*River Source Inc.*

Abstract

There is a growing need to monitor ecological impacts caused by climate change. Our team worked with River Source Inc. to evaluate the feasibility of a repeat photography service to monitor environmental and ecological change, particularly in Santa Fe, New Mexico. Our project evaluated several technologies, particularly a technology called Picture Post, for repeat photography-based environmental monitoring. Our team concluded that Picture Posts offer distinct advantages for the collection of high-quality repeat photos from numerous locations by both professional and amateur photographers. In collaboration with other interested parties identified in this report, we recommend that River Source form a consortium to pursue the revival and expansion of a Picture Post service.

Acknowledgments

Foremost, we extend our sincere gratitude to our sponsor, Rich Schrader of River Source, who made this project possible. Mr. Schrader's innovative feedback and inspiring motivation carried us through the many complex stages of our project. We extend our appreciation to the River Source staff, Anna Archuleta and Carlos Herrera, for their kindness, guidance, and consistent encouragement.

We would also like to thank our advisors – Dominic Golding and Jeffery Solomon – whose expertise, insightful comments, and recommendations immensely contributed to the success of our project.

Furthermore, we would like to express our heartfelt appreciation to the organizations and their dedicated members who contributed to the success of this project. Their collected wisdom and rallied support aided in our accomplishments.

We thank you,

WPI PICS Team

Executive Summary

Climate change is an omnipresent and growing threat to everyday life. It is changing the way ecosystems function across the globe, often to the detriment of humans as well as plants and animals. This is causing a growing need to monitor these changes; without effective monitoring, organizations cannot effectively act to mitigate the more harmful effects.

Repeat photography is an extremely important method for monitoring ecological and environmental changes and is used in a variety of contexts. It has frequently been used to determine change over long periods of time by replicating historical photographs. Some projects also employ repeat photography for systematic monitoring, which involves regularly taking photographs in the same location. The use of repeat photography for monitoring projects is limited by both manpower and technology. As increasingly powerful photography, geolocation, and geographic information system (GIS) tools become more widely available, new strategies for repeat photography monitoring are emerging. Citizen science is becoming more practical as an avenue for this sort of monitoring due to the prevalence of smartphones among the general public. Other emergent technologies that allow for more detailed photograph analysis, such as three-dimensional photo mapping, also have significant potential.

Our team worked with River Source, a company based out of Santa Fe, New Mexico, that focuses on watershed education, community outreach, and ecological resilience projects. Our project goal was to evaluate the feasibility of a repeat photography service to monitor the phenological changes associated with climate change in Santa Fe, New Mexico. We evaluated different technologies and tested prototypes of different methods for repeat photography for environmental monitoring. Of particular interest was Picture Post, a NASA-funded project that began in New England and aimed to promote environmental monitoring by the general public. It consisted of an octahedral 'topper' fixed to a post that allowed consistent 360° repeat photography and a website that stored and displayed images uploaded by users. Unfortunately, despite being widely used, the Picture Post service ceased operations in 2022 due to a server crash and funding challenges. A major portion of our project focused on determining interest in this program and the practicality of reviving it. We hope our assessment of these technologies will help River Source and associated organizations revive the Picture Post service in the future.

Objectives

Our five objectives were to:

1. Evaluate current and best practices in the use of repeat photography to monitor the effects of climate change.
2. Locate sites depicted in historical photographs and collect current photographs in the same locations.
3. Test and evaluate technologies for repeat photography in the Santa Fe region.
4. Explore future use cases and changes to existing technologies via mockups and prototypes based on our evaluations.
5. Evaluate different options that River Source and their potential clients might pursue to implement a repeat photography service.

Methods and Findings

To pursue these objectives, we conducted interviews with experts in repeat photography and related technologies, as well as with organizations that had previously used Picture Post or that might be interested in using it. We tested and evaluated different technologies to determine their feasibility as part of a repeat photography tool. After our initial assessments, we prototyped changes to the Picture Post topper and mocked up a future use case for Realtime Earth, a program currently under development designed to allow real time peer-to-peer information sharing. After completing testing, we analyzed our data and presented an assessment of the different technologies to River Source. Based on our assessment of the different technologies, we provided recommendations for the approach that River Source, in collaboration with others, might pursue for a repeat photography service. Our conclusions and recommendations are summarized below.

Conclusions and Recommendations for Picture Posts

Picture Posts offer distinct advantages for the collection of high-quality repeat photos from numerous locations by both professional and amateur photographers. Picture Posts are extremely user-friendly and allow significant consistency in repeat photos, even between multiple untrained photographers. They also offer unique educational opportunities due to their low threshold of use. Though Picture Post itself is simple and easy to use, collecting, storing, and systematically analyzing photographs, as well as maintaining public interest in the program over an extended period, presents certain challenges. We make the following recommendations:

1.1 River Source, in collaboration with other interested parties identified in this report, should consider forming a consortium to pursue the development of a Picture Post service. This consortium should negotiate with organizations that are able to host, maintain, and make the Picture Post dataset accessible. The consortium can take a lead role in seeking federal, state, and other funding necessary to develop and maintain the network.

1.2 We recommend the consortium consult with software engineers and data experts to gain a comprehensive understanding of what time and resources are necessary to rebuild, host, and maintain a new Picture Post service.

1.3 To further the educational impact of Picture Post, we recommend that the consortium develop a curriculum based on repeat photography and use it for educational outreach with both public and private school systems. This will educate students on repeat photography and their environments and promote awareness of climate and environmental change. Additionally, a curriculum may help garner public interest in Picture Post and maintain its relevance long-term.

1.4 We recommend that involved organizations put resources towards promoting the Picture Post system and engaging users. This might include website pages illustrating use cases for Picture Posts or a regular email showcasing the best pictures of the year. We also recommend that all Picture Posts accessible by the public include proper signage with clear instructions on their use. These instructions should be provided in both English and Spanish or other languages appropriate to the post's location.

1.5 To make Picture Posts more compatible with smartphone cameras, we recommend modifying the topper's design. The base should be expanded to provide more support for rectangular phones, and fins added to the octagonal portion to constrain camera movement.

Conclusions and Recommendations for Other Technologies

Several remote sensing technologies can be used to monitor environmental changes on a scale that is not possible with Picture Posts. Satellites, drones, and planes represent the best methods of collecting big picture, top-down repeat imagery. Aerial photography from planes currently allows better resolution than most satellites. However, we conclude that satellite imagery will likely surpass aerial photography in terms of effectiveness, convenience, and cost in the foreseeable future. Drones present a much more customizable and focused approach to top-down repeat photography. They will likely continue to have a place alongside large-scale, top-down photography, even as the resolution of satellite imagery improves. Our group concludes that Realtime Earth does not currently have the capabilities for effective storage or display of repeat photos. However, Esri StoryMaps presents a free and effective method of displaying repeat photography. They are very accessible, intuitive, and excellent at conveying information.

2.1 We recommend analysts use both drone and satellite imagery for environmental monitoring as a complement to Picture Post photography. As noted above, drones are more useful for focused, customizable mapping (in addition to having higher resolution than satellites), whereas satellites are more useful for big-picture observations.

2.2 We recommend not using RealTime Earth for environmental monitoring, as it is not practical at the moment. It may become practical with advances in the software in the near future, however.

2.3 We recommend the consortium consider using StoryMaps as a method to present repeat photography. The Swipe block feature is particularly effective in showing change over time, and the Map Tour feature is useful to showcase photo points. We recommend Survey 123 be paired with StoryMaps as an effective way to upload repeat photo data and metadata to ArcGIS.

Authorship

During the course of this project, the collaborative efforts of the WPI PICS team were essential in the composition of each section and, subsequently, each chapter. Though team members were individually responsible for drafting specific sections, we adopted a collective approach, with all four members actively engaging in the editing and revision process. Essentially, we worked collaboratively to make suggestions and edits on each paragraph and collectively agreed upon everything before submitting our work. This method proved reliable as we combined our knowledge and skills to ensure we completed our work to the best of our abilities.

Notably, Mateo and Nate took the lead in drafting most sections, particularly in the methods section, while Trinity and Mateo leveraged their writing expertise to play pivotal roles in the editing and revision process. Nathan and Trinity also contributed by overseeing the formatting aspects of our paper to ensure a cohesive and organized final report.

Table of Contents

List of Figures

List of Tables

Introduction

Climate change is an omnipresent and growing threat to everyday life. It is changing how ecosystems function across the globe, often to the detriment of humans as well as plants and animals. This creates a growing need to monitor these changes; without periodic monitoring, organizations cannot act to mitigate the more harmful effects.

Repeat photography is an extremely important method for monitoring ecological and environmental changes and is used in a variety of contexts. It has frequently been used to determine change over long periods of time by replicating historical photographs. Some projects also employ repeat photography for systematic monitoring, which involves regularly taking photographs in the same location. The use of repeat photography for monitoring projects is limited by both manpower and technology. As increasingly powerful photography, geolocation, and geographic information system (GIS) tools become more widely available, new strategies for repeat photography monitoring are emerging. Citizen science is becoming more practical as an avenue for this sort of monitoring due to the prevalence of smartphones among the general public. Other emergent technologies that allow for more detailed photograph analysis, such as three-dimensional photo mapping, also have significant potential.

Our project goal was to evaluate the feasibility of a repeat photography service to monitor the phenological changes associated with climate change in Santa Fe, New Mexico. Our project evaluated different technologies and tested prototypes of different methods for repeat photography for environmental monitoring. We hope River Source and other collaborators can use our findings to develop a repeat photography system. Our five objectives were to:

1. Evaluate current and best practices in using repeat photography to monitor the effects of climate change.
2. Locate sites depicted in historical photographs and collect current photographs in the same locations.
3. Test and evaluate technologies for repeat photography in the Santa Fe region.
4. Explore future use cases and changes to existing technologies via mockups and prototypes based on our evaluations.
5. Evaluate different options that River Source and their potential clients might pursue to implement a repeat photography service.

To pursue these objectives, we conducted interviews with relevant experts in repeat photography and related technologies. We tested and evaluated different technologies to determine their feasibility as part of a repeat photography tool. After our initial assessments, we prototyped changes to the Picture Post and mocked up a future use case for Realtime Earth. After completing testing, we analyzed our data and presented an assessment of the different technologies to River Source. Based on our assessment of the different technologies, we provided recommendations for the approach that River Source might pursue, in collaboration with others, for a repeat photography service.

Background

Repeat photography is not a new technique. It has been used to gauge landscape change since at least the 1940s. This background seeks to explore the varied technologies and techniques used in repeat photography and contextualize the use of repeat photography to track the effects of climate change. Section 1 describes the causes and effects of climate change, as well as some of the tools used to monitor it. Section 2 explores what repeat photography is, how it is used, and some of its associated limitations and best practices. Section 3 focuses on citizen science and how it might be used to conduct repeat photography. Lastly, section 4 provides an overview of our sponsor, River Source, and their goals with repeat photography.

1.0 Climate Change

It is an undeniable fact that human-caused climate change is occurring. The overwhelming majority of current scientific literature (over 99% of relevant papers published from 2012-2020) supports this conclusion (Lynas et al., 2021). Every decade for the last forty years has been warmer than the decade before it — and every other decade since 1850 (IPCC, 2021, p. 5). In fact, average temperatures in the decade from 2011 to 2020 are higher than at any time in the last 125,000 years (IPCC, 2021, p. 5). These changes are being driven by human-produced greenhouse gasses, especially carbon dioxide, as shown in **Figure 1a** (IPCC, 2021, p. 4). Atmospheric greenhouse gas concentrations are higher than they have been in hundreds of thousands, or in some cases millions, of years. The rate at which these concentrations have increased in the last few centuries is practically unparalleled, rivaling or even exceeding what would normally be expected in a multi-millennia timespan (IPCC, 2021, p. 8). This unprecedented warming (**Figure 1b**) is having significant effects on ecosystems across the globe.

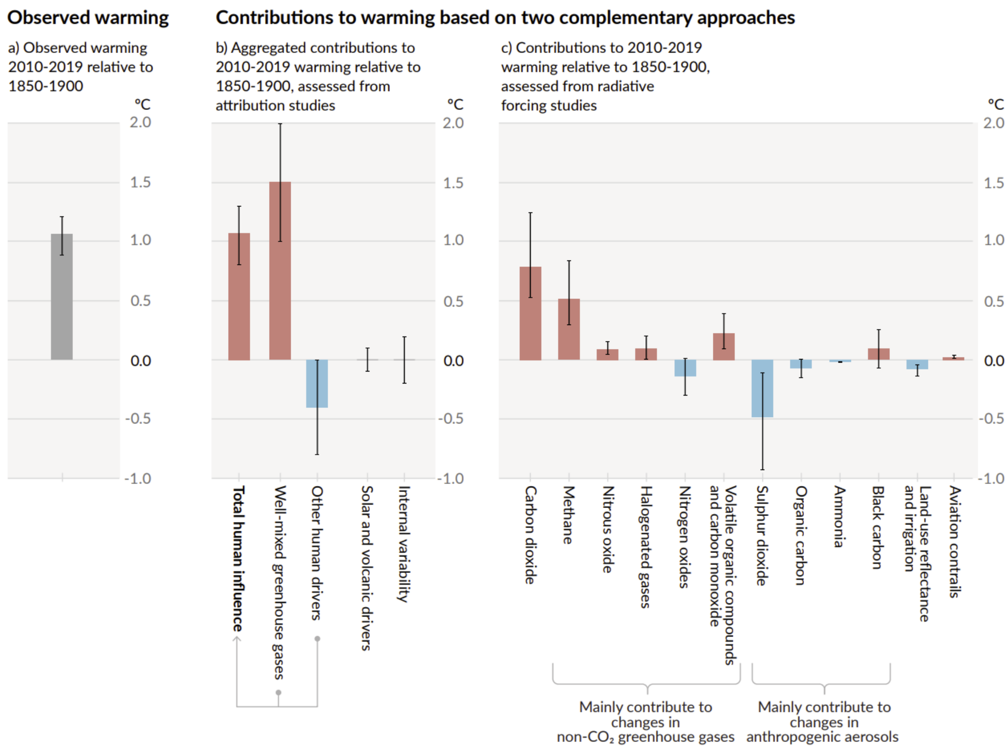

Figure 1a: Causes of Observed Global Warming (IPCC, 2023)

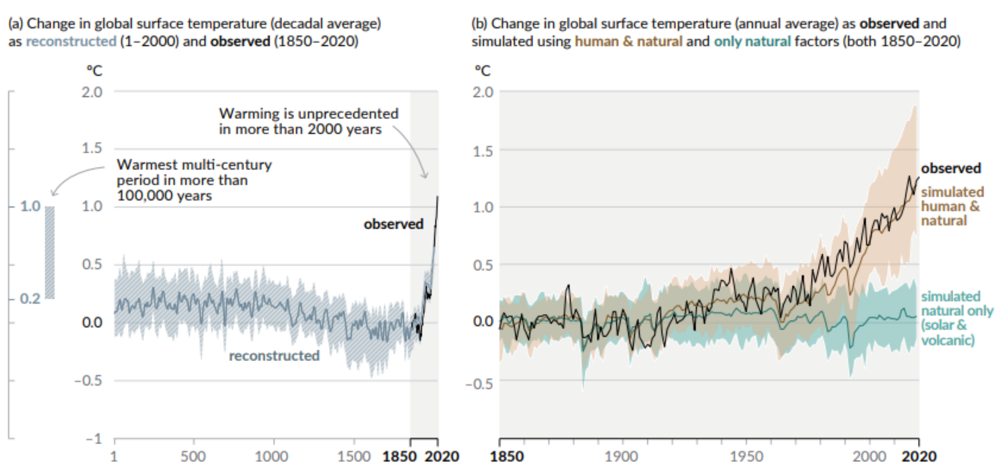

Figure 1b: Changes in Global Surface Temperature relative to 1850-1900 (IPCC, 2023)

1.1 The Effects of Climate Change

Climate patterns are changing in virtually every environment worldwide. Heat waves and heat extremes are becoming increasingly severe, both on land and in marine environments (IPCC, 2021, p. 8). At the same time, the decline in the length, extent, and severity of extreme cold periods in polar and mountain regions is leading to retreating glaciers and shrinking areas of sea ice. For example, **Figure 2** shows that the snout of the Stern Glacier retreated 550 meters between 2006 and 2015. These changing weather norms are also leading to more frequent "compound events" where several risk factors combine and heighten each other. This includes phenomena such as "fire weather," where conditions are both hot and windy, and "compound flooding," where multiple sources combine to create a much more devastating flood (such as a storm surge combining with an overflowing river) (IPCC, 2021, p. 9).

Figure 2: Repeat Photos of the Stein Glacier in 2006 (Left) vs 2015 (Right) (Burkhart et al., 2017).

As climate patterns change, ecosystems are forced to adapt to new conditions or die. Forests have been hit especially hard. In the US, consistently warmer temperatures combined with droughts led to the deaths of hundreds of millions of trees in the 2010s alone (Vose et al., 2018). The colder, wetter weather that once held both fires and harmful insects in check is disappearing, devastating already stressed forests (Vose et al., 2018). Fire seasons are becoming longer and increasingly severe, a trend that will continue. By 2050, the annual area burned by wildfires is predicted to increase by as much as sixfold in the western US (Vose et al., 2018).

Forests provide incredibly important ecosystem services, and as forests are degraded, their ability to provide those services will be greatly diminished. Forests are an important carbon sink (carbon sequestration from US forests 1990-2015 offset 11% of US emissions during that period), but carbon is released when they are destroyed (Williams et al., 2016). Fires are especially harmful in this respect since they cause an immediate release of that carbon back into the atmosphere (Vose et al., 2018). However, the subtler effects of climate change can be just as impactful. Trees stressed by drought, insects, or high heat cannot grow as well, reducing their efficiency at storing carbon (Williams et al., 2016).

Watersheds are also experiencing significant effects from the changing climate. As the climate warms, snowfall becomes more infrequent in many areas, and summers drier (Vose et al., 2018). These changes are significant both for water availability and for water quality. A shorter duration of snowpack can cause nitrogen to leach out of the soil and into the water supply, potentially in problematic quantities (Vose et al., 2018). Forest watersheds are experiencing significant change due to changing forest structures. Fire can clear out forests, causing an increase in water loss from evaporation, hotter stream temperatures, and more significant winter runoff (Vose et al., 2018). In addition, erosion resulting from forest loss can greatly increase sediment levels within the water supply (Goode et al., 2011).

1.2 Climate Change and Cultural Heritage.

In addition to the effects on ecosystems, climate change is having a severe impact on cultural heritage. Climate change-related disasters (such as forest fires, floods, tornadoes, and storms) can devastate cultural heritage by damaging or destroying monuments, historic buildings, and cultural landscapes (Jigyasu, 2019, p. 93). The more subtle effects of climate change can be equally damaging. Changing weather patterns and growing seasons can significantly impact traditional ways of life by changing crop yields and limiting the types of crops that can be grown successfully.

Cultural heritage is a complex topic as it not only constitutes the essence of a people's identity but encapsulates the creative endeavors of those who built monuments and artworks representing different cultural backgrounds (García, 2019, p. 101). Cultural heritage includes myriad different elements, such as tangible and intangible manifestations oftentimes associated with religious, architectural, aesthetic, or historical values, demonstrating how cultural heritage carries a richly diverse meaning for different groups of people from the local community, national, and international levels (Garcia, 2019, p. 101). It is worth emphasizing that cultural heritage is not confined solely to monumental structures; it extends to urban areas wherein these monuments historically reside or are infringed upon by urbanization (Jigyasu, 2019, p. 92). Regrettably, many historic artifacts have been neglected and abandoned and lack the support needed to preserve their structural integrity and safeguard cultural heritage and intrinsic values (Jigyasu, 2019, p. 92).

1.3 Tools for Monitoring Climate Change

With climate change as a pervasive, existential problem for the human race, it is crucial for environmental policy to be based on the best information possible. Good data is the key to developing successful strategies to combat the effects of climate change, and successful strategies save money, time, and lives. It is, therefore, vital that the technologies being used to monitor the effects of climate change are not only of high quality but also able to fill every niche.

Climate is fundamentally the long-term average of "weather variables," such as precipitation or temperature for a given location (NOAA, n.d.). This means that researchers need extensive long-term data to accurately track the extent of climate change. Due to the physical (and temporal) limitations of any given data collection method, climate researchers must employ a multitude of methods.

One of the main sources of climate data is from weather stations across the globe. Weather stations are ground-based observation stations that record climate variables, particularly air temperature, precipitation, and air pressure (Mendelsohn et al., 2007, p. 72). These are set up and maintained by countries around the world. The US alone has thousands of official weather stations set up across the nation (NOAA, n.d.). Interestingly, an extremely important source of climate data is citizen scientists. Thousands of volunteers across the United States record daily temperature and precipitation data and provide it to the National Weather Service (US, 2016). However, these ground-based stations are limited to recording data in their immediate vicinity (Mendelsohn et al., 2007, p. 72). This means that any use of their data requires interpolation for the large areas not directly measured (Mendelsohn et al., 2007, p. 72).

Comparatively, satellites provide data with far greater spatial coverage (Mendelsohn et al., 2007, p. 72). Since they are capturing data from such large swaths, it eliminates the need for interpolating dispersed points, and consequently, they tend to be more accurate for phenomena like temperature (Mendelsohn et al., 2007, p. 72). Satellites are also far more helpful in observing large-scale visual phenomena. Snow coverage, ice cap extent, and land cover data are all recorded by satellites (NOAA, n.d.).

However, satellite data is limited by its resolution. Even with the best modern technology available, the recording equipment still operates hundreds of miles away from its target. Even the best land cover datasets generally only have resolutions on the scale of 10 meters, and many have resolutions on the scale of 100 meters or more (Brown et al., 2022, p. 1). This means that a single pixel on a map composed of many of these sources would represent an area of 100 square meters (Brown et al., 2022, p. 1). While satellite data is adequate for large-scale climate monitoring, it may not effectively track smaller-scale changes to local ecologies and landscapes. This presents a significant issue, as smaller-scale changes, such as the early stages of deforestation, can be critical to understanding ecosystem change (Brown et al., 2022, p. 1). Other, more locally accurate technologies must be employed to monitor these changes.

2.0 Repeat Photography

Repeat photography is a technique used to monitor changes in an area over time. Photos are taken in the same location, in the same direction, with the same framing over time in order to gain a more comprehensive understanding of how an area changes. There are two primary applications of repeat photography. The first is historical comparison, where conditions in a historical photograph are compared to modern conditions. The second is interval monitoring, where photographs are taken at regular intervals to track climate change or other factors over time. Bowers et al. (2003) explain that repeat photography was pioneered in 1888 to document changes in glaciers. Since then, repeat photography has been used as a tool to monitor vegetation and landscape and human influence on them. It is important to note that what we refer to as “repeat photography” is specifically ground-based (non-aerial, non-satellite) repeat photography that is used to monitor long-term phenological change over many years. Bowers et al. (2003) list two main circumstances in which ground-based repeat photography is superior to aerial or satellite imagery. The first reason would be if analyses of species composition or small-scale landscape changes are needed. Aerial and satellite imagery simply cover too much area to focus in detail on a specific area of land. The second reason for ground-based repeat photography would be to reconstruct long-term ecological change.

2.1 Limitations of Repeat Photography

The major limitation of repeat photography is the process itself. Insufficient information about a photograph (such as latitude and longitude coordinates) can make it difficult for a repeat photographer to precisely locate the original location. Even once the location of a repeat photograph has been determined, transportation to that spot may be limited or non-existent. In the case that there is no direct transportation to the photograph location, rough or rugged changes to the landscape since the photo was taken may make it extremely difficult for the repeat photographer to reach their desired location. Areas prone to natural disasters may experience large changes in the short term due to events such as earthquakes or flooding. Sudden extreme changes like these would make it difficult to navigate an environment safely, making the return to a repeat photography location problematic. For example, **Figure 3** is a historical photograph of an area in the Santa Fe water basin that is no longer accessible due to the creation of a lake. If the spot has been located and reached, the final challenge is lining up the repeat photo with the original. Small variations in camera placements, such as the camera’s angle or height off the ground, significantly impact what is captured within the bounds of the photo.

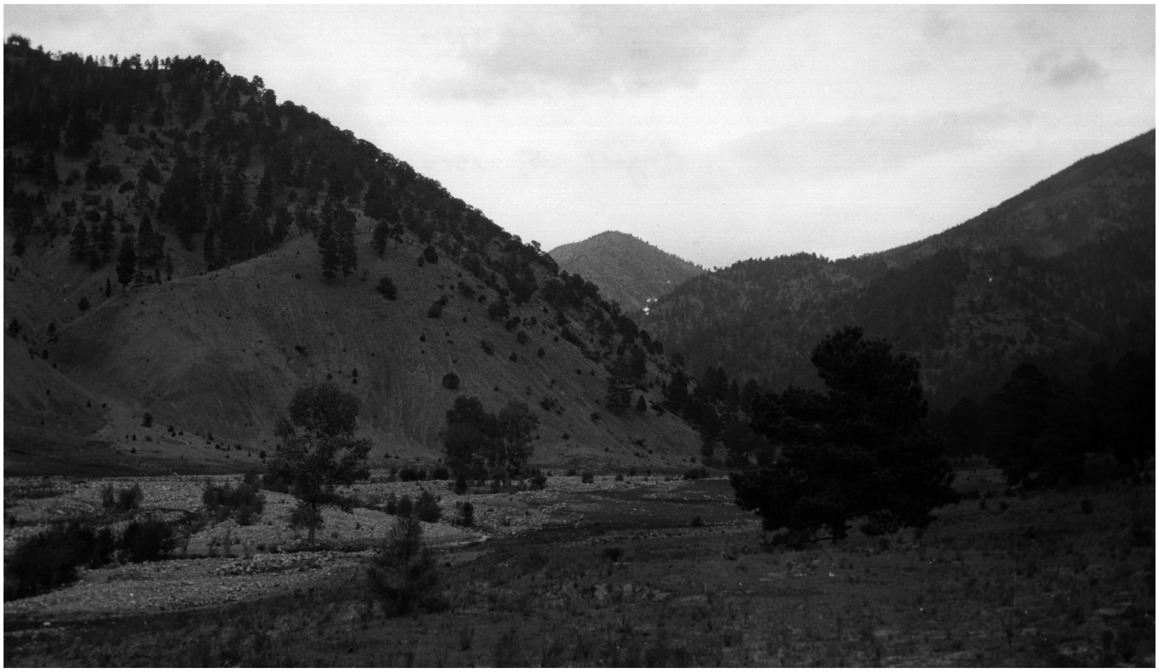

Figure 3: Inaccessible Location in the Santa Fe Water Basin (Roberts, 1917)

2.2 Best Practices for Repeat Photography

Researchers have developed systems and practices to make it easier to collect photographs and ensure that the time-lapse data are consistent and accurate. One of the best methods to do so is to choose a location that is easily identifiable by a physical marker or a unique landscape feature. A location should also be chosen based on how likely it is to be accessible in the future. Neither long-term ecological change nor human interference should render the repeat photography location inaccessible or difficult to reach in the future. For example, it is impossible to know if a hiking trail will still be maintained long into the future. Choosing an area under the protection of a government agency or non-profit for conservation in perpetuity may increase the likelihood of a photo point being maintained as long as possible. Unfortunately, areas that are most in need of ecological monitoring are also most likely to be the areas that are most susceptible to dynamic change. For example, a photo point that monitors the erosion of a river bank may be disrupted by the very erosion it is monitoring. The best solution to this problem is to plan for the future by placing the repeat photography location at a safe distance from any predicted landscape changes, and to create protocols in advance to handle any disruptions to a repeat photography point.

Several systems can be implemented to ensure accurate replication of previous photographs. In implementing any approach, researchers must try to minimize human impact from repeat photography; this means planning ahead, traveling on durable surfaces, disposing of waste properly, leaving what you find, minimizing campfire impacts, respecting wildlife, and being considerate of others (Leave No Trace, 2021).

One may face several challenges when attempting to perform repeat photography. There are several steps that can be taken to minimize problems. Some of the most useful of these methods were outlined by Craig Allen, a retired expert from the US Geological Survey (personal communication, 2023). Accessing some photo locations may require significant amounts of time and energy, so careful planning is essential.

Firstly, repeat photos should be taken at a consistent time of day. This is usually midday when the sun is at its peak, as this minimizes shadows, which can obscure details in a photo. Photos can also be taken in overcast conditions, which also helps minimize shadows. It is also important to bring tools that will help locate the photograph site. A GPS can be used to locate a photograph site if the coordinates are known. A compass should be brought to assist in navigating to the photo site. It can be a physical compass or a digital compass on a smartphone or other device. While navigating to a photo location, one should take note of landmarks along the path for future reference. One can take additional photographs of the landscape around or leading up to the photograph site for additional context on the area of interest.

A physical or digital copy of a past repeat photo of the target location should be brought along to help line up an accurate repeat photo precisely. If the camera being used has a setting to adjust its f-stop, the f-stop on the camera should be turned to the highest setting to maximize the depth of field of the photo. A high depth of field increases the detail of all objects in a photo. If the focal length of cameras varies between photos, the resulting photos may look distorted compared to each other. This problem cannot be completely addressed in the field, but can be remedied by cropping the photo with the wider field of view to match the other one.

2.3 Repeat Photography Using Physical Markers

In addition to replicating historical photos to determine long-term phenological change, repeat photography can also be used for detailed environmental monitoring. Traditionally, this variety of short-term repeat photography has been accomplished using physical markers (Hall, 2002, p. 2; Hammond et al., 2020, p. 14114). Photos are taken repeatedly from the same spot and angle, often annually. This usually involves a post or tripod from which photos are captured and additional markers around the central point to improve accuracy. **Figure 4** shows repeat photography of a ponderosa pine stand over a period of 8 years. A permanently placed meter board is used as the photographic center of each picture to ensure accuracy. (Hall, 2002, p. 1,8; Hammond et al. 2020, p. 14114). However, some projects use only a single permanent marker from which the pictures are taken, such as the Picture Post project (Madden et al., 2007).

In 2011, a collaboration between the University of New Hampshire and NASA led to a program called “Picture Post.” Picture Post was a NASA-funded project that aimed to promote environmental monitoring by students and members within the citizen science community (Wicklein, 2011 para. 2). With digital imagery, users were able to upload images into a database to track climate change in local areas. It was a great tool to “help monitor haze; clouds; precipitation, including snow and ice; and vegetation” (Dunbar, 2012, para. 4).

Figure 5 is an example of a Picture Post. It remains as a permanent marker of the location of the original photograph , and allows the original photo height and angles to be easily replicated. This design reduces the need for additional markers. Permanent markers make replicating the exact conditions of an original picture much easier, but they do have disadvantages. Markers can be toppled or destroyed and will experience weathering. In addition, all repeat photography projects seek to minimize the impact they have on the area they take place in. The more permanent markers a project adds the further it strays from this goal.

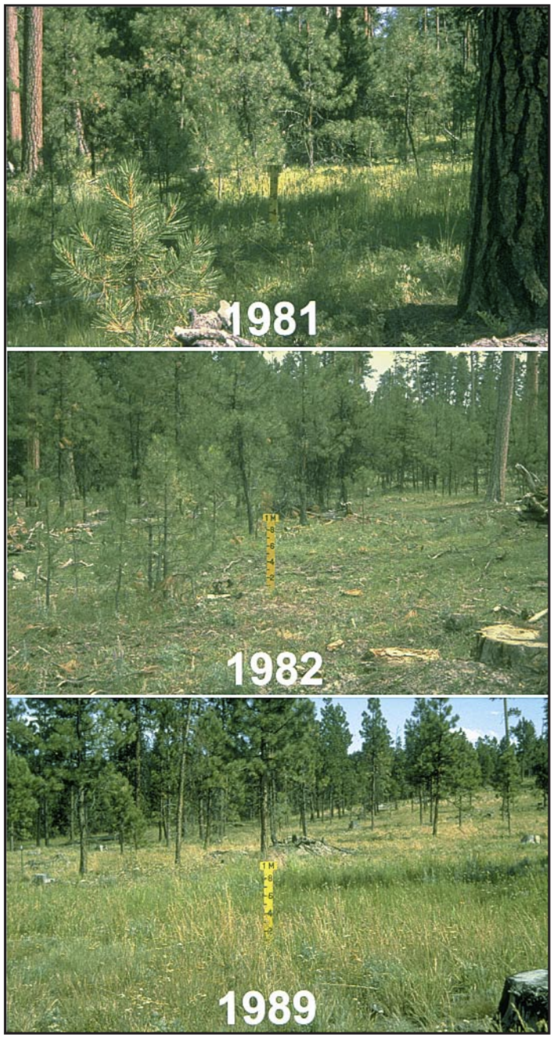

Figure 4: Example of an Additional Marker for Increased Accuracy (Hall, 2002, p. 2)

Figure 5: The Picture Post (Dobosz et al. , 2011)

2.4 Repeat Photography Using Virtual Methods

Another strategy for repeat photography is to have no physical marker at all. Fully virtual repeat photography relies on software that will track the repeat photographer's location using geolocation data and inform the user when they are in the correct location. The software can then use the photographer's camera to guide the user on taking the photo using a process called image matching. An example of image matching would be a smartphone application overlaying a partially transparent photo over the camera application to help the user align their repeat photo properly, such as how Schaffland et al. (2020) uses an overlaid historical image with tracking points to achieve well-aligned repeat photographs as seen in **Figure 6**. Virtual photography is advantageous in the regard that it requires no permanent infrastructure at the location and, therefore, minimizes human impact. A technology that assists in ecological resilience is greatly preferred over a technology that could potentially disrupt an ecosystem. The most significant limitation that virtual repeat photography faces is geolocation accuracy. Many modern GPS units are only accurate enough to determine the location of an exact spot within a few meters (Hammond et al., 2020).

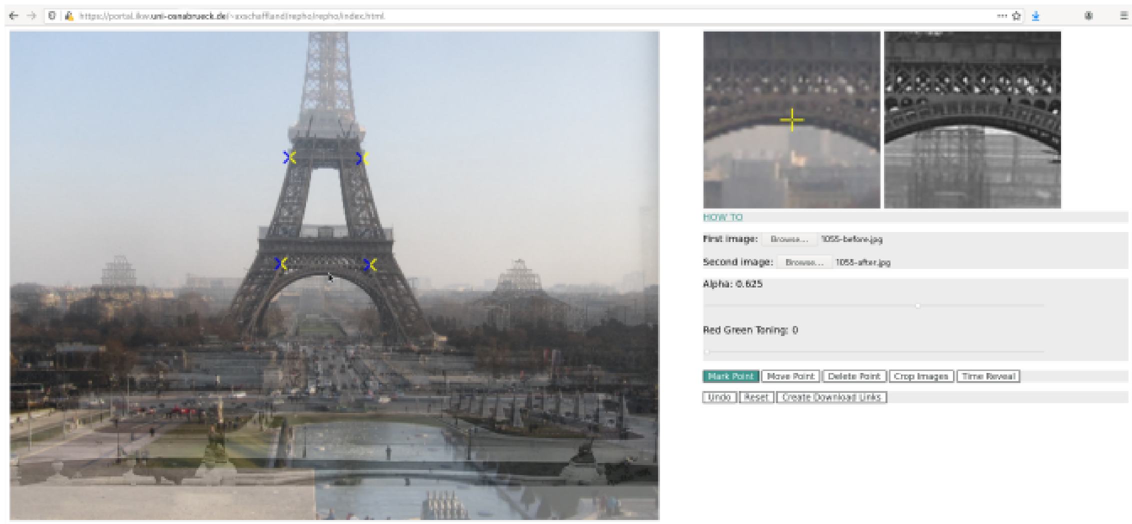

Figure 6: Interactive Overlay Method for Image Registration with Repeat Photography (Schaffland et al., 2020)

A technology that could be utilized for repeat photography is Realtime Earth. Realtime Earth uses a decentralized network of cameras to monitor areas in real-time. The component of Realtime Earth that makes it stand out among other camera networks is that it is capable of projecting a two-dimensional image onto a three-dimensional model of an area. This capability allows Realtime Earth to collect additional data about a photograph that traditional repeat photography cannot. For example, a person would be able to digitally mark the location of a forest fire over time. In **Figure 7a**, a user annotates an image captured from a live camera stream of an ongoing forest fire. These markings would then be able to be analyzed in three-dimensional space to track how fast the fire is spreading. **Figure 7b** shows an example of this three-dimensional projection and analysis. Additionally, Realtime Earth is advantageous for repeat photographs because it is able to calibrate a smartphone camera's orientation in space, photograph aspect ratio, and lens distortion quickly with assistance from machine learning tools (Realtime Earth, 2023).

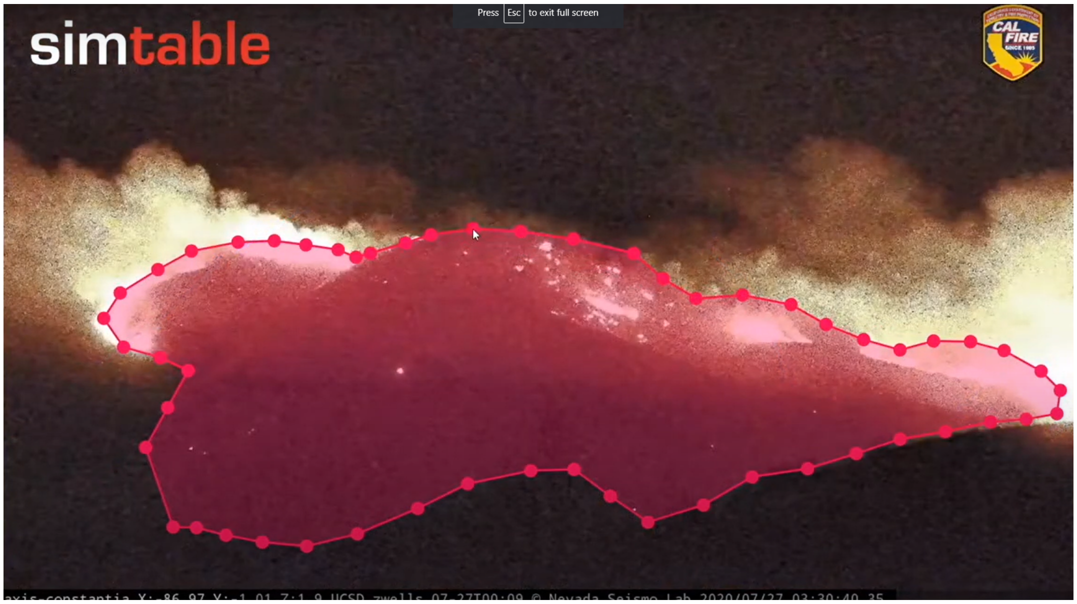

Figure 7a: Forest Fire Annotations using Realtime Earth (Simtable Videos, 2020)

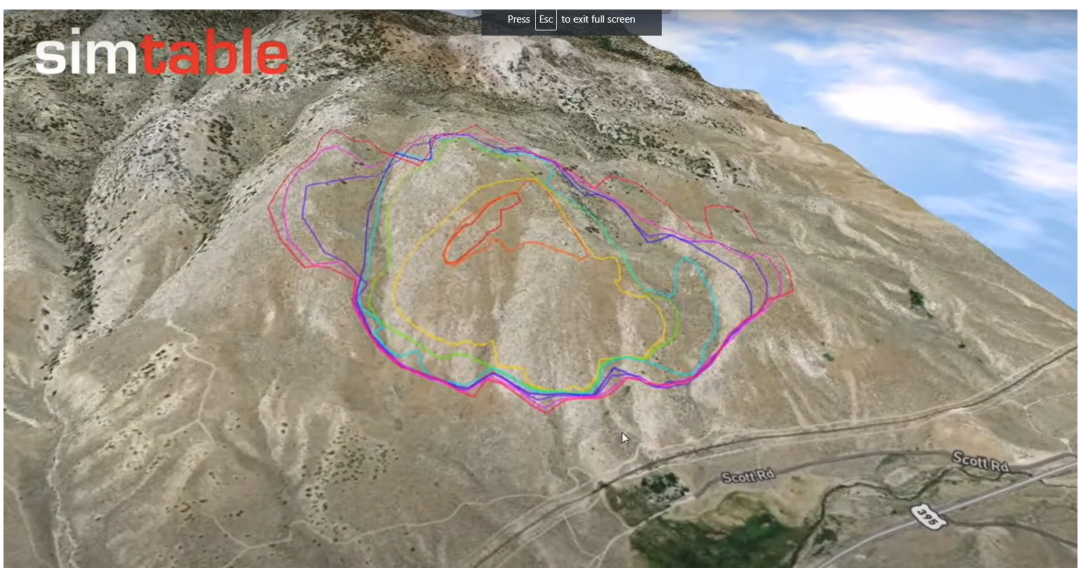

Figure 7b: Three-Dimensional Projection of Forest Fire Annotations Using Realtime Earth (Simtable Videos, 2020)

2.5 Additional and Supplementary Technologies

Repeat photography methods, both ones employing physical markers and ones employing virtual methods to determine location, are powerful yet limited in the amount of data they can collect, process, and store. This section discusses options to supplement repeat photography systems with additional technologies. Drones can be used to increase camera mobility and automate photo collection. The tradeoffs of smartphone cameras versus digital cameras are outlined to give a clearer idea of when one may be advantageous over the other. GIS software is a useful tool for managing and visualizing repeat photography data. Finally, different database structures are discussed as possible solutions for long-term data storage.

2.5.1 Camera drones

Camera drones are an emerging technology that can help to remedy many challenges faced when taking repeat photographs, especially in the case of repeating historic photos. Drones have an advantage over ground-based photography in the fact that they are able to access heights and locations that a person cannot or may not be able to. Many drone cameras are also equipped with gimbals – a tool that is able to physically stabilize photos and videos. The presence of new buildings, foliage, or other objects may obstruct a view of an area that was formerly clear, which can lead to a loss of detail and information. **Figure 8** shows a view of a residential area which is now partially occluded by the growth of trees. In this case, a drone would be able to reach a sufficient height above the foliage to gain a clearer view of the area.

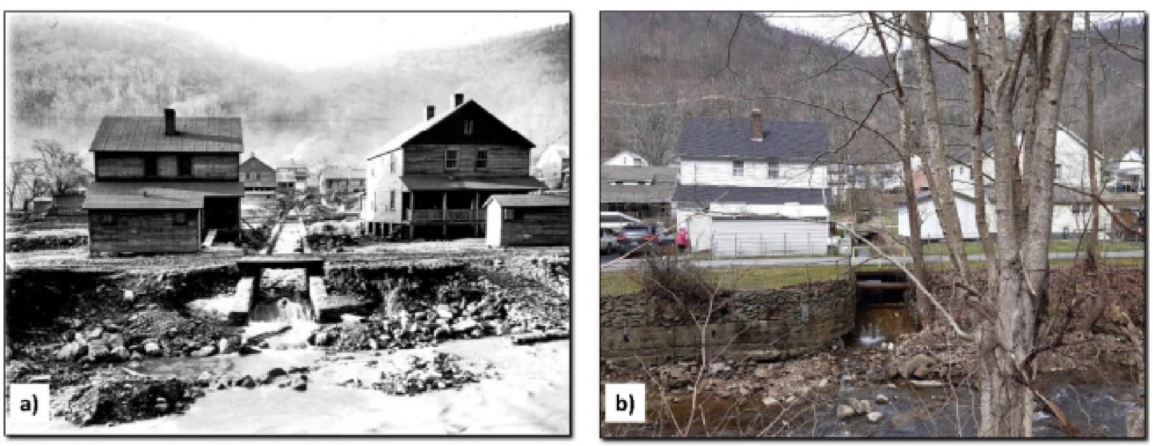

Figure 8: Repeat Historical Photograph, Now Obscured by Foliage (Hodgson, 2021)

In addition, the ground level may change enough over time so that it is impossible to take an accurate repeat photo from the same height. A change in ground level can be attributed to natural events and geological changes such as erosion or human impact like construction (Hodgson, 2021). Drones are capable of flying to heights far above ground level and, therefore, are able to solve the problem of an inconsistent ground level. In the case that an area is now inaccessible or unsafe to traverse by foot, a camera drone would be perfectly capable of visits. However, it is important when taking repeat photos with drones that one is not flying them through private property or restricted airspace.

However, drones are not an all-in-one solution to the problems faced by ground photography. Although drone technology has improved over the technology's lifespan, they still require skill and precision to operate effectively. Camera drones can be prone to technical difficulties, crashing, and getting caught in foliage. Even in cases where a drone is being piloted by an expert operator, drones are still difficult to navigate in high winds, rain, or dense foliage. Unlike static photography methods like a tripod or a fixed marker, drones are constantly readjusting to reach a balance between the forces from gravity, lift, wind, inertia, etc. This means that drones are more reactive to micro-adjustments, which can make lining up a photo burdensome. This problem may be able to be solved by more advanced drones, which are able to automatically fly to specific coordinates based on input data from the drone operator.

2.5.2 Phone and digital cameras

The line between smartphones and digital cameras has become blurry over the years, making it normal for experts to use their "smartphones as their first and sometimes only tool of imagery" (Davies, 2023). According to 2018 national statistics, smartphones were present in 84% of households in the U.S. (*Computer and Internet use in the United States*, 2021). Thus, it is safe to assume that more than three-quarters of Americans have access to a smartphone device. Comparing a smartphone camera to that of a digital camera, the choices usually come down to convenience vs quality.

Sensors are debatably the most crucial part of a given camera. Some cameras have multiple sensors, while others have only one. The number and size of sensors heavily influence image quality by converting light waves, or protons, into electrical signals that can form an image to be analyzed and stored (*Understanding the digital image sensor*). The smaller the sensor, the less likely it is to capture light, making for a blurry image, while bigger sensors can capture light in photographs without issue. The rule of thumb is that the larger the sensor, the higher the image quality (Davies, 2023). Digital cameras tend to have larger sensors because they are typically bigger than a smartphone that is designed to fit in your pocket. This means digital cameras perform better in low light, collect more data, and, for the most part, create higher-quality photographs or videos. Nonetheless, most smartphones feature multiple cameras now, thus entailing multiple sensors (Davies, 2023). These sensors are generally small, given the compact size of a smartphone, but the quality and abilities of sensors are constantly improving.

Smartphone lenses, like their sensors, are very small, inhibiting their ability to take high-quality photographs and videos (Landwer-Johan, 2023). Nevertheless, smartphones are capable of capturing high-quality images under a variety of ambient conditions, especially when they include three or more cameras in one device, such as the iPhone Pro series or the newer Samsung devices. Though these three cameras are highly resourceful, the smartphone still cannot outperform ‘professional’ digital cameras in terms of versatility. Not only are hundreds of different lenses available for digital cameras, but there is also an abundance of adapters to fit lenses from different brands onto particular cameras. Though smartphone accessories for videography and photography are becoming more available, they still do not outshine the versatility of digital cameras.

Digital cameras tend to have larger sensors and interchangeable lenses, which gives them an unparalleled advantage over smartphones in terms of photo quality and versatility (Davies, 2023). Consequently, the image quality from that of a digital camera is much better than that of the average smartphone. However, smartphones are convenient, fast, and very easy to use; almost everyone has access to one. Notably, depending on what attributes of the environment that are being monitored, smartphones may be more adequate for most types of repeat photography. Digital cameras and drone cameras, including ultraviolet and infrared radiation devices, may be needed for more specific types of environmental monitoring and would typically only be accessible by experts in the field. Thus, they are not suitable for citizen science approaches to data collection.

2.5.3 ArcGIS

Esri, creator of ArcGIS and one of the leading producers of GIS software in the world, defines “a geographic information system (GIS) [as] a system that creates, manages, analyzes, and maps all types of data” (Esri). Google Maps is a GIS system that many people are familiar with. It incorporates a base map (such as a basic road map or satellite imagery) on which other data can be overlaid, such as routes or location descriptions. ArcGIS is a more powerful system and the software of choice for many local, state, and federal agencies in the US, as well as many public and private companies. It is used by these organizations to collect, store, and analyze enormous amounts of geospatial data, such as property and political boundaries, the locations of buildings and infrastructure, and land cover and land use. Esri produces both a more powerful downloadable program for ArcGIS and an online version, which includes a data visualization tool called StoryMaps.

ArcGIS StoryMaps can be an extremely effective tool for presenting repeat photography. StoryMaps allows text to be combined with embedded media in an accessible format and have several features that are especially useful for showcasing repeat photography. The Swipe media block allows two images (such as a repeated photograph) to be directly compared. **Figure 9** shows images that are overlapped in the media block, and then a slider can be moved across the block to reveal more of one image or the other. This allows for very intuitive and visually striking representations of change.

Border Monument 77 - LEFT: 1893, The camera is aimed toward the northeast past Monument 77 from the Mexican side of the boundary. The dense honey mesquite growth is seen in this view also. The crown of a cottonwood tree, growing along Black Draw, is seen at the left. Elev. 3,545 ft. (Photograph by D. R. Payne) **RIGHT**: 15-May-1998, The honey mesquite is in leaf in this photograph, taken two months later than the view to the southwest matching this. (Photograph by R. M. Turner)

Figure 9: Example of the Swipe Media Block in ArcGIS StoryMaps (Nichols, n.d.)

Maps can be embedded within StoryMaps to help situate the repeated photography. The Map Tour media block allows a map to be embedded into the system and points of interest to be marked on it. An example of this can be seen in Appendix E. Each point can have an attached image and text. The feature then allows a virtual tour around the map, zooming in on each of the points of interest and displaying the corresponding text and image. This can be used to showcase repeat photo locations and thus contextualize photo points in reference to their surroundings and one another.

ArcGIS can also be used to store information about photo points in a very intelligible way. Much like the Map Tour, ArcGIS allows users to create maps with points. While Map Tour only allows a limited amount of information to be added, actual maps allow much more data to be stored. Map point layers can be used to store location data, photos, and more. This means that data can be added to a table but then easily accessed from points on a map. This makes finding information much more intuitive while also retaining the table storage format.

2.5.4 Databases

Databases are a critical component of any repeat photography system. To enable future analysis, photos must be stored in a safe, reliable, and easily accessible fashion. According to Hart et al. (2016), a system for reliable data storage is important as poor data storage can lead to "data entropy," or the loss of data over time. Data storage can take many forms but generally fall into three categories: physical storage, cloud services, and decentralized networks. Each type has its own advantages and disadvantages in regard to storage capability, reliability, cost, and ownership. It is important to remember that different types of databases are not mutually exclusive and can be mixed and matched in order to meet a person or organization's data storage needs.

The most traditional method for data storage is a physical database. On smaller scales, this takes the form of one or more hard or solid state drives and server rooms on larger scales. Physical databases can store large amounts of data, and ownership of the data is decided by who keeps and maintains the physical drive. Unfortunately, physical databases can lose data as a result of unexpected hardware failures, and therefore it is good practice to maintain multiple copies of identical data across multiple drives. Cloud databases allow data to be stored remotely in multiple server rooms. Most cloud databases are maintained by larger organizations, and therefore those organizations maintain the data stored on the server. The reason cloud services are popular is because, in most cases, they can store large amounts of data reliably at a low cost relative to other data storage methods (Elzeiny et al., 2013). Finally, decentralized databases allow data to be stored through peer-to-peer networking. Peer-to-peer networking refers to the data being shared and stored across the devices in the network, such as in the case of Realtime Earth (Guerin, personal communication, 2023). According to Gribble et al. (n.d.), the data is owned by no single device or person in the network. The amount of data a peer-to-peer database can store is correlated to the amount of data that devices in the network are capable of and willing to store. One disadvantage is that if there are not enough devices participating in the network to provide enough data storage necessary, data will be lost.

3.0 Citizen Science

Citizen science is the involvement of the public in scientific research. These research projects can cover a variety of topics but generally involve collecting or analyzing data on a local level. Anyone can participate in citizen science and can access the data generated from the project. There are three main types of citizen science: participatory, collaborative, and co-produced, which all have different engagement levels (Levesque, 2019, ch. 14). Participatory citizen science involves mostly data collection. There is no involvement in developing the methods for gathering data or the data analysis itself. Collaborative citizen science has a higher degree of engagement, usually through data analysis and project refinement. Participants can help provide input on how to gather the needed data, revise aspects of a project, and help analyze information. Co-produced citizen science is the highest engagement model. These types of projects allow participants to be fully involved throughout the entire research process (Levesque, 2019, ch. 14). Citizen science benefits the scientific community in data collection, but it also benefits the participants. Exposing communities to real-world problems and engaging them with local issues can foster a feeling of responsibility for a particular area or part of the natural environment.

Citizen science pertains to the analysis of data involving community members from a specific geographical area, emphasizing collaborative and communal efforts. This approach finds diverse applications across various domains and has gained increasing recognition, particularly within the scientific discipline of environmental and ecological sciences. In this field, typically, non-professional participants actively engage in the data collection processes, thereby advancing scientific research (Fraisl et al., 2022, p. 1). In this section, we offer an overview of the fundamental principles and benefits of citizen science as it pertains to the climate change crisis and discuss several case studies.

3.1 Using Citizen Science to Monitor Ecological Change

Cultural heritage preservation and environmental conservation share a joint mission to protect and sustain resources. Such efforts have the potential to foster public interest and awareness in addressing climate change threats while gathering and disseminating crucial data. Projects that bring together the fields of cultural heritage preservation, nature conservation, and sustainable development strategies are key to effective collaboration (Berenfeld, 2008, p. 67). By employing methods for citizen engagement as a source of motivation, it is possible to encourage climate change mitigation efforts among the residents of Santa Fe. This strategic approach has the potential to amplify this project's influence and formulate a stronger sense of community involvement while simultaneously tackling the pressing issue of climate change.

Citizen scientists have been used to gather photos to monitor ecological change. The value of citizen science and the effectiveness of local communities monitoring ecological change is demonstrated in two cases below. One approach collected photos and videos to help improve the understanding of mammal biodiversity and distribution, and the second approach used repeat photography of flowers and insects in twenty-minute intervals to measure the effects of urbanization on community composition, affinities of specific pollinators, and pollinator habitats.

3.1.1 Case one: MammalWeb

MammalWeb was established in 2015 in the northeastern region of England, United Kingdom, and has since extended its outreach to encompass numerous European nations. The project adopts a participatory citizen science methodology aimed at enhancing the comprehensive understanding of mammal biodiversity and distribution. To join, "participants provide their own motion-triggered camera traps or borrow one from *MammalWeb* and deploy these cameras for observations. Collected photos and videos are uploaded with spatiotemporal metadata to *MammalWeb* and classified by registered users" (Parsons et al., 2018, p. 9). Spatial data analysis has revealed an "improved understanding of the diversity and distribution of wild mammals, revealing temporal patterns in animal behavior, and may aid future analyses and estimations of population structure through occupancy modeling" (Parsons et al., 2018, p. 9). This shows the potential for data collection through citizen participation.

3.1.2 Case two: Spipoll

In 2010, the Photographic Survey of Flower Visitors, known as *Spipoll*, was inaugurated through a collaborative effort between the French National Museum of Natural History (MNHN) and the Office for Entomological Information (OPIE). The primary objective of this project was to investigate the temporal and spatial alterations in plant-pollinator interactions occurring throughout France. To participate, "wherever participants find a flowering plant — from dense urban centers to natural areas — they photograph all invertebrates landing on its flowers during a 20-minute period. After having identified insects and plants using a dedicated online identification tool, participants upload their photographs and associated identifications, as well as the date, time, and location of observations and climatic conditions, to the *Spipoll* website" (Parsons et al., 2018, pg 10). Consequently, "data from *Spipoll* have led to new scientific knowledge on the effects of urbanization on community composition, contrasted affinities of pollinators with different land use, and the role of domestic gardens as favorable pollinator habitats [...] The online communication platforms provided by *Spipoll* play a pivotal role in fostering the development of a cohesive learning community among its participants. These digital spaces not only facilitate the enduring engagement of contributors but also serve as a valuable means to enhance the quality of gathered data" (Parsons et al., 2018, p. 10). Consequently, *Spipoll* exemplifies the significance of online interaction mechanisms and participant support tools in the successful pursuit of the diverse objectives inherent to contributory citizen science initiatives (Parsons et al., 2018, p. 10).

3.2 Citizen Science for Repeat Photography

Citizen science approaches have also been used to gather repeat photographs to monitor ecological change. We review three cases here.

rePhotoSA is a citizen science project that aims to understand how South Africa's landscapes are changing. Using a photographic database, users can look for images in specific areas and help track climate change (rePhotoSA, 2023). In **Figure 10,** a photographic comparison of two locations in central Cape Town showcases the dramatic changes in the landscape there. Scott et al., (2021, para 1) identify four key activities to ensure the long-term success of the project; “attracting and keeping citizen scientists involved, maintaining data quality, providing accurate photo-site location information, and effective dissemination of scientific knowledge to the public.” Citizen science projects depend on citizen participation. Without community involvement, understanding ecological change on a local level presents a significant challenge. Educating communities on the importance of repeat photography and tracking climate change is required to ensure a better future for generations to come.

Figure 10: Historical Photographs to Modern Day Scenery Comparison (rePhotoSA, 2021)

A recent study of southwest Alaska’s national parks provided valuable information for developing a repeat photography website that aimed to help track climate change in the area. “Facilitating the Development and Evaluation of a Citizen Science Website: A Case Study of Repeat Photography and Climate Change in Southwest Alaska's National Parks” was conducted in 2014 with the mission of developing a website as a climate change communication tool (Mullen et al., 2013, p. 1). The article lays out a guide explaining the essential needs for website development, such as a proper user interface, data tracking, and storage, as well as ease of use for all ages. It is important to identify a usable hands-on learning program using repeat photography that would be appealing to park visitors. **Figure 11** shows a website landing page showcasing many different ways to contribute to climate change monitoring.

Figure 11: Interactive Repeat Photography Website to Track Environmental Changes (Mullen, 2014)

One standout project, which was conducted through WPI, aimed to find strategies that would help increase participation in citizen science (Dobosz et al., 2011). The main focus of the project was designing and implementing a new, fun educational system utilizing Picture Posts. Working with potential participants and science experts at the Blue Hill Observatory and Science Center in eastern Massachusetts, the group worked on programs to help increase volunteer participation in monitoring the health of the local vegetation (Dobosz et al., 2011, p. 1). Initially, three posts were installed as part of the Blue Hill Observatory's education program. **Figure 12** shows a plane view of the post, which includes an octagonal plate that allows for an 8-image panoramic view of the landscape. The WPI team made posters, instructional signs, and informational brochures to teach the user how to accurately use the posts. The authors argue that data collection methods, such as Picture Post programs, can be used to understand how climate change affects local environments. It is important to learn from this previous research group, as most of our projects correlate with their past objectives.

Figure 12: Top Blue Hills Picture Post Prototype (Dobosz et al., 2011)

4.0 River Source

River Source is a small organization based in Santa Fe that focuses on restoration projects and long-term ecological monitoring, particularly of watersheds. The organization emphasizes community-driven programs and provides educational as well as community services. River Source is especially interested in developing repeat photography methods that could be used to monitor ecological change.

Rich Schrader founded River Source in 1997 as a sole proprietorship and has remained the director ever since. As a response to alarming threats of climate change, River Source is driven by a mission to cultivate watershed resilience through community-based stewardship. In 1995, before even incorporating, River Source began developing watershed planning in collaboration with high school students affiliated with the Santa Fe Indian School's Community-based Education Program (CBE) (River Source Education, 2023). One endeavor involved engaging with local elders and enlisting community scientists to gather precise data and formulate enduring restoration initiatives.

4.1 River Source's Goals with Repeat Photography

In addition to community engagement, River Source has also helped people develop systems for gathering and organizing quality-assured data. One example of a system used is Mappler, a mobile GIS system that helps visualize points of interest to meet project needs. River Source has used the Mappler system to track fisheries health data in crucial watersheds across New Mexico and parts of Colorado. With this technology, they can measure the performance of a fishery within the area's social, economic, biological, and environmental framework.

River Source wants to utilize repeat photography tools that engage the local community in Santa Fe. The two most applicable technologies for this goal will be the aforementioned Picture Post and Realtime Earth. Both of these technologies are accessible to a general population, as they rely on smartphones as camera hardware. River Source is specifically interested in reviving the Picture Post system. The advantages and disadvantages of these repeat photography methods will be evaluated on their ability to act as a service to monitor climate change.

Methodology

Our project goal was to evaluate the feasibility of a repeat photography service to monitor the phenological changes associated with climate change in Santa Fe, New Mexico. Our project evaluated different technologies and tested prototypes of different methods for repeat photography for environmental monitoring. We hope River Source, in collaboration with others, will be able to use our assessment of these technologies to develop a repeat photography service. Our five objectives were to:

1. Evaluate current and best practices in the use of repeat photography to monitor the effects of climate change.
2. Locate sites and collect repeat photographs from locations depicted in historical photographs and design a captioning activity and lesson plan around repeat photography.
3. Test and evaluate technologies for repeat photography in the Santa Fe region.
4. Prototype potential repeat photography methods based on our evaluations and test those prototypes among ourselves and with volunteers.
5. Evaluate different options that River Source and their potential collaborators and clients might pursue to implement a repeat photography service, specifically for Picture Post.

Figure 13 illustrates our project goals, objectives, and tasks breakdown.

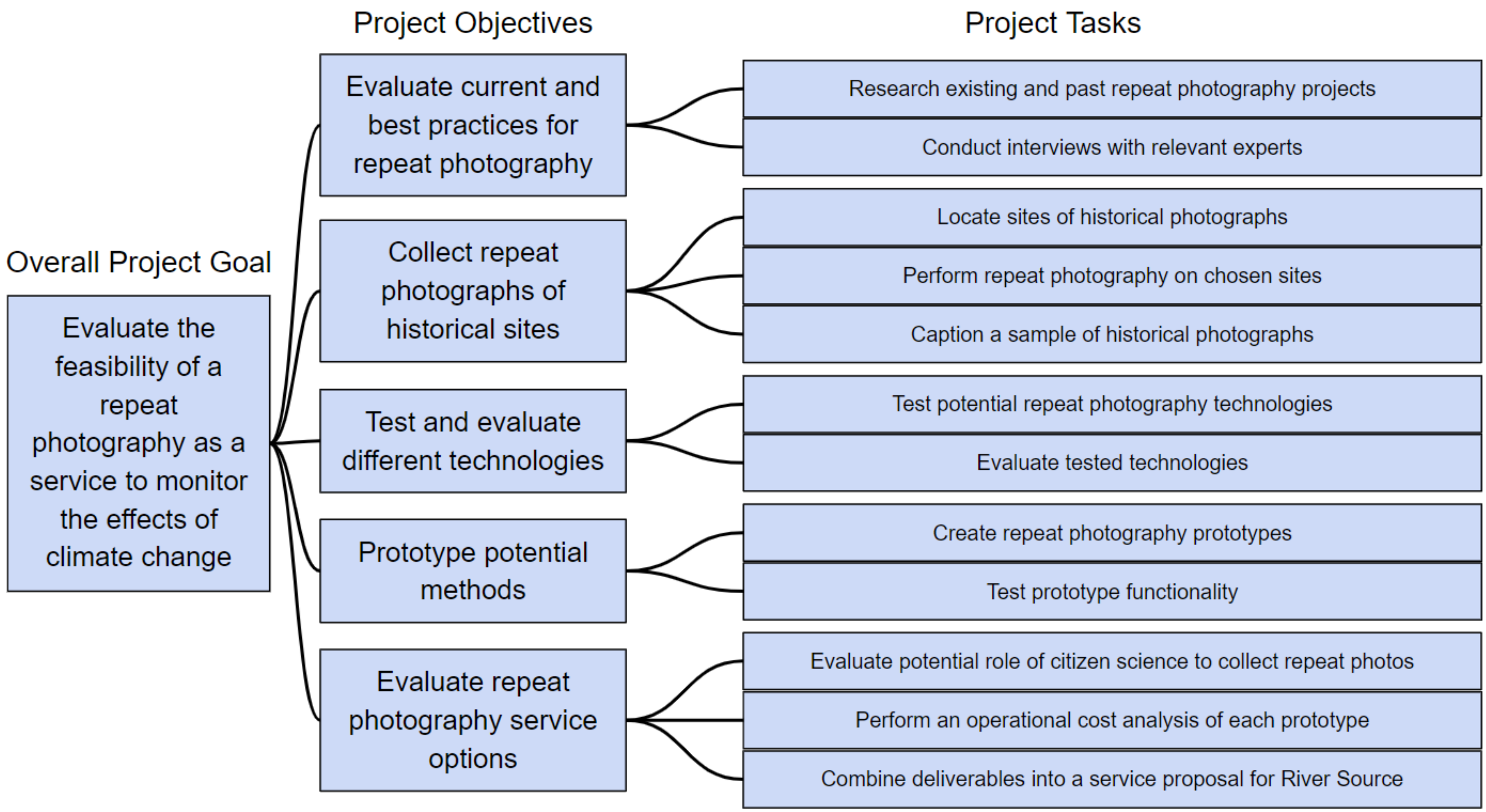

Figure 13: Project Goals, Objectives, and Tasks.

1.0 Evaluating Current and Best Practices for Repeat Photography

We expanded on the background research presented above by conducting interviews with various experts in the field, including those who have used or are using repeat photography to monitor the effects of climate change.

We identified several repeat photography and technology experts during the course of our background research, including Stephen Guerin and Craig Allen. We were particularly interested in talking to members of organizations previously involved in applying PicturePost, including representatives from the Blue Hills Observatory in Massachusetts. We also interviewed other individuals who have participated in repeat photography projects, such as Micah Kiesow of the Forest Service, Eytan Krasilovsky of the Forest Stewards Guild, and Nav Khalsa of the Northern New Mexico Master Naturalists. Each interviewee was asked to recommend other relevant experts, thus allowing us to develop a referral sample. All of our interviews conducted are outlined in **Table 1**.

Name(s)	Affiliation	Role	Date of Interview/Meeting
Craig Allen	United States Geological Survey	Research Ecologist (retired)	Thursday 10/26/2023
Mori Hensley	Santa Fe Watershed Association	Executive Direction	Tuesday 10/31/2023
Stephen Guerin	Simtable	CEO, Founder	Tuesday 10/31/2023, Tuesday 11/14/2023
Donald McCasland	Blue Hills Observatory	Program Director	Wednesday 11/01/23, Thursday 11/16/23
Alyssa Gallagher-Moran	Blue Hills Observatory	Director of STEM Education	Wednesday 11/01/23
Craig Austin	Blue Hills Observatory	Picture Post Volunteer Contributor	Wednesday 11/01/23
Eytan Krasilovsky	Forest Stewards Guild	Deupty Director	Wednesday 11/01/2023
Micah Kiesow	United States Forest Service	Soil Scientist	Wednesday 11/8/23
Kris Herbst	Self-employed	Journalist (retired)	Monday 11/13/2023
Nav Khalsa	Northern New Mexico Master Naturalists	Volunteer Coordinator	Wednesday 11/15/23
Melanie Alvarez	Santa Fe Conservation Trust	Stewardship Associate	Thursday 11/16/23
Stacy Timmons	New Mexico Institute of Technology and Mining	Associate Director for Hydrogeology	Monday 11/27/2023
Staci Matlock	New Mexico Forest and Watershed Restoration Insititute	Public Information Specialist	Thursday 11/30/2023
Corey Beinhart	New Mexico Forest and Watershed Restoration Insititute	Data Manager	Thursday 11/30/2023
Nathan Tomczyk	New Mexico Forest and Watershed Restoration Insititute	Research Associate	Thursday 11/30/2023
Patti Dappen	New Mexico Forest and Watershed Restoration Insititute	GIS Program Manager & Administrator	Thursday 11/30/2023

Table 1: Interviewees by Their Affiliations, Roles, and Interview Dates

We attempted to conduct in-person interviews with experts, but if this was not possible (due to timing, location, or interviewee preference), we conducted interviews virtually. We presented a preliminary set of questions in **Appendix A**. We tailored the questions according to the interests and expertise of our interviewees.

All interviews started with a standardized summary of our project and purpose and a request to use information from the interview in our final report. This preamble also includes a brief explanation of the purpose of our research, our project goals, a general summary of the questions that were asked, a reminder that the interview is voluntary and questions can be skipped, and an invitation to ask any questions about our project or the interview before it begins. We asked for permission to quote our interviewees anonymously and gave them the right to review any quote we used from them prior to the publication of our report.

2.0 Repeat Photography of Historical Photographs

The second objective our group accomplished was the documentation of historical photos. The project provided a unique opportunity to showcase the use of repeat photography with a dramatic example. Although the main focus of our project was to prototype a consistent method of repeat photography, repeating historical photographs serves an essential purpose for educating communities on local climate and ecological change. The locations of digitized historical photographs were determined with the assistance of Craig Allen, who was part of the team that repeated several of them in the early 2000s . From these photographs, we selected three to replicate. Following that, we visited photo points of the historical photos we had selected and collected repeat photographs to the best of our ability.

2.1 Determining the Location of and Selecting Historic Landscape Photographs

River Source provided us with a collection of historical photographs of different locations in and around Santa Fe. The black and white photographs are over 100 years old. Craig Allen, a renowned expert from the US geological survey (retired), agreed to help us identify the locations of the original photos. He was involved in locating and performing repeat photography on many of these sites in the 1990s. In addition, Dr. Allen has since worked with the Forest Stewards

Guild to digitize these photos. The Forest Stewards Guild is currently involved with stewardship projects in the Santa Fe region and had more recent information about the locations of the historical photos. We identified the locations of many of the photographs with the help of Dr. Allen and the Forest Stewards Guilds' expertise.

2.2 Performing Repeat Photography on Chosen Sites

Once the general locations of the chosen photographs were identified, the next step was to replicate the original photo with the greatest degree of accuracy possible. Craig Allen offered some tips on proper landscape photography. These included increasing the depth of field, lowering the capture speed, and shooting the image in RAW format. For our team, it was satisfactory to approximate the original view, as the zoom and camera height of the original photographs are unknown. It is likely, if not certain, that our photos were taken from a slightly different location than the original. We used a tripod and a smartphone camera with variable zoom to compensate for this. Ultimately, this allowed us much greater flexibility in our location, as the combination of zoom and variable height provided by a tripod could simulate a photo taken from a point closer to the target view. We brought along printed physical copies of the original historical photograph to each respective site to assist in replicating the original photograph as closely as possible.

2.3 Captioning Photographs for Storytelling and Education

We worked with journalist Kris Herbst to caption a sample of historical photographs of the Santa Fe region. This sample included some of the historical photographs we collected in the field. Captioning means writing a brief text to accompany a photograph. This text gives valuable background information that is not necessarily visually apparent. Captions can, therefore, be used to elaborate on a photograph and provide further educational value. Well-written, succinct captions are invaluable for storytelling with photography. This process gave us the practical experience and confidence necessary to inform others how to write compelling captions.

Using experience gained from our meeting with Mr. Herbst, we developed a caption writing activity and lesson plan based around Picture Post. The activity provides advice on how to effectively observe a landscape as well as how to turn those observations into a compelling and informative caption. It also includes instructions on how to use Picture Post, with the idea that a Picture Post can be used to collect the images to be captioned. This lesson plan can be found in **Appendix C**. We hope it can be used to both generate and maintain interest in Picture Post.

3.0 Testing and Evaluating Repeat Photography Technologies

An important focus of our project was testing and evaluating the feasibility of various technologies to be used for repeat photography. Each technology was assessed based on the criteria we considered necessary for us to gain a comprehensive understanding of them. In **Table 2**, we present an initial list of the technologies we expected to evaluate and the criteria we expected to use to evaluate them. We decided that, if necessary, we could draw on our background research and consult with our sponsor to develop a more extensive set of criteria. Technologies to be evaluated were identified through background research. We evaluated specific technologies based on defined criteria both for their individual utility and for their ability to connect and be used with other technologies. A large part of our evaluation came from discussing these technologies with experts and gaining information about their experiences using them. Some technologies appear to have more use as a supplementary tool rather than as an independent device.

Criteria	Ability to determine precise location	Ability to measure orientation of camera	Consistency between photographs	Longevity	Set-up difficulty	Skill needed to operate	Potential for citizen science	Potential as a supplementary tool
Technology								
Picture posts	☐	☑	☑	☑	☑	☑	☑	☐
Other physical markers	☐	☑	☑	☑	☑	☑	☑	☐
Arc GIS	☑	☐	☐	☑	☑	☑	☑	☑
Survey123	☑	☑	☑	☐	☑	☑	☑	☑
StoryMaps	☐	☐	☐	☐	☑	☑	☑	☑
Drone photography	☑	☑	☑	☑	☑	☑	☑	☐
Phone GPS	☑	☑	☑	☐	☑	☑	☑	☑
RealTime Earth	☑	☑	☐	☑	☑	☑	☑	☑
Google Earth Pro	☐	☐	☐	☐	☑	☑	☐	☑

Table 2: Evaluation Criteria for Technologies

3.1 Evaluation Criteria

3.1.1 Ability to Determine Precise Location

Although we expect the general location of a repeat photography site to be easily located with the aid of maps and GPS, identifying the precise location may be more difficult. We defined "precise" as within one meter of the location of the original photographer. Many of the technologies we identified rely to varying degrees on GPS, which generally has a lower accuracy than this standard. It was expected that only technologies with a fixed marker (such as PicturePost) would be able to locate the exact spot consistently, but we evaluated other technologies anyway.

3.1.2 Ability to Measure Camera Orientation

This refers to how capable a technology is in measuring the height and angle of a camera. It would be especially useful if the technology could use this information to assist in adjusting the orientation of the camera for an accurate photograph.

3.1.3 Consistency Between Photographs

One of the most crucial aspects of repeat photography is consistency between photos. We measured camera height, angle, lens distortion, focal length, and aspect ratio. Our capacity to measure these properties was dependent on the technology being assessed.

3.1.4 Longevity

Longevity is an important characteristic of many repeat photography devices, but it can be difficult to evaluate. We evaluated longevity for physical devices, not software, and based our evaluations on both research and expert opinion. The material lifespan of the components of each technology was the primary standard for this evaluation. We also took into account different potential environmental conditions in this evaluation. If significant differences in longevity were predicted for different conditions, we included this information when evaluating potential services in section five.

3.1.5 Set-Up Difficulty

We considered how difficult a technology is to set up or implement, especially if citizen scientists were used as the primary photographers. We considered how much travel, manpower, or physical exertion is needed to set up a technology. In addition, we aimed to determine what training, experience, or background knowledge a person needs to set up the technology. This is a separate criterion from the skills needed to operate, but it may overlap with some technologies. We expected that a more difficult initial set-up process would allow a lower skill threshold for operation in some methods.

3.1.6 Skill Needed to Operate

Skill needed to operate examines how much skill is needed for someone to use a technology properly and confidently. We considered how much time it took to learn the basic operation of the technology as well as how high the potential is for damage to any components from an untrained user. This was based on background research and our experience using each technology.

3.1.7 Potential for Citizen Science

An important factor we needed to consider was how well a technology could work with citizen science. Our sponsor is highly interested in encouraging community engagement, so this is an important aspect to include. We made a subjective decision based on the ease of use of the technology and its learning curve. This criterion was heavily influenced by the “skill needed to operate” and other criteria.

3.1.8 Potential as a Supplementary Tool

From our background research, it appeared that certain technologies might be more useful when joined with another technology than if used by itself for repeat photography. This mostly applies to software such as Realtime Earth and ArcGIS, which have the potential for image georeferencing. When evaluating these technologies, we considered how they could be combined with other technologies to create a more effective whole.

4.0 Prototypes and Mockups

After the criteria for each technology were evaluated, we created several respective mockups and prototypes for different technologies. Prototypes were created to trial minor changes/improvements to technology design, while mockups were created to explore potential use cases. Specifically, several prototypes for new Picture Post toppers were created, along with a mockup for using Realtime Earth for repeat photography.

Once prototypes were constructed, our group did a separate evaluation of them without external feedback. This evaluation used the same list of criteria with which we evaluated the initial technologies, except longevity. We could not assume that a technology would perform as well in practice as our research might indicate.

4.1 Picture Post

The original Picture Post topper was designed for use with standard digital cameras. Its design makes it very easy to center pictures from a digital camera and get consistent shots. However, smartphones have since eclipsed dedicated digital cameras as the most common type of camera. While the original Picture Post design is absolutely usable for smartphone cameras, it is not optimized for them. Our prototypes explore simple changes to the topper to better accommodate the new age of cameras.

4.2 Realtime Earth

As Realtime Earth is still in development, it was more practical to create a mockup rather than a prototype. Our mockup explores the potential of a future iteration of Realtime Earth.

5.0 Evaluate Different Options as a Repeat Photography Service

After evaluating various methods of repeat photography and their associated technologies, we summarized our findings for River Source. Our evaluations of the usability of different methods were combined with additional data that might be relevant to an organization developing a repeat photography service. We estimated community interest for each approach in addition to compiling our own data from evaluations conducted in section three. Our team asked each organization specifically about their knowledge of Picture Post and experience using it in order to gauge how interested they may be in a new and improved Picture Post service. We worked closely with River Source and the Blue Hills Observatory to find people and organizations that would have use cases for Picture Post. River Source's hope is that with enough planning and institutional support, the parties interested in Picture Post may be able to secure reliable funding to host the system again.

5.1 Gauging Interest in Citizen Science Repeat Photography

Determining the level of community interest in and knowledge of repeat photography is a critical part of determining whether a citizen science-based approach to repeat photography would be successful. We gauged community knowledge of, interest in, and experience with repeat photography, climate monitoring, and citizen science via interviews. Once in Santa Fe, we worked with our sponsor to identify local organizations, such as the Santa Fe Watershed Association of the Northern New Mexico Master Naturalists. We aimed to identify groups who were both willing to participate in climate monitoring projects and were likely to collect accurate data. For example, River Source had expressed interest in working with the Nature Conservancy to assist in monitoring preserved lands. The set of template questions in **Appendix A** were also used for these interviews.

5.2 Picture Post Collaboration

Our team worked with River Source in collaboration with the Blue Hills Observatory to outline a plan to relaunch the Picture Post system. We decided on the following steps that would be necessary to relaunch the project successfully.

Our team worked with River Source to find people who may be interested in using Picture Post for repeat photography. Through interviews, we discussed what potential use cases they may have for Picture Post in their fields of work. We worked with River Source to bring these people and organizations together to hold a meeting to determine what common features they may want out of Picture Post.

Through many of the interviews conducted, our team came up with a handful of ideas of what Picture Post should be capable of providing. It is difficult to determine the scope of Picture Post at the moment as interested organizations are still being identified.

Our team reached out to many organizations with the capability to host this network, including the New Mexico Forest and Watershed Restoration Institute, the New Mexico Institute of Mining and Technology, and the Environmental Data Initiative Repository.

We discussed the logistics of hosting Picture Post with both the New Mexico Institute of Mining and Technology and the New Mexico Forest and Watershed Restoration Institute. We talked about what resources and costs would be necessary to host and manage a large dataset like Picture Post.

Our team discussed different ways to obtain funding for Picture Post, determining the most effective method for securing the needed funds would be to rely on heavy institutional backing from many interested organizations.

5.3 Recommendations to River Source

We present the findings, conclusions, and recommendations that flow from these objectives and tasks in the next chapters.

Findings

Our team found the following results applicable to completing our main objectives. This was done through gathering expert information from interviews and meetings, technology evaluations, and additional research:

- We identified the challenges relating to repeat photography, specifically historical repeat photography. We then developed a captioning activity to create a list of characteristics that make an effective caption. We then designed a captioning activity to learn how to effectively teach people about repeat photography and Picture Post.
- We found the advantages and disadvantages of several repeat photography technologies through research, expert experience, and hands-on testing.
- We prototyped Picture Post toppers to adapt them to modern smartphones, tested StoryMaps' uses, and mocked-up what a repeat photography system may look like in Realtime Earth.
- Our team talked with organizations and communities in Santa Fe to gauge what would be needed for a comprehensive repeat photo service. Furthermore, we identified the scope, challenges, and costs associated with relaunching Picture Post as a service.

With these findings, we build conclusions concerning what technologies currently are most applicable for River Source's and other organizations' use cases, and present recommendations for how River Source and others should pursue relaunching Picture Post.

1.0 Repeating Historical Photographs

The goals of repeating historic photos were to (1) monitor changes in the landscape in Santa Fe County to show the usefulness of repeat photography over an extended period of time (2) Give our team hands-on experience repeating photos to understand the challenges of repeat photography firsthand and (3) learn effective captioning to be able to design a captioning activity around repeat photography. Our team carefully selected and repeated three of the historic photographs. We learned to write effective captions, and worked with River Source to design a captioning activity focused on repeat photography and Picture Post.

1.1 Finding and Selecting Locations

In our efforts to collect repeat images of historical photographs, we selected locations with images taken in the last 30 years that presented high educational value, and were physically accessible. We assessed a photograph's educational value by its ability to provide historical insight, visual interest (e.g., an expansive mountain range view is more visually engaging than a close-up photograph of a dense thicket), and that showcased ecological change. A photograph location was considered inaccessible if it was on private property or in a restricted location. Some locations were inaccessible because of subsequent ecological change (e.g., significant overgrowth, or a new reservoir) or geological changes (e.g., rockfalls). By consulting with Craig Allen (U.S. Geological Survey, Research Ecologist, October 26th, 2023), we were able to determine three locations that met our criteria. These locations encompass a variety of landscape features to reflect River Source's areas of interest, specifically watersheds, forests, post-fire landscapes, and erosion.

- The first photo point is at the intersection of the Winsor and Skyline trail in the Santa Fe Forest, looking toward the peak of Mount Baldy. This repeat photo showed tree regrowth on the mountain after it was ravaged by a fire in 1879-80.
- The second photo is at the McClure Reservoir, which is part of the Santa Fe watershed. The original historical photos were taken before the valley was flooded for the reservoir, and the repeat photos show how the area has changed since.
- The third photo is also at the McClure Reservoir, looking at an unnamed hill that was affected in the past by heavy deforestation and goat grazing.

1.2 Performing Repeat Photography

Before hiking out to photo points, our team planned ahead. In order to minimize our impact on the environment, our team followed the "leave no trace" principles relevant to our objectives. To capture the repeat photos at the most optimal time, we scheduled ourselves to arrive at the photo locations approximately when the sun was at its peak for the day. This minimized the amount of shadow occluding objects, allowing for more information to be captured for each photo. Our repeat photography method of choice for these excursions was a smartphone camera mounted on a tripod.

We followed Craig Allen's advice, and found the photography process of repeat photography to be relatively simple. We had no difficulty using a phone GPS and compass app for navigation. We did have difficulty finding the location of the original Mount Baldy photograph due to unclear information about trail intersections and the lack of geographic coordinates. This difficulty emphasizes the importance of annotating all photos with adequate locational information for future reference. We also found that bringing a physical or digital copy of a past repeat photo as a reference was especially helpful for lining up the camera to repeat the original picture. Our main difficulty in replicating historical repeat photos was the difference in focal length and zoom. As expected, our cameras did not have the same lenses as past cameras, and therefore it was impossible to perfectly replicate the past photos without any differences in lens distortion. As a result, we had to approximate the original zoom as best we could by taking a wider shot and then cropping our image accordingly.

Our team developed a report for the City of Santa Fe Municipal Watershed Division, presenting our repeat historic photographs, accompanied by captions and a short summary of our purpose for taking the photos. This report can be found in **Appendix D**. **Figures 14a and 14b,** shown below, are maps of the photo points and their points of focus. **Figures 15a - 15l** show the historic photos and our repeats.

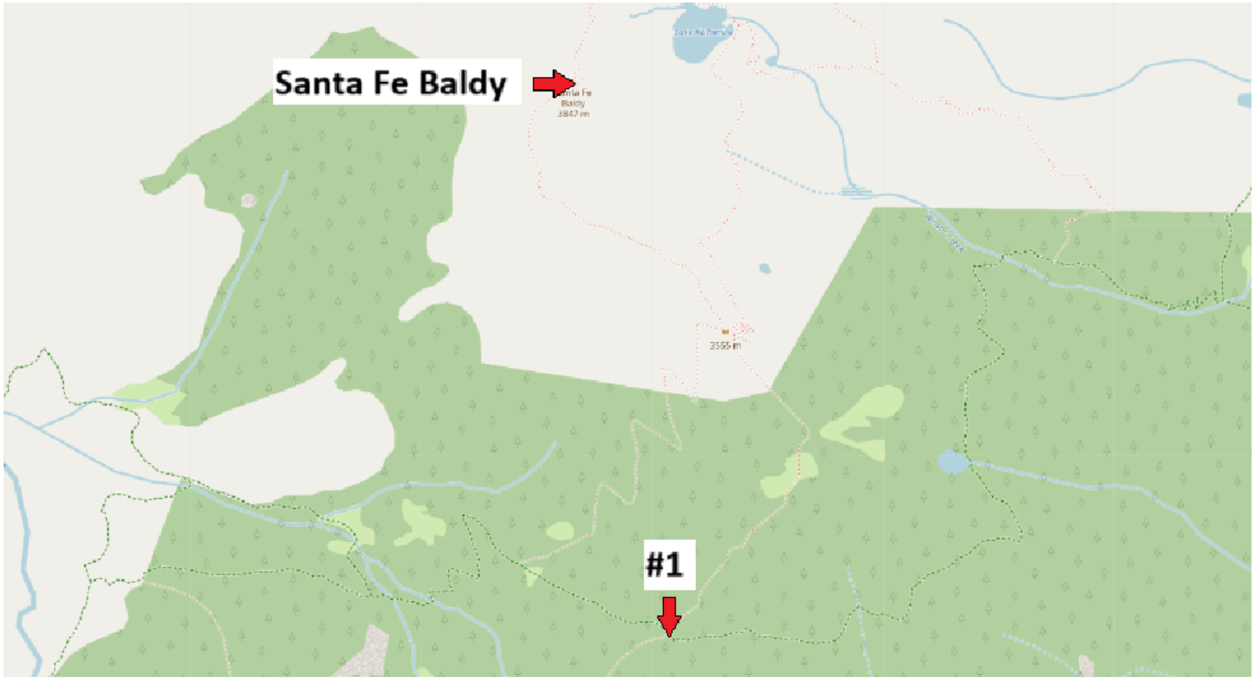

Figure 14a: Map showing photo point #1 looking towards Santa Fe Mt Baldy

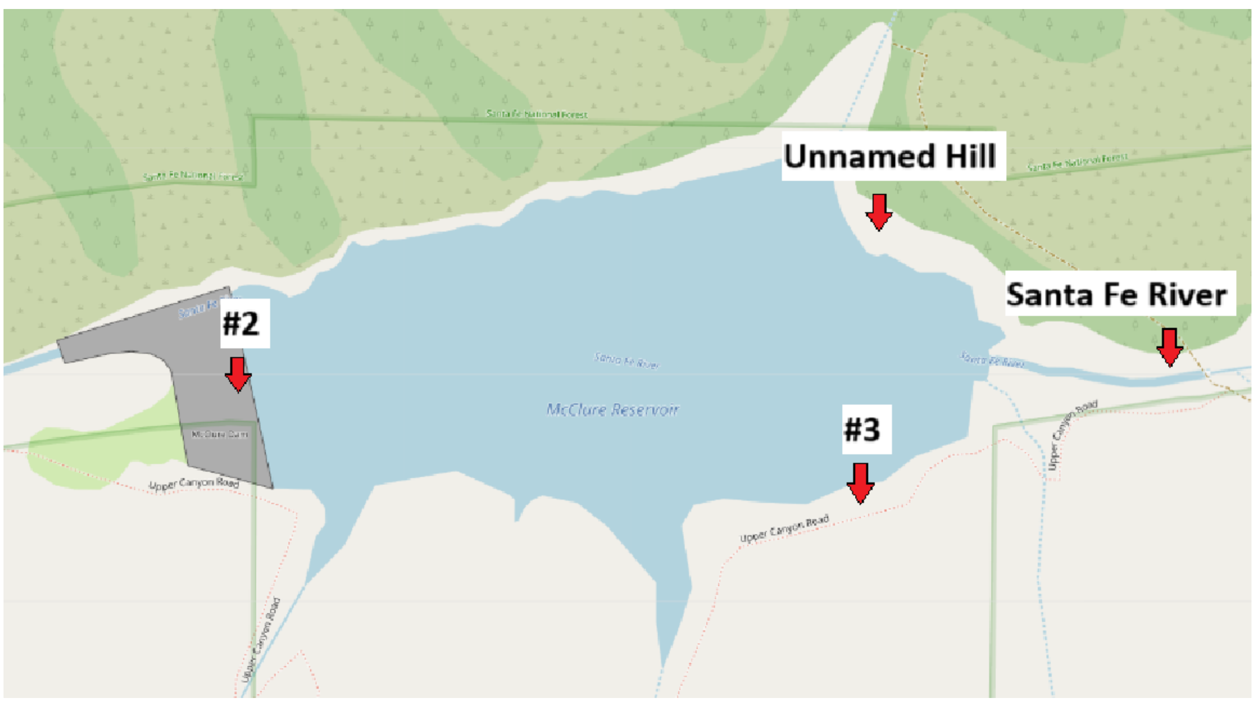

Figure 14b: Map showing photo points #2 and #3 on the McClure Reservoir

Figure 15a: Photo point #1, Santa Fe Baldy (Parkhurst, 1916)

Original photo of Santa Fe Baldy taken in 1916 by T. Harmon Parkhurst showing the aftermath of fires between the growing seasons of 1879 and 1880. Photo point is in the vicinity of 35º48’49” N 105º45’39” W, facing north.

Figure 15b: Photo point #1, Santa Fe Baldy (Elson, Hogan, Tharnstrom, 1999)

First repeat photo of Santa Fe Baldy taken in 1999 by a USGS team. Significant regrowth is apparent compared to the original.

Figure 15c: Photo point #1, Santa Fe Baldy

WPI team repeat of Santa Fe Baldy in 2023. Significant vegetation regrowth in the foreground partially obscures the slopes of Santa Fe Baldy, but it is apparent that the forest is significantly more dense than the 1999 repeat.

Figure 15d: Photo point #1, Santa Fe Baldy

WPI team repeat of Santa Fe Baldy in 2023 taken from a tree. Since the slopes of Baldy were obscured by foreground vegetation in the first retake, a photo from a higher elevation (approximately 20 feet up a tree) was acquired. This more clearly shows the significant reforestation of Baldy even since the 1999 repeat.

Figure 15e: Photo point #2, Santa Fe River Before Construction of the McClure Reservoir (Lewis, 1926)

Original photo of the Santa Fe River before the construction of the McClure Reservoir taken in 1926, likely by Amy Louis. This photo was actually taken the same year the reservoir was created. Photo point is in the vicinity of 35º41’18”N 105º50’10”W, facing east northeast.

Figure 15f: Photo point #2, McClure Reservoir (USGS 226, 2000)

Initial repeat of the McClure Reservoir, taken in 2000 by a USGS team. It is likely that the original photo point is submerged, so the repeat was taken from the top of the McClure Dam.

Figure 15g: Photo point #2, McClure Reservoir

WPI team repeat of the McClure Reservoir in 2023, taken from the top of the McClure Dam. Only minor changes are apparent from the 2000 retake. Most significantly, the tower present in the lower left corner of the 2000 retake is missing due to the dam being remodeled in the intervening years.

Figure 15h: Photo point #3, Hill Alongside Santa Fe River Before Construction of the McClure Reservoir (Blanchard, 1916)

Original photo of a hill along the banks of the Santa Fe River taken in 1916 by the USDA Forest Service. Significant erosion is visible, likely due to excessive logging and grazing. Photo point is in the vicinity of 35°41’15”N 105°49’40”W, facing northeast.

Figure 15i: Photo point #3, Hill Alongside McClure Reservoir (USGS 119, 2000)

Initial repeat of the McClure Reservoir Hill, taken in 2000 by a USGS team. Significant reforestation is apparent compared to the original image. This is likely because public access to the Santa Fe Watershed was restricted in the intervening years, allowing vegetation to recover. Changes to the base of the hill caused by the creation of the McClure Reservoir are also visible.

Figure 15k: Photo point #3, Hill Alongside McClure Reservoir (Allen, 2023)

Second repeat of the McClure Reservoir hill, taken in June of 2023 by Craig Allen. Whereas the reservoir's water level in the 2000 retake was quite low, this retake shows what a full reservoir looks like.

Figure 15l: Photo point #3, Hill Alongside McClure Reservoir

WPI team repeat of the McClure Reservoir Hill in November 2023. It is apparent that a significant portion of the reservoir has been drained since the June retake.

1.3 Writing Effective Captions

Kris Herbst (Journalist, November 13th, 2023) assisted us in designing a caption writing activity to accompany the collection of historical photographs. Our goal with this captioning activity was to educate students and teachers about the importance of using repeat photography to monitor climate change. The interactive activity includes instructions on effectively using Picture Posts for repeat photography and then writing accurate captions for the photographs taken. This meeting was extremely productive in terms of learning how to caption pictures effectively. Our main takeaways from the meeting were as follows:

Engage the Reader:

Engage the reader early with a 'lead'. A lead is a sentence at the beginning that captures the attention of the reader to encourage them to keep reading. Part of the purpose of a caption is to tell a story, so it is important to convey the details of that story to the reader as soon as possible. After engaging the reader, one should keep the caption as concise as possible to make sure the reader does not stop reading early.

Put the Most Important Information First:

Even with a good lead, it is difficult to engage every reader sufficiently so that they read the whole caption. It is therefore important to put the most important information at the beginning of the caption. This allows the reader to learn the most relevant or interesting information early, and the reader gains diminishing returns on knowledge as they keep reading. This is another reason to keep captions as concise as possible.

Demystify Scientific Processes:

Tell the reader how an event happened or why something appears the way it does is crucial. Communicating to a reader in easily intelligible language how a landscape feature was created allows them to understand it better and find interest in the subject matter. As a result, the reader is taught to recognize patterns in the landscape around them and connect with it on a more personal level.

River Source wanted us to use our newfound skills to develop an activity that they could use to teach students about Picture Post and environmental monitoring. They wanted the captioning aspect of the activity to engage students and teach them to observe the ecology that surrounds them. More importantly, River Source wants to use this captioning activity to show a use case for Picture Post. By showing that Picture Post has a wide range of scientific and educational applications, River Source and other organizations may be able to secure funding for a renewed Picture Post system. Using these takeaways from our meeting with Kris Herbst, we developed a lesson plan to achieve River Source's goals.

1.4 Designing a Captioning Activity

An educational activity includes two parts: (1) the educational activity for students; and (2), the lesson plan that identifies the learning outcomes and guides the teacher in how to achieve them. The final lesson plan and captioning activity can be found in **Appendix C**.

We developed a teacher guide for the captioning activity. The guide simply summarizes the purpose of the activity, outlines the objectives for the students participating, gives background on Picture Post and the captioning exercise, and lists materials the students need to complete the activity. The purpose of this lesson plan is to inform the teacher about the captioning activity and its goals. As a result, this guide empowers the teacher to effectively educate students about the importance of repeat photography and the usefulness of Picture Post.

Following Kris Herbst's advice, we created an easy to understand guide on captioning. The first step in the activity teaches students about Picture Post, its uses for monitoring ecological changes in the environment, and how to use it. Students are then instructed to take photos using the Picture Post. The second step prompts students to write down observations about the pictures they just took. The third and final section teaches students what captioning is, what its purpose is in relation to photos, and provides tips on how to write good captions. Students are given a short bullet-pointed guide on how to start writing captions and are asked to write a short 3-5 sentence caption for one or more of the photos they took using the Picture Post.

2.0 Evaluation of Potential Technologies

Our team evaluated the following technologies: Picture Post, other physical markers besides Picture Post, ArcGIS Survey123 and StoryMaps, camera drones, phone GPSs, and Realtime Earth. A significant portion of our evaluation was not done in the field, but rather was sourced from the conclusions of experts that have used these technologies for repeat photography projects themselves. Many of these experts had overlapping opinions that made us confident that these conclusions are ones that a majority of repeat photographers would reach if they were to trial these technologies. Although interviewing seasoned experts was useful, words alone were inadequate for giving us a full understanding of how useful certain technologies are for repeat photography. Therefore, it was necessary for us to physically test and interact with many of these technologies ourselves to gain a complete understanding of their usefulness. Our evaluations were also supported by our background research from the literature review section of this report.

2.1 Picture Post

Like others, River Source was interested in the potential use of Picture Posts to collect repeat photographs using a citizen science approach. The two major advantages of Picture Post are that (1) it makes finding the precise location of a photo point easier, and (2) helps to standardize the height and direction of repeat photos. The design of the device does this by constraining cameras along four degrees of freedom, two translational and two rotational. This allows all nine photos to be taken from nearly the same position every time. Donald McCasland (Program Director, Blue Hills Observatory, November 1st, 2023) informed us that the design of the Picture Posts allows people of all skill levels to take consistent photos almost without fail, as long as they are informed about how to use the device. Although the post is easy to use, it can be difficult to encourage people to use it. In Blue Hill's experience, interest was highest when a new Picture Post was first installed but tended to dwindle over time. They concluded that the host organization of the post needs to be actively involved, either directly or indirectly, for the best chance of success. Direct involvement might mean that the host organization has staff use the Picture Posts, rather than relying on citizen science. More indirect involvement might involve the staff showcasing lesson plans to prospective users, like tours or school groups, and enlisting those groups to interact with Picture Posts instead. Donald McCasland suggests that the most important part of having others take pictures is to show them beforehand that the data collection is valuable. By doing so, people will make a greater commitment to collecting it.

In our meeting with the Blue Hills Observatory, we discussed the physical life-span of Picture Posts and what challenges may be faced when manufacturing or maintaining them. According to BHO staff, the Picture Posts at the observatory have not degraded beyond use since they were installed about 10 years ago. The longevity of the posts depends primarily on material choices. Wooden Picture Post toppers split and crack easily, and wooden posts may bend over time. Metal posts and machined metal toppers are the most resilient material option but are cost-prohibitive . Right now, the most favorable materials include cedar wood “posts” with “toppers”, the top section of the Picture Post that is mounted on the post, made of UV-resistant plastic called acrylonitrile styrene acrylate (ASA), which are created using a 3D printer. Plastic Picture Post toppers are much more resistant to the weather and do not degrade due to solar radiation. Care should be taken during printing, however, to avoid warping due to shrinkage caused by the plastic rapidly cooling.

Our group observed points of failure in plastic Picture Posts when we joined River Source at the McClure Reservoir in Santa Fe. As shown in **Figure 16**, there is a Picture Post with a wooden post and a plastic topper. The main points of failure were at the octagon-circle interface. Our team hypothesizes that these failures are caused by the localized stress at the interface and the way 3D printed objects are made. 3D printed objects are printed in layers of plastic, each layer being essentially a cross-section of the object at that height. This makes any 3D printed object much less resistant to stress directed parallel to the layers, much like how it is easier to slide two sheets of paper across rather than into one another. The high stress caused by the corners at the interface, combined with this property, makes that part of the post the most prone to shearing. This stress is caused by thermal expansion and contraction, mainly from the sun and water that has found its way inside the toppers. Our team worked with River Source to replace three Picture Post toppers at the McClure Reservoir. We found that installing the toppers is very easy. The only tools required are a drill, two screws, and level, and the process takes around 10 minutes. The most difficult part about setting up a Picture Post would be installing the post component, as that needs to be sunk into the ground and cut flat on top.

Figure 16: Warped Picture Post Topper

Although Picture Posts are useful as locational markers, they may not be appropriate for certain locations or monitoring projects. For example, Donald McCasland explained that Picture Posts may not be applicable in areas subject to soil erosion or other landscape changes such as flooding, fires, or volcanic activity. Craig Austin (Volunteer Contributor for Picture Post, Blue Hills Observatory, November 1st, 2023) also explained that in heavily forested or overgrown areas, Picture Posts would be hard to locate by a potential user without additional locational data such as latitude and longitude coordinates. Even if the user were able to find the post, dense foliage would decrease the photographer's ability to replicate an image and would reduce the amount of data that could be collected.

Our group experienced this problem with obscuration when performing repeat photography of the peak of Mount Baldy. The significant growth of pine trees in the foreground of the image obscured our view of the growth happening on Mount Baldy in the background of the image. Micah Kiesow (Soil Scientist, U.S. Forest Service, November 8th, 2023) discussed his experience with repeat photography projects. He has worked with photo points to monitor stream restoration, and he is aware of Picture Post. Given his relevant experience with repeat photography, Micah Kiesow was able to provide us with detailed information about the advantages and disadvantages of different repeat photography technologies. He voiced concerns that certain areas may be unsuitable for Picture Posts due to fires. Wooden Picture Posts are flammable and plastic Picture Posts have a low melting temperature, and so in high fire-frequency areas there is no guarantee that the post will survive at length. It also means that Picture Posts made of wood or plastic would not be useful for monitoring the effects of prescribed burns, as they would likely be destroyed in the initial fire. In this case, a heat resistant metal Picture Post would need to be used.

Nav Khalsa (Volunteer Coordinator, Northern New Mexico Master Naturalists, November 15th, 2023) also had many ideas about how to improve Picture Posts to make them more approachable and user friendly. She suggested that Picture Posts in New Mexico should have both English and Spanish text, as those are the two dominant languages in the area. The languages used on a post should reflect the dominant languages used in the surrounding area. She also suggested that instructions should be included with the Picture Post program to add an optional step stool so that small children can interact with Picture Posts as well. She explained that getting kids involved with Picture Post at an early age would be a great way to spark interest in community science and stewardship. Khalsa was also excited about the possibility that Picture Post toppers could be made by any person with access to a 3D printer, which could make it a much more accessible technology to local groups and communities.

2.2 Other Physical Markers

Other physical marker systems besides Picture Posts typically are made with stakes driven into the ground or tags attached to trees. The markers are usually low tech, and require the photographer to use either a monopod or a tripod to line up repeat photos correctly. Eytan Krasilovsky (Deputy Director, Forest Stewards Guild, November 1st, 2023) discussed the Santa Fe Forest Resiliency Project, a project involving a coalition of organizations including the United States Forest Service. The project's goal is to develop a resiliency strategy and multi-party monitoring plan for the Santa Fe Forest, and one of the monitoring tools that the Forest Stewards Guild is interested in is repeat photography.

The current repeat photography protocol created by the Forest Stewards Guild is a rudimentary system based on physical markers. Rebar markers are planted in the ground, and aluminum tags are attached to two nearby trees containing the photo point ID, azimuth to plot center, and distance to plot center. Photos are taken in all four cardinal directions and straight up. The metadata and photos are taken and submitted using a Survey123 form. Some advantages of this technology are that it tends to be resistant to the environment due to its metal construction, and its small profile leaves a minimal environmental footprint. This repeat photo system's goal is to tell a story about the change in vegetation and ground coverage of the Santa Fe Forest through visual means. Eytan Krasilovsky sees the project as a way of communicating landscape change and ecological improvement. For him, it is important to demystify information about forests in a way that helps limit the spread of misinformation about forests and forest fires. It avoids the mischaracterization of what a resiliency project does and strengthens trust for the Forest Service and Forest Stewards Guild. Unfortunately, the Forest Stewards Guild has faced many challenges with this system.

As repeat photography is not the main focus for the Santa Fe Resiliency Project, it has been difficult for the Forest Stewards Guild to secure funding for it. The setup, driving metal stakes into the ground, can be physically demanding and the actual use of the system is manually intensive and imprecise. There are no attached instructions, so the user must be given a guide on what to do. Ideally, the skill needed to follow a guide is low, but this means that a detailed guide is necessary to ensure the quality and consistency of the data. For example, the marker itself has no ability to align or measure the orientation of the camera being used, as there is no physical mount for a camera. Therefore, the guide must tell the user at exactly what height and angle to put their tripod (or monopod) mounted camera. This means that the user has a much greater degree of freedom than a Picture Post, and can make collecting consistent data over time extremely difficult. Micah Kiesow stated that in some cases, markers can be hard to locate due to vegetation growth or erosion and are also easily stolen.

In Micah Kiesow's experience, the repeat photography protocols with the most uniform data collection are the ones that have the same person repeating the photos. If a technology like physical markers is being used to collect repeat pictures, possibly the most effective method to increase photo uniformity is to have the same people collect the same photographs over time. Therefore, it is probable that simplistic physical markers by themselves are not a valid avenue for community-based repeat photography. This technology should mainly be reserved for professional organizations that have the same people assigned to photo points. However, more complex physical markers (such as Picture Post) may be able to alleviate this issue. The more constrained the photo taker is, the less likely that variation will occur between users.

2.3 Supplemental Technologies

2.3.1 Esri Technologies: Survey123, ArcGIS, and StoryMaps

Survey123 is a useful technology for collecting repeat photography using GPS capable smartphones. Survey123 is able to measure the precise location a photo was taken using the phone's GPS. Micah Kiesow explains that although Survey123 can locate the general area a photo is taken quite easily, the precision of the location is limited by the precision of the user's phone's GPS. According to River Source, the accuracy is around three to four meters for the average smartphone. The technology also cannot measure the camera's orientation to allow users to take consistent photographs. The Forest Stewards Guild has the most interest in and already uses Survey123 forms for their repeat photography system, as it is able to show a lot of data. Survey123 forms are easily customizable and, therefore, can be made to be understood by the target user, no matter their skill level. This makes Survey123 ideal for data collection by the general public, such as in the campus assessments that River Source does with schools in Santa Fe. The protocol that the Forest Stewards Guild already uses for repeat photography shows Survey123s potential as a supplementary technology that can upload data collected by users to an online database.

ArcGIS is extremely useful for tracking repeat photography. ESRI offers free "public accounts" which allow users to access certain features of ArcGIS online. This includes the creation of maps and map layers, which can easily be used to plot photo points. Additional information can also be stored in these point layers, such as photographer identity and location and photo details. In addition, these maps allow certain analysis to be performed, such as measuring distances between photo points. Most importantly, maps can be embedded into StoryMaps. All together, ArcGIS presents a dynamic way to store photo data which can easily be presented and shared using StoryMaps.

StoryMaps are among the better ways of showcasing repeat photography. They have numerous operational and logistical advantages, and very few disadvantages. Firstly, StoryMaps are easily accessible by anyone. Access from free ESRI “public accounts” allow users use of most features of StoryMaps, including video and image embeds, ArcGIS web maps, Swipe blocks, and guided map tours. While a few features do remain locked for free users, all ones necessary to create a compelling repeat photography StoryMap are publically available. In addition, no account is needed to view publicly available StoryMaps. This means that even if a user is using a paid account, the created StoryMap can be widely distributed with no barrier to viewing it. The user interface for creating StoryMaps is also very intuitive, even for someone with little design experience. Addable features are clearly labeled and easy to understand. Secondly, StoryMaps contain many features that are ideal for displaying repeat photos in an engaging and informative way. The Swipe block allows two images to be directly compared. Embedded maps and map tours can be used to dynamically show photo point locations. Embedded videos can be used to give additional context in a more exciting way. Combined with general features like sidecars and slideshows, StoryMaps can be used to make an attractive and captivating product to showcase repeat photography.

To determine the ease of use of Esri StoryMaps, we created a simple prototype of a map tour showing our photo points (**Appendix E**). Although intuitive, it did take quite a bit of time. Originally, we had planned to make a full StoryMap showcasing our repeat photography, but we determined that this was not worth the time commitment. From our experience, it is clear that while StoryMaps are intuitive to use and very good at showcasing repeat photography, they should not be used for everything. Due to the time commitment, shareability, and permanent nature of a StoryMap, they are better used for showcasing finished projects. In these cases, spending the time to create a compelling StoryMap is absolutely worth it, and leaves you with an easily shareable and visually appealing presentation of work. However, for lesser uses and interim reports it is likely better to use something easier and faster, such as PowerPoint. It is also likely that a more experienced user would be able to create an effective StoryMap far more quickly, thus lowering the threshold for practical use.

Mori Hensley (Executive Director, Santa Fe Watershed Association (SFWA), October 31st 2023), explained to us that the Santa Fe Watershed Association works to monitor the health of the Santa Fe Watershed with a primary focus on the Santa Fe River Watershed. They have been working with River Source to conduct a Santa Fe River Leading Edge Survey, which is a citizen science based approach to collecting data about the flow extent of the Santa Fe River. She informed us that community members had significant questions about the flow of the Santa Fe River, and therefore the SFWA saw the need for a repeat photography program. The program allows people to take a picture of the leading edge of the Santa Fe River, a picture in the upstream direction of flow, and three pictures in the future downstream direction of flow. and send it to the SFWA using Survey123. The user is asked to fill out additional information about their precise location, the current date and time, the characteristics and surface appearance of the water, and weather observations. The SFWA then tracks this data with StoryMaps. The points are plotted on a map on a publicly accessible StoryMaps website which is shown in **Figure 17**.

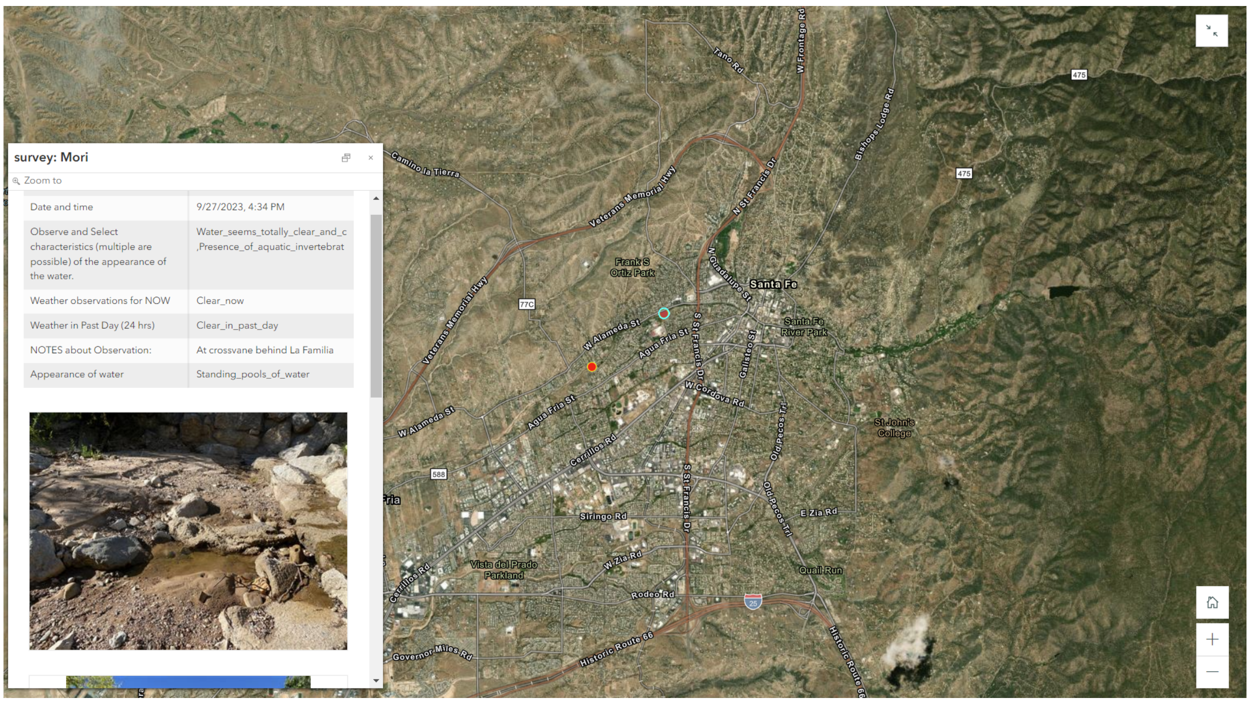

Figure 17: Esri StoryMap Showing Data Points from the Santa Fe Leading Edge Survey (River Source and watershed community scientists, 2023)

So far, the only two contributors to the data have been Hensley and River Source. This leads back to the problem mentioned earlier, where it is very difficult to get the general public involved with a repeat photography service, and it may see more use if designated persons from an organization collect the data instead. However, it is hard to say how much use the system will see, as it is only a few months old as of 2023 and in its relative infancy.

2.3.2 Drone Photography

We found that drones are already heavily used by River Source and other organizations for environmental monitoring. Many modern drones have the capability to track their location, height, and camera orientation using built in tools like GPSs and accelerometers. This means that drone software can precisely track a drone's flight path and rerun the same flight route many times. This also applies to the movement of drones' cameras. Many drones are also able to use complex sensors such as LiDAR to create a three-dimensional virtual map of the area they fly over. Stephen Guerin says that some of the most popular softwares for flight planning and mapping are Drone Deploy and DJI Flight Planner. He says that many drones are able to track their height more accurately than their locational coordinates. Many camera drones, such as the DJI drone River Source uses, have a camera gimbal that stabilizes photos and videos taken with the drone while in the air. Because the drone has a communication range of two miles with the drone operator, River Source is able to take LiDAR maps of large swaths of land with minimal user input. According to Micah Kiesow, these capabilities of drones mean that photographs and videos taken with camera drones are easily reproducible. The Forest Stewards Guild uses drone monitoring to capture top down views of forest canopies in addition to ground photos. River Source uses Adobe Lightroom to track their drone maps and flight paths.

The major disadvantages of drones are that they are cost prohibitive and require knowledge and skill to operate. Most drones sell for hundreds of dollars, and many high-end drones sell for thousands of dollars. The capabilities of a drone and the resolution of a drone's camera and sensors tend to correlate with the price of a drone. It can take time to learn how to use drone software and pilot a drone. Micah Kiesow says that some of this piloting can be automated with software. Even so with more user-friendly interfaces, automation softwares, better stabilization, and decreasing prices over time, the cost and skill associated with operating camera drones means that this technology is essentially off limits for citizen science based repeat photography. This technology is, in most cases, limited to professional use cases.

Improving drone technology over the past decade has shown more use cases from drones in science, technology, and research. Our team hypothesizes that drones will continue to be used for environmental and phenological purposes as long as they are the best option for automated wide-spread land monitoring and data collection.

2.3.3 Phone GPS

We evaluated the use of a phone GPSs during our replication of historical photos. Some of the historical photos we repeated had metadata regarding their GPS coordinates, so our team was able to use our smartphone GPSs to find these locations. For other photos where there were no accompanying coordinates, we were able to record their coordinates once the photo point was physically located. This was done with the assistance of the iPhone application "Compass", which is a default application on any iPhone. This application can tell the user their cardinal direction, angle, latitude and longitude, and elevation. It does not need any cellular signal to operate. Our team found the app extremely easy to set up and operate. Unfortunately, this specific app is only able to provide the latitude and longitude to the accuracy of a "second", or around 30 meters. This makes locating the general location of a repeat photography spot easy, but limits the user to other tools or information for finding the precise spot. Any user equipped with basic knowledge about how to use a smartphone should be able to use a GPS application without difficulty. Therefore, this technology is useful as a supplementary tool for repeat photography. This is especially true for citizen science based repeat photography, as phone GPSs are accessible to a large majority of the population.

2.4 Realtime Earth

Stephen Guerin is the Founder and CEO of Simtable LLC. Rich Schrader was interested in utilizing his technology, Realtime Earth, as a method for visualization and analysis of repeat photography data. Stephen Guerin was able to meet with us to discuss implementing a repeat photo system into Realtime Earth. Stephen Guerin was also able to provide us with information about other emerging technologies that may have uses for repeat photography.

In our meetings with Stephen Geurin, he was able to give us live demonstrations of the currently under development Realtime Earth application. Despite the capability of Realtime Earth for other uses, there are many current characteristics of the program that prevent it from being a good candidate for citizen science, repeat photography, or a combination of the two. It is still under development, and so some features are still not user friendly. Its interface is difficult to understand for a new user, and it takes time to learn how to use the navigation panels. As the software is still in development, the interface actively changes with new updates. There are currently no in-built features that allow for repeat photography or georectification of repeat photography. Because of this, Stephen Guerin suggested we attempt georectification of our repeat photos with Google Earth Pro, a free desktop tool that allows visualization of geospatial data. This served as a sufficient analog for what Realtime Earth could potentially do. This, along with a mock-up as suggested by Guerin for a potential Realtime Earth repeat photography tool, will be discussed in later sections.

River Source does not want the data to be controlled by government organizations, due to concerns that changes in political agendas would prevent guaranteed funding for the system and access to the data. This is the main reason River Source wants the data to be managed by an academic institution or non-governmental organization. One solution to this problem of data ownership is a decentralized data storage solution. We discussed the logistics of using a decentralized network, or a digital "acequia," of devices as a storage medium for repeat photographs. The term acequia is a reference to a community-controlled irrigation system. In the digital sense, the flow of data, instead of water, is controlled by the community. However, the digital infrastructure needed for large scale implementation of this concept does not (yet) exist. Our main concern was the lack of permanent storage. Since the data is stored on personal devices, there is no person or organization that is responsible for maintaining the data. If the network does not have a sufficient number of devices with enough storage space to store the data, any photos or metadata about the photos could be lost and unrecoverable. One possible solution to this problem is to create a hybrid data model, where data is still shared openly among users, but there are also designated data stored centers put in place as failsafes in case the network collapses. Stephen Guerin proposed that this idea should be taken even further. Rather than having the people in the network own the data, people should be able to transfer ownership of their data to the landscape they are taking a picture of. He gave an example of donating data to a watershed. People could take repeated photos of a lake to monitor its health and give that data to the lake as a legal entity. Organizations could then ask the lake for data in order to pursue ecological improvement or resiliency projects focused on the lake. While this approach may be possible at some point in the future, there is currently little legal precedent to do so. It is unlikely to be a feasible management method for the foreseeable future.

Given the sophistication of the technology, there is a high likelihood that a repeat photography tool utilizing Realtime Earth will become available and user friendly with time. If Simtable so chooses, Realtime Earth could eventually become a ready-to-ship application that allows for peer-to-peer repeat photography. Our team is excited about what opportunities the software may present in the future, but feels that its utility is currently limited.

2.5 Google Earth Pro

Google Earth Pro offers fairly simple georectification, so its utility for repeat photography is somewhat limited. It appears that the functionality works best for satellite and other top-down images rather than ground-based ones. The main problem is that Google Earth projects all parts of the image onto a 3D model of the terrain, including any sky visible in the image. **Figures 18a and 18b** are an example of our tests georectifying repeat photography from Mount Baldy compared to the original picture, and is an example of how ground-based photos can present serious distortions and problems getting other parts of the image to track correctly.

Figure 18a: Original 1999 image of Santa Fe Baldy (Elson, Hogan, Tharnstrom, 1999)

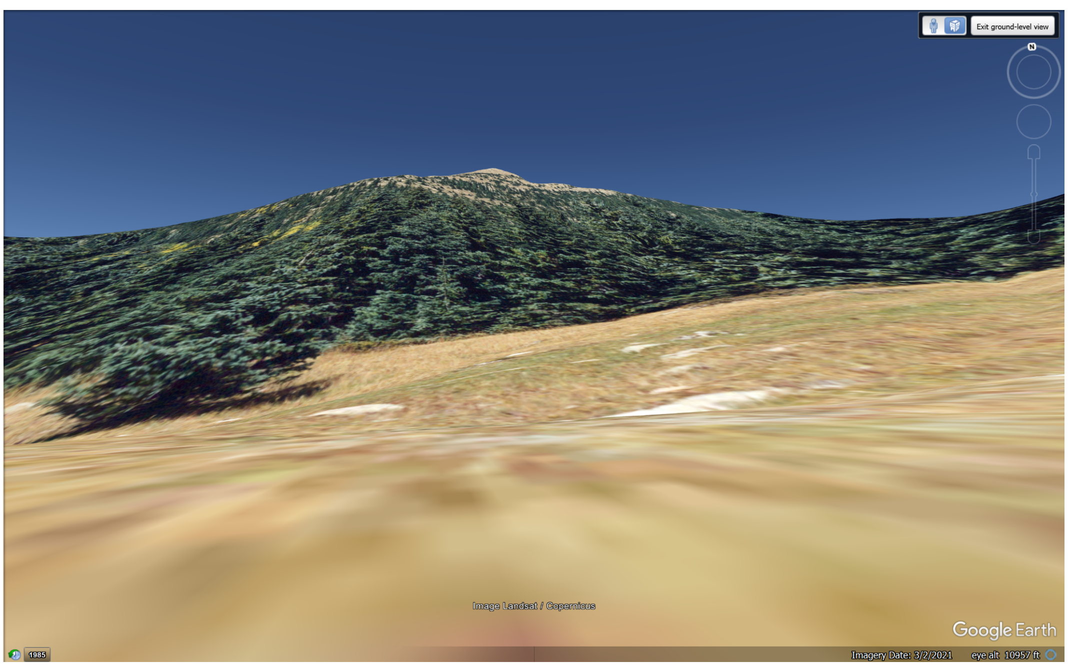

Figure 18b: Georectified image of Santa Fe Baldy (using google earth)

In addition, any vegetation in the foreground will be projected onto the 3D map as if it were far larger than it actually is, which can make the image very confusing to view. Google Earth Pro holds some functionality for those ground-based images which have 1) little or no sky, 2) little obstruction in the foreground, and 3) clear landmarks in the background. However, for most repeat photography, including the repeat photography included in this report, georectified images in Google Earth Pro were less compelling than those same images displayed in 2D space.

3.0 Prototyping and Mockups

Our team was tasked with prototyping different technologies we deemed viable for a repeat photography service. Through our evaluations, enough information was gathered to create changes to the current Picture Post system, as well as designing mock-ups for what potential services could look like. This includes redesigning the Picture Post topper to be easier to use with phones, as most people utilizing the Picture Post no longer carry a digital camera with them. We also considered different materials to be used for the physical post, as we had to take wildfires and other natural occurrences into account. We also designed a mock-up of what a potential service could look like using Realtime Earth's technologies, although it seems very unlikely this will be used in the near future.

3.1 Picture Post Topper Changes

Phone cameras have advanced incredibly far since the invention of Picture Post. River Source noted that most of their repeats have been used with phone cameras – something the original toppers were not necessarily designed for. Changes to the topper were made to ease the repeat photography with phone use. **Figure 19a** shows the original Picture Post topper design, and **Figures 19b and 19c** show the new prototype designs.

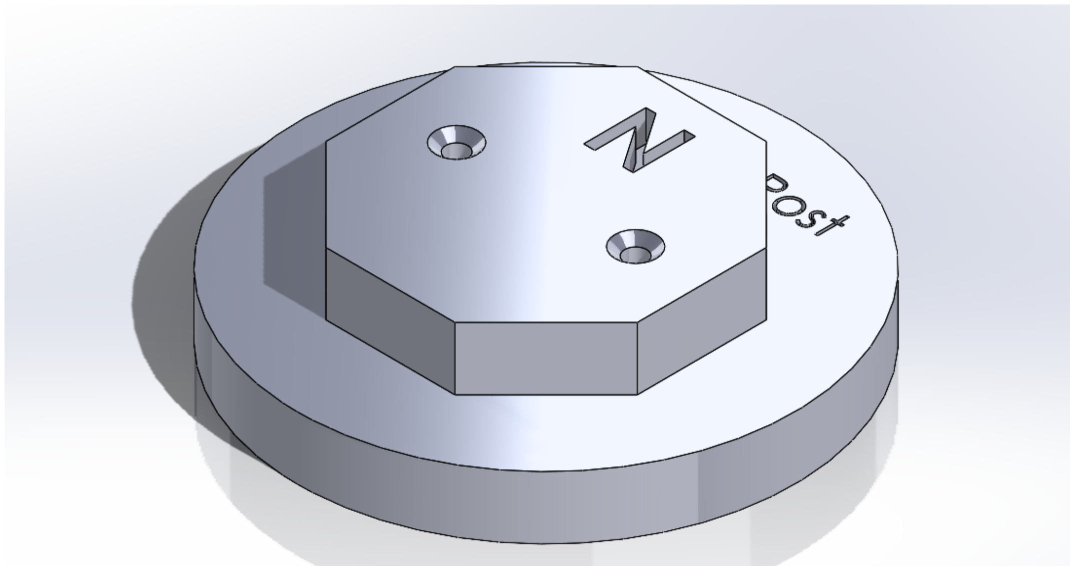

Figure 19a: Original Picture Post Topper Design

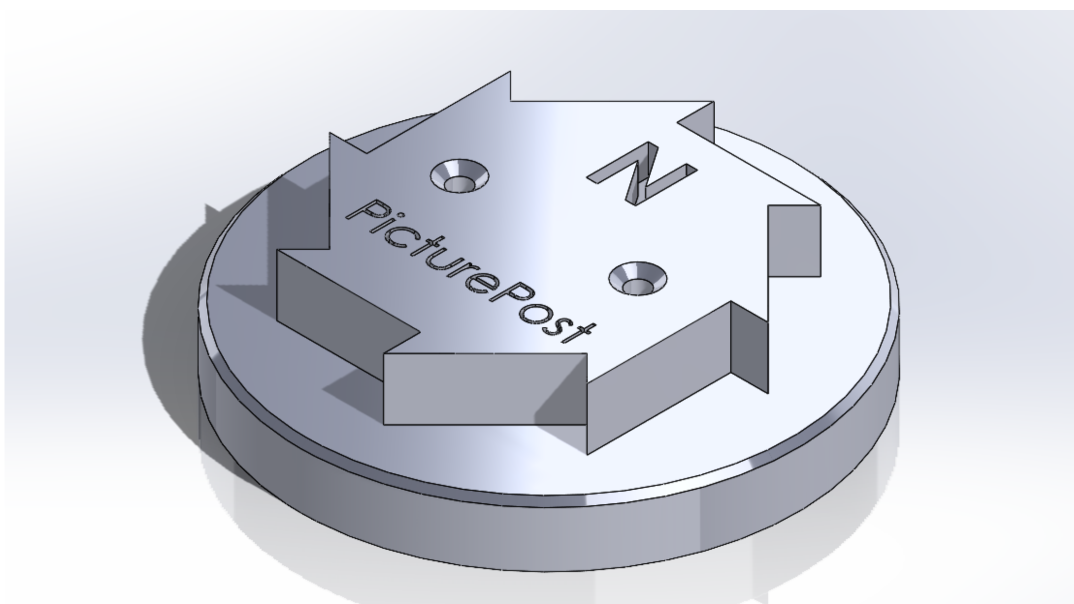

Figure 19b: Redesigned Picture Post Topper with Fins

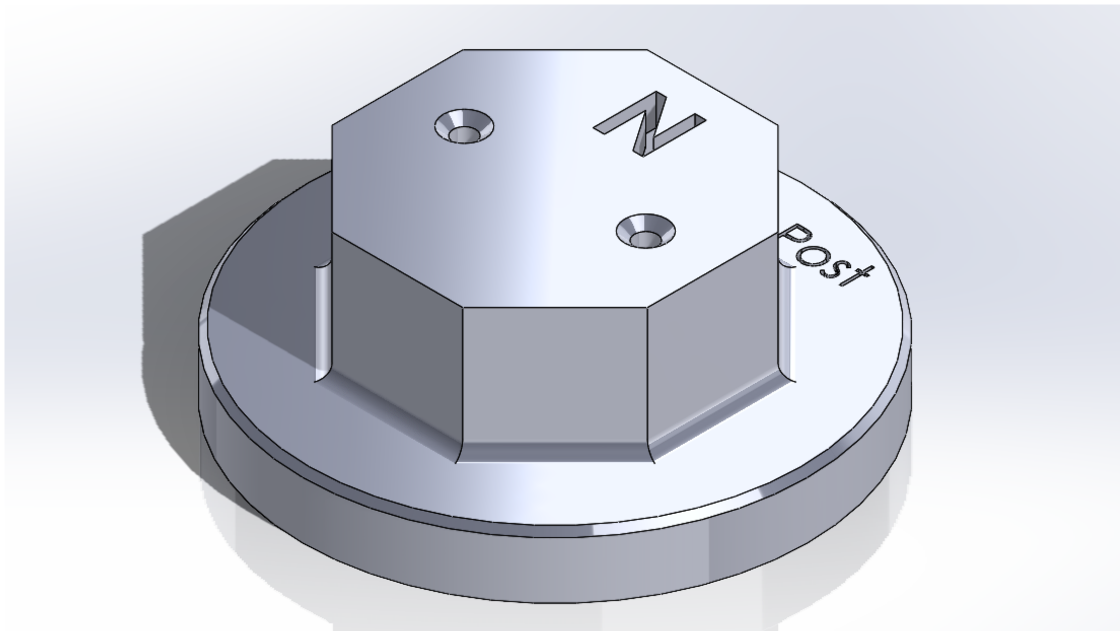

Figure 19c: Redesigned Picture Post Topper with Taller Octagon

We printed all three designs and prototyped them. The original topper depicted in **Figure 19a** was used as a control in our experiment to gain a better understanding of what limits the current design. Our team hypothesized that the finned design in **Figure 19b** would constrain smartphones enough to capture consistent pictures on four or more degrees of freedom, and the taller design depicted in **Figure 19c** would provide more support to smartphones to help them stand upright. Our team tested multiple types of iPhones and Android phones to gain a representative sample of smartphones. Our hypotheses surrounding the redesigns were confirmed, and we concluded that a redesign that is a hybrid of both ideas would provide the most consistent repeat photos from smartphones. We also found that the current size of the topper was too small for the large size of modern smartphones. Our team suggests increasing the size of the topper by 25-50%, and expanding the base by around an inch on top of the size increase to allow instances where digital point-and-shoot cameras are used instead.

Research was conducted into post-print smoothing for the new design, as the current toppers suffered from moisture damage and began peeling on the top layers or were completely destroyed. Our team corresponded with Professor Adam Powell (WPI, Associate Professor of Mechanical and Materials Engineering, November 29th 2023) about few cost effective ways of post-processing the Picture Posts to resist weathering. One option is using a solvent liquid such as acetone to partially dissolve the surface layer of the plastic topper, thereby making it smoother. Smoothing the surface of the print with acetone could help with water ingress, as acetone smoothing does not cause structural damage. A quick immersion in acetone followed by wiping down the print with a cloth would most likely be sufficient. Isopropyl alcohol or ethanol may also work. This would extend the lifetime of the topper and avoid having to replace it every 4 to 5 years, which would help lower the costs of each Picture Post. Coating the toppers in a layer of epoxy may be a more approachable option to prevent water damage. There is a higher entry cost associated with epoxy, which is something to consider for ease of install and use of Picture Post.

3.2 Realtime Earth Mockup

As per the advice of Stephen Guerin, our team mocked up what a peer-to-peer repeat photography system may look like on Realtime Earth. The application would be divided into three main steps.

In **Figure 20a** the user attempts to take a repeat photo. Realtime Earth would use the phone's GPS to locate the closest repeat photo point to the user. Once the user has reached the photo point, they use their camera to line up their photo with a transparent overlay of a past photo. Key points are identified by Realtime Earth to confirm that the user's photo is lined up with the past photo. This is achieved with a combination of the phone's accelerometer and machine learning. The overlay image can be moved, scaled, and have its transparency adjusted by the user. Once the photo is lined up within a certain margin, the user takes the repeat photo.

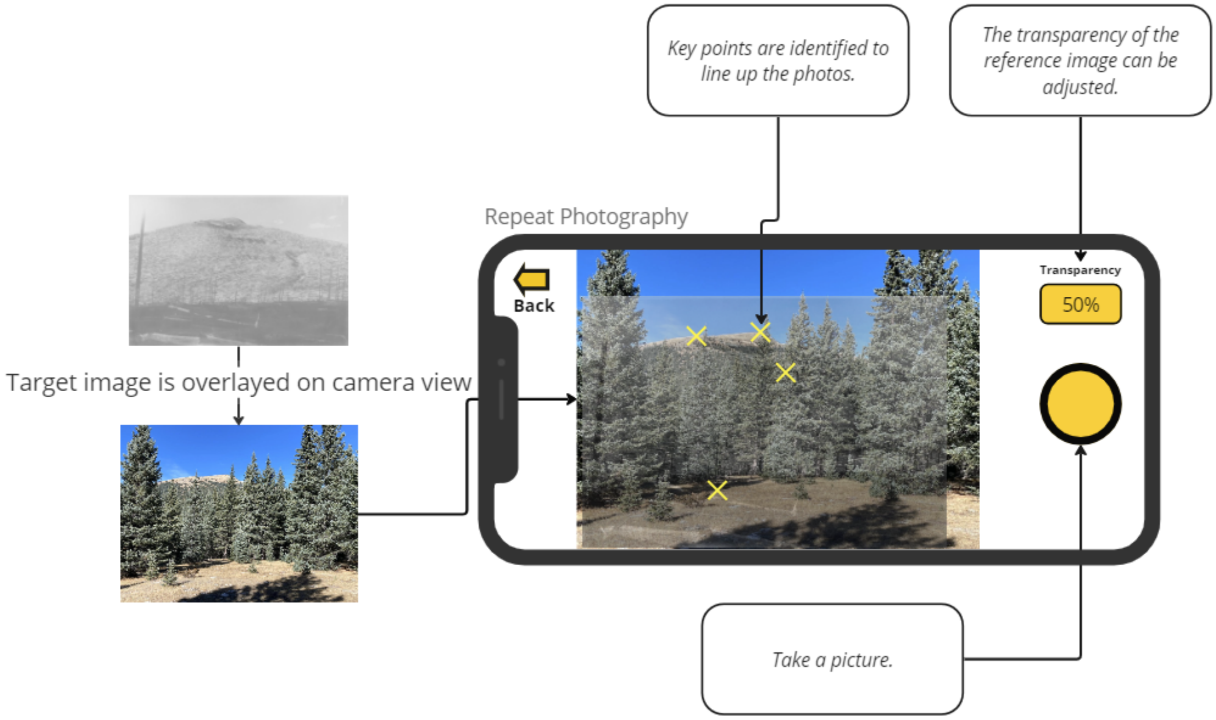

Figure 20a: Mockup of Repeat Photography Using Realtime Earth

Next, in **Figure 20b** the user is able to view the image they just took. The image is automatically cropped by Realtime Earth to fit to past images. If the user is not satisfied with the photo, they can go back to the camera to take another photo. The user now has one or more options. They can (1) upload the photo to the peer-to-peer database for the repeat photo to be viewed by others, and (2) view a timeline of past repeat photos taken by other users in the network. The user has the option to select a photo and georectify it onto a three dimensional map.

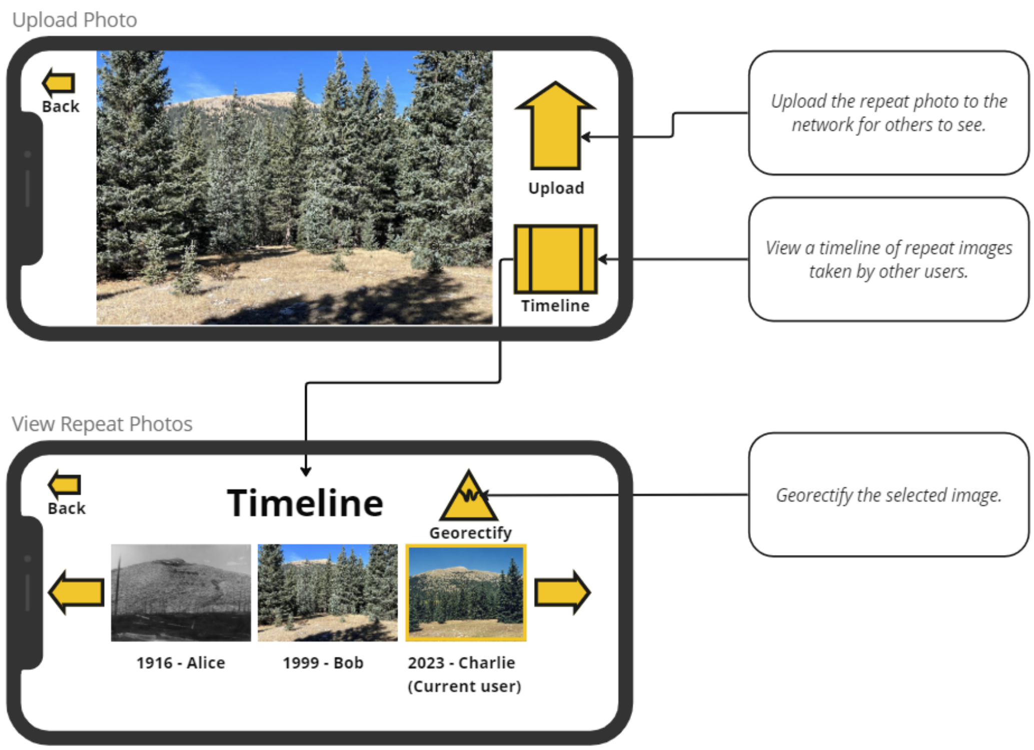

Figure 20b: Mockup of Peer-to-Peer Photo Sharing Using Realtime Earth

Lastly, in **Figure 20c,** Realtime Earth automatically rectifies the image onto the three-dimensional map using the locational and camera metadata stored along with the photo. The user has the option to manually adjust the image on the landscape as needed. The image and the map can then be shared to other applications for further processing or analysis.

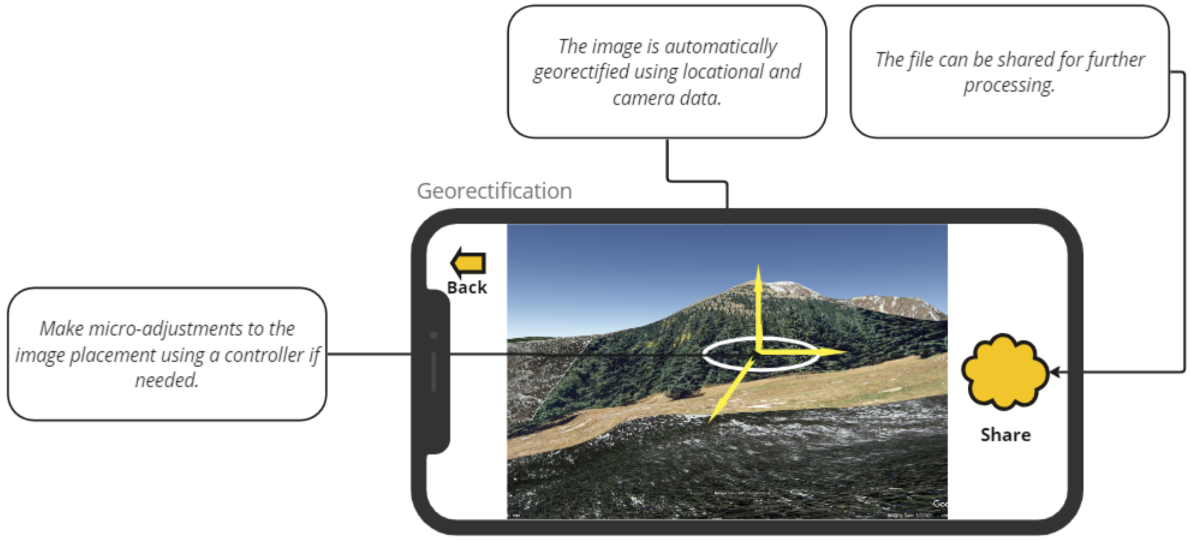

Figure 20c: Mockup of Georectification Using Realtime Earth

4.0 Evaluation of Different Options as a Repeat Photography Service

Understanding specific needs for a repeat photography service is crucial for development and longevity. Some key parts of ascertaining the needs for a service include determining community interest and narrowing down specific issues that could appear once development and hosting of a service begins. Like River Source, the Blue Hills Observatory is not interested in hosting a revived Picture Post website. However, they are interested in partnering with River Source to assemble a consortium of organizations interested in revitalizing Picture Post. This consortium would ideally be able to swing significantly more influence, and funding, behind the project than either River Source or BHO by themselves. Their hope is to begin building the consortium from both organizations in New Mexico and Massachusetts, especially from organizations who were previously involved with Picture Post before the crash. Once the core of the coalition had been established, Blue Hills suggested a methodological approach by 1) gauging who is interested in joining a coalition to relaunch Picture Post 2) determining the scope of what the coalition wants Picture Post to be, 3) finding what organization would be willing and capable of hosting the data, 4) consulting database and software experts for a cost estimate, and 5) securing funding for the system.

4.1 Interest in a Repeat Photography Service

River Source and the Blue Hills Observatory are highly interested in relaunching Picture Post. Micah Kiesow of the U.S. Forest Service and Eytan Krasilovsky of the Forest Stewards Guild, are both interested in securing funding for Picture Posts in order to use the technology as a part of their respective forest and fireshed monitoring projects.

Mori Hensley explained that the SWFA plans to use data from their Leading Edge Survey to advise the Santa Fe River Commision, a body made of public citizens, on how to manage the River and how it flows. Mori believes that citizen science tools, like Picture Post, are helpful for keeping organizations and communities up to date on the latest ecological or landscape problems in a region and that repeat photography could be a valuable tool in this regard.

Melanie Solis Alvarez of the Santa Fe Conservation Trust talked with our team about a possible use for Picture Post. The Santa Fe Conservation Trust's primary goal is securing conservation easements, which restrict certain uses of a property, including development on private land, and obligate independent monitoring of the land and the restrictions in perpetuity. Conservation easements are monitored annually – ground monitoring occurs every three years with remote monitoring the other years. For most of these easements, ground monitoring is performed every three years, and arial monitoring is performed every two years. However, this type of ground monitoring does not necessarily require a fixed point. Rather, the whole property is surveyed through multiple photos locations that are rotated every year. Melanie explained that there may be interest in a repeat photography system like Picture Post for certain restoration projects, but it would be unlikely to be useful for monitoring conservation easements.

Nav Khalsa talked about some potential uses of Picture Post with her organization. The Master Naturalists is a collaboration between the Santa Fe County, Audubon Center, and the Botanical Garden. They train community members to be stewards of the environment and offer education about ecology and biology across Santa Fe. The group has participated in climate change monitoring projects in the past, including monitoring animal populations and invasive species removal. She expressed significant interest in using Picture Posts for her organization and mentioned that she already does very informal repeat photography.

4.2 Scope

The scope of the revived Picture Post remains unclear. Since key organizations are still being identified, it is likely that the desires of all parties have not been accounted for. However, certain desired aspects of the revived system seem clear.

Many organizations seem interested in a divided system, with a base version for general use and education, and a segregated section for more professional use. The general version would have all the capabilities of the original Picture Post website, and be publicly accessible. This would be used by organizations and individuals for general outreach and education; anything not sensitive. The segregated section would be private, with pictures only accessible by the organizations that upload them. Several of the organizations were concerned that public access to their photos would be problematic. For example, photos on private property and in protected areas, might expose sensitive areas or private information. Having a separate private repository for these organizations could allow a renewed Picture Post much wider use, while keeping the educational and outreach aspects of the program unaffected.

An intuitive user interface, especially for photo uploads, also seems to be a key feature. Simplicity and ease of navigation makes it much easier for untrained parties to use a Picture Post. This simplicity is key for citizen science-based uses. The easier it is for an amateur user to navigate, the more likely that good data will be captured. Changes might also be required to the original uploading system, due to changes in camera technology. As phone camera resolution increases, it is possible that larger upload limits may need to be implemented to match.

Another key feature appears to be the timeline feature, which was available on the original Picture Post website. This allows users to easily view a slideshow of shots from a particular Picture Post view, organized by date. This allowed very compelling visual storytelling of the changes taking place.

Several interviewees indicated that reloading the old Picture Post images into the system would be a great benefit. Several of the current key players were users of the old Picture Post system, and retained the images they took. These existing images could be used to kick start a revived system. Restoring this legacy data would make the system much more valuable to researchers and educators.

Finally, some desire has been expressed in developing an app for Picture Post. This would be a significant undertaking as no legacy infrastructure exists, but it could have significant advantages. An app would allow an inbuilt uploading system and could further simplify the picture taking process. Pictures could be marked for upload on the app when out of cell reception, and then automatically uploaded when a user returned to reception. It could also simplify captioning, and provide better instructions than would be able to fit on a sign.

A revamped Picture Post would also likely be able to include an educational curriculum to accompany it. The Blue Hills Observatory is currently developing a curriculum to use with their legacy Picture Posts and photos. If Picture Post is revitalized at a national level, this curriculum could be modified to match. A repository of repeated photos from across the nation opens up new educational avenues for comparing and contrasting changes in different parts of the country.

4.3 Data Storage, Management, and Operational Costs

Corey Beinhart (Data Manager, New Mexico Forest and Watershed Restoration Institute, November 30th 2023) explained that the code for Picture Post is already a fully functional web application, and therefore there is no need to rewrite the program for it. The main obstacles would be finding a place to host the application and managing the resultant data and databases in perpetuity. He says that in the modern day, the best commercial options for data storage would be a cloud storage service like Amazon Web Services or Microsoft Azure. This is because cloud data storage is much more reliable than a singularly maintained physical server or drive. One issue with this cloud storage solution is that River Source prefers the data be maintained by an organization that has a long-term stake in the project, such as an academic institution.

Nathan Tomczyk (Research Associate, New Mexico Forest and Watershed Restoration Institute, November 30th, 2023) suggested that the Environmental Data Initiative (EDI) Repository might be a possible data repository to host Picture Post. EDI Repository is a collaboration between the University of New Mexico, University of Wisconsin Madison, and University of California at Santa Barbara, and is funded by the National Science Foundation. They provide services for preserving environmental data through technical expertise. (EDI Repository, 2023) They have distributed servers across the country and a full staff of engineers that may be capable of hosting and maintaining Picture Post. They also employ data experts who would be able to review and curate Picture Post data and its associated metadata, and secure the data for long-term access. There is the potential for them to act as both the host and technical advisory group for Picture Post. Beinhart said that another option for guaranteed long-term operation and maintenance of the Picture Post system would be to hire a contractor.

He suggested that the best way to gauge the costs of getting Picture Post to work again, and maintaining it, would be to consult front and back-end website developers, such as those from the EDI Repository, that have a lot of experience working on projects like Picture Post. Additionally, they would be able to assess the costs associated with the server size needed for a large data set like Picture Post and the server bandwidth required to support the use of Picture Post by many users concurrently.

4.4 Funding

The final and perhaps most important step for relaunching Picture Post is securing funding for the project. Donald McCasland outlined the three main possibilities for funding. The most effective method for securing funding would be to rely on the support from participating organizations. Since Picture Post was originally funded by NASA, there is the possibility that a revitalized Picture Post could once again be funded by NASA given a sizable enough coalition of interested organizations. McCasland also suggested that there may also be a way for the University of Oklahoma to secure funding if they decide to rehost Picture Post. Finally, he says that the BHO may be able to secure funding for themselves through partnering with respected organizations like River Source and others. Ultimately, the best means to secure funding would be to show use cases for Picture Post that are uniquely effective for monitoring and educating people about the environmental effects relating to climate change.

Conclusions and Recommendations

1.0 Picture Post

Picture Posts offer distinct advantages for the collection of high-quality repeat photos from numerous locations by both professional and amateur photographers. Picture Posts are extremely user-friendly and allow significant consistency in repeat photos, even between multiple photographers. Though Picture Post is useful and easy to use, collecting, storing, and systematically analyzing photographs over an extended period presents certain challenges. We make the following recommendations:

1.1 River Source, in collaboration with other interested parties identified in this report, should consider forming a consortium to pursue the development of a Picture Post service. This consortium should negotiate with organizations that are able to host, maintain, and make accessible the Picture Post dataset. The consortium can take a lead role in seeking federal, state, and other funding necessary to develop and maintain the network.

1.2 We suggest using Picture Posts with wood posts and plastic toppers whenever possible but using simpler physical markers (e.g., rebar hammered into the ground) where Picture Posts are not feasible. Simple in-ground metal markers are more practical than Picture Posts in harder to reach areas, or areas more prone to fires and extreme weathering. Additionally, in certain fire-prone areas, Picture Posts made entirely of metal with machined toppers may be desirable but should be used sparingly because of their increased material and manufacturing cost.

1.3 We recommend the consortium consult with software engineers and data experts to gain a comprehensive understanding of what time and resources are necessary to rebuild, host, and maintain a new Picture Post service.

2.0 Other Technologies

Several remote sensing technologies can be used to monitor environmental changes on a scale than is possible with Picture Posts. Satellites, drones, and planes represent the best methods of collecting big picture, top-down repeat imagery. Planes currently allow better resolution than most satellites, but we conclude that satellite imagery will likely surpass aerial photography in terms of effectiveness, convenience, and cost in the foreseeable future. Drones present a much more customizable and focused approach to top-down repeat photography. They will likely continue to have a place alongside large-scale top-down photography, even as the resolution of satellite imagery improves. Our group concludes that Realtime Earth does not currently have the capabilities for effective storage or display of repeat photos. However, Esri StoryMaps present a free and effective method of displaying repeat photography. They are very accessible, intuitive, and excellent at conveying information.

2.1 We recommend analysts use both drone and satellite imagery for environmental monitoring as a complement to Picture Post photography. As noted above, drones are more useful for focused, customizable mapping (in addition to having higher resolution than satellites), whereas satellites are more useful for big-picture observations.

2.2 We recommend not using RealTime Earth for environmental monitoring, as it is not practical at the moment. However, it may become practical with advances in the software in the near future.

2.3 We recommend the consortium consider using StoryMaps as a method to present repeat photography. The Swipe block feature is particularly effective in showing change over time and the Map Tour feature is useful to showcase photo points. We recommend Survey 123 be paired with StoryMaps as an effective way to upload repeat photo data and metadata to ArcGIS.

3.0 Data Collection

Our team concludes that a primary reason for the lack of usage of Picture Post by ordinary citizens was due to a lack of long-term public interest. We conclude that professional data collection ensures data quality, but takes time and money to support. Trained volunteers are less expensive to deploy, but still require time to train. Citizen science is cheap and has educational value, but the quality of data being collected can vary even with the assistance of Picture Posts.

3.1 We recommend that organizations requiring a high degree of data accuracy invest in training for staff or volunteers to collect Picture Post photos rather than relying solely on untrained volunteers.

3.2 Organizations that require lesser data accuracy likely do not need dedicated staff, and trained volunteers may still provide valuable data collection.

3.3 We recommend that all Picture Posts accessible by the public include proper signage with clear instructions on their use. These instructions should be provided in both English and Spanish, or other languages appropriate to the post's location.

3.4 We recommend that involved organizations should put resources towards promoting the Picture Post system and engaging users. This might include website pages illustrating use cases for Picture Posts or a regular email showcasing the best pictures of the year.

4.0 Education

We conclude that PicturePosts offers unique educational opportunities due to its low threshold for use and ability to integrate into educational outreach. Development of an environmental monitoring curriculum based around Picture Post is in the best interests of both the consortium and the general public.

4.1 We recommend the continued development of a captioning activity that educates students on observing their surroundings and the importance of recognizing ecological change.

4.2 To further the educational impact of Picture Post, we recommend that the consortium develop a curriculum based around repeat photography and use it for educational outreach with both public and private school systems. This will educate students on repeat photography and their environments, and promote awareness of climate change. Additionally, a curriculum will help garner public interest in Picture Post and maintain its relevance long-term.

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Appendices

Appendix A: Sample Interview Questions for Experts

We are a group of students from Worcester Polytechnic Institute (WPI) in Massachusetts conducting a research project in collaboration with River Source to evaluate different methods for repeat photography. We would be delighted if you would take 10-15 minutes to answer some questions about ________________. Your participation in this interview is completely voluntary and you may stop at any time. No personal information will be recorded or saved; We do ask permission to quote you anonymously. You have the right to review any quotes we use in our report prior to its publication. We would also be happy to provide you with a copy of our report when it is completed.

Thank you for your support in this research. Do you have any questions before we begin? If you have any concerns or questions after the interview, you can contact us via our email alias at gr-sf23pics@wpi.edu or our faculty advisors, Dominic Golding (golding@wpi.edu) and Jeffery Solomon (solomon@wpi.edu).

1. Can you describe the responsibilities of your position at [organization]?
2. How would you define repeat photography?
3. Can you describe your experience with repeat photography?
    a. What have you used repeat photography for?
4. What methods have you used for repeat photography?
5. Were these methods for repeat photography able to capture consistently similar photographs?
    a. What did you find allowed them to take consistent photos?
6. What repeat photography projects have been most successful in the past?
7. Have you ever used community collected data in a repeat photography project?
    a. If yes, was it useful? How hard was it to use?
        1. Are there any strategies you have pursued to help retain member engagement?
    b. Do you believe citizen science has a place in your field of research?
        1. Where would it be helpful?
        2. Where would it not be helpful?

8. What are the challenges you regularly face when trying to perform repeat photography in the area?
9. How are funding and resources currently being used to promote repeat photography?
10. How do you evaluate the effectiveness of the methods you have used for outreach and project administration?
11. Are there any upcoming projects that you're particularly interested in?
12. Do you have any other suggestions or concerns we should be aware of?
13. Do you have any suggestions for people within or outside of your organization that we should contact to get more information on repeat photography?
14. (PicturePost related questions, if applicable)
    a. With your experience, would you recommend PicturePost technology for long-term climate mitigation in a given area? Why or why not?
    b. What are the challenges you regularly faced while trying to perform repeat photography using the PicturePost technology?
    c. What conditions did you find PicturePost applicable?
    d. What conditions did you find that PicturePost was non-applicable? (e.g. bad weather, location, no signal, no GPS).
    e. Are there any specific strategies you suggest to help retain community engagement?

Appendix B: Sample Interview Questions for Gauging Community Interest

We are a group of students from Worcester Polytechnic Institute (WPI) in Massachusetts conducting a research project in collaboration with River Source to evaluate different methods for repeat photography. We would be delighted if you would take 10-15 minutes to answer some questions about ________________. Your participation in this interview is completely voluntary and you may stop at any time. No personal information will be recorded or saved; these questions are completely anonymous. Any feedback given will be completely anonymous. We would also be happy to provide you with a copy of our report when it is completed.

Thank you for your support in this research. Do you have any questions before we begin? If you have any concerns or questions after the interview, you can contact us via our email alias at gr-sf23pics@wpi.edu or our faculty advisors, Dominic Golding (golding@wpi.edu) and Jeffery Solomon (solomon@wpi.edu).

1. Have you ever heard of repeat photography?
    a. If so, can you describe what you know about repeat photography?
2. Are you or members of your organization interested in climate change monitoring projects?
3. Have you ever participated in climate change monitoring projects?
4. Would you be interested in participating in a community-based repeat photography project to monitor climate change?
5. Do you or members of your organization have experience with photography?
6. If we created a prototype of an easy method for performing repeat photography, would you be willing to test it?
7. [explain PicturePost] If you saw a sign advertising a device like Picture Post while in a national park, how likely would you be to use it?
    a. What would make you more likely to use it? Less likely?
8. What steps do you think can be taken to make a repeat photography prototype more attractive to potential users?
9. What steps do you think can be taken to make a repeat photography prototype easy to understand?
10. What steps do you think can be taken to make a repeat photography prototype more engaging/enjoyable to use?

Appendix C: Captioning Activity

Picture Post Lesson Plan

Summary

The purpose of the *Student Activity Sheet* is to educate students on the importance of repeat photography to monitor ecological change. This interactive activity includes instructions on effectively using PicturePost for repeat photography and then writing an accurate caption for the photographs taken.

Objective

Students will:

- take eight photos using Picturepost OR will be provided eight photos that were taken using PicturePost.
- analyze one of eight photos, listing any observations about the environment.
- write a compelling caption that is 3-5 sentences long, telling a story about what they analyzed, bringing awareness to climate change as this data can aid the process of environmental restoration.

Materials

- Copies of eight repeat photos from a PicturePost (student will choose only one to write a caption about).
- Pencil/Pen.

Optional

- If interested, try writing a caption about more than one photo and tell a compelling story!

Background

Picture Post is a NASA-funded project that was based out of the University of New Hampshire. Picture Post promoted environmental monitoring by students and citizens using digital imagery. A few years ago, the PicturePost program collapsed, causing years of vital environmental data to be lost. Students from Worcester Polytechnic Institute are working with their sponsor, River Source, to revitalize this project while also incorporating an educational outreach. In this assignment, you will be asked to write captions that are 3-5 sentences long. This cationing activity contributes to an individual's understanding of the history of their land, and thus connects people to their cultural heritage.

Student Activity Sheet

The goal of the *Student Activity Sheet* is to educate students on the importance of repeat photography to monitor ecological change. This interactive activity includes instructions on effectively using PicturePost and then writing an accurate caption for the photographs.

Name: ________________________________

Date: ________________________________

Picture Post

This Picture Post enables repeat photos of forests, rivers, and the impact of restoration projects intended to improve conditions. PicturePost is an octahedral-shaped post planted in a location that needs to be monitored. A smartphone can easily take repeat photos from each of the eight topper sides.

Step 1 - Take Photos

Using your phone, put the device flat, the screen facing you, against one of the edges of the PicturePost. Make sure the device is flat against the edge before taking your photo with the back camera. Repeat this on all eight sides. This ensures that the photos taken using Picturepost will retain the same view no matter who uses the post, providing accurate information about the environment for long-term monitoring.

Step 2 - Observations

List observations from the photos you took.

Captioning

Captioning a picture means writing a few sentences to provide more background information on the photo. The purpose of a caption is to engage the reader and help them learn more about what is going on in the picture.

Step 3 - Write a Caption

Now it's your turn; write a caption!

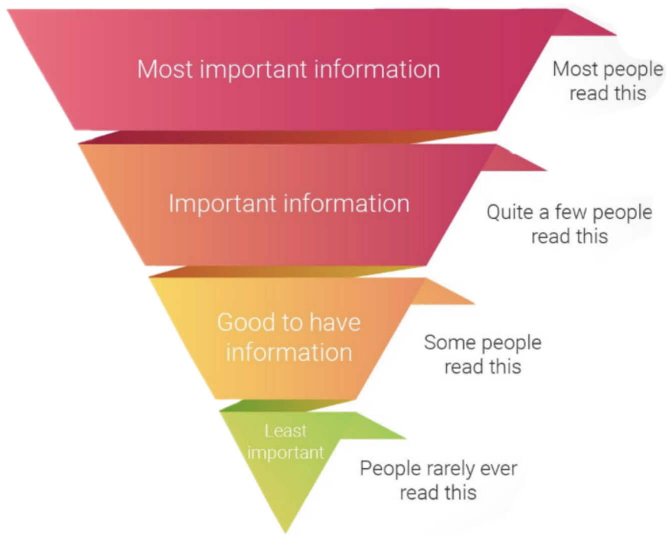
Tips:

- Captions should be short and concise, around 3-5 sentences.
- Don't assume that the reader knows what you know. Be sure to explain things so that everyone can understand.
- The caption should capture the reader's interest. Start with something interesting to "hook" the reader.
- Some people won't read the whole caption, so put the most important information in the beginning.
- Be sure to always ask yourself, "so what?" Don't include information that isn't useful or interesting.
- Remember, every caption is different. Don't worry about writing the perfect caption.

How to start:

- To start, look at the pictures and think about what you want to focus on. Choose one of the 8 PicturePost view photos to write your caption about.
    - What is the most interesting thing you see?
- Next, imagine you are trying to describe the picture to a family member or a friend. How would you describe it?
- Begin writing with a sentence to engage the reader. Think about what would make you want to keep reading.
- Next, add some important information. What do you want the reader to remember from your caption?
- After the important information, you can now add more descriptive details. What else is happening in the picture? Why is it important?

Inverted Pyramid Style of Writing



Santa Fe Baldy in 1916

Caption 1: Gazing up at Santa Fe Baldy in 1916, the landscape is a barren slope filled with burned trees. Almost 40 years prior, in late 1879 or early 1880, a massive fire raged on Santa Fe Mt Baldy. Even after decades, the forest has not regrown. Only a few things stand out in a landscape of fallen, burnt, logs. One of those things is a splash of trees at the ridge of the mountain, hard to make out in the black and white photo. A stand of old growth pine remains, alone on the tree line. It is likely that they survived due to the sparse nature of trees at such high elevations, and now represent the last of the old forest. Controlled burns and forest thinning work on this same principle. They create space in the forest, and prevent fires from being as devastating.

Santa Fe Baldy in 1999

Caption 2: Even with over 100 years to regrow, the slopes of Santa Fe Mt Baldy are still sparse. However, the same pine patch near the tree line still stands out. The grove which survived the 1879 fire is spilling across the ridge, while the rest of the forest inches back up the slopes.

Appendix D: Repeat Photography Report

Interactive Qualifying Project

Repeat Photography and Captioning of Historical Photographs to Monitor Ecological Change in Santa Fe, New Mexico

November 28th, 2023

Mateo Blumenthal *Environmental Engineering, Environmental & Sustainability Studies*
Trinity Gibbs *Mechanical Engineering, Professional Writing*
Nathan Holmes *Mechanical Engineering*
Nate Levine *Mechanical Engineering*

Summary

This report is a collaboration between WPI students and River Source to monitor the ecological change of specific locations in Santa County using repeat photography. Digitized historical photographs of these locations were provided to us by the Forest Stewards Guild. Some of these photographs were repeated in the late 1990s and early 2000s by Craig Allen's team. With the assistance of Craig Allen (a retired expert from the US Geological Survey) and the Forest Stewards Guild, our team was able to locate and repeat a sample of these photographs.

Content

This report contains 3 sets of repeat photographs of the following locations:

- Mount Baldy, taken from the intersection of the Winsor and Skyline Trails
- An unnamed hill in the northeastern portion of McClure Reservoir
- McClure Reservoir, taken from the dam.

Each set of pictures consists of a photo from the early 20th century, a photo from the late 1990s or early 2000s taken by Craig Allen's team, and photos from 2023 taken by Craig Allen's team or our team. Each set is accompanied by one caption per picture to provide more context about the location. This selection of photographs may be updated in the future to include more locations in Santa Fe County.

1.1) Santa Fe Baldy in 1916

This image shows the south side of Santa Fe Mt Baldy in 1916. Fires between the growing seasons of 1879 and 1880 burned much of the area. The slope and the foreground show the severity of these fires. Burnt trees still litter the ground, but the lack of color in the image makes it hard to tell the extent of succession that occurred post-fire. Based on later photos, the shadowy shapes close to the ridge are trees that survived the initial fires **(Parkhurst, 1916).**

1.2) Santa Fe Baldy in 1999 (Craig Allen's Team Retake)

This image shows the same side of Santa Fe Mt Baldy in 1999. With over a century of regrowth, the once-charred terrain is filling out once more. The slope and foreground are no longer littered with burned logs, and the resurgence of trees is most pronounced near the ridgeline (middle, far left), where a small number of trees thrived after surviving the initial fires. This photo was taken approximately 20 meters southwest of the junction of the Windsor Trail to Spirit Lake and the Skyline Trail **(Elson, Hogan, Tharnstrom, 1999).**

1.3) Santa Fe Baldy in 2023 (WPI Retake)

This image shows the same side of Santa Fe Mt Baldy in 2023. Trees in the foreground have experienced significant growth – so much so that the view of the mountain is partially obscured. The visible part of the slopes shows much thicker foliage than in the 1999 repeat, but it is difficult to determine the extent of this regrowth. This photo was taken approximately 20 meters southwest of the junction of the Windsor Trail to Spirit Lake and the Skyline Trail, in the vicinity of 35º48’49” N 105º45’39” W.

1.4) Santa Fe Baldy in 2023 (WPI Retake, From a Tree)

This image shows the same side of Santa Fe Mt Baldy, also in 2023. To better capture forest regrowth on Mt Baldy, this photo was taken from a tree approximately 20 feet above ground level. This repeat makes the significant thickening of foliage on the mountain's slopes much more visible. The stringer along the middle ridge has grown down to meet the new forest growth up from below. This photo was taken approximately 20 meters southwest of the junction of the Windsor Trail to Spirit Lake and the Skyline Trail, in the vicinity of 35º48’49” N 105º45’39” W.

2.1) McClure Reservoir Hill in 1916

This historical photograph shows the south side of a hill situated along the Santa Fe River (what would become the northeastern portion of the McClure Reservoir) in 1916. The impact of deforestation, combined with severe and widespread goat grazing, led to significant erosion in the area. The lower portion of this hill showcases the consequential erosion with numerous deep rills cutting down into the slope **(Blanchard, 1916).**

2.2) McClure Reservoir Hill in 2000 (Craig Allen's Team Retake)

This image, captured in the year 2000, showcases the same side of the unnamed hill. Substantial regrowth has taken place, and the rills from overgrazing and deforestation are no longer visible. The foreground has also significantly altered, as the hill now sits alongside the McClure Reservoir rather than the river. The bank at the base of the hill reveals that the reservoir was quite low during this retake. It is likely that the closing of the watershed to the public after the creation of the reservoir has allowed the hill to be reforested. The photo was taken in the vicinity of (NAD83) 425340E 3949680N **(USGS 119, 2000).**

2.3) McClure Reservoir Hill in 2023 (Craig Allen Re-Retake)

This image shows the same side of the unnamed hill in early June, 2023. The McClure Reservoir is much more full than in the 2000 repeat, and the trees are somewhat thinned **(Allen, 2023).**

2.4) McClure Reservoir Hill in 2023 (WPI Retake)

This image shows the same side of the unnamed hill, taken in late November 2023. A significant portion of the reservoir has been drained, leaving the visible portion dry. The hill also appears much more pink than the June 2023 repeat, likely due to low lying foliage and grasses going dormant for the winter and exposing the underlying pink granite. This photo was taken in the vicinity of 35º41’15”N 105º49’40”W.

3.1) McClure Reservoir in 1926 (Before Reservoir)

This image shows the Santa Fe River as it flows west towards Santa Fe. Visible in the background is the west side of the same hill from 2). Significant erosion is also present in this view. Part of the background is obscured by what appears to be fog, but the lack of color makes it difficult to determine. The picture is taken facing east, towards the Sangre de Cristo mountains. **(Lewis, 1926)**

3.2) McClure Reservoir from Dam in 2000 (Craig Allen Retake, After Reservoir)

This image shows approximately the same view as 3.1). It is likely that the original photo point is submerged in the McCluer Reservoir. The hill present in the foreground of the original photo has been removed entirely, and the valley widened and deepened to create the reservoir. The eroded hill spotlighted in 2) is still visible, and has been significantly reforested. Looking at the banks, it is clear that the reservoir is fairly low during this retake. The photo was taken in the vicinity of (NAD83) 424350E 3949720N, from the top of the McClure Dam. **(USGS 226, 2000)**

3.3) McClure Reservoir from Dam in 2023 (WPI Retake)

This image shows the same view of McClure Reservoir as 3.2). The concrete tower visible in the 2000 retake no longer exists. Trees on the unnamed hill from 2) (on the left of the photo) are noticeably thinner. The reservoir is once again fairly low. This photo was taken from the top of McClure Dam, in the vicinity of 35°41'18"N 105°50'10"W, and is meant to mimic the 2000 retake.

Appendix E: ArcGIS StoryMap

The ArcGIS StoryMap can be accessed here, or at:
https://storymaps.arcgis.com/stories/8cfa667717574ea3a49029f06ca0008d