Humans are Earth too: Hydrology, stream restoration, and the human side of Earth science

A DISSERTATION

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Abstract

Human beings (*Homo sapiens*) influence the Earth in profound and multifaceted ways. Humans directly alter geologic processes, including sediment transport, altered hydrologic pathways, and more. Humans also benefit and suffer from geologic processes – access to water, greenspace, and hazards. And human processes, including discrimination and power dynamics affect where and how science is done. My dissertation addresses each of these dimensions of human/Earth interaction. I begin with a human → Earth interaction by analyzing the influence of climate change and land-use change on streamflow in Minnesota and Wisconsin. We find that precipitation change has been consistent across the region, but streamflow response has been variable. Watersheds in (geologically) recently glaciated central and western Minnesota had greater streamflow increases than watersheds in eastern Minnesota and the western Wisconsin Driftless Area. This streamflow response also maps onto land-use change, as watersheds with glacial till have more agriculture drainage. Information-theory metrics reveal inconsistent patterns in the relationship between precipitation and streamflow, underscoring the hydrologic complexity of the upper Midwest. I then explore an interrelated human ↔ Earth system by developing a new stream restoration database for the state of Minnesota and exploring the environmental justice implications of restoration siting. We find that restoration projects are systematically located in whiter and more affluent locations compared to the overall population of the state. Restoration projects are also responsive to environmental degradation, as restored streams are more likely to be impaired than average streams in the state. Finally, I explore human aspects of the geosciences through three chapters: I present reflections and recommendations from my time balancing life as a geoscientist and a black resident of South Minneapolis following the murder of George Floyd in summer 2020, with a focus on how greater institutional risk is needed to truly advance visions of diversity equity and justice. I describe the pedagogical underpinnings of field learning via a literature review in geoscience, environmental science, and ecology. We find that active learning, co-creation of knowledge, rapid feedback, and place-based learning are key reasons that students learn during field trips. Finally, I offer reflections from a community science event hosted between local organizations and the Department of Earth & Environmental Sciences. Attendees considered the event a success and there were many positive and negative lessons to implement in future attempts to bridge the divide between university and non-university partners. These diverse projects illustrate a multitude of ways that humans influence and interact with the Earth, and underscore the need to consider human processes as a key element of the Earth system.

Table of contents

List of Tables

List of Figures

Chapter 1. Introduction

By some estimates, humans are the most effective geological agent in the world. Humans may move more sediment than any natural process (Hooke, 1994), have significantly altered the water cycle in most of the world (e.g. Cooley et al. 2021), contribute CO_2 to the atmosphere at extremely high rates (e.g. Friedlingstein et al. 2019), annually produce millions of tons of synthetic materials that may persist for decades to centuries (Geyer et al. 2017; Ward and Reddy, 2020), and humans even influence solid Earth processes via induced seismicity (Keranen and Weingarten, 2018). For these reasons and more, some geologists have proposed that the Earth has entered a new geologic era, the Anthropocene, marked by the dominance of humans on Earth processes (e.g. Zalasewicz et al. 2011). Though the Anthropocene is not formally recognized by international governing bodies, the magnitude of human influence on the geologic world is unequivocal.

Given that humans are an integral geologic agent, there is a pressing need to explicitly incorporate humans in our geologic understanding. This does not mean that all Earth scientists need to become or work with social scientists, but conceptualizing the Earth sciences apart from humanity fundamentally limits our ability to understand the world (e.g., Phillips, 1991). Additionally, human processes like political power, economic decisions, and discrimination influence the practice of science. This is clearly illustrated by data gaps that correspond to economic levels (Fritz et al. 2019), the prevalence of sexual harassment in field settings (Clancy et al. 2014), gender gaps in first authorship (Pico et al. 2020), funding disparities from national organizations (Chen et al. 2022), and the lack of racial minorities in the geosciences (Bernard and Cooperdock, 2018), among other examples. All of these human processes affect the way that science is done, and ultimately color our understanding of the Earth system.

Earth surface processes in particular are intimately tied to human society. Geomorphologists have long recognized the influential role of humans on Earth surface processes (e.g. Gilbert, 1917). Within the last decade, there has been a push to more deeply interrogate that role, particularly among geographers (e.g. Lave et al., 2014). For example. Harden (2014) calls for geomorphologists to “move beyond unidirectional cause-and-effect (human impacts), and develop research frameworks that better integrate the ongoing interactions between humans and landscapes.” In this dissertation, I attempt to go beyond unidirectional impact with examples that illustrate the interconnectedness of humans and the Earth. I also provide examples and recommendations to address issues on the human-side of Earth science.

In Chapter 2, I explore the impacts of climate change and land-use change on streamflow in Minnesota and Wisconsin. We find that precipitation and streamflow have changed considerably across the region, with greater streamflow changes in catchments with more agricultural drainage. Unraveling the precise role of climate and land-use change is a significant challenge, as illustrated by equivocal results using information theory metrics, which have not previously been applied to this geographic region.

In Chapter 3, I present a new stream restoration database in Minnesota and explore the physical and environmental justice implications of restoration project siting. We find that stream restoration is driven by both social and physical factors, leading some rivers to be more likely to be restored than others. This influences both geomorphic processes and the people who have access to restored ecosystem services, with implications for environmental justice.

In Chapter 4, I offer reflections and recommendations for how to advance diversity, equity, and inclusion in the Earth sciences based on my experience as a Black Earth scientist who lived in Minneapolis during the racial uprising that began in 2020.

In Chapter 5, I present reflections and recommendations from a community science effort in the Earth Science Department at the University of Minnesota. Community science is a relatively small, but (hopefully) growing movement within the Earth sciences to expand the types of people who have access to scientific tools and decision-making power. Our team organized a meeting between community partners and university members, which led to a few university–community collaborations and a subsequent event.

In Chapter 6, I explore the pedagogical benefits of field trips in higher education. Teaching geoscience is a critical part of how we prepare future scientists and communicate the culture of the geosciences. Field trips in particular can be a place of great learning, but also a place of difficulty due to harassment and discrimination. Uncovering the pedagogical strengths of field trips helps us teach so that students can learn, both in the field and the classroom.

And finally, in Chapter 7, I summarize this diverse body of work by discussing the complex role of humans as a geologic agent by highlighting contributions from feminist studies and science and technology studies.

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Chapter 2. Humans → rivers. Everything, everywhere has changed: Agricultural drainage augments the effect of climate change on streamflow in the Midwestern US

Abstract

Streamflow has increased in rivers across the agricultural Midwest, USA, but the cause of this increase is debated. Previous studies suggest that both land-use change and climate change influence streamflow, but the relative role of each is unclear. I analyzed long-term land cover, precipitation, and streamflow data from eleven watersheds across a gradient of glacial history and agricultural intensity in Minnesota and Wisconsin. Results show that increased precipitation and increased agricultural drainage have greatly amplified streamflow across the entire region. The timing and magnitude of precipitation change has been similar across the region, but watersheds with more agricultural drainage have experienced greater increases in streamflow. This suggests that both climate and land use drive streamflow in the region, meaning that management solutions must consider both in order to mitigate negative environmental impacts.

2.1. Introduction

Streamflow has increased in many rivers in the Midwestern United States in recent decades, but there is ongoing debate about the cause of these changes and the actions needed to manage and remediate streams (Baeumler & Gupta, 2020; Belmont et al., 2016a, 2016b; Belmont & Foufoula-Georgiou, 2017; Cho et al., 2019; Gupta et al., 2015, 2018; Hansen et al., 2021; Mitchell et al., 2018; Williams et al., 2015). Agricultural drainage can decrease the residence time of soil water, leading to increased streamflow in response to rain and changes in the seasonality of streamflow (Foufoula-Georgiou et al., 2015; Frans et al., 2013; Kelly et al., 2017; Magner et al., 2004; Schilling et al., 2010; Schottler et al., 2014; Xu et al., 2013). At the same time, studies show that precipitation has increased in the region and some authors attribute flow changes primarily to increased precipitation and soil moisture (Frans et al., 2013; Gupta et al., 2015, 2018; Novotny & Stefan, 2007). Both climate and land use play a role in streamflow generation, but understanding the relative role of each is important to prepare for future climate scenarios and to determine what mitigation efforts are needed to protect riverine resources (Belmont & Foufoula-Georgiou, 2017; Hansen et al., 2021; Kumar et al., 2018a; Mitchell et al., 2018).

The use of subsurface drainage is implicated in observed streamflow changes in the Midwest. Direct measurements from drain tiles (subsurface pipes typically made of corrugated plastic) show that they are an active hydrologic pathway. King et al. (2014) collected discharge measurements in drain tiles in small watersheds in Ohio, USA and found that an average of 21% of total annual precipitation was drained through tiles. This aligns with several other studies that find that 15-40% of annual precipitation is drained through drain tiles at sites in the Midwest (Helmers et al., 2005; Randall, 2004; Williams et al., 2015). Macrae et al. (2007) collected high temporal resolution data in Ontario, Canada and found that drain tiles accounted for 0-90% of daily streamflow and 42% of total annual streamflow. End-member mixing analysis has produced similar results, with studies in Iowa, USA showing that 40% of total streamflow drains through tiles (Arenas Amado et al., 2017; Schilling et al., 2019). These studies also find a seasonal signal in tile drainage, with most water draining from April-June, when soil water is high and crop water uptake is relatively low (Arenas Amado et al., 2017; Cain et al., 2022; Goeken et al., 2015; Helmers et al., 2005; King et al., 2014; Randall, 2004; Schilling et al., 2019; Williams et al., 2015)

In addition to direct evidence linking drainage tiles and streamflow, numerous studies document that the timing of streamflow changes in the Midwest is coincident with the expansion of drain tiles. Schottler et al. (2014), used a water balance approach to analyze trends in 21 Minnesota watersheds. They found that precipitation change accounted for about 10% of observed streamflow changes, and that seasonal trends in precipitation did not match seasonal changes in streamflow. Foufoula-Georgiou et al. (2015) used wavelet analysis of streamflows in two tributaries in the Minnesota River basin to show that the distribution of flows significantly changed after soybeans became the dominant watershed crop. In both studies, streamflow changes were most pronounced in spring and early summer, coincident with the most active time for drain tiles. And many region-wide studies demonstrate a correlation between agricultural intensity and streamflow changes, as agricultural watersheds have increased total annual flow, increased baseflow, and decreased travel time of subsurface water (Ayers et al., 2019, 2021; Bendorf et al., 2021; Danesh-Yazdi et al., 2016; Kelly et al., 2017; Li & Quiring, 2021; Slater & Villarini, 2017; Xu et al., 2013).

Since the 1970s, precipitation has increased in much of the Upper Midwest, which has a direct effect on streamflow (Pathak et al., 2017). To analyze the impact of climate and land-use change in the Upper Mississippi River Basin, Frans et al. (Frans et al., 2013) constructed a hydrologic model with three different land use and land cover scenarios. They found that observed climate was the primary driver of streamflow change between 1918 and 2007, though they acknowledge that artificial drainage (modeled as enhanced soil moisture loss) amplifies streamflow trends. Novotny and Stefan (Novotny & Stefan, 2007) also found that precipitation and streamflow were strongly correlated for rivers across Minnesota, and that temporal trends in streamflow matched those of precipitation. They also note the potential influence of artificial drainage in the Red River and Minnesota River basin, though they do not consider it explicitly in their analysis. Gupta et al. (2015, 2018) suggest that land-use and land-cover change have had minimal effects on streamflow in the Upper Midwest. They demonstrate that observed changes in annual streamflow are correlated with the precipitation in the previous year, increases in annual precipitation, and changes in soil moisture, though their approach received criticism for (among other things) considering annual trends, when the influence of drainage manifests at shorter timescales (Belmont et al., 2016b; Foufoula-Georgiou et al., 2016).

Clearly, climate, land use, and streamflow have all changed in the agricultural Midwest over the last century. Resolving the role that climate and land use play in driving streamflow is essential for managing rivers but has proven difficult due to the co-evolution of climate, land use, and streamflow. Detailed analysis of long-term land use, precipitation, and streamflow records can provide insight into the relative role of each. Information theory, a set of statistical techniques to measure the relationship between variables, has received increasing attention in hydrology as a method to assess hydrologic connectivity, but has received limited use in the agricultural Midwest (Franzen et al., 2020; Goodwell et al., 2020; Goodwell & Kumar, 2017; Moges et al., 2022). In this chapter, I use statistical analysis of land use, precipitation, and stream flow data, including information theory to analyze hydrologic change across a gradient of watersheds in Minnesota and Wisconsin.

2.2. Study area

The regions currently known as Minnesota and Wisconsin were at the margin of the Laurentide Ice Sheet during the most recent continental glaciation in North America. As a result, different parts of the region have dramatically different surficial geology and topography (Anders et al., 2018; Jennings & Johnson, 2011; Lusardi et al., 2011). Western and south-central Minnesota were glaciated by the Des Moines lobe of the Laurentide Ice Sheet, which deposited many meters of glacial material across the region (Dalton et al., 2020; Jennings & Johnson, 2011;

Lusardi et al., 2011). In many areas, the till deposits are clay rich and poorly drained (Lusardi et al., 2011). Topographically, the post-glacial landscape of central and western Minnesota is marked by local depressions, low relief, and poorly integrated watersheds (Figure 2.1) In contrast, parts of southeastern Minnesota and southwestern Wisconsin were not glaciated during the most recent glacial advance (Dalton et al., 2020; Syverson & Colgan, 2004). This region is referred to as the Driftless Area due to the lack of glacial drift, though a strict definition of driftless only applies to parts of southwestern Wisconsin and northwestern Illinois that were never glaciated during the Quaternary (*sensu* Knox, 2019). The Driftless Area has well-developed drainage networks and moderately dissected topography with rolling hills. In the Driftless Area, subsurface material differs by landscape setting, with variation between ridges, hillslopes, and valleys (Juckem et al., 2008; Knox, 1972; Stout et al., 2014). In general, upland soils in the Driftless Area are relatively thin and are formed from loess and Paleozoic bedrock, though there are local areas with significant sand as well (Bockheim & Hartemink, 2017; Mason et al., 2019).

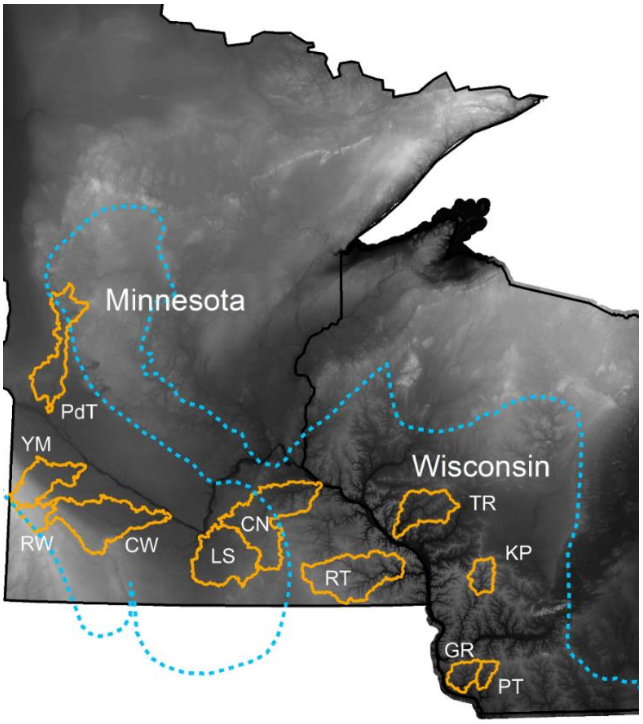


Figure 2.1. Digital elevation model of Minnesota and Wisconsin showing watersheds used in this study. Dashed blue line represents the extent of glaciation at 19.3 ka (calibrated radiocarbon age, Dalton et al., 2020). Watershed abbreviations: CN – Cannon, CW – Cottonwood, GR – Grant, KP – Kickapoo, LS – Le Sueur, PdT – Pomme de Terre, PT – Platte, RT – Root, RW – Redwood, TR – Trempealeau, YM – Yellow Medicine.

The glacial history of the upper Midwest strongly controls the distribution of soil types and pre-colonial vegetation. The high clay content in soils and the low relief landscape created by the Des Moines lobe led to the development of prairie and wetland vegetation, which created mollisols across much of central and western Minnesota (Anderson et al., 2001). In contrast, the relatively thin, well drained soils of the Driftless Area created conditions for hardwood forests and oak savannah ecosystems and produced alfisols (Bockheim & Hartemink, 2017). These soil types have different drainage ability, pH buffering capacity, and carbon content, and have different agricultural potential as a result.

Prior to Euro-American colonization, Indigenous peoples, including the Dakota, Ojibwe, and Ho-Chunk inhabited the region. Early Europeans came to the region in the 1600s and European fur traders interacted with Indigenous communities for centuries, with many social, legal, and economic consequences (Allard, 2020; Brophy, 2019; Nute, 1930). Land in Wisconsin and Minnesota was ceded to the United States through a series of treaties in the 19th Century. Many treaties were signed under coercion and all were later violated by the U.S. government (including the absolution of unproven trade debts), leading to Indigenous land dispossession and an influx of Euro-American colonists (Čhaŋtémaza & McKay, 2022; Clemmons, 2005). Settler colonialism brought sweeping landscape changes – drained wetlands, cleared forests, and intensive agricultural use. This led to widespread geomorphic and hydrologic changes, including expanded drainage networks, increased soil erosion rates, and altered ecological composition of terrestrial and aquatic communities (Auclair, 1976; Goring et al., 2016; Happ, 1944; Jelinski et al., 2019; Rhemtulla et al., 2009; Rhoads et al., 2016; Trimble, 1999; Urban, 2005; Urban & Rhoads, 2003).

I chose 11 watersheds that span this gradient of glacial history and agricultural intensity (Figure 2.1). Each of the watersheds is home to a long-term USGS stream gage with minimal streamflow regulation (Table 2.1). The drainage area of the watersheds ranges from 370 km^2 to 3500 km^2 and the glacial history includes areas that were completely covered by glacial ice, areas that were partially covered, and areas that were not covered by glacial ice during the most recent glaciation (Dalton et al., 2020). As a result, the soils and topography of the watersheds reflect a wide range of rivers in the region (Table 2.1). Modern-day agricultural intensity maps onto the glacial history, with more intensive agriculture in the fully glaciated areas where there are deep, productive soils.

Table 2.1. USGS gage information for watersheds used in this analysis.

Gage name	USGS gage Number	Drainage Area (km^2)	% Group C soil*	Average slope (%)	Period of record
Cannon River at Welch, MN	05355200	3471	23.6	4.42	July 1, 1909 – Dec 31, 1913 Oct 1, 1925 – Sept 30, 1926 Dec 1, 1930 – Sep 29, 1971 Oct 1, 1991 – Present
Cottonwood River near New Ulm, MN	05317000	3367	37.4	2.43	July 1, 1909 – Nov 30, 1913 April 1, 1930 – Present
Grant River at Burton, WI	05413500	697	66.9	18.8	Oct 1, 1934 – Present
Kickapoo River at La Farge, WI	05408000	689	48	27.9	Oct 1, 1938 – Present
Le Sueur River Rapidan, MN	05320500	2875	47.8	2.45	Oct 1, 1939 – Sep 30, 1945 Aug 1, 1949 – Present
Platte River near Rockville, WI	05414000	368	54.4	20.3	Oct 1, 1934 – Present
Pomme de Terre River near Appleton, MN	05294000	2344	38.2	3.74	April 1, 1931 – Sep 29, 1999 June 12, 2003 - Present
Redwood River near Marshall, MN	05315000	671	41.2	3.28	April 1, 1940 – Present
Root River near Houston, MN	05385000	3237	20.3	9.1	Oct 1, 1901 – Sep 29, 1917 May 1, 1929 – Nov 22, 1983 Oct 1, 1990 – Sep 30, 2000 Jan 1, 2004 – Oct 21, 2008 Sep 21, 2012 – Present
Trempealeau River at Dodge, WI	05379500	1665	21	21.8	Dec 13, 1913 – Sep 29, 1919 April 19, 1934 – Present
Yellow Medicine River near Granite Falls	05313500	1725	36.7	2.54	April 1, 1931 – Sep 29, 1938 October 1, 1939 – Present

*Hydrologic Group C soil is defined as having “moderately high runoff potential when thoroughly wet.” (USDA National Engineering Handbook)

2.3. Data and methods

2.3.1. Land cover data

To analyze changes in land use and land cover, I compiled county level agricultural data from the USDA National Agricultural Statistics Service following the method of Foufoula-Georgiou et al. (2015). The USDA measures the number of acres that are planted in different types of crops in each county. I calculated the acreage of crops harvested in each watershed based on the area of each county in each watershed. I did this for each year from 1921 to 2017 for three classes of crops: corn, soybeans, and hay and small grains (barley, flax, oats, rye, and wheat).

Corn and soybeans are the dominant products in modern commercialized agriculture, whereas hay and small grains were more common in the early 20th Century (Foufoula-Georgiou et al., 2015; Kelly et al., 2017; Schottler et al., 2014). Studies of evapotranspiration show that different crop types have different ET signatures, leading to seasonal differences in water demand (Baeumler et al., 2019; Kjaersgaard et al., 2014; Yang et al., 2017). As a direct measure of watershed drainage, I extracted the percentage of watershed area drained by tile drains and ditches from U.S. Census of Agriculture reports. These are compiled at approximately decadal intervals and include data for the acreage of land drained by ditches and drain tiles at the county scale (U.S. Census Bureau, 1922, 1932, 1942, 1952, 1961, 1971, 1981; U.S. Department of Agriculture 2014, 2019). The data from before 2012 is only contained in physical reports, and the data in these reports is inconsistent, as particular data tables change format or are not included in every Census report, but they represent the best historical source of drainage data (Kelly et al., 2017). The data from 2012 and 2017 are archived online and is more complete.

2.3.2. Precipitation data

To analyze changes in precipitation across the region, I compiled two complementary datasets: daily precipitation observations for 68 stations in the National Climatic Environmental Information (NCEI) network (Figure 2.2) and modeled daily precipitation from Pierce et al., extracted using the LivnehPierce-hydro-extractor (2021; Wickert, 2022). The Pierce et al. developed dataset is a gridded daily product that interpolates precipitation from stations within the NCEI network, with topographic corrections in locations with no precipitation stations (Livneh et al., 2013, 2015; Pierce et al., 2021). The modeled data were extracted as daily precipitation averaged over each watershed.

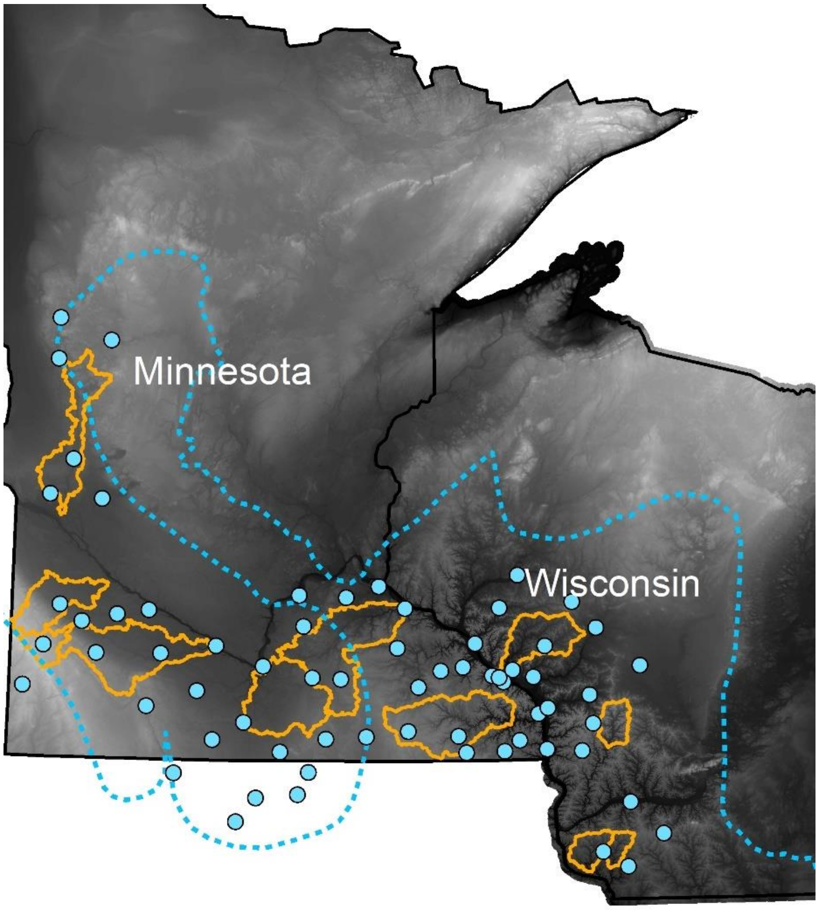


Figure 2.2. Location of precipitation stations and watersheds used in analysis.

I conducted analyses using R statistical software to derive annual and decadal statistics from the NCEI stations and gridded precipitation data. Annual statistics included total annual precipitation, total monthly precipitation, mean daily precipitation, and maximum daily precipitation. Decadal statistics include decade-averaged monthly and annual precipitation. I also conducted cross-correlation analysis to test whether precipitation is regionally consistent or if there are major differences between watersheds. I conducted a changepoint analysis for daily and annual precipitation using a Pettitt test (Pettitt, 1979).

2.3.3. Streamflow data

To analyze changes in streamflow among watersheds, I compiled data from USGS gages in each of the eleven watersheds (Table 2.1). I used R statistical software to analyze trends in the time series of discharge. I extracted several flow metrics, including flow exceedance percentiles at the annual scale. For each watershed, I tested whether there was a significant changepoint, using a Pettitt test.

2.3.4. Information theory

Information theory is a set of statistical techniques to measure the amount of statistical information contained in a dataset. Information theory is a powerful tool for hydrologic inference and has been used to identify streamflow regimes and to measure changes in hydrologic connectivity through time (Franzen et al., 2020; Goodwell et al., 2020; Goodwell & Kumar, 2017).

Shannon entropy describes the amount of uncertainty in the probability density function of a random variable. Shannon entropy is calculated as

$$H_J = -\sum_j p(j) \cdot \log\big(p(j)\big) \tag{2.1}$$

where H_J is Shannon entropy of the random variable J, *j* is the potential outcomes of the random variable *J*, *p(j)* is the probability distribution of *J*, and *log* denotes log base 2. If J is assumed to evolve under a Markov process where the probability of observing a given value of J is conditioned on prior values of the system, Shannon entropy can be expressed as

$$h_J(k) = -\sum_j p\left(j_{t+1}, j_t^{(k)}\right) \cdot \log\left(p\left(j_{t+1} | j_t^{(k)}\right)\right) \tag{2.2}$$

$$j_t^{(k)} = (j_t, j_{t-1}, \dots, j_{t-k+1}) \tag{2.3}$$

where *k* is the number of previous observations used to resolve the value of *J* at time *t+1*.

Transfer entropy measures the reduction in uncertainty of a target variable given knowledge of a predictor variable. In this case, how much does knowledge (measurement) of precipitation reduce the uncertainty in the streamflow timeseries. Transfer entropy is calculated as

$$T_{J\to I}(k,l) = \sum_{i,j} p\left(i_{t+1}, i_t^{(k)}, j_t^{(l)}\right) \cdot \log\left(\frac{p(i_{t+1} | i_t^{(k)}, j_t^{(l)})}{p(i_{t+1} | i_t^{(k)})}\right) \tag{2.4}$$

where $T_{J\text{->}I}$ is transfer entropy, *I* and *J* are discrete random variables with probability given by *p(i)* and *p(j)* and joint probability *p(i,j*), *t* is time, referring to a single instance in the time series, and k and l are the number of previous values used to resolve values in the Markov process that describes the probability density function of $p(i)$ and $p(j)$, respectively (Behrendt et al., 2019). The k and l variables can be thought of as a time lag, representing the number of entries in the predictor time series that effect the value of the target (Moges et al., 2022). Transfer entropy can also be calculated in the opposite direction, from I to J.

Transfer entropy is subject to randomness in the time series, such that measurements of transfer entropy, especially for small sample sizes, can be biased by spurious interactions rather than a true signal. A common approach to evaluate this potential for bias is to randomize the predictor time series and recalculate the transfer entropy. The randomized transfer entropy subtracted from the original transfer entropy is termed effective transfer entropy. The RTransferEntropy package uses a Monte Carlo block chain procedure to randomize the time series and calculate effective transfer entropy (Behrendt et al., 2019). Mathematically, effective transfer entropy is given by

$$ET_{J\rightarrow I}(k,l) = T_{J\rightarrow I}(k,l) - T_{J_{shuffled}\rightarrow I}(k,l) \tag{2.5}$$

where ET is effective transfer entropy and $J_{shuffled}$ is the time series J with its values shuffled in time. Transfer entropy can be normalized by dividing it by the Shannon entropy of the target series, such that the result is interpreted as the percent reduction in uncertainty. I used the effective transfer entropy and divided by the Shannon entropy for the streamflow time series to calculate the percent information transfer from precipitation to streamflow.

Using daily precipitation from the daily gridded dataset and daily streamflow from the USGS gages, I calculated effective transfer entropy. For each watershed, I calculated the effective transfer entropy at seasonal (defined as Jan-Mar, Apr-Jun, July-Sep, Oct-Dec) timescales for each year, as well as an overall annual value. I tested lag times between 1 and 14 days, based on results from Moges et al. for watersheds in neighboring states (2022). In order to reduce interannual variability and assess long-term trends, I also calculated decadally-averaged seasonal and annual values.

2.4. Results

2.4.1. Land-cover change

The overall percentage of land used for agriculture has remained relatively consistent since the 1920s (Figure 2.3A). In the Wisconsin Driftless Area, 15-30% of total watershed area is used for row-crop agriculture. There are consistent temporal patterns among watersheds in the Driftless Area, with an increase in corn, soy, and small grains in the mid-1960s, though there may be a reporting error during this time period accounting for a sudden increase. Agriculture in the Driftless Area declined beginning in the 1980s. Row crop agriculture is more common in the partially and fully glaciated watersheds in Minnesota. The Cannon and Root River watersheds were partially glaciated, and consistently had 50% of their watershed area used for row-crop agriculture in the period of record. More land is used for agriculture in the western, formerly glaciated sections of both watersheds. The fully glaciated watersheds in central and western Minnesota have the highest percentage of land used for row-crop agriculture, with 50-90% of total watershed area used for agriculture, depending on the watershed. There are also temporal trends in the watersheds in Minnesota, with row-crop agriculture expansion reaching a peak in the 1970s, with slight decreases in subsequent decades. Throughout the 20th Century, crops changed from a mixture of grains to the dominant corn and soy rotation that exemplifies modern agribusiness.

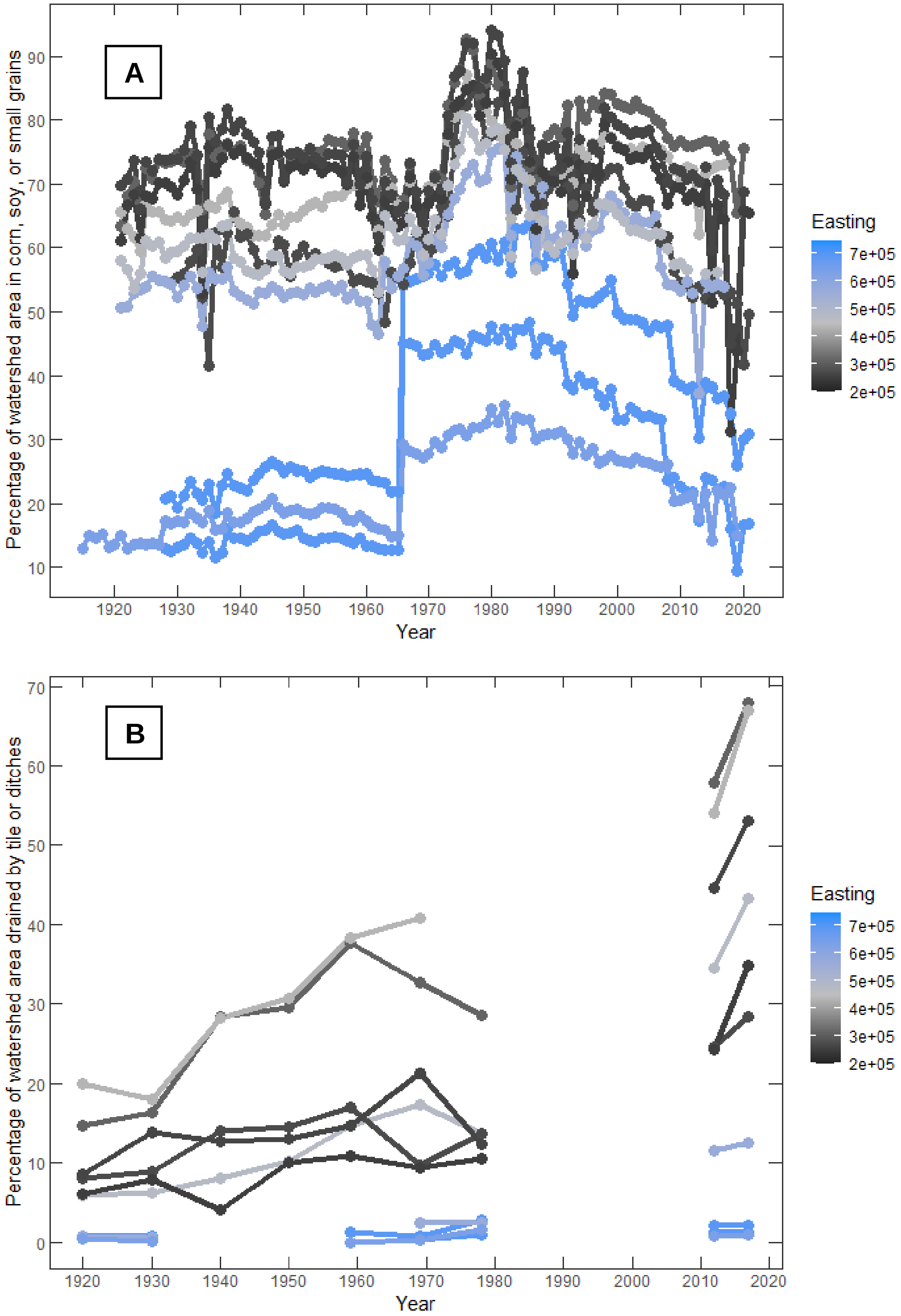


Figure 2.3. A) Percentage of watershed area used for agriculture and B) percentage of watershed area drained by ditches and drain tiles. Color corresponds to Easting of the watershed outlet in UTM 15N, where larger is further east and smaller is further west.

Spatial patterns in agricultural drainage follow the patterns of agricultural land use and soil type. Soils in the Driftless Area are relatively well-drained and the natural drainage networks are well developed, so there is little need for artificial drainage. Watersheds in the Wisconsin Driftless Area have less than 5% of their total watershed area drained by ditches or drain tiles (Figure 2.3B). There are large data gaps for these watersheds because so little area in the counties was artificially drained, so the values are not reported in every Census of Agriculture report. Watersheds in Minnesota have greater artificial drainage, and the percentage of watershed area drained increased during the 20th Century. For all watersheds outside of the Wisconsin Driftless Area, tile drains account for the vast majority of drainage (Table 2.2). The Root River had low rates of artificial drainage through the 1970s, but currently 12% of the total watershed is drained. In the Cannon River watershed, 40% of the area is drained, primarily in the western part of the watershed, which was glaciated during the most recent glacial period. The Le Sueur and Cottonwood watersheds in central Minnesota have the greatest drainage, with nearly 70% of the total watershed area drained by ditches or tile drains. Watersheds in western Minnesota have drainage that does not reflect overall agricultural land use – the Yellow Medicine River watershed has 50% of its total land area drained, the Redwood River 34%, and the Pomme de Terre River 28%.

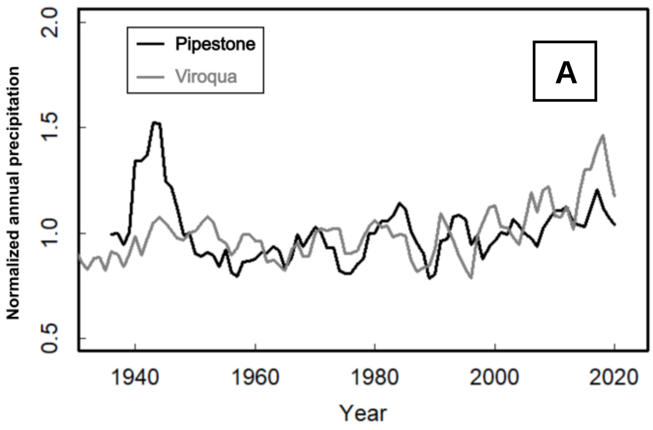
Table 2.2. Percentage of watershed area drained by ditches and drain tiles.

	Percent of watershed area drained (% watershed area drained by drain tiles)								
Year	1920	1930	1940	1950	1959	1969*	1978*	2012	2017
Cannon	2.9 (0.2)	6.3 (0.6)	8.0 (1.0)	10.3	14.6	17.4	13.7	34.5 (26.1)	43.2 (37.6)
Cottonwood	14.6 (0.3)	16.4 (2.4)	28.4 (4.3)	29.6	37.7	32.7	28.5	57.9 (49.9)	67.9 (59.0)
Grant	-**	-	-	-	-	0.3	0.9	2.0 (0.9)	2.2 (1.0)
Kickapoo	0.8	0.8	-	-	1.3	0.8	2.8	1.2 (0.3)	1.3 (0.4)
Le Sueur	19.9 (3.2)	18.0 (5.2)	28.2 (8.1)	30.7	38.4	40.8	-	54.1 (45.1)	66.9 (57.5)
Platte	-	-	-	-	-	0.3	0.9	2.0 (0.9)	2.2 (1.0)
Pomme de Terre	8.0 (0.9)	8.9 (0.6)	14.0 (0.5)	14.6	17.0	9.6	13.8	24.6 (12.9)	28.4 (16.4)
Redwood	6.0 (0)	7.9 (0.6)	4.1 (2.4)	10.0	10.9	9.4	10.5	28.2 (20.9)	34.9 (30.8)
Root	0.9 (0.01)	0.6	(0.1)	-	-	2.4	2.4	11.6 (9.5)	12.5 (10.6)
Trempealeau	0.4 (0)	0.08	-	-	0.01	0.4	1.5	0.8 (0.4)	1.0 (0.3)
Yellow Medicine	8.5 (1.7)	13.9 (2.2)	12.8 (7.0)	13.0	13.7	21.3	12.4	44.7 (36.2)	53.0 (44.6)

Notes: *Table format is different in 1969 and 1978 reports, leading to apparent decreases from 1959, ** some counties did not have any drainage reported

2.4.2. Precipitation change

Precipitation in the region is variable on decadal timescales, driven by teleconnections such as the El Nino Southern Oscillation and the Pacific Decadal Oscillation (Pathak et al., 2016). Despite this variability, there is a clear increasing trend over the last 30-60 years. Pettitt tests show that most precipitation stations had a statistically significant change in distribution during the 20th Century. The changepoint is variable among different stations, with the majority having a change point between 1961 and 2004 (with one outlier in 1934). For all of these, the change is an increase in total precipitation and variability after the changepoint, as illustrated by Viroqua, WI and Pipestone, MN, sites with long records (Figure 2.4A). The gridded daily precipitation shows similar changes in annual metrics, with high inter-annual variability, decadal cyclicity, and an increase in precipitation since the late 20th Century (Figure 2.4B). Though there are some years where precipitation differs from east to west, the overall magnitude of precipitation change is consistent among watersheds. There is no clear geographic pattern in the changepoint year among the NCEI stations (Figure 2.5). The changepoint from the gridded daily data has a similar spatial trend.



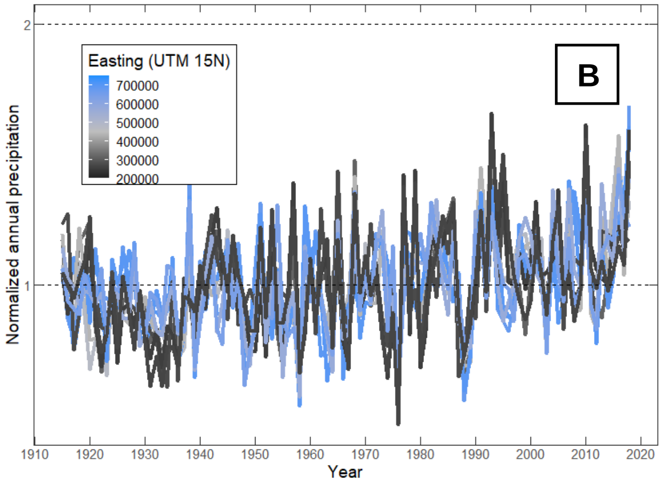


Figure 2.4. Normalized annual precipitation for A) Viroqua, WI and Pipestone, MN and B) daily gridded precipitation values for all watersheds in our study. Watersheds are colored by Easting of the watershed outlet in UTM 15N. Annual values are normalized by the mean for the period of record.

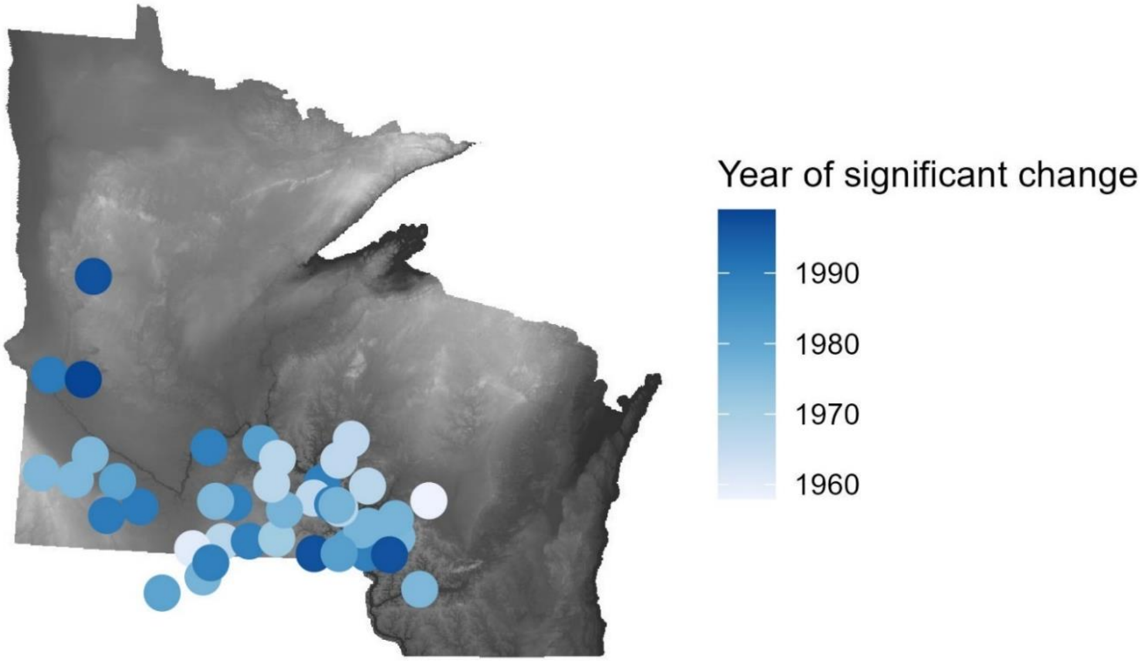


Figure 2.5. Year of significant changepoint from Pettitt test in precipitation time series.

Cross-correlation analysis further illustrates that trends in precipitation are generally congruent across the region (Figure 2.6). Figure 2.6 shows the correlation for each site to the Viroqua station. As expected, cross-correlation is highest for sites that are geographically close, and four sites have a cross-correlation greater than 0.75. Cross-correlation is greater than 0.25 for all but four sites, and none have negative cross-correlation values. The sites with the lowest correlation have the shortest record of any stations.

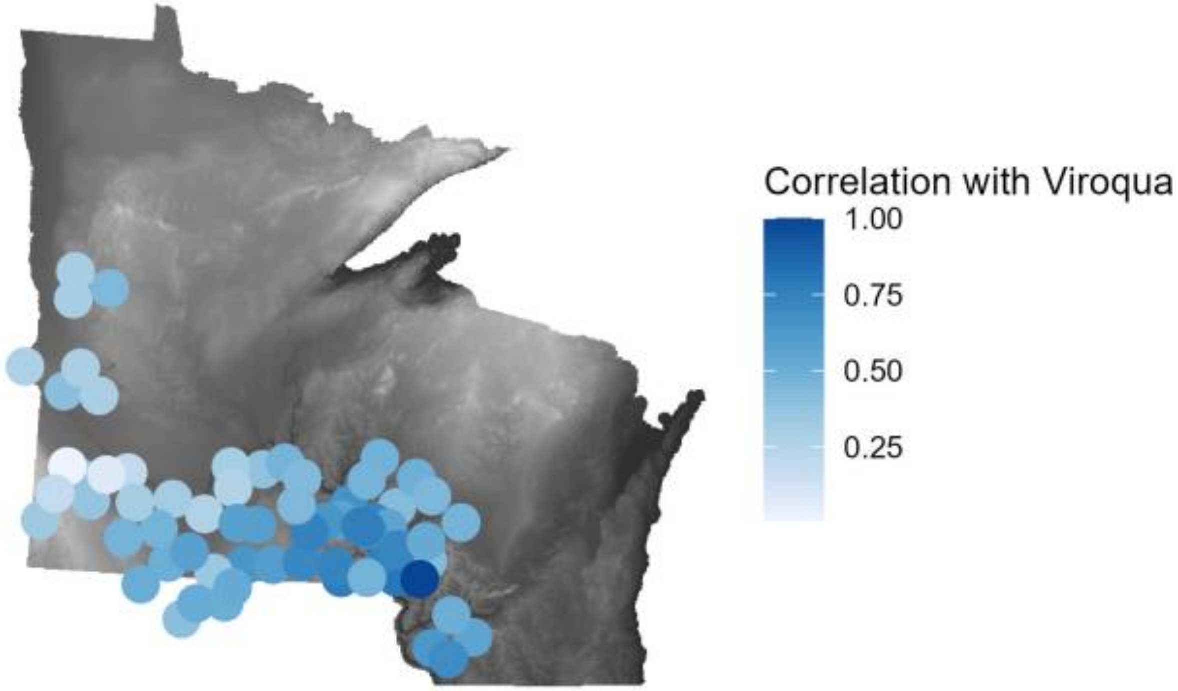


Figure 2.6. Cross-correlation between precipitation stations, plotted as cross-correlation with Viroqua, in western Wisconsin.

In addition to daily and annual metrics, analyzing individual months provides insight into shifts in the seasonality of precipitation. Looking at annual totals in each month, April is the month with the most significant change across the region. 58.7% of stations have a significant positive trend in April precipitation through their period of record (Table 2.3). October and December also have significant precipitation changes, with 52 and 37.3% of stations, respectively. There is high interannual variability in precipitation, which is reduced by averaging over decadal periods. Monthly trends are largely the same using decadal averages – April, October, December, and May have significant positive trends at the most stations. Watershed-averaged gridded precipitation data has similar monthly trends, with 9 of the 11 watersheds having significant increases in April precipitation, followed by July, August, and December, which have significant increases in 8 of 11 watersheds. Through June only has a long-term trend at 12-22% of stations, the decade of the 2010s had particularly high June precipitation across the entire region.

Table 2.3. Percentage of NCEI stations with significant monthly precipitation increases.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Annual	13.3	32.0	10.7	58.7	34.7	12.0	8.0	25.3	14.7	52.0	6.7	37.3
Decadal	18.7	25.3	6.7	46.7	25.3	22.7	5.3	13.3	13.3	44.0	4.0	44.0

2.4.3. Streamflow change

Changepoint analysis for streamflow shows that all watersheds had significant changes in streamflow during the period of record. The changepoint year is within one year of the precipitation changepoint from the daily gridded data. For all watersheds, the period after the changepoint has higher streamflow (Figure 2.7). Figure 2.7 shows the normalized median streamflow in each year for each watershed. There is high interannual variability in streamflow, but clear differences in the magnitude of the variability between watersheds. In particular, the watersheds with less agricultural drainage have less variability than those with more drainage. Watersheds with widespread drainage have experienced extremely high flow years in recent decades, and high interannual variability. Flows across the entire distribution have changed in these watersheds. The temporal trends are similar to the median flow, with increases beginning at the same time that precipitation began to increase. And the trends among watersheds are similar as well, with greater flow changes in more agricultural watersheds.

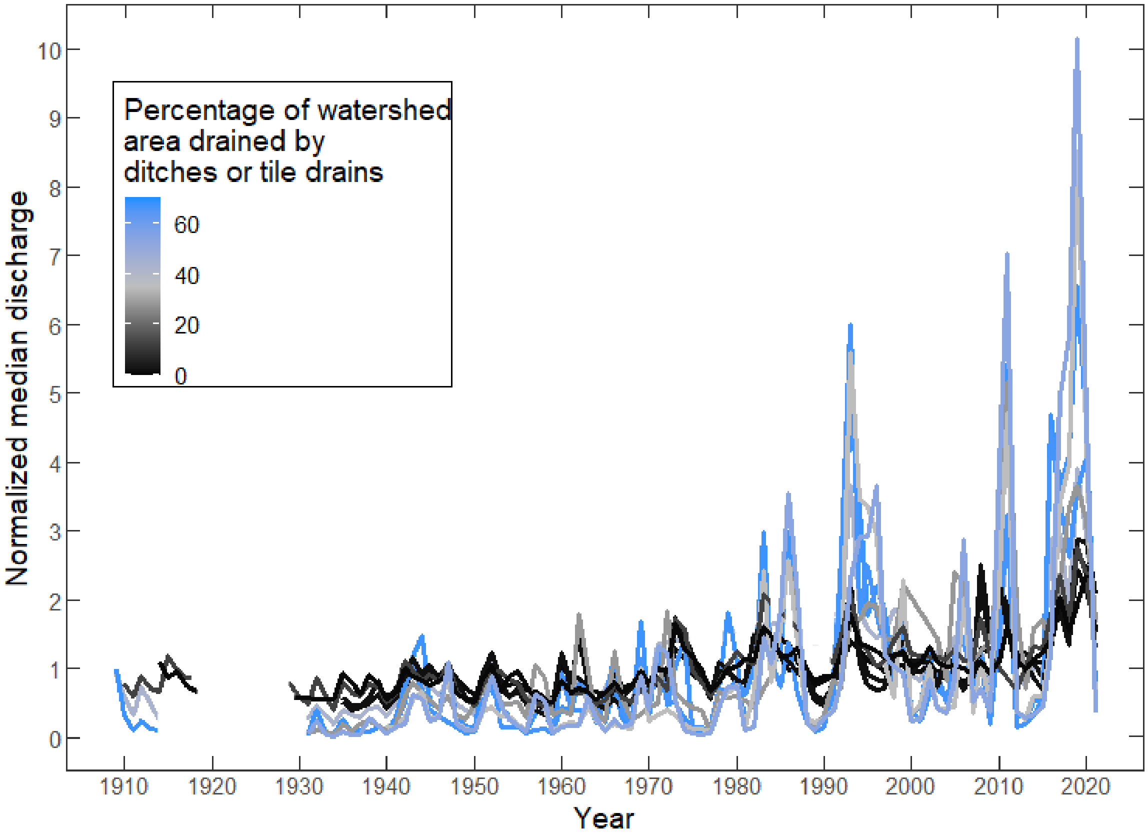


Figure 2.7. Normalized median annual discharge for all watersheds, colored by percentage of watershed area drained by drain tiles or ditches. The value in a given year is normalized by the average of the entire period of record to allow for direct comparison of changing magnitude between watersheds.

2.4.4. Information theory

The transfer entropy analysis reveals the complex relationship between precipitation and streamflow in the upper Midwest. In general, the information transfer is very low for these watersheds, with precipitation records reducing uncertainty in streamflow by less than 10% even in years with the highest ETE. And many years do not have significant transfer entropy for any lag length. Despite the changes in precipitation and streamflow noted above, there is no long-term trend in the magnitude of information transfer or the lag times that are significant. Instead, inter-annual and decadal variability dominate the signal. There is no temporal trend in whether or not years have significant ETE, with equal likelihood that a year would have significant ETE before and after the change point identified by the Pettitt Test.

2.5. Discussion

Understanding the causes of amplified streamflows in the Midwest is essential for managing river systems, especially in the face of a changing climate (Belmont & Foufoula-Georgiou, 2017; Kumar et al., 2018a). I document that agricultural practices, precipitation, and streamflow have all changed over the past 100 years in the Midwest. Total agricultural land use has been relatively stable, but continued adoption of tile drainage has occurred throughout the period of record. I find that total precipitation and precipitation variability began increasing during the mid-20th Century across the study area, with largely congruent patterns. Streamflow began increasing during the same time period, with larger streamflow changes in watersheds with more intensive agriculture. Information theory metrics showed low information transfer from precipitation to streamflow, and no temporal trends in information transfer.

The widespread use of tile drains in western and southern Minnesota creates new hydrologic pathways compared to the pre-drainage landscape. Numerous studies have documented that tile drains are a highly active hydrologic pathway, accounting for up to 40% of annual discharge in watersheds in the Midwest (Helmers et al., 2005; King et al., 2014, 2014; Macrae et al., 2007; Randall, 2004). The watersheds with the most drainage in this study have nearly 70% of their total land area drained, with drain tiles accounting for 60%. This represents a fundamental change in the hydrology of these watersheds compared to 100 years ago. Cain et al. (2022) present a conceptual model of discharge through tiles, where both groundwater below the tile drains and soil water above the drains contribute to discharge through the tiles. As a result, the presence of tile drains lowers the threshold volume of water needed to generate significant subsurface flow, which decreases subsurface storage (Cain et al., 2022; Muma et al., 2016; Schottler et al., 2014). In watersheds where a significant portion of the land area is drained, this leads to greater baseflow and greater streamflow response to storms (Ayers et al., 2019; Foufoula-Georgiou et al., 2015; Kelly et al., 2017).

Changing crop types have also been implicated in driving hydrologic change, primarily through changes in evapotranspiration. Measurements and models of evapotranspiration show that at an annual time scale, soy beans, corn, and grains have similar ET demands. But there are seasonal differences in ET demand related to when crops are planted and their life history. In particular, corn and soybeans are planted later than grains and thus have lower ET demand in April, May, and June. Several studies note that these months have seen particularly large streamflow change (Boland-Brien et al., 2014; Foufoula-Georgiou et al., 2015; Kelly et al., 2017; Schilling & Helmers, 2008; Schottler et al., 2014). However, spring streamflow has also increased in the less agricultural regions, as this is the time of year with the highest total precipitation in the region. Studies of shorter timescale streamflow changes illustrate that drain tiles impact the way that water is routed through a watershed in response to individual precipitation events (Foufoula-Georgiou et al., 2016; Kelly et al., 2017). Thus, total water yield at annual or monthly timescales can have similar trends but different dynamics at shorter timescales. It is important to note that many of these studies did not include precipitation data from the 2010s, which was a particularly wet decade and had high precipitation yields in June in particular. Precipitation is the main input driving streamflow so monthly water yields reflect the high precipitation of the 2010s, but the internal pathways differ between drained and undrained watersheds.

Changes in the timing and relative magnitude of precipitation change are generally consistent across the region (Figure 2.4). Despite similar changes in precipitation, there are large differences in streamflow between watersheds, with greater increases in more agricultural watersheds (Figure 2.7). This trend has been illustrated in previous studies, through both data analysis and modeled land-use change (Boland-Brien et al., 2014; Kelly et al., 2017; Schottler et al., 2014). An important contribution of this work is explicit comparison between watersheds with similar physical characteristics (soil type, slope) but differing agricultural practice. As noted in the study area, the glacial history of the region has created spatial heterogeneity that complicates comparison among watersheds. Even though no two watersheds are perfectly comparable, explicitly pairing watersheds with similar characteristics provides a means for comparison. For example, the Cannon and Root Rivers have similar properties, with moderate runoff potential Group C soils across 23.6% and 20.3% of the watersheds, respectively. The average slope differs between the two, with an average slope of 4.42% for the Cannon and 9.1% for the Root. The Cannon has greater agricultural intensity compared to the Root (43% drained compared to 12%). The Cannon has experienced greater streamflow changes in recent decades. The Pomme de Terre and the Yellow Medicine Rivers have similar soil types and slope, but the Yellow Medicine has much higher drainage, 53% to 28%. And the streamflow increase in the Yellow Medicine is much greater than the Pomme de Terre. One important difference between the two is that the Pomme de Terre has more pond and lake area, underscoring the complexity of direct comparisons between watersheds.

Information theory metrics have not been applied to this portion of the United States. Moges et al. (2022) conducted an analysis of daily precipitation and streamflow records that included 671 watersheds in the conterminous United States, but did not include any in our study area. Their analysis includes watersheds in the nearby states of Iowa, Michigan, North Dakota, South Dakota, and Wisconsin. These watersheds had low transfer entropy values, similar to the results presented here. They attribute the low transfer entropy values to two primary factors: snow-dominated runoff in the early spring and the influence of groundwater. Both of these mechanisms represent long hydrologic pathways that complicate the relationship between precipitation streamflow. In addition, the previously glaciated regions of central and western Minnesota have many topographic depressions that may lead to local stormwater accumulation when overland flow occurs. Although the presence of tile drains may drain these areas more efficiently, topographic effects still influence stormwater routing and soil moisture patterns (Maestrini & Basso, 2018; Plach et al., 2022; Price, 2011). The low transfer entropy values recorded here and in Moges et al. suggest that information theory has low explanatory power in watersheds with snowmelt and groundwater-driven streamflow.

Modeling provides an alternative mechanism to evaluate the influence of precipitation and land use. Previous studies have incorporated models and find similar results to data-driven studies. Models range from simple reduced-complexity models to 3D groundwater models, and results are broadly consistent across multiple modeling frameworks (Basu et al., 2010; Muma et al., 2016)., Linear reservoir models have been found to accurately predict streamflow in tile-drained watersheds (Basu et al., 2010; Boland-Brien et al., 2014). This reflects the homogeneity of processes – despite complexities in soil type and topography, the presence of drain tiles provides a preferred pathway across large parts of the watershed (Basu et al., 2010; Boland-Brien et al., 2014; Foufoula-Georgiou et al., 2015). More complex models also show that drain tiles, either represented as increased hydraulic conductivity or explicitly modeled, are a major hydrologic pathway at scales from individual fields to large watersheds, with particularly strong effects on baseflow (Frans et al., 2013; Schilling et al., 2015, 2019; Sloan et al., 2017).

Better characterization of changing hydrology is essential to better manage rivers in the agricultural Midwest. From a geomorphic perspective, increased streamflow has led to channel widening and increased channel migration in Minnesota (Belmont et al., 2011; Donovan & Belmont, 2019; Kelly & Belmont, 2018; Lauer et al., 2017; Lenhart et al., 2013; Schottler et al., 2014). These geomorphic changes present risks to infrastructure and are part of wider environmental issues facing rivers in the region. In addition to geomorphic change, agricultural practices directly influence water quality. Water from tile drains can have high nitrogen and phosphorous concentrations, and is often the main pathway for nutrients to enter rivers in drained watersheds (Arenas Amado et al., 2017; Bishop et al., 2005; Cain et al., 2022; Dolph et al., 2019; Hansen et al., 2021; Macrae et al., 2007; Masarik et al., 2014; Vidon & Cuadra, 2011). The combination of geomorphic and geochemical change has significantly stressed aquatic organisms, leading to degraded ecological conditions (Blann et al., 2009; Hansen et al., 2016; Hornbach et al., 2019; Lenhart et al., 2013). Previous studies suggest that upland water storage will restore some functions that were lost when land was drained – improved nutrient cycling and reduced streamflow (Cho et al., 2019; Kumar et al., 2018b; Mitchell et al., 2018). Based on the data presented here, which show greater streamflow increases in watersheds with more drainage, I agree with this recommendation. I also acknowledge that climate change is significantly increasing the amount of precipitation entering watersheds. As a result, effective management of aquatic resources will require unique solutions (including working with rivers as they widen and shift) to ensure that we mitigate the worst effects of current and future environmental issues.

2.6. Conclusion

Land use, precipitation, and streamflow have all changed in the Upper Midwest over the last 100 years. I analyzed data from eleven watersheds that span a gradient of glacial history and agricultural intensity to investigate the role of land-use change and precipitation change in driving streamflow. Agricultural intensity differs among the watersheds, areas in southern and western Minnesota generally have more of their watershed area used for agriculture and artificially drained. Precipitation change has been largely congruent across the region, with increasing precipitation beginning in the mid-20th Century and continuing to the present. Monthly changes in precipitation are also similar across the region. Streamflow has increased in all the watersheds, but the most prominent increases occurred in the watersheds with the most artificial drainage. Paired with previous studies that demonstrate the influence of drain tiles, this analysis confirms that agricultural intensity amplifies the effects of climate change in the Upper Midwest.

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Chapter 3. Humans ↔ rivers. Environmental management and justice considerations from a new stream restoration database in Minnesota

This work was undertaken in equitable partnership by myself, Lucy Andrews, Jessica Balerna, and Jenny Rempel. I constructed the stream restoration dataset, conducted the biophysical data analysis, and led the writing, Balerna and Rempel led the regression analysis, Andrews led code optimization and data architecture efforts, and writing and editing was performed collaboratively.

Abstract:

Stream restoration is a common practice to restore hydrologic, geomorphic, and ecological function to degraded rivers. Many studies have highlighted the shortcomings of restoration with respect to monitoring and assessment, and there is a growing awareness that there are environmental justice concerns regarding the siting of stream restoration. We expand on this growing body of literature by building a database of stream restoration projects in Minnesota, a state with strong environmental policy and a unique physical and human geography. We examine the siting of restoration projects with respect to biophysical and sociodemographic factors to assess whether or not there is bias in where stream restoration takes place. We find that restoration in Minnesota is responsive to both environmental and social factors. At the scale of HUC 8 watersheds, the number of restoration projects is positively associated with measures of geomorphic degradation and income. At the local scale, restoration projects occur in areas that are whiter and higher income than the average statewide population. Our results highlight both data and practical considerations – the need to be conscious of scale when addressing questions of distributive justice and the need to explicitly consider equity when implementing environmental initiatives that may seem neutral with respect to societal factors.

3.1. Introduction

Natural and engineered freshwater systems around the world are imperiled due to intense social, political, and economic pressure (Reid et al., 2019). While these threats are widespread, the impact is distributed unequally, with marginalized communities suffering the impacts of freshwater degradation earliest and most intensely (Bullard, 1994; Grineski et al., 2012; Kovalenko et al., 2023; Shepherd & KC, 2015). Stream restoration is a long-standing practice to address ecological degradation by making physical alterations to improve biological, ecological, geomorphic, or hydrological conditions (Wohl et al., 2015). Stream restoration grew in popularity in the United States after the 1960s and 1970s, when environmental legislation such as the Clean Water Act and the Endangered Species Act introduced strong federal regulation for water bodies (Lave, 2016; Wohl et al., 2015). Restoration activities have a wide variety of approaches and objectives, depending on the biophysical context of the stream, the expertise of the practitioners, and the available funding for the project (Bernhardt et al., 2005; Wohl et al., 2015).

In addition to enacting a biophysical change, stream restoration is a situated social activity. Decisions about where and how to restore streams are informed by complex social and political dynamics, including notions of scientific validity, ecological value, and political will (Allison, 2004; Díaz-Pascacio et al., 2022; Hillman, 2004; Lave, 2012, 2016; Moran, 2007, 2010; Morandi et al., 2014; Smith et al., 2016). Restoration also represents a significant investment of public funds, and as of 2005, was a billion dollar industry in the United States alone (Bernhardt et al., 2005). Despite the widespread practice, data documenting where restoration projects take place and the amount that is spent on them is scattered across different agencies, if available at all (Bernhardt et al., 2005; Morandi et al., 2014; Nakamura et al., 2006; Stanford et al., 2018; Welch, 2019). The only attempt to build a comprehensive database of restoration projects in the United States was in 2005, and the authors document many difficulties in assembling the records (Bernhardt et al., 2005).

There are well-documented shortcomings in monitoring, assessment, and record keeping of stream restoration projects. Multiple meta-analyses reveal that projects regularly do not have clear goals at the onset, do not have sufficient pre-project data, and do not measure the correct metrics to evaluate their goals (Bernhardt & Palmer, 2011; Dos Reis Oliveira et al., 2020; Miller et al., 2010; Morandi et al., 2014; Rubin et al., 2017). Projects are often limited by a lack of funding to support multi-year post-project monitoring needed to assess geomorphic and ecosystem response. Even when robust restoration and assessment methods are applied and sufficient data are available, results of stream restoration projects are mixed, with some studies finding improved ecological functions and others finding little change (Brettschneider et al., 2023; O'Neal et al., 2016; Roni et al., 2019; Sievers et al., 2017).

Stream restoration gained prominence as part of the environmental movement of the mid-20th Century that sought to improve degraded ecosystems, preserve natural areas, and ensure recreation opportunities for users (Lave, 2016; Wohl et al., 2015). Parallel to the development of this conservation-focused environmental movement, environmental justice emerged as a movement that ultimately seeks to abolish environmental harm. Both activist-led and academic-led discussions of environmental justice and environmental equity emerged in response to inequitable siting of toxic facilities, with landmark cases in the late 1970s and early 1980s (Bullard, 2018; General Accounting Office, 1983; United Church of Christ, 1987). The earliest environmental justice cases were led by communities of color, and the environmental justice movement continues to be catalyzed by voices from marginalized communities.

As the environmental justice movement has grown, scholars and activists have defined three core components of environmental justice: distributive, procedural, and recognition. Distributive justice is the most widely recognized and refers to the distribution of environmental outcomes, including benefits, burdens, risks, and hazards. The seminal Toxic Waste and Race in the United States report is an early example of distributive injustice, as the authors mapped the racial composition of ZIP codes that contained toxic waste facilities and found that waste facilities disproportionately occur in areas with high percentages of people of color (United Church of Christ, 1987). Procedural justice is the meaningful involvement of diverse stakeholders in the planning, implementation, and evaluation of environmental projects. Environmental impact statements present an example to evaluate procedural justice. Ulibarri et al. (2019) illustrate that public comments on draft environmental impact statements in the United States do not result in significant changes to the final statements, suggesting that the process has a limited capacity to meaningfully incorporate public opinion. And recognition justice is the meaningful recognition and inclusion of diverse viewpoints, stakeholders, and values. Recent resistance against oil pipelines and legal developments around recognition of rivers illustrate the power and complexity of recognition justice, as Indigenous conceptions of nature can fundamentally challenge existing legal frameworks (Ruru, 2018; Valandra, 2019).

In addition to expanding the conceptual definitions of environmental justice, activists and scholars have expanded its scope to consider a wider portfolio of environmental benefits and ills, including disparities in heat (Hsu et al., 2021), disaster risk (Wing et al., 2022), and access to green space (Wolch et al., 2014), alongside green gentrification (Walker, 2021). Relatively few studies have considered the intersection of environmental justice and stream restoration, though there is recent momentum to incorporate equity and community engagement in restoration (Díaz-Pascacio et al., 2022; Murphy et al., 2022; Scoggins et al., 2022). Several authors note the importance of community engagement to encourage future support for restoration work (Collier, 2017; Kondolf & Yang, 2008; Moran, 2010; Scoggins et al., 2022). Expanding community engagement to consider justice by bringing local communities into restoration work has the potential to incorporate more diverse values into restoration, expand the types of solutions that will be considered, and can prevent communities from being ignored in decisions about their local environment (Díaz-Pascacio et al., 2022; Metcalf et al., 2015; Moran, 2010; Moran et al., 2019; Murphy et al., 2022; Usher, 2023). Excluding communities from these processes reinforces environmental and economic inequity through unequal investment and green gentrification (Anguelovski et al., 2020; Díaz-Pascacio et al., 2022; Howard, 2010; Metcalf et al., 2015; Moran, 2010).

Attempts to quantify distributive justice in stream restoration are less common. We know of two studies that analyze large restoration datasets and evaluate their geographic siting based on demographic factors. Stanford et al. (2018) analyzed restoration sites in coastal California and found that social factors, as well as ecological factors, correlated positively with the number of restoration sites in a catchment. The social factors included income, percentage white non-Hispanic residents, and percentage of residents with a college degree. Welch (2019) found similar results in Pennsylvania, as a mixture of biophysical and social variables correlated with stream restoration sites at the county scale. Among the social variables they tested, median household income and percent of people holding an advanced degree were positively correlated with the number of restoration sites, while percent below the poverty line and median age were negatively correlated with the number of restoration sites.

These important studies document that investment in stream restoration mirrors other types of environmental spending, with more financial investment in whiter, more affluent areas (Hendricks & Van Zandt, 2021; Shokry et al., 2020; Watkins et al., 2017). However, there is a pressing need for more data to evaluate whether this pattern is generalizable beyond these two studies. Additionally, the studies from Stanford et al. and Welch are focused on large spatial scales, exclusively evaluating social and biophysical factors at the HUC 8 watershed and county level, respectively. The effects of stream restoration are likely to be more localized than this, as restoration projects are typically between hundreds of meters and a few kilometers in length. Anecdotally, procedural and distributive injustices occur in restoration efforts (Díaz-Pascacio et al., 2022; Metcalf et al., 2015), but a more systematic analysis at smaller spatial scales would provide increased nuance to evaluate which communities have access to the benefits of restoration.

We add to the growing body of literature considering the justice implications of stream restoration by analyzing restoration projects from a large environmental fund in the U.S. state of Minnesota at the local, watershed, and statewide scale. Minnesota has a strong record of environmental legislation and funding, as well as several distinct physiographic areas due to its unique glacial history. The human geography of Minnesota also presents an interesting case for analyzing restoration siting, as the state has one large, racially diverse population center, several smaller regional cities, and is otherwise rural, with distinct industries in different parts of the state.

We use three separate analyses to examine the data from Minnesota:

1. Characterization of the biophysical characteristics of restoration sites.

2. Socioeconomic characteristics of the area around restoration sites in comparison to the socioeconomics of the state of Minnesota.

3. Social and biophysical factors associated with the presence of stream restoration at the hydrologic unit code (HUC) 8 watershed scale.

3.2. Data

3.2.1. Restoration data acquisition, cleaning, and filtering

The state of Minnesota has multiple statewide grant programs that support environmental initiatives. In 1988, Minnesota voters approved a constitutional amendment establishing the Environment and Natural Resources Trust Fund. This fund was established to provide “long-term, consistent, and stable funding for activities that protect and enhance Minnesota’s environment and natural resources for the benefit of current citizens and future generations” (https://www.legacy.mn.gov). And in 2008, Minnesota voters passed the Clean Water, Land and Legacy Amendment. The Legacy Amendment increases the state sales tax and distributes the sales tax revenue into four funds: 33 percent to the Clean Water Fund, 33 percent to the

Outdoor Heritage Fund, 19.75 percent to the Arts and Cultural Heritage Fund, and 14.25 percent to the Parks and Trails Fund.

These funds are collectively referred to as Minnesota Legacy Funds, and are administered and distributed via different agencies. The Environment and Natural Resources Trust Fund (ENRTF) is administered via the Legislative–Citizen Commission on Minnesota Resources, a board of citizens and legislators who evaluate and rank proposals based on given criteria, then present a list of proposals and funding requests to the legislature where the final allocation is written into law. ENRTF funds are available to anyone in Minnesota “with fiscal capacity” to perform the work (according to the request for proposals). Clean Water Funds are divided into several categories; the relevant category for our work is administered by the Minnesota Board of Soil and Water Resources and is only available to government agencies. The Outdoor Heritage Fund has two grant lines, one administered via the Department of Natural Resources and one via the Lessard–Sams Outdoor Heritage Council (LSHOC), a separate council of citizens and legislators that make recommendations to the state legislature. LSHOC grants are available to governmental and nonprofit groups. All these grant lines are competitive, though the Legacy Funds do fund noncompetitive grants to government agencies as well.

Projects funded by these sources are archived by the Minnesota Legislature via the Minnesota Legacy website (https://www.legacy.mn.gov). The website includes a project index, where (as of February 28, 2023) projects can be filtered by the agency that was awarded the funds, county in which the project occurred, funding source, and subject (e.g. archeology, water resources). A previous version of the tool allowed users to filter by activity type. Our initial data download was conducted on July 22, 2021, using the filter “Restoration/Enhancement,” which included projects where a habitat restoration or enhancement was performed. A second download was conducted on September 10, 2021 using the filter “Contracts,” which included grant contracts for a variety of activities, including habitat restoration.

The initial data downloads included many projects that do not qualify as stream restoration. We filtered down the initial list of projects to on-the-ground stream restoration efforts. This excluded projects that included diffuse, watershed-wide initiatives, projects on lakes disconnected from rivers, wetland restorations that were not attached to a river, stormwater management, and others. We also excluded projects that were funded beginning in 2020, as these have not completed their grant cycle at the time of our analysis. The information to make decisions about which projects to exclude came from project descriptions in the original project list as well as information from agency websites and grant reports. For some projects, we were not able to find sufficient geographic data and had to exclude those, even if they would qualify based on activity type.

After filtering the dataset to stream restoration projects, we began to assemble geographic locations for the remaining projects. The Minnesota Legacy website retains some geographic information for projects, but does not have information for every project and many of the projects are associated with an agency headquarters rather than the actual project location. To find project geographic locations, we searched across numerous sources: project reports hosted on agency websites and the Minnesota Legacy website, project maps, Clean Water Stories from the Minnesota Board of Soil and Water Resources, newspaper reports, and engineering firm websites. The geographic information in these reports was often not provided as latitude and longitude, but rather as township sections or images pulled from Google Maps. The act of determining a precise location was an iterative process of consulting resources and Google Earth imagery. This process is similar to Stanford et al. (2019) who compiled site locations from "coordinates, place names, or catchment unit numbers, as available." Once we determined the project location, we added the latitude and longitude to the project list.

3.2.2. Biophysical and socioeconomic data

We compiled biophysical data from a number of publicly available sources (Table 3.1). We used the National Hydrography Dataset to determine stream locations and drainage areas of stream segments. We found the impairment status of stream segments using the EPA 303d impaired waters list. The Minnesota Department of Natural Resources (DNR) produces statewide Habitat Quality Index, based on a number of biotic and abiotic factors (metadata available at https://resources.gisdata.mn.gov/pub/gdrs/data/pub/us_mn_state_dnr/env_watershed_health_assessment/metadata/metadata.html). They assign a single metric for overall habitat quality, but also include indices for hydrology, water quality, biology, connectivity, and geomorphology. We assembled data for federal, state, and county owned lands from the Bureau of Reclamation and the Minnesota DNR. This measure of public land excludes city-owned properties and Lake Superior. Finally, we found the percentage of agricultural land in each county from the USDA National Agricultural Statistics Service.

Table 3.1. Biophysical and socoiodemographic variables assembled for analysis.

Category	Variable/dataset	Spatial scale/resolution	Source
Restoration sites	Restoration sites	Point	This study
Physical attributes	Drainage area	Stream segment	National Hydrography Dataset
	Length of streams	County/watershed	National Hydrography Dataset
	Percent public land	Polygon	Minnesota Department of Natural Resources, U.S. Bureau of Reclamation
	Percent agricultural land	County	U.S. Department of Agriculture National Agricultural Statistics Service
Ecological integrity	Impairment status	Stream segment	Environmental Protection Agency 303d impaired waters list
	Aquatic index	HUC 8 watershed	Minnesota Department of Natural Resources
Socioeconomic	Percent white residents	Block group, county, state	U.S. Census Bureau
	Median household income	‘’	‘’
	Median home value	‘’	‘’
	Percent households below poverty line	‘’	‘’
	Population	‘’	‘’

We accessed socioeconomic data from the US Census Bureau via the R package tidycensus (Walker & Herman, 2023). We downloaded data at the census tract and census block group for 2019. The variables included (self-identified) White residents, Black residents, Asian residents, Native American residents, Hawaiian and Pacific Islanders, people living below the poverty line (only available at census tract), median income, median home value, and total population.

3.3. Methods

3.3.1. Characterization of biophysical characteristics

Documenting the spatial distribution of stream restoration sites and the types of streams that receive restoration is valuable to illustrate the human impact on geomorphology, hydrology, and ecology. To document the spatial distribution, we calculated the number of restoration projects in each county and each HUC 8 watershed. We also determined the number of agencies that received funding and the total amount spent for the projects we were able to locate geographically. To characterize the physical attributes of the restoration sites, we extracted the drainage area of the nearest stream segment, determined whether or not the site was on an impaired stream segment, and determined whether or not the project occurred on public land.

3.3.2. Socioeconomic characteristics of restoration sites

To determine which communities have access to restoration through the Legacy funds, we extracted area-weighted census data in a 1 kilometer buffer around each restoration point. This included racial and ethnic composition of residents, median household income, median home value, and total population. We used a 1 kilometer buffer as an estimate for the spatial extent of social benefits from a stream restoration project, though sensitivity analysis found little difference in sociodemographic composition for buffer sizes from 100 meters to 2 kilometers. We note that the actual extent of the benefits from a restoration project will depend on the activities and extent of particular projects. Given that uncertainty, we chose 1 kilometer as a representative scale, though the actual social benefits associated with stream restoration are poorly quantified (Basak et al., 2021).

To compare the population in restored areas with a control population, we extracted soicoeconomic characteristics at the statewide level, using data at the census block group scale. We also constructed a 1 kilometer buffer around every stream segment in the state and calculated area-weighted socioeconomic characteristics within this buffer (Figure 3.1). This method represents the statewide population that could be impacted by restoration, assuming that every stream segment is restorable. We used the nonparametric Wilcoxon rank-sum test and the Kolmogorov-Smirnov test to compare the mean and distribution of the buffer around restoration points with the statewide population and the stream buffer population.

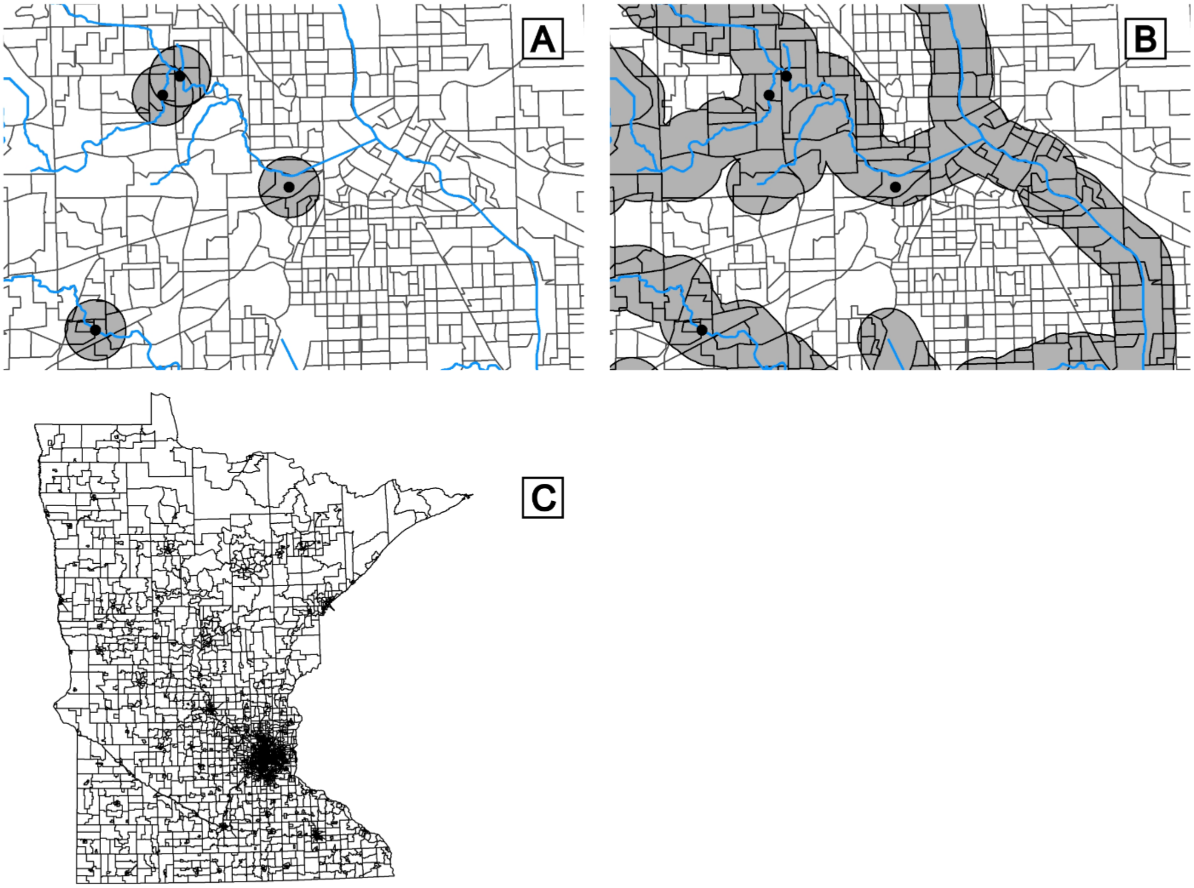

Figure 3.1. Illustration of the three different geometries used to extract census data. Black points are the location of stream restoration projects, blue lines represent stream segments and black lines represent census block groups. A) 1 km buffer around stream restoration points, B) 1 km buffer around stream segments, C) statewide census block groups.

3.3.3. Negative binomial regression model

We estimated associations between the number of restoration projects, stream-condition indices, and sociodemographic variables within HUC 8 watershed units using negative-binomial models with a log-link function. Negative-binomial models are used to fit over-dispersed count data, where the variance is much greater than the mean (Zuur et al., 2009). We selected variables for our model via principle component analysis and correlation plots, to ensure that we were capturing important socioeconomic and biophysical factors, but with minimal redundancy in variables (Appendix A). The full model included the water quality index score mean – a composite index created by the DNR that includes measures for aquatic life, recreation, and pollutants, geomorphology health index score mean – a composite DNR index that includes soil erosion, slope, and discharge, population, percent of the population that self-identified as white, and the median household income. The latter three variables were assigned to HUC-8 watershed units using areal interpolation. We scaled median household income by 1,000 for ease of comparison. We also produced a reduced model that included water quality index score mean, geomorphology health index score mean, and median household selection. We assessed model fit using quantile-quantile (Q-Q plots), the Akaike information criterion (AIC), log likelihood, and Moran's Index, which we used to test the spatial autocorrelation of model residuals.

3.4. Results

3.4.1. Characterization of biophysical characteristics

In total, we compiled geographic locations for 548 stream restoration sites in the state of Minnesota (Figure 3.2). This is not a comprehensive list of restoration sites due to limitations of data accessibility, but represents a significant proportion of restoration projects funded by the Minnesota Legacy funds. The 548 sites are associated with 287 individual grants awarded to more than 150 entities across the state. The majority of grants were awarded to governmental agencies, such as the Department of Natural Resources and county soil and water conservation districts. In total, these 287 grants included more than $120 million in funds. Of any single entity, the Minnesota Department of Natural Resources received the largest number of grants through the program (14), which accounted for more than $37 million.

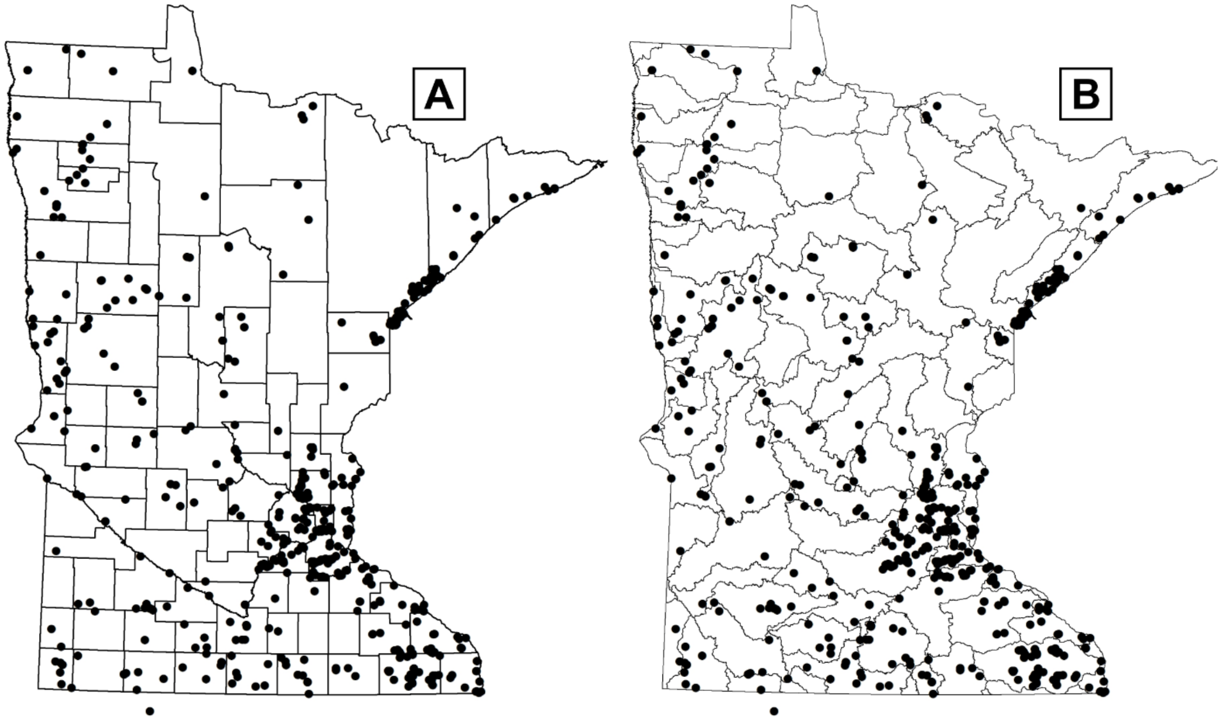

Figure 3.2. Stream restoration sites identified in Minnesota shown with A) county and B) HUC 8 watershed boundaries.

The projects spanned the entire state of Minnesota, though there are clear geographic concentrations (Figure 3.2). 76 of 87 counties in Minnesota had at least one site, and 64 of 81 HUC-8 watersheds had at least one site. The largest concentrations of projects are in the population centers of the Twin Cities metro in east-central Minnesota, Duluth in the northeast, and the trout-populated region in southeastern Minnesota. 56% of sites were located on public land or within 500 m.

The sites are varied in physical characteristics as well as geographic location. Sites span a range of stream sizes, from small gullies to the mainstem Mississippi River. Compared to the overall distribution of streams in the state, project sites tend to have a greater drainage area, suggesting that small ditches and headwater streams receive less restoration than their overall proportion in the state (Figure 3.3). In addition, 68% of the stream segments nearest to each restoration site were listed as impaired. This compares with only 22% of total stream segments in the state.

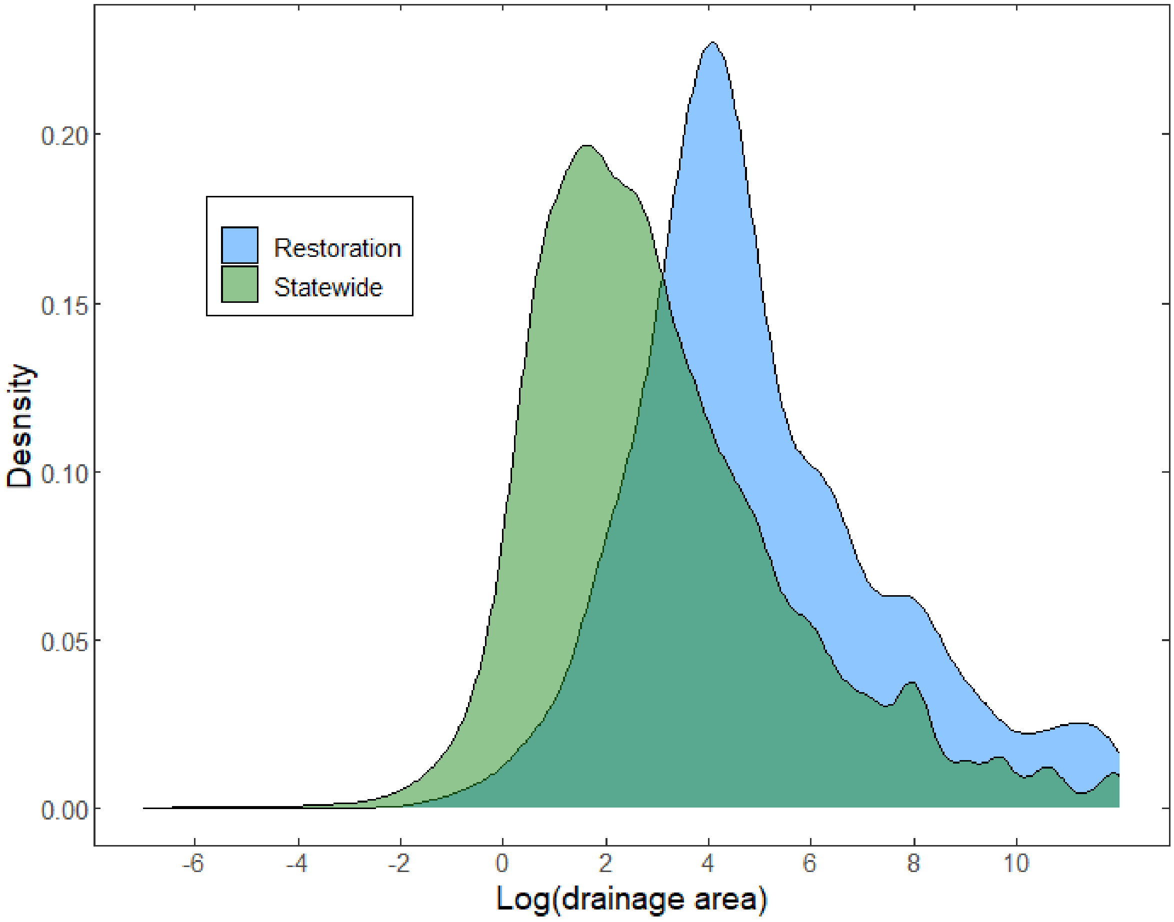

Figure 3.3. Probability density function of Log_{10} of drainage area for the nearest stream segment to restoration projects (Restoration) and all stream segments in Minnesota (Statewide).

3.4.2. Socio-economic characteristics of restoration sites

To assess whether people in the area around stream restoration sites are representative of the overall state population, we compared the population of people living in a 1 km buffer around each restoration site with the total statewide population, and the population living within a 1 km buffer around every stream segment in the state. Table 3.2 shows the mean value for median income, median home value, and racial demographics for project areas, the 1 km buffer around stream segments, and the statewide population. For the project areas, these values are calculated as the mean of the value within each buffer. For the statewide values, this is the mean of values for every block group, and for the stream buffer, it is the mean of every block group within 1 km of a stream segment. Figure 3.4 shows the distribution of percent people of color, median income, and median home value. Kolmogorov-Smirnov tests reveal significant differences in the distribution of income and all race/ethnicity variables. These data illustrate that sites receiving restoration are systematically whiter and higher income than the buffer around streams across the entire state, as well as the state as a whole.

Table 3.2. Average socioeconomic characteristics of the area within 1 km of restoration points, the statewide population, and a 1 km buffer around every stream segment in the state.

Variable	**Project area**	**Statewide**	**Stream buffer**
Median income ($)	73107	74406	73168
Median home value ($)	217035	223917	220961
% Black	1.60	5.94	5.22
% Asian	1.41	4.21	3.90
% Native American	1.27	1.02	1.15
% Latino	3.17	5.42	4.79
% White	89.83	80.70	82.33

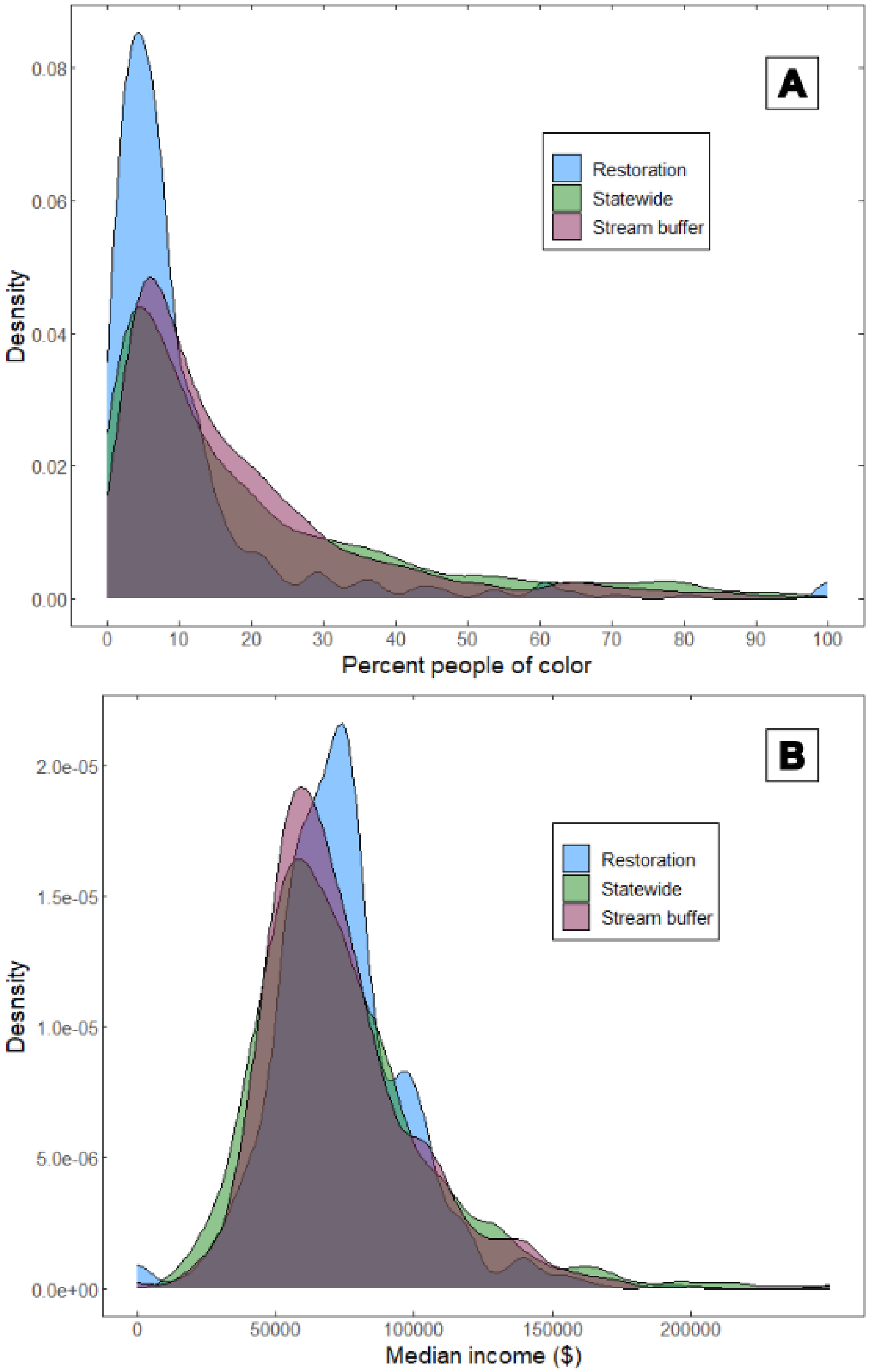

Figure 3.4. Probability density functions of A) percent people of color and B) median household income for the 1 km area around restoration points, the statewide population, and the 1 km area around all stream segments in Minnesota.

When racial demographics are weighted by population, the trends are slightly different. Weighted by population, restored sites have a higher percentage of Black and Asian residents than the statewide or stream buffer population (Table 3.3). This demonstrates that the number of people within 1 km of the restoration projects in our dataset is disproportionately Black compared to the statewide population, driven by the large number of people in racially diverse, high population density areas in the Twin Cities metro. The implications and limitations of this distinction are explored in the discussion.

Table 3.3. Population weighted race and ethnicity estimates for the 1 km area around restoration points and the statewide population.

Variable	Project area	Statewide
Percent White	76.21	80.70
Percent Black	9.10	5.94
Percent Latino	5.87	5.42
Percent Asian	4.94	4.21
Percent Native American	0.65	1.02

3.4.3. Negative binomial regression

The results of the negative binomial regression models are given in Table 3.4. The incident rate shown in the table is a measure of how much a one unit change in the predictor variable will change the output variable. Numbers greater than one means that the variable has a positive relationship with the number of restoration projects, and numbers less than one indicate a negative relationship with the number of restoration projects. In the full model, we found that geomorphology index and median household income were the only significant variables, which was true in our reduced model as well. Geomorphology index is negatively associated with number of restoration projects, meaning that there are more projects in watersheds with lower geomorphology index scores. In particular, the models predict a 3.2% decrease in number of projects for every 1% increase in geomorphology health index score. Median household income has the opposite relationship, watersheds with a higher average median income are associated with a higher number of projects. The models predict that a $1000 increase in median household leads to a 4.5% and 5.9% increase in number of restoration projects for the full and reduced models, respectively.

Table 3.4. Results of negative binomial regression models for HUC 8 watersheds.

Variable	**Full Model incident rate**	**Reduced Model incident rate**
Intercept	9.23 (0.11, 555.78)	0.90 (0.05, 14.12)
Water Quality Index Score Mean	1.00 (0.98, 1.02)	1.00 (0.98, 1.02)
Geomorphology Health Index Score Mean	0.97 (0.95, 0.99)***	0.97 (0.95, 0.99)**
Median Household Income ($1000s)	1.04 (1.01, 1.08)**	1.06 (1.03, 1.09)***
Population	1.00 (1.00, 1.00)	
Percent Non-Hispanic White	0.99 (0.95, 1.03)	
Model performance		
AIC	442	441
Log Likelihood	213.9 (degrees of freedom = 7)	215.5 (degrees of freedom = 5)
p-value for Moran's i	0.18	0.16

Note: 95% confidence intervals are reported in parentheses. **, *** indicates significance at the 0.05 and 0.01 level, respectively.

3.5. Discussion

Stream restoration in Minnesota is responsive to both environmental and social factors. The majority of stream restoration sites in this dataset are located on impaired stream segments and public land, even though a minority of stream segments in the state are impaired and only 25 % of the state is publicly held. At the watershed scale, household income and measures of geomorphic quality are the strongest predictors of restoration abundance. Population and racial demographics also correlate with restoration, though with stronger trends at smaller spatial scale.

3.5.1. Spatial clustering of projects

The human and physical geography of Minnesota clearly influence the distribution of stream restoration sites supported through Minnesota Legacy funds. There is strong spatial clustering of restoration projects in our dataset – the population centers of the Twin Cities metro area and

Duluth have the highest numbers of projects, followed by the trout-rich region of southeastern Minnesota. Stanford et al. (2018) found that population density was positively associated with human and ecologically-focused restoration projects in coastal California. They attribute this to the highly degraded state of human-dominated catchments, as poor habitat quality was associated with high population density. Poor water quality in densely populated areas is true in Minnesota as well, as the counties and watersheds that surround the Twin Cities metropolitan area and Duluth have lower habitat quality scores than sparsely populated regions in north central Minnesota. Locating restoration projects in highly populated regions also means that more people may benefit from restoration action (Moran, 2010, Stanford et. al., 2018).

Stanford et al. (2018) found that the percentage of white residents was positively associated with restoration projects at the watershed scale. The nature of population in Minnesota, where people of color primarily live in the large urban areas, means that percent white residents is negatively associated with restoration at the HUC 8 scale, though it was not a significant predictor in the negative binomial regression. When we analyze demographics in the 1 km area immediately surrounding restoration sites, we find that these locations have a higher percentage White population than the statewide population and the population living within 1 km of all streams in the state (Figure 3.4). This underscores the importance of accurately documenting the local communities around restoration projects, as county or watershed-scale trends may obscure local dynamics, and the social impact of a restoration project is unlikely to be felt at the scale of an entire county.

Median household income is positively associated with restoration across all our scales of analysis. This aligns with Stanford et al. (2018) and Welch (2019), who found positive correlation between median household income and stream restoration prevalence at the watershed and county scale, respectively. Both studies highlight that higher income areas tend to have more political and economic support for environmental initiatives, which may explain the association. In Minnesota, the areas with the highest income are those around the Twin Cities metropolitan area, which is also where nearly 50% of the state population lives. The association of restoration projects in these areas may reflect the large population, or may be reflective of the economic inequality that is closely associated with many environmental amenities (Hendricks & Van Zandt, 2021; Leong et al., 2018; Shokry et al., 2020; Watkins et al., 2017).

When weighted by population, the demographics of people within 1 km of restoration projects is different than when averaging across buffers. Weighted by population, the demographics of the 1 km buffer around restoration points have a significantly higher percentage of Black residents than the statewide average. This is driven entirely by high population density and high racial diversity in the Twin Cities. A single restoration project in the Twin Cities will have a larger number of people within 1 km compared to a project in a rural area, and the people in the Twin Cities are racially diverse, meaning that the people within that 1 km area are disproportionately people of color compared to the statewide average. We exercise caution in interpreting this data, as we are making assumptions about the distribution of people within census block groups (i.e., that they are distributed uniformly across the area). And by weighting the population within this linear assumption, we are further distorting the census data. Further, the actual benefits that people enjoy as a result of restoration are poorly understood, so the 1 km buffer may or may not be a fair representation of the extent of benefits. Regardless of the uncertainty in the data, this illustrates that proper measurements of community benefits and explicit consideration of scale are essential to evaluate the distribution of environmental services provided by stream restoration.

The geomorphic index is a significant predictor of stream restoration in our dataset, but it is a unique metric developed by the Minnesota Department of Natural Resources. The geomorphic index is a composite of soil erosion susceptibility, pollution sensitivity of near-surface materials, climate water balance (precipitation – evapotranspiration), and steep slopes near streams. Collectively, these variables are meant to represent the erosional susceptibility of the watershed. The geomorphic index is closely associated with trout habitat in Minnesota – designated trout streams generally have lower geomorphic index values. The average geomorphic index is 63.5 for counties with designated trout streams compared to 69.1 for counties with no designated trout streams. In this stream restoration database, the relationship between geomorphic index and number of restoration projects reflects investment in economically valuable trout fisheries. Stanford et al. (2018) also found that projects in coastal California were predominantly located in perennial watersheds and those with salmonids, meaning that species in ephemeral streams were not prioritized in the same way. In our dataset, the high number of projects in trout-rich southeastern Minnesota reflect the same type of investment in charismatic, economically valuable species.

3.5.2. Rural populations have less access to restoration in Minnesota

Our results show that rural areas in Minnesota received fewer restoration projects than urban areas. North central Minnesota is forested, rural, and has less ecological degradation than other parts of the state, so streams there may be less in need of restoration. However, agricultural areas of southern and western Minnesota have highly degraded streams but are not receiving restoration at the same rates as urban areas. This is in contrast to Welch (2019), who found that percent agricultural area was positively correlated with stream restoration in Pennsylvania. There are a number of potential mechanisms to explain this trend: There is significantly less public land in agricultural areas, meaning that restoration projects have to be undertaken on private lands, and there may be a lack of willing land owners. Areas with higher population may have more resources and/or political, social, and economic will to pursue restoration initiatives. And the process used to solicit and evaluate proposals may disadvantage rural communities. For example, Metcalf et al. (2015) found that rural ranchers felt that they were not fairly engaged in restoration and mitigation planning on the Clark Fork River, whereas restoration action in Missoula (the local urban area) was largely viewed as a success.

Regardless of the mechanism, agricultural streams are among the most impaired in the state, meaning that there may be potential benefits to restoration. The lack of restoration in these areas may be a missed opportunity for ecological improvement. However, there are also arguments that local scale restoration in the most impaired ecosystems cannot actually restore ecosystem health. If ecosystem stressors are at the scale of an entire watershed, reach-scale restoration projects will likely have limited efficacy (Bernhardt and Palmer, 2011; Brettschneider et al., 2023; dos Reis Oliveros et al., 2020). If degraded ecosystems in agricultural regions of Minnesota require watershed-wide initiatives to achieve results, a more efficient use of funds might be to design projects elsewhere. But efficiency is not the only metric that should be used to evaluate siting, as using a purely efficiency-based framework can ignore historic dynamics and social benefits (e.g., Heck, 2021).

3.5.3. Beyond distributive justice

Some agencies are better equipped to submit successful grant proposals than others, regardless of environmental need. In the Minnesota Legacy dataset, the Department of Natural Resources is the single largest grantee, and they are a large statewide institution. This type of imbalance in social and political capital is well-documented in environmental literature, and can lead to inequalities in environmental amenities (Anguelovski et al., 2020; Matsler et al., 2023; Moran, 2010; Scoggins et al., 2022). The Legacy funds are not the only funding mechanism to address environmental concerns in the state, but they represent a significant investment of public funds. Future studies that apply a lens of procedural justice to the application and evaluation process would elucidate barriers to access, and could improve the fairness of the process. At the national scale, there is evidence of unequal funding from many supposedly meritocratic funding sources, so the same may be true in the Minnesota Legacy process (Chen et al., 2022; Ginther et al., 2018). It is important to note that funding equity and environmental equity are not explicit evaluation criteria for the Minnesota Legacy program, and may not be goals of the program. But as Minnesota continues to contend with climate change, and as the population of the state continues to diversify, ensuring access to environmental funding will be important for all populations in the state.

In order to ensure that environmental benefits are equitably distributed, we need to measure them accurately. The actual social and environmental benefits of restoration projects are difficult to quantify and very few attempts have been made to measure them. In this study, we used a 1 kilometer buffer as an estimate for the spatial extent of social benefits from restoration. We found no difference in socioeconomic demographics for buffers between 100 m and 2 km, but we cannot estimate the actual spatial impact of a given restoration project. This is in part because different restoration activities provide different ecosystem services, which will have different spatial footprints (Saidi & Spray, 2018; Vermaat et al., 2016). But there is also a dearth of information about the actual spatial scale of benefits, which highlights a clear research need in restoration science (Basak et al., 2021).

3.5.4. Improved stream restoration databases/recordkeeping

Many others have called for improved record-keeping in restoration databases, and we join that call. The only comprehensive national database in the United States was compiled in 2005 (Bernhardt et al., 2005). At the time, thousands of new restoration projects were completed every year, and the restoration industry has likely expanded in the 18 years since then. Better record keeping is essential to understand the impact of restoration activity on geomorphology, hydrology, and ecology (Bernhardt et al., 2005; Morandi et al., 2014; Nakamura et al., 2006; Stanford et al., 2018; Welch, 2019). And as we demonstrate, documenting the location of restoration projects is a critical first step to determine whether or not restoration spending and the resultant ecosystem services are distributed equitably.

Green gentrification related to stream restoration is an additional concern that can be evaluated with improved record keeping. Green gentrification occurs when residents are displaced by increased housing costs as a result of environmental investment (Gould & Lewis, 2012). Green gentrification related to stream restoration has not been systematically analyzed, if analyzed at all. There are a number of complications to consider in evaluating green gentrification related to stream restoration projects. For example, the scale of the project, the type of restoration work that is done, the infrastructure that is built as part of the project, the regulatory environment, and local community involvement can all play a role in the social and economic impacts of a restoration project (Moran, 2010; Scoggins et al., 2022; Taguchi et al., 2020). In order to fully evaluate the impact of projects, data on these aspects needs to be collected and made available.

3.6. Conclusion

We present a new stream restoration dataset for the state of Minnesota. We document that the siting of restoration projects is responsive to both environmental and social factors. From an environmental perspective, we find that most restored streams occur on impaired waterways and that the siting of projects at the watershed scale is tied to measures of environmental degradation. On the social side, we find different results at small and large spatial scales. At the watershed scale, restoration is best predicted by median income, and is associated with high population and lower percentage of white residents. This is driven by the human geography of Minnesota, as people of color predominantly live in the Twin Cities region. When we analyze a 1 km buffer around the restoration sites, we find that restoration occurs in areas that are whiter and higher income than the average population in the state, but there is nuance to these trends when the demographics are weighted by population. This highlights both a data and a practical consideration - we need to be conscious of scale when addressing questions of distributive justice and we need to be conscious of equity when implementing environmental initiatives.

Chapter-specific acknowledgements

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Apprendix A. Statistical and spatial attributes of variables

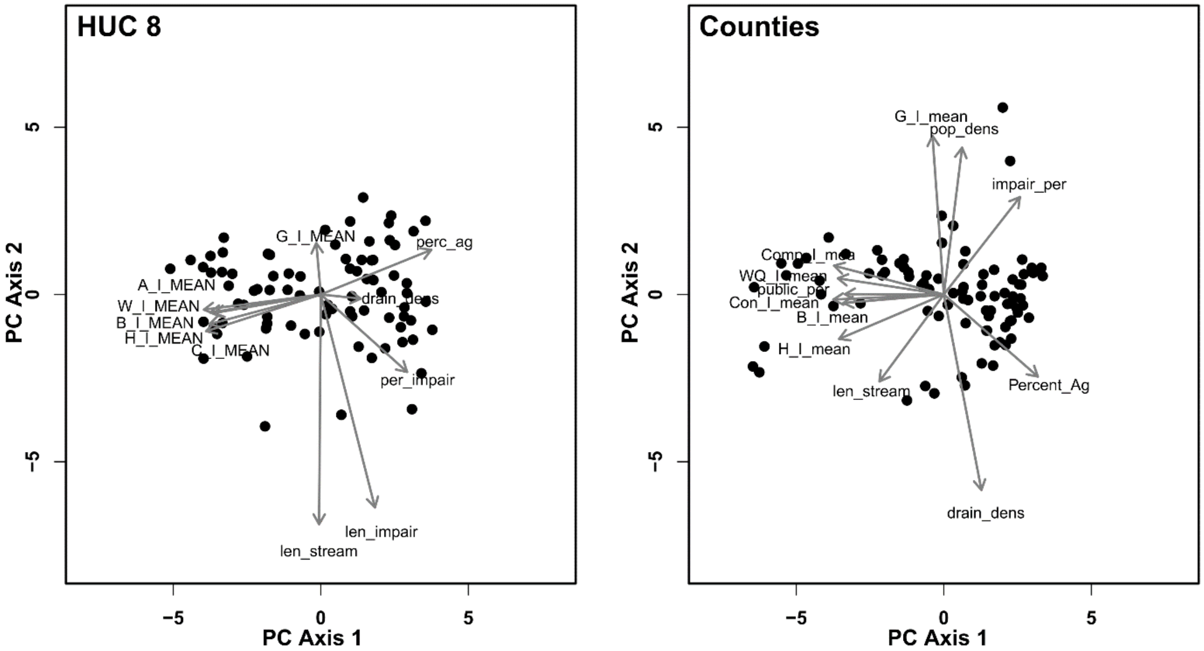

Figure A1. Principal component analysis plots for biophysical data in HUC 8 and counties in Minnesota. A_I_MEAN is mean aquatic index (same as Comp_I_mean), B_I_MEAN is mean biological index, Con_I_mean is mean connectivity index, G_I_MEAN is mean geomorphic index, H_I_MEAN is mean hydrologic index, len_stream is the total length of streams, len_impair is the length of impaired streams, per_impair is the the percentage of streams that are impaired, perc_ag is percent agriculture, drain_dens is drainage density, pop_dens is population density.

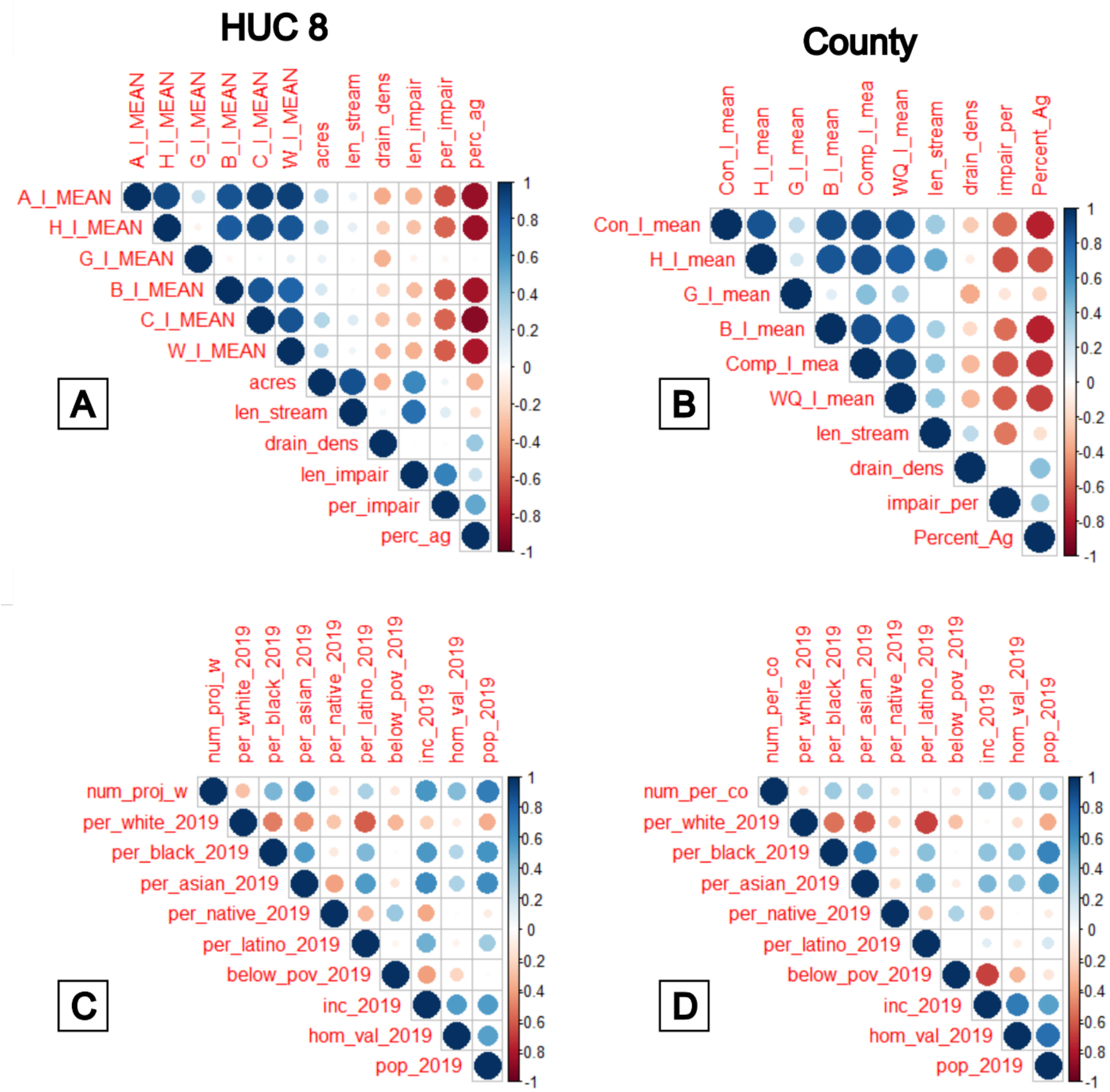

Figure A2. Correlation plots for biophysical and socioeconomic variables. A) Biophysical variables for HUC 8 watersheds, B) biophysical variables for counties, C) socioeconomic variables for HUC 8 watersheds, D) socioeconomic variables for counties.

Figure A3. Biophysical and socioeconomic variables for counties Minnesota. A) Number of projects, B) Percent impaired streams, C) Mean water quality index, D) Mean geomorphic index, E) Percent below poverty line, F) Percent white, G) Log_{10} population density.

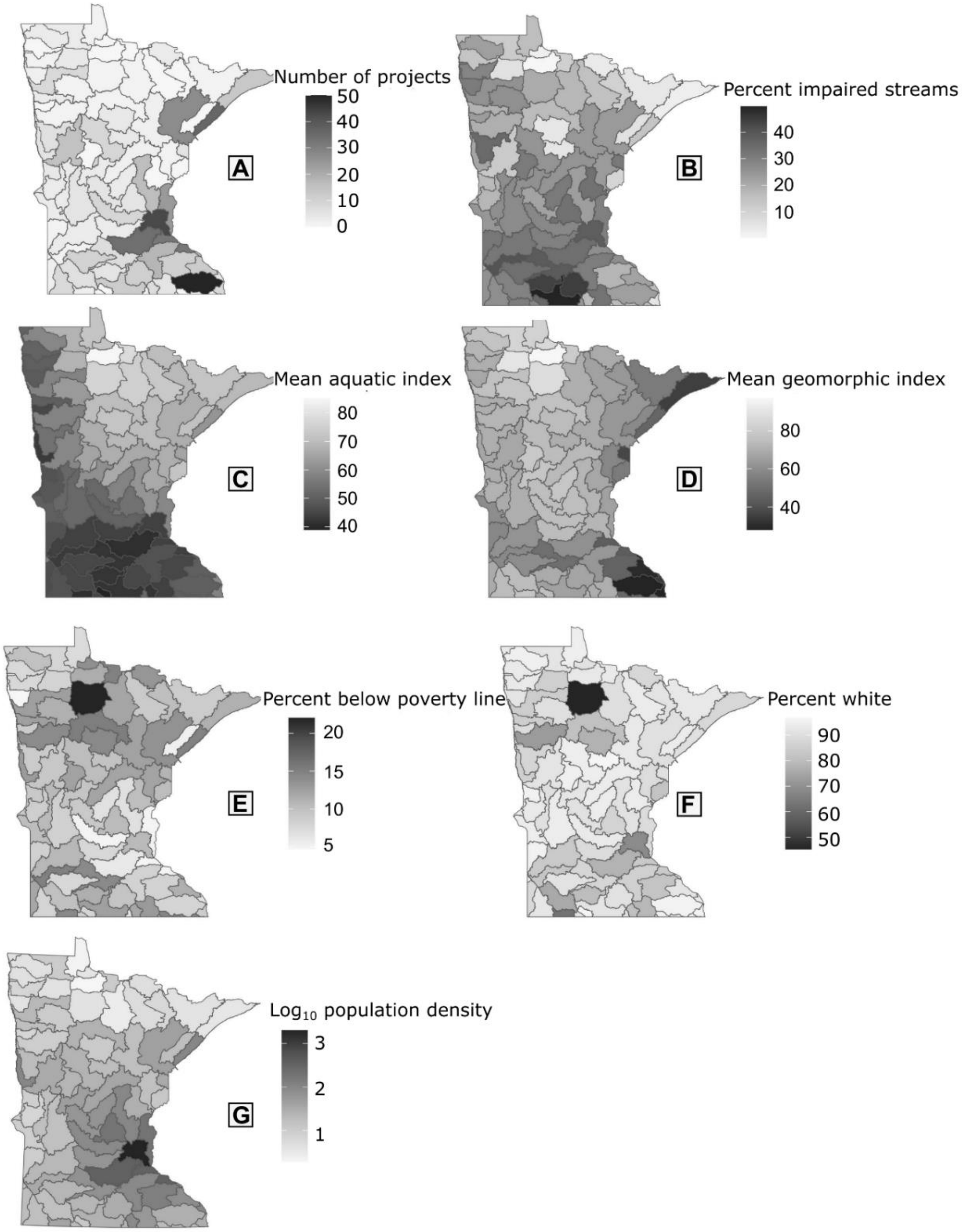

Figure A4. Biophysical and socioeconomic variables for HUC 8 watersheds in Minnesota. A) Number of projects, B) Percent impaired streams, C) Mean water quality index, D) Mean geomorphic index, E) Percent below poverty line, F) Percent white, G) Log$_{10}$ population density.

Chapter 4. Which humans, part 1? We need accomplices, not allies

This work was previously published in AGU Advances as *Jones, 2021. We need accomplices, not allies in the fight for a more equitable geoscience.*

Abstract: The killing of George Floyd on May 25, 2020 sparked a global movement for black lives that extended into the geosciences. Nearly a year later, some momentum has been sustained, but the appetite for transformative change to generate a more equitable geoscience is lacking. In this article, I detail my struggles to balance science, activism, and anguish as a black geoscientist in Minneapolis over the last year. I suggest that a riskier and deeper involvement in the work of equity and inclusion is necessary to transform our discipline into a diverse, equitable, and inclusive space where all people can thrive.

4.1. Introduction

Since the killing of George Floyd in May 2020, I have heard repeated calls to center the voices of black, indigenous, and other people of color in discussions around diversity, equity, and inclusion (DEI), and the editors of AGU Advances make it clear that “we must learn from our colleagues who have experienced bias and barriers and listen to their ideas of what kind of change is needed for the Earth and space sciences to function as a diverse and inclusive community.” (Zeitler et al., 2021). I believe that in order to elevate DEI in the geosciences, we need to find and create venues to hear, validate, and uplift the experiences of the people who do geoscience – particularly those from underrepresented and marginalized groups. So as we approach the one-year anniversary of the killing of George Floyd, I feel compelled to write about what I have learned balancing community work, diversity work, and science since May 25, 2020.

4.2. Personal reflection

I may be the geoscientist who has been most affected by the killing of George Floyd. As a mixed-race black man who has spent 25 of his 28 years in South Minneapolis, the killing of George Floyd was closer to home than any of the police-involved killings that have made headlines in recent years. In the days following May 25th, 2020, I saw a video of a black man being killed on a sidewalk just a few blocks from my home by a police department funded by my tax dollars, then was among friends and neighbors met with tear gas, flash grenades, and lesslethal munitions at protests. I watched businesses that I've supported all my life burn to the ground, heard the constant buzz of helicopters above my neighborhood, and saw a movement sparked at 38th & Chicago spread around the globe. And throughout the summer, I fought hard in defense of my community; I helped board up businesses in preparation for riots, stayed up until 3 AM to protect my neighborhood from the threat of white supremacist violence, volunteered in emergency food relief, and came face-to-face with National Guard soldiers and SWAT teams at protests.

And to be frank, I rarely saw my geoscience colleagues in the streets with me. Of course, I wasn't everywhere and I don't know what actions people took in their private lives (e.g. monetary support, political advocacy). But I saw that our city needed boots on the ground in the struggle for security and justice, and very few of the boots I saw came from my fellow geoscientists. And this led to a question that has haunted me since last summer – if it had been me instead of George Floyd pinned under those three police officers, would my colleagues have showed up in the streets to advocate for justice on my behalf? And I honestly believe that, for many of them, the answer is no. And it's hard to sit in meetings about science, inclusion, or anything else when I don't believe that the people in the room value my life more than their work or their comfort.

At this point, you may be wondering how my experience during the summer of 2020 is relevant to the geosciences. While I was doing work in the community, I was also working as a research assistant, preparing to teach my first course as a sole instructor, and finding ways to advance my own research amid a global pandemic. That is to say that none of the responsibilities that I carry as a geoscientist disappeared, but they had to take a back seat as the world presented a mortal threat and a moral obligation. And while mine was a special case due to geographic proximity, scientists and students from minoritized groups are routinely forced to juggle these types of societal and scientific demands. I leveraged what I was learning in the streets in my classroom and my research - by incorporating lessons, discussions, and speakers on environmental racism and justice into my geomorphology class, joining a group of graduate students to write a letter advocating for change in our department, working collaboratively to build a research project at the intersection of environmental justice and stream restoration, and working to create a community-university research summit for my department.

While the apparent groundswell of support for racial justice in the geoscience community in the summer of 2020 was a good step, it brought to mind all the times when nothing was done or said. I recall many times that I cried alone in my office following verdicts, dismissals of charges, or decisions not to charge in cases of police brutality and hardly heard a word from white colleagues. Even this year, when Daunte Wright was killed in Brooklyn Center, MN (while the Derek Chauvin trial was ongoing), communications from our department did not include Daunte Wright's name. Although avoiding these topics may be a function of professional decorum, where conversations that skew into taboo subjects like race and politics are discouraged, racial dynamics and politics have real consequences for all of us, particularly for people of color. And staying silent in the face of prejudice, violence, and injustice makes us complicit in systemic racism, and is part of what has led the geosciences to be the least diverse STEM discipline (Bernard & Cooperdock, 2019; Dutt 2019).

Protestors in the Twin Cities routinely chant that "we ain't going back" to the way things used to be, but there are already signs that the rest of the world is moving on. Some momentum from last summer has been maintained within the geosciences through the work of organizations like URGE, but the fatigue of another academic year amid the COVID pandemic has slowed the work and decreased the urgency. I have spoken to numerous students, faculty, and staff from across the United States who bemoan the lack of tangible progress, the indifference or disinterest of colleagues, and the structural impediments to change. At the same time, the overall sentiment in the US has moved back towards the status quo: polling from FiveThirtyEight found that the surge of support for Black Lives Matter following the killing of George Floyd had returned to previous levels by the shooting of Jacob Blake in late August 2020 (Baon, Jr., 2020). Polling in March 2021 from USAToday revealed drastic changes in opinion compared to June 2020 regarding police reform, Black Lives Matter, and the George Floyd case, with wide differences by race and political affiliation (Blow, 2021). Even in Minneapolis, I didn't hear a word from my departmental colleagues when Dolal Idd, a 23-year old Somali man, was killed by the Minneapolis Police Department on December 30, 2020. I spent hours that night protesting outside a gas station in 10-degree weather and don't know if others in my department even know that it happened.

4.3. Accomplices, not allies

So how can we remain vigilant and committed to DEI work and to uplifting the lives of marginalized people? I'll offer a perspective from George Floyd Square, the autonomous protest zone that surrounds the corner where George Floyd was killed. I visit the Square at least once a week to stay up to date on what's happening in the neighborhood and to be renewed in my own fight for racial justice. At a community meeting in the Square in November 2020, one of the community members said, “We don’t need allies, we need accomplices” after an incident. I’ve reflected on that thought for months, and I believe it is applicable for DEI work in the geosciences as well.

As the concept of allyship has grown in recent years, so too have criticisms surrounding the roles and motivations of allies. Some critics note that allyship is plagued by false allies –those who practice tone policing, offer conditional support, center their own feelings, and generally engage in behaviors that are counter-productive to advancing the work of justice (Matthew et al., 2021; Owens, 2017). Others note that allyship can be wielded temporarily – so-called allies take part until there is a social, political, or economic risk, and then excuse themselves to a safer position (Matthew et al., 2021). And some criticize the commodification of allyship, where so-called allies leverage their status as an ally for personal gain, often at the expense of qualified people from marginalized communities (Indigenous Action, 2014).

The concept of an accomplice to racial justice has risen as an alternative framework in response to this critique of allyship (Gumberg-Muñoz, 2018; Indigenous Action, 2014; Powell & Kelly, 2017; Squire, 2019; Suyemoto et al., 2020). An accomplice, in a legal sense, is one who is complicit in the activity of a crime. Thus, they are liable if the criminal is caught and have a stake in ensuring the success of the criminal. In the context of DEI work, an accomplice is “complicit in a struggle towards liberation” (Indigenous Action, 2014). To be an accomplice is to work in solidarity with minoritized groups as they attempt to overthrow systems of oppression. For some activists, the legal implications of the word accomplice are essential to its use in this context. Although it may not be illegal to challenge systems of oppression, it is a transgression against the status quo that upholds the oppression (Indigenous Action, 2014; Squire, 2019). Compared to an ally, an accomplice assumes a greater amount of risk to take an active, substantive role to challenge and overthrow the systems, institutions, and norms that lead to inequality. Accomplices confront their own status and privilege to determine what risks they can take, and embed justice across all aspects of their work (Gumberg-Muñoz, 2018; Indigenous Action, 2014; Powell & Kelly, 2017; Squire, 2019).

In the geosciences, there are many potential ways to be an accomplice for diversity, equity, inclusion, and justice. These might include admitting and investing in minoritized students from a variety of academic backgrounds, implementing salary cuts for faculty to fund community initiatives, establishing enforceable diversity goals with penalties for failure, or writing research grants in collaboration with professors from community colleges, HBCUs, and other minorityserving institutions. All of these require a deeper personal and structural investment and present greater risk than typical allyship, but could be profoundly impactful to promote DEI in the geosciences.

4.4. Suggestions for change

Up to this point, I've provided my own experience and shared my fears about the current movement failing. I want to provide a few more suggestions for enacting diversity, equity, and inclusion, and justice across the geosciences. These ideas are informed by my own lived experience, conversations with other geoscientists, reading outside of geoscience literature, and the insight of social-justice organizers in the Twin Cities:

- **Establish extensive, age-appropriate K-12 outreach programs.** The factors that determine students' interest in STEM are complex, but studies suggest that self-efficacy, support structures, and knowledge of career choices during K-12 education influence students' interest in STEM careers (e.g. Nugent et al., 2015). Additionally, 60% of the top 100 geoscience programs identified in Nelson (2017) are located in municipalities with public school systems that predominantly serve students of color. How many of them have sustained public school engagement programs to support and enrich geoscience education? Imagine how impactful it could be for students to see a geologist once a month from kindergarten through high school and to learn interesting and relevant information about the Earth.
- **Build connections with environmental organizations.** From local citizen groups working on water quality problems to national and international organizations trying to mitigate the disproportionate effects of climate change, there are many opportunities for geoscientists to do impactful research in collaboration with communities. Models like the AGU Thriving Earth Exchange provide examples for how to conduct community-engaged science.
- **Recognize and reward DEI work.** If we expect our departments to promote research excellence, we measure it and reward it through fellowships, tenure and promotion, and awards. If we expect excellence in DEI efforts, similar rewards (and consequences) should be present.
- **Create employment opportunities in DEI.** Hire diversity officers, provide monetary support for university-wide positions, establish graduate fellowships and student

employment positions to serve on DEI committees, create programming, develop curriculum, and identify speakers.

- **Incorporate DEI in research and teaching; don't relegate it to service.** Geoscience has a great deal to contribute to conversations on environmental racism and climate justice, but those causes need to be championed by researchers and organizations. Even for scientists who don't work in directly related fields, the training geoscientists receive in data analysis, visualization, and communication can be leveraged for the greater good. Similarly, the disproportionate impacts of environmental harm should be taught in geoscience departments and intertwined across the curriculum.
- **Put the goal of equity ahead of yourself**. Overthrowing systems of inequality is difficult work, and we won't always agree on the best way forward. It is human nature to be defensive when challenged, but if we truly believe in the work of equity, we can't let our own feelings stand in the way of achieving the goal.
- **Do more than listen when scientists, students, and citizens from marginalized groups speak.** There is no shortage of bold and brilliant ideas among people who have persevered through hostility, harassment, and systematic disinvestment. This is not only true for DEI efforts, but scientific innovation as well (Hofstra et al., 2020). Listen to their voices, reflect on their words, and take action.

Finally, I want to encourage everyone who reads these words to stay in the fight. This work is hard; injustice has existed in our world for a long, long time. Truly achieving the goals of creating a more equitable and inclusive science is a radical transformation that will require radical thinking and radical action. My favorite sign at George Floyd Square has a quote from Angela Davis that reads, "You have to act as if it is possible to radically transform the world. And you have to do it all the time." I hope that each and every one of us commits to working towards a more equitable science with that level of hope, dedication, and urgency.

Chapter-specific acknowledgements

Many thanks to my advisor Andy Wickert for his patience and flexibility as we navigated historic events in our backyard. Many thanks to colleagues working on issues of justice, equity, diversity, and inclusion. And perhaps most of all, thanks to the keepers of George Floyd Square, who have maintained a radical space for blackness and community.

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Chapter 5. Which humans, part 2? Community science in the Earth sciences

This work was previously published in the Community Science Exchange Hub as *Jones, Nyblade, and Cantner, 2022. Reflections from a relationship building university-community summit.* Jones, Nyblade, and Cantner co-organized all activities, Jones and Nyblade co-wrote the manuscript and Cantner provided editorial support.

The Initial Challenge:

Following the murder of George Floyd by Minneapolis police in May 2020, a wave of activism spread across our city of Minneapolis, our Earth and Environmental Sciences Department at the University of Minnesota, and our national and global geoscience community. Motivated by the local, in-the-streets calls for racial justice, undergraduate and graduate students in our department wrote a letter to faculty and staff advocating for change across our academic community. One call to action was increased department engagement within our surrounding Twin Cities community, specifically those traditionally marginalized in the geosciences (e.g. urban residents, people of color). Rather than waiting for faculty leadership, a group of students and staff (this writing team) organized and hosted a summit between members of the department and local community organizations with a focus on environmental issues. The goal of this summit was to initiate and support meaningful relationships, with the hope that they would grow into research and curricular partnerships in support of the community's priorities and self-determination. Along the way, our organizing team connected with and learned from community engagement scholars and practitioners both within the University of Minnesota and within community organizations partnering with UMN. Informed by these relationships, we hosted the summit in November of 2021, which brought together 19 department members and 23 members of environmental community organizations including neighborhood associations, urban gardening organizations, youth outdoor programs, and water rights activist groups. Following the event, a few collaborative projects have taken root, and yet we still have more work to deepen and maintain these relationships and transform our department to support this work. This paper details our process to develop the summit, advice for anyone envisioning a similar event, and personal reflections from the organizers and some participants. While this event had an overwhelmingly positive reception, we also share our challenges, mistakes, and struggles in both creating this event and moving forward with building these relationships. We believe that these personal stories of our efforts to build relationships are critical within the conversation and process of transforming the geosciences to work towards justice.

Context for Activism

On May 25, 2020, George Floyd was killed during an attempted arrest in South Minneapolis, about 4 miles from the campus of the University of Minnesota-Twin Cities. His death set off widespread protests around the world, and Minneapolis was thrust into the center of the international conversation on Black Lives. Geoscientists also joined this conversation, including at the University of Minnesota. The Department of Earth & Environmental Sciences published a communally written statement in the days following George Floyd's murder that decried the act and affirmed the department's commitment to combatting racism and making our department a more inclusive and equitable place.

Numerous individuals and groups within the department took action in the following months. Undergraduate and graduate students began organizing in June 2020 to brainstorm action items that they (we) wanted to see implemented in the department. In the fall of 2020, students presented a letter to the department, with many suggested action items under the categories of improving department diversity, inclusive pedagogy, and community research partnerships. With regards to community partnerships, students advocated for the department to "build meaningful and long-term relationships with local environmental justice organizations, and find ways to support these organizations with department resources and community-driven science."

Faculty wrote a letter in response in which they grouped the student action items into three categories: current actions, doable or potentially doable in the foreseeable future, and more complex or longer-term issues and/or items that require significant discussion. Students wrote a second letter over winter break that provided more resources and concrete plans. This second letter was motivated by frustration for the lack of attention given to certain issues within the faculty response. The faculty decided that exchanging letters was not a productive way to move forward, and did not provide a further immediate response. Faculty and students organized a facilitated conversation about these concerns and ideas that took place the following semester in November of 2021.

While the conversation between faculty and students stalled during the Spring of 2021, a push for activism remained among graduate students in the Earth & Environmental Sciences department. We were interested in improving our department's relationships with local environmental organizations. This was one of the items identified by graduate students in the original letter that was categorized as "doable or potentially doable" in the faculty response letter. Though the department has existing outreach activities, our perspective was that meaningful connections between our department and our local community were lacking. We saw this as a failure of our land-grant mission, an opportunity to build meaningful, local relationships with communities underrepresented in the Earth Sciences, and potentially an avenue to attract, support, and grow our departmental diversity.

We recognized that our department was generally interested in community partnerships, but we were wary of repeating exploitative patterns with community partners. We know that community partners have expertise that our department lacks: local environmental concerns and lived experiences, skills in building relationships, disrupting institutional and racial power structures, and knowledge of local history and relationships. We wanted to do something that would bring our department in conversation with community organizations interested in connecting with us, but we also recognized that we needed to compensate non-UMN folks for their time and knowledge.

A Note on Language

Throughout the paper, we use the term "community groups" to refer to non-university participants. We recognize this as problematic, given that university members are also a part of their local communities. But we use the term in the vein of community-based scholarship. Additionally, there are many words to describe community-based scholarship, including community engagement, community science, community-driven science, and community-based research. While these terms are distinct, we use these terms interchangeably to mean partnerships between University folks and community organizations that center community priorities and work to support their self-determination.

The Methods:

Organizing Timeline

Thankfully, our department has an internal grant fund for outreach, established by two alumni in honor of their advisor, Sam Sawkins. In Spring 2021, authors MN, JJ, and KC, along with one undergraduate, Kali Mansur, applied for funding through the Sawkins fund to hold a summit with local environmental organizations (application provided in Resources). In our application, we noted that Earth scientists are uniquely positioned to help people face environmental challenges and inequities, but that there is a need to establish connections outside of the academy in order to address those challenges. This event was intended to begin developing those connections.

We also requested funding to compensate the student organizers for their time in this work. We were committed to contributing our time and energy to this project in service of racial justice in the Twin Cities community, but we also did not want to set the precedent that the department should expect free labor and expertise from the student body. Most local outreach in our department has been done by graduate students without compensation. Rather, we wanted to set the standard that this work is important, should be valued within the academy, and is worth compensating. Before we submitted the proposal, we were informed that this funding was not intended to pay graduate students, but we included this in our budget anyway. In May of 2021, our proposal was fully funded by the Sawkins fund.

While our organizing team collectively had previous experience working on community-driven research projects (Matson et al., 2021), taken coursework in Indigenous and community-based participatory research methods, participated in workshops through the National Socio-Environmental Synthesis Center, and done community organizing, we knew we still had more to learn. So our first step was to draw on existing expertise in community-engaged research both within and outside of the university. We wanted to make sure that our approach was in line with best practices, and we wanted to pay special attention to the unique dynamics in Minneapolis and St. Paul. We started with folks in the University of Minnesota: we met with individuals from the Center for Urban and Regional Affairs, the Urban Research and Outreach-Engagement Center, the Office for Public Engagement, and the Institute on the Environment - offices within the University of Minnesota that work with community partners. These meetings happened throughout the course of 2021 and helped us frame our organizing approach (Figure 5.1).

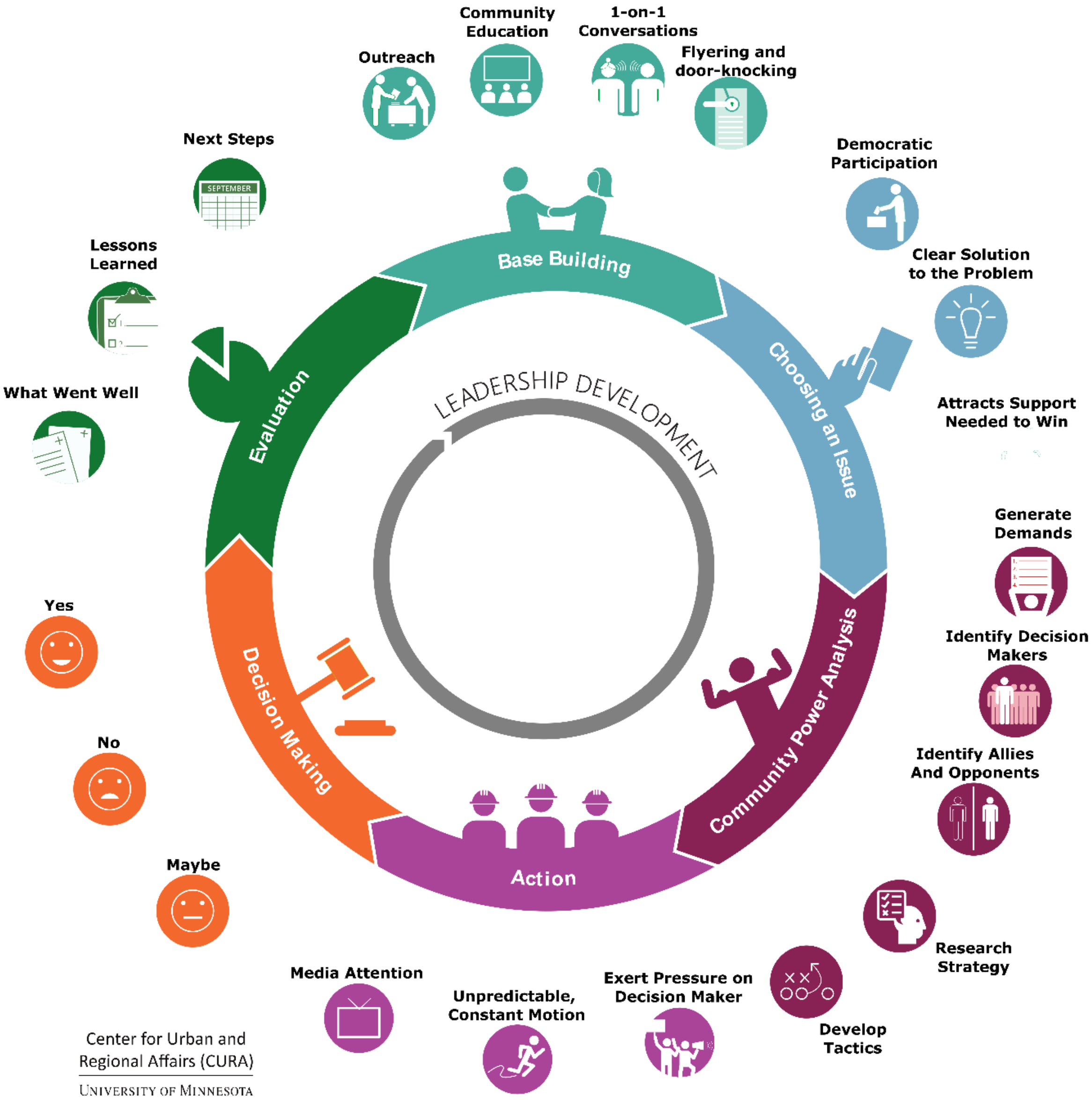

Figure 5.1. Life Cycle of an Organizing Campaign. C Terrence Andersen of the Center for Urban and Regional Affairs encouraged us to envision our work as part of an organizing campaign to shift the culture of our department. This diagram outlines the steps of an organizing campaign beginning from base building all the way through program evaluation. Figure adapted from the Center for Urban and Regional Affairs, University of Minnesota. Original accessed at https://www.cura.umn.edu/sites/cura.umn.edu/files/2019-08/Life_Cycle_of_an_Organizing_Campaign.pdf

At the same time that we were meeting with University collaborators, we began to reach out to community organizations. We compiled organizations in a number of ways: some from existing personal connections with students and faculty who had done community-based work, some based on recent news coverage/notoriety, and some from online searches. We prioritized groups based in Minneapolis and Saint Paul and organizations founded or operated by people of color. We focused on these groups because the campus of UMN-Twin Cities is in both Minneapolis and St. Paul, and because urban populations and people of color have historically been ignored or excluded by the geoscience community.

We sent cold call emails to organizations inviting them to an initial meeting to introduce ourselves, learn about them and their organization, detail some of the expertise and research interests in our department, and explain what we were trying to accomplish with this event. We reached out to 18 organizations, 8 of which didn’t respond, 3 of which said they were not interested in working with us, and 7 of which said that they were interested. The organizations that participated in the event included neighborhood associations, urban gardening organizations, youth outdoor programs, and water rights activist groups. The specific organizations were: Rights of Mississippi River, Frogtown Neighborhood Association, Urban Roots, SE Como Neighborhood Association, Global Peace Farms, and Minneapolis Edible Boulevards.

Figure 5.2. Vegetable garden at George Floyd Square in South Minneapolis. Plants, flowers, and food have been a key part of George Floyd Square since it was established in May 2020, with gardens maintained by Jay Webb of Global Peace Farms.

During the fall semester, we began preparing people in our department for the upcoming event. We sent surveys to faculty and researchers to gauge their interest in taking part in the event. We also hosted two workshops with the Office for Public Engagement during a pre-existing internal seminar time. These workshops were an introduction to community-engaged research and provided institutional perspective about the value of community-based research and the resources available to university members. Serendipitously, Dr. Raj Pandya of the Thriving Earth Exchange was scheduled to present a department seminar in November 2021. Dr. Pandya gave a seminar detailing the work to the Thriving Earth Exchange and spoke about the need for and mentality required to do research in support of community priorities.

The final piece of internal preparation was to recruit facilitators for our discussions. We invited graduate students in our department to contribute as facilitators, knowing that they were interested in connecting with community groups and suspecting that they would be a good intermediary between faculty, researchers and non-university participants. We held a meeting with all of our facilitators to answer their questions and provided them with a facilitation guide (guide provided in Resources).

The Summit

The summit took place on Saturday November 13th, 2021 in the Urban Research and Outreach-Engagement Center building in North Minneapolis (a university-owned, off campus facility). We welcomed department and community members into the space for a 4 hour event split before and after lunch. At the door, we had people sign in, create name tags, and share their address so that we could mail out financial compensation after the event. In an attempt to create a welcoming environment, we arranged the tables and chairs into a big circle and provided coffee and a few breakfast treats.

Once most people had arrived, we began by introducing ourselves, the main organizers of the event, and the purpose for this gathering. We outlined the norms for the discussion as well as our department's history and current action with respect to Indigenous communities and community-based scholarship. We then opened up the conversation for each person to introduce themselves, their community, and what they were hoping to get out of this summit. With a room full of 45 people, this took us an hour and a half and took us up to lunch time.

For lunch, we provided box lunches and invited people to move around the room and converse with each other. During lunch, one of our organizers asked each community organization which department members they would like to talk with during the event. After lunch, we began World Cafe style conversations: each community group was stationed at a table and university researchers rotated between tables every 30 minutes. We placed researchers at specific tables initially based on our lunch-time check-ins with community groups. Each table also had one graduate student facilitator who guided the conversation around discussion prompts and invited all people at the table to participate. To conclude each conversation, we had facilitators prompt conversations about what next steps might look like for building relationships between these department members and community groups.

After three rotations in the World Café style conversations, our event came to a close. We invited all participants to reflect on their experience. We asked everyone to write down their response to these questions: 1) What is something that you learned during the event today and

2) What are the next steps that you are going to take after today? We then had a few folks share their answers with the larger group to close out the day.

We also had participants fill out an evaluation of the event. Our evaluation questions were: 1) Did you find today to be useful? If so, why? If not, why not? and 2) What could have improved this event? We collected and compiled responses to these questions and they helped to inform our reflections and recommendations in this article.

Lastly, we invited participants to exchange contact information and make plans for following up with each other. To assist in their next steps, we provided a resource document for both university and non-university participants. The resource guide included a brief biography and contact information for all the university participants, local and national funding opportunities available to university and non-university folks, logistical resources such as organizations that do science consultation for community groups, training resources for professors and students, a list of relevant courses at the University of Minnesota, a list of organizations and societies that support community-drive science, and readings on community-based research (resource guide included in Resources).

Follow-Up Activities

Following the event, we submitted community member's addresses to our accountants to get their financial compensation ($200 checks) mailed out. We also had a COVID-19 exposure during the event, so we quickly communicated this to all participants. A month after the event, we followed up with everyone thanking them for their participation and inviting them to share feedback and any actions they had taken so far. At this time, we learned that participants still hadn't received their checks, so we followed up with our accountants and communicated the timeline with all of the participants.

In January, we convened a conversation with department members who had participated in the summit to hear what they were doing and what road-blocks they had experienced. Several people informed us that they had been working with community groups. We also heard about challenges, which have informed our following reflections on this event.

One of the community participants also reached out to us about hosting the summit again in the Fall of 2022, possibly at George Floyd Square in Minneapolis. This conversation has pushed us to start talks with our department leadership about hosting this event annually and how to create a sustainable process for organizing this event. We believe that continuing to show-up in community and continuing these conversations, especially when invited, would be a powerful step in building relationships and transforming our department and our science.

The Results

We held this event to start the process of building relationships with Twin Cities communities marginalized within the field of earth science. While this work must be a long-term commitment, some short-term connections have emerged from the summit:

- Two university researchers hosted a GIS workshop for Minneapolis Edible Boulevards to develop interactive digital maps of community garden sites and soil test data sites in the two Minneapolis Green Zones. These maps are being shared citywide to help community members find spaces where they can grow fresh produce and identify what the lead levels are in or near their neighborhoods.
- One university person has been joining the meetings of Rights of Mississippi River.
- A lab group in ESCI is working to find funding to support a project with Urban Roots.
- We have been invited by Jay Webb of Global Peace Farms to host a similar event at George Floyd Square.
- One university person is helping to run soil samples for Global Peace Farms and facilitate connections with other departments.

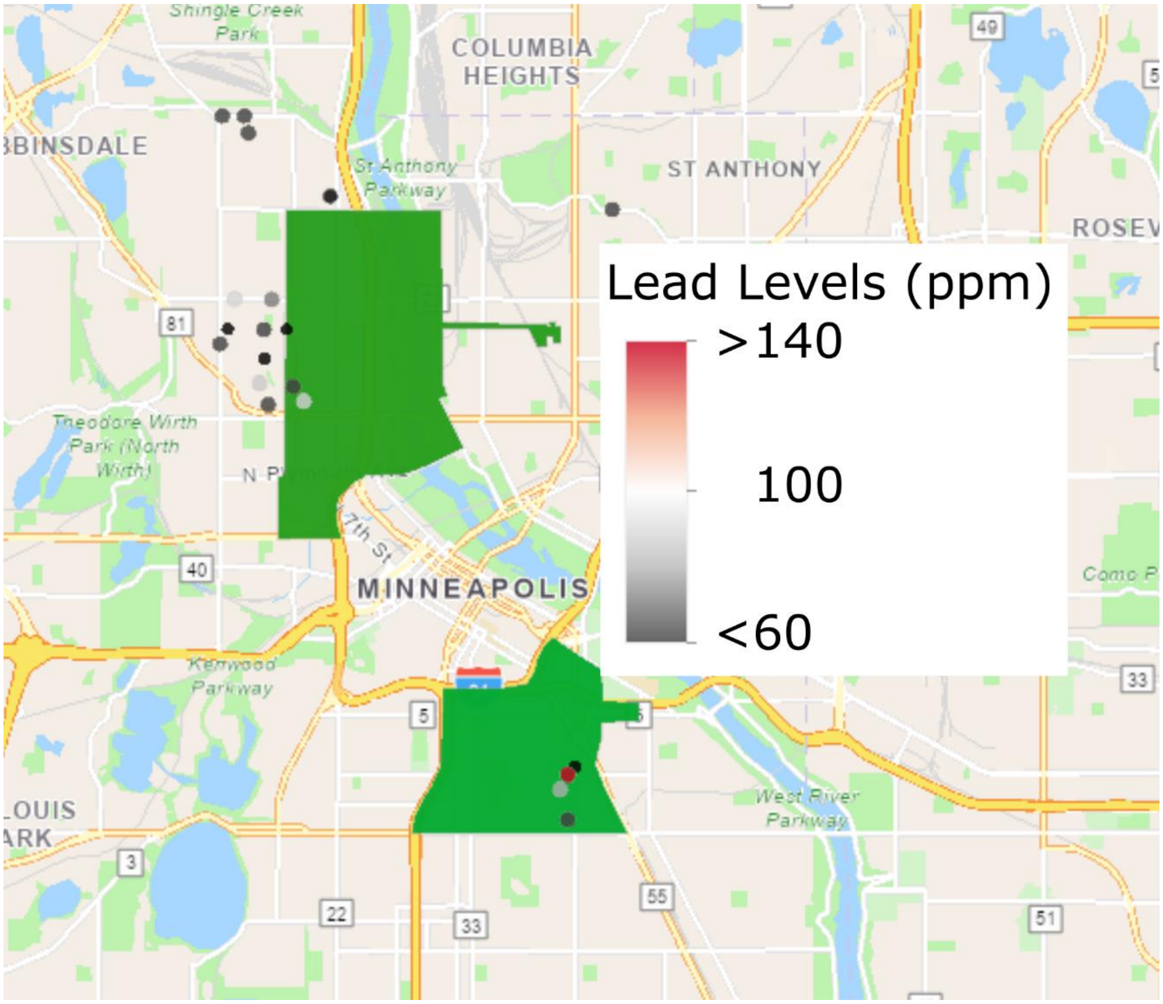

Figure 5.3. GIS map of soil sample locations from Minneapolis Edible Boulevards and Minneapolis Green Zones. This data visualization was generated during GIS workshops hosted for Minneapolis Edible Boulevards, with support from the Minneapolis Green Zones' Task Force Initiative that funded two young community leaders.

Reflections

Knowing Our History

We learned early on that understanding the history and context of our department, university, and local community was a critical first step to appropriately engage with community members. Both university and community members come to these conversations with different backgrounds and levels of understanding about the University of Minnesota, the Twin Cities, and earth science. Many university people, including two of the authors, are transplants who only live in the Twin Cities temporarily, making it difficult for them to learn the complexities of local issues.

We learned that many local groups have had negative experiences with the university or local government contributing to their suspicion or disinterest in our relationship efforts. In our conversations with community groups, we did our best to share the honest state of our department. Several groups told us that they were not interested in working with us, including one person who told us that our plan for compensation was not fair.

Given this history and context, we realized we would cause harm to community organizations, as the University has done in the past, by failing to follow through on our commitments, failing to provide adequate compensation, creating an intimidating, unwelcoming environment, and perpetuating power dynamics that privilege the University. How we proceeded needed to be informed by this context so we could do our best to avoid these harms and create the change we wanted to see.

Embracing Humility

While we attempted to approach this work thoughtfully and with good intentions, we were working within structures set up to benefit those already in power. So we inevitably ran into road-blocks and made mistakes in pursuit of the goal of shifting power away from the University. Therefore, it was important for us to operate from a place of humility, where we were open to learn and change based on feedback.

Being Honest

We found that being honest with our community groups about where our department was essential in building meaningful relationships. We were open with community organizations that community partnerships have not been a central priority of the department but we are working to change that. Department members are just learning how to work outside of academia and both time and money are limited to engage with community groups. We also were respectful when community groups declined to engage with us, especially given how much learning we all still have to do. While these rejections stung, we also were able to find partners who wanted to participate in the event and potentially collaborate with the department in its current form.

Prioritizing Hospitality

Our efforts towards hospitality were essential in making this event a success. Throughout the entire process we strove to make people feel welcomed and valued. Some community participants shared these reflections following the event:

> “I feel so supported.” ~ Community Group Member
>
> “Seems like you thought of ways to make everyone comfortable and move at a reasonable pace.” ~ Community Group Member

We met with every group ahead of time to start building relationships, hear their concerns, and to communicate our intention to prioritize their experience. We held these meetings at a location convenient to the community group, mostly over Zoom but also one meeting in person at George Floyd Square. The summit was directly informed by their goals and suggestions. During the event, we provided food, free parking, ample time for introductions, and a gathering space off campus large enough for us all to gather without extensive limiting on participant numbers. Renting a space unaffiliated with the University, locally-owned by any of our community partners, may have provided a deeper way to connect with these community organizations.

We also chose to hold our event over several hours on a Saturday, as that seemed to work best for most community groups. Originally, we had envisioned a 2-day event, but realized that would be asking for a lot of time from everyone. We also learned that Saturdays are generally a hard time for most faculty to attend due to family and professional obligations (and, in this case, COVID concerns), limiting their attendance:

> “5 hours was difficult. Also I wish there were more faculty. I wonder if some would have liked to come, but 5 hours on a Saturday just didn't work.” ~ UMN Department Member
>
> “Would have been nice if more faculty stayed throughout the event but I'm grateful for the time they committed all the same.” ~ UMN Department Member

During our initial survey of the faculty, we learned that Saturdays would not work for a lot of them, but decided to move forward with this date in order to prioritize our community groups. Unfortunately, this did mean fewer faculty were able to attend. Additionally, our event did happen before an increase of COVID-19 cases due to the Delta variant, and we did have a COVID-exposure at the event.

Intentionally Structuring Conversations

Our efforts to structure conversations through a large group introduction and then World Café conversations helped break the ice, make each person feel welcome and valued, and generated the space for relationship building. We were also intentional about who we invited, bringing together community organizations interested in local environmental concerns. Here are some quotes from participants:

> "The structured networking helped, the day took its time didn't feel rushed while also not feeling as if my time is being wasted." ~ Community Group Member
>
> "I feel hopeful after meeting so many committed and passionate people. I got some good ideas from talking with others. I feel excited about possible collaborations with the university." ~ Community Group Member
>
> "I met people I would love to connect with about community change - mixing art with science to create change." ~ Community Group Member
>
> "My conversations w/community members and others at the U alike both expanded on existing ideas and passions and introduced me to new ways of thinking. There were some tangible outcomes (e.g. grant ideas) & some more ideological (how do we think about natural systems and people?) - all useful!" ~ UMN Department Member
>
> "It felt like a safe place to ask naive questions, and I genuinely feel that this was the most meaningful step towards community engaged science that I've made during my time in the department." ~ UMN Department Member

But in our effort to provide flexibility, some people felt they didn't have enough structure to envision concrete plans:

> "It was great as a non U of MN affiliate to hear of honest outreach work that you all are looking to do with partners but the open endedness can also be a challenge in learning what is possible." ~ Community Group Member

And while we were intentional about who we invited, we were also given feedback that we should invite more youth and elders into future events.

Building Internal Community

Having people supportive of community-engagement and DEI efforts within the department was an important catalyst for this event. And, the event itself helped to strengthen and grow a sense of community within the department. Our department has grown around DEI issues since the murder of George Floyd, and this event was another step in that process. We also have had one very visible community-engaged project in our department: Kawe Gidaa-naanaagadawendaamin Manoomin (First We Must Consider Manoomin/Psiŋ), a collaboration between University members and local tribes to understand declines in Manoomin/Psiŋ (wild rice) abundance. Graduate students who work on the Manoomin project were important supporters of this summit, including co-authors MN. Additionally, this project's publicity has highlighted the value and increased the awareness of community-based research to everyone in our department.

While we are grateful for the supportive community present in our department, community-based work is still relatively new for many. So we hosted internal workshops to provide university folks with resources and to open a space to talk about barriers and opportunities. These workshops served as a space to continue building support and capacity for community engaged research in our department. Spending more time within the department before the summit would have improved this event, but we were limited with time and resources. Specifically, one of our participants suggested that we provide additional help for faculty in thinking through how their skills and expertise may be relevant and useful to community partners:

> "Maybe address whether people have to have directly applicable expertise. I think everyone can get involved! And some people maybe didn't come b/c they thought they had little to offer." ~ UMN Department Member

Shifting Department Culture

In our meeting with C Terrence Anderson from the Center for Urban and Regional Affairs, he encouraged us to think of this event as the beginning of an advocacy campaign (Figure 5.1). This was not a one-time event, but a step in shifting the culture of our department and our discipline. He challenged us to see our summit as a visible example of the change we envisioned and a tool for building a coalition of supportive people. This summit would not bring about a complete transformation from day one. From that initial coalition, we could continue to build and grow our network. As more and more people become involved and committed, they push the institution to make sustainable changes. C Terrence Anderson's advice of building out our coalition aligned with feedback we received during the summit about how we could improve this event:

> "More faculty + people w/power & resources present perhaps presence from other environmental-related departments like SWAC & CFANS" ~ UMN Department Member

Creating Sustainable Change

Given our commitment to shifting the department culture, we recognize the need to create change that will outlast our tenure as graduate students. Looking forward, we are seeking to build a coalition of faculty, staff, and students willing to seriously champion this work with their time and energy. We are especially interested in faculty leadership, because faculty have a large role in department culture through teaching and research. However, we recognize the difficulties faculty face in committing to community-driven work given the institutional constraints and rewards structures of many academic institutions. We also know that this kind of labor often falls on the groups of people who regularly engage in DEI and outreach: women (Guarino and Boden, 2017), faculty of color (Jimenez et al. 2019), and students.

Sharing this Work

One barrier to shifting department culture is that we have limited venues for sharing community engagement, DEI, and teaching innovations. We have several departmental seminar timeslots, but the majority are used for academic research talks, with fewer people discussing teaching or service (though this has been changing over the last year). We believe that talking about community engagement and DEI work in the same venues as research affirms its importance and value. And we hope that sharing and receiving feedback on this particular work will inspire others to pursue further community-engaged research.

Navigating Personal Tensions

Author JJ feels personal tension between working for the university and trying to do community work. As a fourth-year graduate student, I do not feel that I represent the university, or agree with all of its priorities and strategies. And yet, I'm employed by the University, and am reliant on certification from the University to provide credibility and legitimacy to my career. Even in approaching community groups, our email opened by saying that we are a team from the University of Minnesota. We were intentional to describe where our department is with respect to community engagement, and one of our goals is to redistribute resources (money, researcher interest, access to scientific equipment) to people outside the university.

Recommendations

Lean on Existing Institutional Knowledge

We were fortunate to work with colleagues from a number of offices and departments who already engage in community-driven scholarship. These sources are dispersed across the university and coordinating meetings was no small undertaking, but the knowledge and connections we gained was invaluable. We also relied on an existing funding source to support our event. And there are many other creative funding sources spread across the university that we considered. We didn't consider non-university resources for this event, but that possibility was raised by a university participant:

> "Perhaps consider opening this kind of event in the future to AIPG, AWG, and other professional geoscience chapters. Many of the companies participating in those societies might be willing to financially sponsor future events." ~ UMN Department Member

Figure Out Compensation Well Beforehand

We knew that it was important to compensate community members for their time and expertise, and we made sure to include this in our budget. But the logistics of paying 20+ people through the university accounting system was complicated. Due to unforeseen circumstances, it took nearly two months after collecting everyone's information for them to receive payment, and we fielded many frustrated questions about why the process took so long. This threatens to erode the trust that we worked so hard to establish. Having checks or even cash at the event to give out to participants would have been more efficient, but likely difficult within the restrictions of the University.

The House Doesn't have to be Completely in Order to Invite Guests

We felt it was important to provide training and resources to members of our department prior to the event, so that there were clear expectations that this event was directed towards community members. However, not everyone in our department attended the training or the event. Rather than pushing for complete consensus and agreement from our department, we chose to engage with people who were interested. And through those workshops and discussions, we recruited faculty who previously had no experience with community-engaged work, including some who did not see their research as immediately relevant to community priorities. And while we wanted clear pathways for collaboration between community groups and faculty to emerge from this event, several community group members shared their gratitude for simply being able to connect with a university professor:

> "It was a rare opportunity to pick the professor brain." ~ Community Group Member

From this, we learned there is value in bringing people together for conversations, even if all of our faculty were not sure of what they had to offer and project plans did not emerge right away.

Involve Staff and Faculty to Sustain Effort

This effort was initiated by students, who are always transient within the university system. To create more sustainability moving forward, we are involving more university outreach staff from multiple environmental-related departments and academic centers for future planning. We hope these staff will provide continuity and institutional support to current and future student organizers. Also, by diversifying the departments involved we aim to spread out the workload, connect with more faculty, and leverage more funding sources.

We hope that with time and institutional change, faculty will be able to fully engage in and champion community-driven work. Our department is currently in the process of revising tenure and promotion documents, including language to support community-engaged research. We also believe that a flow of student leaders is vital to this work, to bring in new ideas and constantly push for change. We also hope that future students receive professional credit and financial compensation for their work.

Provide Time for Community Groups to Meet with Each Other

From our summit evaluations, we learned that community groups would have appreciated more time to connect with each other. We had structured the event to specifically connect university members with community groups, and did not build in time for each group to connect with each other:

> "More time for community groups to connect" ~ Community Group Member

We learned that the opportunity to gather organizations with common goals is rare due to all the scheduling and time constraints that people have.

Connect More Often, More Deeply, with More Folks

Lastly, we heard feedback about connecting with more community group members, especially youth. Other feedback shared called for more workshops to increase our interactions and provide more time for community groups to talk with all of the researchers. Additionally, thoughtful facilitation tips were also shared to deepen our connections with one and other:

> "Healing exercises or breathing intro, ice breaker in the beginning and lunch" ~ Community Group Member

Summary

Following the murder of George Floyd in Minneapolis, students, staff, and faculty at the University of Minnesota increased their efforts around diversity, equity, and inclusion. We were interested in building relationships between our department and local environmental organizations, with a special emphasis on urban residents and people of color. We hosted a summit that brought together 6 community groups and members of our department to have conversation and begin building community. Reception of the event was overwhelmingly positive, and several collaborations resulted from our time together. We learned and great deal from organizing this event and have several insights that can inform others interested in hosting a similar event: draw on existing expertise, be honest about institutional history and current situation, provide compensation for community members, provide training for university members, build in sustainable practices, and work to maintain relationships. We plan to host similar events moving forward, and look forward to continued learning and growing.

Sources

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Matson, L. et al. 2021. Transforming research and relationships through collaborative tribal-university partnerships on Manoomin (wild rice). *Environmental Science & Policy* 115, p. 108-115. DOI: 10.1016/j.envsci.2020.10.010

Resources

Sawkins fund application: https://bit.ly/EJSawkinsApp

Resource document: https://bit.ly/ESCIresources

Facilitation guide: https://bit.ly/ESCIFacilitationGuide

CURA Life Cycle of an Organizing Campaign: https://www.cura.umn.edu/sites/cura.umn.edu/files/2019-08/Life_Cycle_of_an_Organizing_Campaign.pdf

Chapter 6. How to train your humans (to be Earth scientists) – the pedagogy of field trips

This work was previously published in the Journal of Geoscience Education as *Jones and Washko, 2021. More than fun in the sun: The pedagogy of field trips improves student learning in higher education.* Jones and Washko contributed equally to the research and writing.

Field experiences are a fundamental and well-loved tool for teaching in the natural sciences. However, a number of concerns threaten continued incorporation of field experiences into courses, including increased class sizes, strained finances, legal liability, accessibility concerns, and the effects of COVID-19. Because of these barriers, it is critically important to investigate and articulate the value of field trips to better advocate for their continued implementation. By reviewing existing literature on traditional field trips and courses, virtual field experiences, and accessible field trips, we have identified several attributes that contribute to the value of field trips as a pedagogical tool. The strength of field activities lies in 1) the integration of active learning, 2) the co-creation of knowledge through collaborative, problem-based activities, 3) place-based learning that provides real-world context, and 4) rapid feedback between peers and instructors. These strategies are well-represented in scholarship on teaching and learning, and further, strategies implemented in field learning may help to reduce the achievement gap for underrepresented groups. Applying the four attributes of field trip pedagogy to classroom and virtual classroom activities, as well as to virtual field trips, can improve teaching and learning when field trips are not possible. Instructors should aim to re-create as many of these attributes as possible to design courses that are as impactful as those involving traditional field trips.

Introduction

Field trips, here defined as any formal field experience with a learning objective, are a long-established tradition in the natural sciences (Behrendt & Franklin, 2014; Fleischner et al., 2017; Malbrecht et al., 2016; Malone, 1999; Mogk & Goodwin, 2012). Field trips are viewed as a crucial component to teach students the skills and content that they need to be successful scientists. In particular, field trips provide hands-on experience with professional equipment and measurement techniques (Fryar et al., 2010; Fuller, 2006; Ghail & Standing, 2019; Malbrecht et al., 2016) and promote professional and study skills like note taking, sketching, and hypothesis testing (Hefferan et al., 2002; Malone, 1999; Wheeler et al., 2011). Field trips can also enhance personal skills like self-efficacy, autonomy, and sense of ownership over work, and interpersonal skills like collaboration, ability to provide feedback, and building a peer network (Atchison et al., 2019; Fleischner et al., 2017; Fuller, 2006; Hefferan et al., 2002; Houser et al., 2011; Larsen et al., 2017; Lei, 2010; Wheeler et al., 2011). Importantly, field trips have been shown to increase student learning gains, particularly in higher-order forms of learning from Bloom's Taxonomy, such as applying and analyzing knowledge (Bowler et al., 1999; Elkins & Elkins, 2007; Houser et al., 2011; Kern & Carpenter, 1986; Kolivras et al., 2012; Seifan et al., 2020).

Field trips promote higher-order learning because of the ingrained pedagogical practices. Students take knowledge learned in the classroom and apply it in the field setting, actively contextualizing their knowledge and transitioning it from being theoretical to practical (Kent et al., 1997; Krakowka, 2012; Schiappa & Smith, 2019). By allowing students to embody their learning, work in groups, and hear lectures, instructors can vary the delivery of information (Kent et al., 1997). This type of varied content delivery, known as multimodal learning, is an important component of inclusive instruction and assessment (Qualters, 2016). Though the benefits of field trips are widely recognized, the pedagogies that lead to learning in the field have not been synthesized to create a template for reaching higher-order thinking and student learning.

Despite their pedagogical and disciplinary benefits, field trips are declining at many academic institutions (Barrows et al., 2016; Fleischner et al., 2017; H. Wilson et al., 2017). Whether it be for lack of institutional support (H. Wilson et al., 2017), lack of funding (Behrendt & Franklin, 2014; Lei, 2015), large class sizes (Lei, 2015), students having family duties (Zavaleta et al., 2020), the potential for liabilities (Lei, 2015), the threat of disease (Scott et al., 2006; personal experience with COVID-19 pandemic), online class offerings (Bursztyn et al., 2017), or accessibility concerns (Carabajal et al., 2017; Hendricks et al., 2017), field trips are more difficult to implement. This is detrimental to courses where field experiences are central, such as in the natural sciences. Understanding the value of field trips helps to ensure administrative support for their continued use. Further, applying the pedagogical practices learned from field trips to emerging virtual and asynchronous field experiences will improve student learning and boost the value of online or hybrid courses.

Both authors were privileged enough to attend small liberal arts colleges as undergraduates, where fieldwork was well-incorporated into the curriculum. We have both moved to larger institutions in our graduate careers and do not see fieldwork incorporated to the same degree. In light of our personal experiences and studies that document an overall decline of fieldwork in higher education (Barrows et al., 2016; Fleischner et al., 2017; H. Wilson et al., 2017), we came to this work with several research questions: Do field trips actually enhance student learning? What is it about field trips that affects learning? And how do we re-create the part of the pedagogy that makes field trips successful when we cannot bring students into the field?

Literature Processing

To answer these questions, we reviewed existing literature on traditional field trips and courses. We did not attempt a systematic review of literature, rather we were reading literature that related to our questions. Our process was similar to the qualitative evidence synthesis described by Grant & Booth (2009), which aims to identify and interpret themes across multiple studies in order to broaden understanding of a subject. Using Google Scholar and Web of Science, we searched terms like *field trip*, *field course*, *field experience, and virtual field trip* with terms like *higher education*, *undergraduate*, *graduate*, *natural science*, *science*, *ecology*, *environmental*, *geology*, and *teaching*. We eliminated papers that were field trip or lab lesson plans and other papers that did not address learning attributes of field experiences, drawing mainly on higher education literature (not K-12). The papers we considered were those specifically describing the effects a field trip, field course, or field experience had on students' skills, learning, attitudes, and growth as scientists.

After reviewing all the skills and concepts associated with field trips, we looked for themes aligned with highly regarded teaching practices and summarized our findings into four categories: active learning, knowledge co-creation, feedback, and place-based values (Figure 6.1). Though these categories are not exhaustive (i.e. field trips engage other teaching practices), they capture much of the value that we identified and are well-known learner-centered practices (Hoidn & Klemenčič, 2020; Snyder et al., 2019). Below we describe each of these in the context of traditional field trips, and provide guidance on how these attributes can be applied to non-field activities. We also discuss the potential of these high-impact teaching strategies to promote recruitment, learning, and retention of students from underrepresented groups.

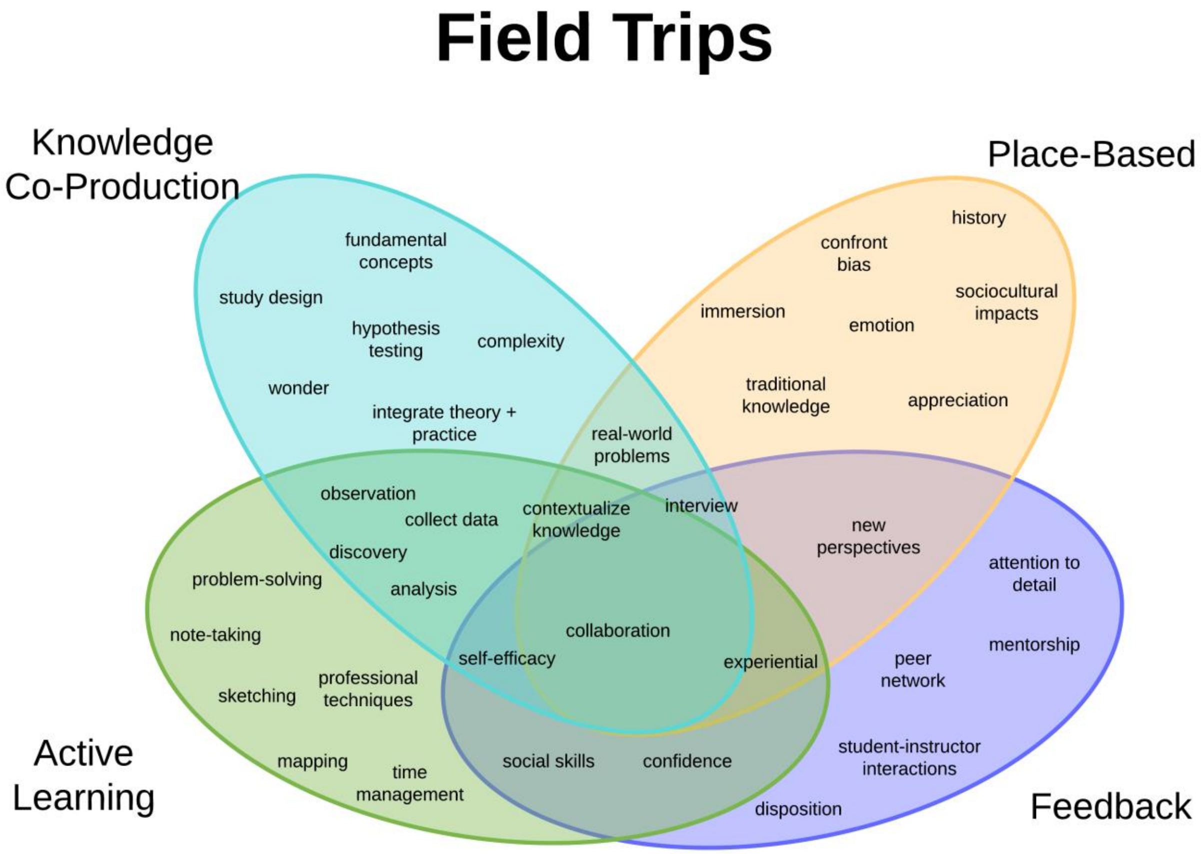


Figure 6.1. Field trips are important to the natural sciences because they promote enhanced technical skills, content knowledge, and personal growth. We found examples of these in the literature and arranged them around existing highly-regarded teaching methods (active learning, co-production of knowledge, place-based education, and feedback). In this figure, activities, skills, or other attributes involved in field trips are listed inside the bubbles associated with specific pedagogies. However, these attributes can be associated with multiple pedagogies, fitting in the overlaps of multiple bubbles. Due to their multiple associations, these attributes could be arranged within the diagram in numerous ways, of which we have provided one example.

Considering pedagogy: Why field trips are effective

One: Integration of active learning

Active learning involves "activities that students do to construct knowledge and understanding" (Brame, 2016). In other words, active learning is an instructional practice where students complete activities, use higher-order thinking to consider what they are doing, and focus more on skills than information. Sometimes a field trip is simply a lecture in the field (Higgs & McCarthy, 2005), but most often, field trips are active (Krakowka, 2012). When field trips provide hands-on, problem-based activities, students engage in higher-order thinking and develop as scientists.

Field trips offer experiences unavailable in a classroom that allow students to engage all of their senses. Being immersed in a complex, new place supports real-world problem solving and hands-on work, which students both appreciate and enjoy (Bruening et al., 2002; Fuller, 2006; Jolley et al., 2019; Lei, 2010; Schiappa & Smith, 2019; Tonts, 2011). Because the experiences on a field trip are grounded in the complex occurrences of the real world, students can actively engage in experiential learning, where the purpose of the trip is to solve a problem or make a discovery (Malbrecht et al., 2016; Malone, 1999). Connecting classroom ideas to real-world experiences demonstrates the relevance of theoretical concepts and allows students to integrate their lived experience with course content. This uplifts the student perspective as a valuable, empowering part of the learning process (Tuitt et al., 2018). By extending learning beyond the content and forcing students to confront the complexity of the real-world, field lessons become an especially valuable mode of learning (Lei, 2010; Pyle, 2009).

The active, experiential nature of a field trip promotes higher-order thinking and skill development. Field experiences cause students to observe, question, re-evaluate, and inspire the search for explanations (Fleischner et al., 2017). Students have the opportunity to experience something new, reflect on it, analyze their data or knowledge, and test the idea to develop new knowledge (Behrendt & Franklin, 2014). These deep-thinking effects are accompanied by numerous skills, both personal and professional. For example, attributes strengthened during field-based lessons can include attention to detail, keen observing, personal organization, a sense of ownership of one’s work, interpersonal skills, self-efficacy and autonomy, time management, scientific identity, creating and evaluating hypotheses, and more (Jolley et al., 2019; Wheeler et al., 2011). In addition to problem-based field lessons, student-led teaching in the field can deepen learning and create a sense of place and empowerment (Marvell et al., 2013), as well as allow students to bring their culture and emotions to the lesson (Tuitt et al., 2018).

Two: Co-creation of knowledge

The co-creation of knowledge is a collaborative process where students and instructors generate ideas, learn skills, and produce data, culminating in novel information for both parties (Gorzycki, n.d.). Many of today's college students want to be active partners in higher education courses, working closely with their professors to become valuable members of the field (Dollinger et al., 2018). Field trips can provide a setting for this kind of student-instructor collaboration and co-creation of knowledge where, in addition to mastering course content, students contribute to the discipline. Mogk and Goodwin describe, “The field setting is one of the important crucibles where science and scientists codevelop: Learning in the field has always been about creation of new knowledge by direct observation of Earth while providing an important foundation in the training and professional development of the next generation of geoscientists” (2012). Posing as valuable to the instructors’ and students’ knowledge and discipline-specific advancements, field trips are fundamental to the higher education process, especially in the natural sciences.

Field trips can promote the co-creation of knowledge because they are often project-based and exploratory. When field trips are used to conduct a study expanding on class content, the knowledge is not being handed from the professor to the students, but rather, they are discovering it together. In my [author SW] personal experience at Allegheny College, ecological and environmental science field trips were often centered around a question, sometimes involving a local land management or private partner. The whole class participated in data collection in the field, analysis during later classes, and writing of a report, which was sometimes publishable later on (such as Bowden et al., 2019; Wayman et al., 2014; also see ‘Allegheny Environmental Publications’ at https://sites.allegheny.edu/envsci/student-resources/). These discovery-based activities promote collaboration between established scientists and scientists-in-training.

Three: Peer-instructor feedback

The collaborative and intensive nature of field experiences creates opportunities for rapid feedback between students and instructors. Rapid feedback is beneficial to reinforce positive interpretations and skills and to dispel misconceptions before they become solidified (Friess et al., 2016; Mogk & Goodwin, 2012; Wheeler et al., 2011). Instructors can also help direct students if they feel overwhelmed by the amount of information in a new field setting

(Bentley, 2009). Some studies suggest that students receive more feedback in the field than in a classroom (Demirkaya & Atayeter, 2011).

Though not explicitly stated in literature about field trips, this type of feedback can be viewed as a type of formative assessment. Formative assessment is a set of practices that elicit, interpret, and use evidence about student learning to guide decisions about instruction. Using this type of assessment will likely lead to better instruction than would have been offered in the absence of the evidence (Black & Wiliam, 2009). In effect, instructors use formative assessment to understand what students are learning and to adjust their teaching to increase student learning. This can take a variety of forms that can be (and already are) implemented in field experiences, including informal conversations, peer feedback, self-reflection, daily presentations, turning in draft materials, and drawing diagrams in the sand (e.g. Fagan & Sturm, 2015; Hesthammer et al., 2002) . Formative assessment has been uplifted as a valuable learning tool that increases student learning, promotes self-efficacy and autonomy, and improves teaching by forcing instructors to reflect on their teaching (Gibbs & Simpson, 2005; Kingston & Nash, 2011).

Feedback between students and instructors can also lower perceived barriers in the hierarchical educational structure. Informal moments such as transit between field sites, cooking, and sitting around a campfire at night allow students to ask questions and express ideas in a low stakes environment (Núñez et al., 2020). This builds the relationship between students and instructors and reduces the intimidation that students feel to ask for help from professors. This extends beyond the time in the field, as students feel more comfortable visiting office hours and asking questions in class after field experiences (Houser et al., 2011; Kamen & Leri, 2019; Kern & Carpenter, 1986; Stokes & Boyle, 2009).

Field trips also provide opportunities for interaction and feedback among peers. These interactions produce academic benefits, including active engagement, greater investment in the material, and greater depth of understanding (Duran, 2017; Goldschmid & Goldschmid, 1976). The social aspect of group work is also important. Interpersonal skills are valuable career skills, as most professions require collaborative work. Students also leverage the social connections that they build during field experiences to form study groups (Hefferan et al., 2002; Houser et al., 2011). Further, students consistently rate the social aspects of field trips as highly valuable, regardless of the learning benefit. These social connections contribute to a positive affective (i.e. feelings, emotions, and attitudes) response, which can improve learning outcomes and encourage students to remain in the natural sciences (Kortz et al., 2020; Mogk & Goodwin, 2012; Stokes & Boyle, 2009).

Four: Place-based education learning

Formally, place-based education is a relatively new teaching philosophy, first detailed in the 1990s (Elder, 1998). Place-based education (PBE) aims to teach students by situating learning in a place- using local context, knowledge, and understanding. A ‘place’ in this usage is distinct from a geographic location because it is given meaning by human experience. Though the strict definition of PBE is relatively new, the practice parallels methods of teaching before formal schools were established, traditional Indigenous ways of knowing and teaching, and the practices of natural history, which center human relationships to physical locations (Semken et al., 2017). PBE has clear ties to the natural sciences through the collection of spatially explicit data and the recognition of the uniqueness of places. Semken (2005) identified five central characteristics of a geoscience-based PBE model: a focus on the natural attributes of a place, acknowledgment of the diverse meaning that a place holds, creation of authentic experiences within that place, promotion of sustainable living, and enrichment of sense of place. Ultimately, place-based education aims to increase students’ engagement with a place by allowing them to experience it fully and develop their own sense of meaning.

Traditional field trips typically engage three of these five characteristics. Trips are focused on the processes and features of the location where they are held, providing specific local examples and context to concepts covered in the classroom. These trips provide authentic experiences such as self-paced exploration and the collection of primary data, as opposed to instructor-moderated exercises in classrooms. Participants are imbued with a sense of place by physically operating in the space and having new experiences that are tied to a specific locale (Jolley et al., 2019). Less frequently in the natural sciences, field trips discuss the diverse meanings that a place holds (e.g. discussing the history of a National Park when observing the geology) or engage in discussions of sustainable practices (though some disciplines are explicitly concerned with these aspects). By incorporating the diverse meanings of places and issues of sustainability, field trips can be enriched with multicultural and multidisciplinary viewpoints. Many of the great challenges in the natural sciences require cross-disciplinary collaboration, and explicitly introducing these concepts can help students understand and appreciate interdisciplinarity (Gosselin et al., 2016).

The development of a sense of place can improve student retention in the natural sciences. Many natural scientists cite early field experiences as strong determinants of their interest in science. By camping, working, and interacting with peers in the field, students develop attachments to the places where they work (Jolley et al., 2019). These experiences are also important to developing an identity as a scientist, which is tied to retention (Atchison et al., 2019; Streule & Craig, 2016). Aesthetic beauty, a sense of wonder, and affinity for nature promote positive emotional response and enhance sense of place (LaDue & Pacheco, 2013; Semken et al., 2017; Stokes & Boyle, 2009). The importance of place continues into our professional work as field scientists; we think of places where we conduct research as 'our' field sites due to numerous hours of work and important personal and professional experiences that occur in the field, and we often return to these locations to teach or as visitors.

Important considerations for underrepresented groups doing field work

Inclusive Pedagogy

We have demonstrated that the specific pedagogies employed on field trips support student learning. There is also research to suggest that these pedagogical approaches are particularly impactful for students from groups underrepresented in science, technology, engineering, and math (STEM). Here, we explain how active learning, co-production of knowledge, feedback, and place-based education can provide learning gains for underrepresented students and improve the inclusiveness of higher education natural science courses. Our conclusions align with recent work suggesting field-based courses contribute to reducing the achievement gap for underrepresented groups (e.g. Beltran et al., 2020) and improve retention of underrepresented students by stimulating the development of scientific identity and confidence (Zavaleta et al., 2020).

Active Learning & Equity

As a teaching technique, active learning has been shown to benefit all students; however, those from underrepresented backgrounds reap the most benefits (Theobald et al., 2020). The combination of increased structure within the activities and the promotion of self-confidence and belonging through team interactions renders active learning beneficial for students (Ballen, 2020; Collins et al., 2019; Jordt et al., 2017). Further, actively working in groups can make large classes feel smaller, improving participation and reducing the feeling of invisibility among students (Ballen, 2020). Consequently, field trips may play a role in equitable learning experiences in higher education because field activities are often inherently active and group-oriented, providing the foundation for the aforementioned benefits.

Co-Producing Knowledge & Anti-Racism

Co-constructing knowledge has been identified as an anti-racist pedagogical practice. By engaging with students through the co-production of knowledge, the instructor demonstrates humility, openness, and allyship (Akamine Phillips et al., 2019). Further, the collaborative nature of the practice reduces the hierarchical structure of the class, allowing more voices within the class to be heard and building a learning community where many types of knowledge and beliefs are valued (Cooper, 2006). In the field, co-producing knowledge may involve students and instructors collecting data for a class research project. Working together in this manner can make students feel like colleagues and give them a sense of what it’s like to be a scientist (e.g. Fleming, 2015). Structured undergraduate research projects, such as through the Research Experience for Undergraduates (REU) programs, which involve a high proportion of underrepresented students and occur in field settings, have been shown to help students envision themselves in science careers and increase retention in STEM (Blake et al., 2013; A. E. Wilson et al., 2018). Further, underrepresented REU students have been shown to make greater learning gains through their experiences (Lopatto, 2007). Taking advantage of natural settings by incorporating research projects into field (and classroom) activities may benefit learning and retention of underserved students.

Feedback & Belonging

Receiving constructive feedback and having shared experiences with peers and instructors helps students feel more comfortable within their discipline. Peer and instructor feedback may be especially beneficial for first-generation students and students from other underrepresented groups. First-generation students may be less likely to ask questions during lecture and attend office hours, so lowering the barrier between professor and student is helpful (Collier & Morgan, 2008; Kim & Sax, 2009; Means & Pyne, 2017). The frequency and informality of communication in the field can help students feel more comfortable talking with their instructors and asking questions, even after returning from the field (Kern & Carpenter, 1986;

Stokes & Boyle, 2009). Similarly, peer connection and group work have been shown to be effective for students of color and first-generation students (Eddy & Hogan, 2014; Nelson, 1996; Toven-Lindsey et al., 2015; Treisman, 1992). Working in groups helps to build social and intellectual contacts, create a sense of belonging and self-efficacy, and to de-stigmatize academic achievement. A strong sense of belonging is important for students of color in predominantly white disciplines, who may doubt their ability to succeed without prior knowledge of the discipline or representative role models (Karsten, 2019; Zavaleta et al., 2020). Field trips often involve group work and provide an opportunity to build interpersonal connections with peers and instructors.

Place-based education & Identity

Place-based curricula provide a more meaningful method to teach natural science in urban settings. Focusing on natural attributes and explicitly linking them to the structure of cities (and vice versa) allows students to view the city as a complex natural environment (Apple et al., 2014; Barnett et al., 2006; Fleischner et al., 2017; Kirkby, 2014; Semken et al., 2017). Further, the inclusion of diverse values in place-based education allows students to incorporate their prior knowledge and lived experiences, deepening their connection to the course material (Kirkby, 2014). This approach is beneficial for schools located in urban and suburban areas that do not have the ability to take students far from campus, and urban field trips have been successfully implemented asynchronously as well (Kirkby, 2014; Shinneman et al., 2020). Additionally, centering natural science in urban areas helps students to see their homes as settings that are worthy of study, rather than believing that interesting science only occurs in ‘more natural’ areas (Apple et al., 2014; Barnett et al., 2006; Fleischner et al., 2017; Kirkby, 2014; Semken et al., 2017). This can increase the number of students from urban areas interested in science, particularly if conducted in partnership with K-12 education (Blake et al., 2015; Bouillion & Gomez, 2001; DeFelice et al., 2014). There are obvious implications for racial diversity in urban recruitment, as cities have greater proportions of students of color (Snyder et al., 2019).

Place-based education has also been championed as a method to engage Indigenous students with the natural sciences. As noted, PBE parallels Indigenous teachings that emphasize the interconnectedness of humans and the natural environment and stands in stark contrast to the discipline-dominated view of western science (Ericson, 2017; Semken et al., 2017). There are many examples of place-based curricula that explicitly incorporate Indigenous viewpoints; these include the use of knowledge from tribal elders, direct work with tribal resource managers, and artwork and cultural narratives (as reviewed by Semken et al., 2017). In all of these cases, Indigenous knowledge was incorporated through collaboration and relationship-building with Indigenous communities. This is critical, because trying to incorporate these elements without the involvement of Indigenous communities can be harmful and further promote colonial habits of knowledge appropriation and extraction (Cartier, 2019; Gewin, 2021; Held, 2019). However, when Indigenous knowledge is authentically incorporated, it is uplifted as a legitimate way to understand the world (Johnson et al., 2014; Lemus et al., 2014). This can be especially impactful for Indigenous students by validating their cultural heritage and allowing them to see themselves reflected in their scientific learning (Semken, 2005; Semken et al., 2017).

Equity on field trips

While field learning is undoubtedly valuable, and can be especially impactful for students from underrepresented groups, the pedagogical benefits will not be effective without considering factors that affect the equity of the learning experience. Field work has historically been a barrier for students from underrepresented groups for a variety of reasons, including finances, family responsibility, accessibility, comfort in the outdoors, and safety (O’Connell & Holmes, 2011; Posselt et al., 2019; Sherman-Morris & McNeal, 2016). The many identities that students bring to the field, including race, nationality, gender, class, ability, and others, impact comfort and learning (Demery & Pipkin, 2021). If instructors do not plan with these factors in mind, field trips will continue to be barriers to students from underrepresented groups (O’Connell & Holmes, 2011).

Financial status is one barrier to participating in field trips or having an equitable field experience (Table 6.1). Course fees associated with field trips or field courses can prevent some students from signing up (Zavaleta et al., 2020). Dedicating a scholarship program to cover field trip fees could help to alleviate financial burdens, and fully enumerating the expected cost of a course (e.g. fees, gear, time away) will help students make informed decisions. Additionally, low-income students may not have information, access, or funds to acquire field gear required for a variety of situations (Anadu et al., 2020; Giles et al., 2020; Núñez et al., 2020). I [author JJ] struggled to afford outdoor gear as an undergraduate and occasionally dealt with physical discomfort on field trips (e.g. being cold and wet). Creating clothing guides for different field settings and having a borrowing closet or gear drive could help students feel more prepared for field trips (Table 6.1). In an internship or professional setting, field research positions that offer low or no salary may not be viable for students from low-income families, preventing them from gaining field experiences (Jensen et al., 2021). Ensuring a fair wage and potentially accommodating childcare needs, e.g. through explicit funding in a grant budget (Fournier & Bond, 2015), could help students afford to participate in field experiences; funding for both personal and professional needs has been identified as a key component for the success of REU programs (A. E. Wilson et al., 2018).

A student's living situation can also impact their ability to attend field trips. Students with jobs and family duties may have limited time to attend a field trip or field course, which may disproportionately impact first-generation and minoritized students (Hughes, 2016; Shinneman et al., 2020). Establishing the field trip schedule as early as possible, designing asynchronous field experiences, and having a policy for accomodations can help prepare students for the course. When conducting field activities asynchronously and from home (as during the COVID-19 pandemic), socioeconomic status can affect the level of biodiversity and amount of green space that students have access to (Table 6.1). Lower-income neighborhoods are less biodiverse than wealthy neighborhoods (Kinzig et al., 2005; Lerman & Warren, 2011; Melles, 2005; Schell et al., 2020). Additionally, there are differences in home ownership rates and proximity to green or blue space among racial groups in the United States, so students from some groups will have less opportunity to sample soils, make field observations, etc (e.g. Wolch et al., 2014). Rather than ignoring these differences, instructors should emphasize the diversity of settings and spatial patterns, to emphasize the importance of all habitats and the differences in student experiences (Washko, 2021).

Fear of racial violence is another barrier that prevents students from having equitable field experiences. Visiting largely white, rural areas can be uncomfortable and even unsafe for students of color (Anadu et al., 2020; Demery & Pipkin, 2021; Hughes, 2016). This may be especially true of students who do not have much experience recreating or working outdoors. Discussing risks and how problems will be addressed prior to the field trip can help students feel more safe, prepared, and understand that the instructors are allies who want to protect them (Table 6.1). Scaffolding field experiences - so that field trips in early courses are less intensive and those in upper level courses are more involved - can build competency and comfort as well

(Hughes et al., 2016). Speaking from personal experience, I [author JJ] am African-American from an urban, lower-middle class family and I have done extensive fieldwork in rural, largely white areas in the US. I have felt uneasy on numerous occasions - encountering Confederate flags on the way to field sites, coming across hunters in secluded locations, and I once had camping equipment stolen during a personal trip at a remote site. Though anecdotal, my experience is not unique, and illustrates that extra safety and logistical considerations are important when bringing students of color into the field.

Another safety aspect to consider is sexual harassment and gender-based violence. Some individuals, often women and members of the LGTBQ+ community, are at higher risk of being sexually harassed or assaulted in the field, especially when constituting the minority of the group (Clancy et al., 2014; Olcott & Downen, 2020; Sexton et al., 2016; Warren et al., 2018). Demoralizing comments about competency, value, and ability based on gender role norms can cause students to lose confidence in their capabilities in the field (Hill et al., 2021; Warren et al., 2018). Harassment may occur more frequently in field situations where the physical conditions are strenuous or remote (Hill et al., 2021). Having a clear and enforced safety policy or code of conduct for all participants, mandating allyship training, using gender-neutral language, focusing on team-building, and giving all students a chance to be leaders while in the field can reduce the risk of gender-based violence in the field and empower students (Table 6.1). Further, taking care of participants' physical needs and safety can lead to fieldwork positively influencing mental health (John & Khan, 2018).

Lastly, physical accessibility is a barrier for many disabled students interested in field experiences. Field sites may be inherently inaccessible, taking place in areas that are steep, unstable, require a lot of walking, are underwater, etc. Mobility-disabled outdoor recreationists have limited access to wilderness, preventing them from having equitable outdoor experiences (Lovelock, 2010), and the same could be said of natural science students. Selecting accessible field trip locations and embracing universal design during field trip planning (Table 6.1) can allow mobility-impaired students to participate in field experiences (Atchison et al., 2019; Carabajal et al., 2017). Further, providing tactile diagrams for visually-impaired students and captions or interpreters for hearing-impaired students enhances the inclusivity of field trips (Hendricks et al., 2017).

Table 6.1. Inclusion issues to consider when designing field experiences for students and recommendations for preventing and mitigating those issues. Sources listed provide a starting foundation for concerned instructors.

Inclusion Issue	Recommendations	Sources
Accessibility: students with mobility impairments may not be able to access remote field sites; students with visual and hearing impairments may require accommodation	**Design for accessibility:** Select field sites that are accessible (road cuts, parks with walkways, etc.), pair students with disabilities with students who do not have a disability, implement Universal Design for Learning, create tactile versions of diagrams, captions for those with hearing impairment	Atchison et al., 2019; Carabajal et al., 2017; The International Association for Geoscience Diversity (https://theiagd.org/)
Sexual Harassment: biases based on perceived and self-identified gender can lead to self-doubt and withdrawal, as well as harassment or assault from peers or strangers	**Prioritize safety and allyship:** departmental safety policy, signed behavior agreement, gender-neutral language, implement an ethic of care, diverse class leadership	Clancy et al., 2014; Hill et al., 2021; John & Khan, 2018; Sexton et al., 2016; Warren et al., 2018
Racialization of the outdoors: students of color may be uncomfortable or unsafe entering predominantly white spaces	**Prioritize student safety:** faculty bystander and antidiscrimination training, identify risks before going to the field, discuss risks/apprehension with students, address problems when they occur	Anadu et al., 2020; Demery & Pipkin, 2021; Giles et al., 2020; Hughes, 2016
Racialization of access to green space: socioeconomic and racial inequality determine access to green spaces, level of landscaping, and biodiversity	**Strength in a diversity of observations:** in asynchronous settings, design learning objectives that can be met in a variety of settings, explicit discussion of spatial patterns/inequality	Kinzig et al., 2005; Lerman & Warren, 2011; Melles, 2005; Schell et al., 2020; Washko, 2021
Financial burdens for students of lower socioeconomic status: extra costs for field courses and trips, cost of outdoor gear	**Ease student financial burden:** scholarships, include costs in course fees for financial aid, consider weather conditions, have a departmental gear closet, alumni funding/gear drives	Anadu et al., 2020; Giles et al., 2020; Núñez et al., 2020; Zavaleta et al., 2020

Adapting field trip pedagogies

Shifting from the field to the classroom or virtual classroom

We have established that field trips are important components of natural science curricula and beneficial for student learning. Certain circumstances, however, prohibit field trips from occurring. To overcome biases and barriers and give students the best learning experience despite a lack of field opportunities, we can bring attributes of field trips to the classroom by designing problem-based activities involving a sense of place and the opportunity for constructive feedback. Further, the activity could encompass a novel question, allowing for the co-creation of knowledge between the instructor and the students.

Active Learning

In the field, students partake in active learning through hands-on work like taking measurements. In the classroom, the hands-on work is indirect. For example, if students could not take a field trip to a nearby outcrop and measure fracture spacing, the instructor could create an activity where students can measure fracture spacing in the classroom or virtual classroom (Figure 6.2). The instructor could provide photos of the fractures and include a meter stick in the photos. The student groups could use ImageJ (or similar software) to measure the fractures with the reference meter and log the data. Despite taking place indoors, these activities allow students to complete measurements and somewhat grasp or visualize what it's like to work in the outdoors. Although these activities require preparation by the instructor, the engaging activity is worthwhile. For an in-depth explanation of how to combine inclusive teaching and active learning in online instruction, see Harris et al. (2020).

Knowledge Co-Production

By designing experiments, students and instructors can co-construct knowledge. For example, if students learning about aquatic food webs wanted to know how larval caddisflies contribute to the breakdown of leaf litter in a local wetland, they could create multiple treatments of leaf packs or litterbags, deploy them in a nearby wetland, and later retrieve them and analyze the data. The instructor simultaneously learns how the local wetland functions and can build upon this knowledge during subsequent iterations of the course. If repeated trips to the field for measurements are not possible, students could scour literature for studies similar to what they would have done in the field, solicit data from the authors or collect data from an online repository, and analyze the data as a class to create a meta-analysis (Figure 6.2). While students do not experience setting up a field experiment, they can still co-construct knowledge with their mentors, form hypotheses similar to those involved in field studies, contribute to the discipline, and gain experience with scientific exploration.

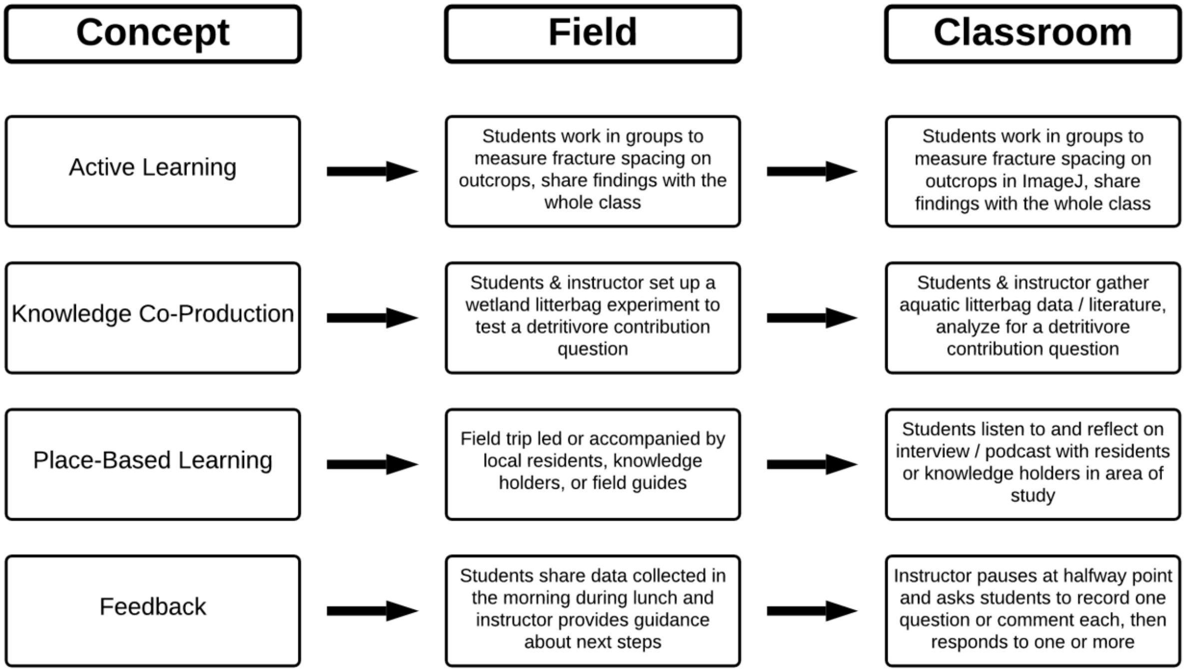
Feedback

One of the advantages of feedback in the field is the informality and frequency, which helps to guide students in a low-stakes environment. Most classroom activities and assignments incorporate feedback from instructors, but that often comes exclusively as grades. Students may have difficulty differentiating useful feedback from criticism when feedback is attached to grades, depending on the nature of the comments and other factors (Guskey, 2019). In the classroom, providing opportunities for routine and low-stakes feedback can recreate the benefits seen in the field. For example, students could submit anonymous questions after each lecture that would be addressed via email to the class or at the beginning of the next class session (Figure 6.2). This can quickly dispel misconceptions and provide extra context that students deem relevant. For larger assignments, drafts or individual consultations can be required so that students can receive feedback prior to turning in work. Both of these strategies may help students see their instructors as more approachable, and remove barriers between instructors and students.

Place-Based Teaching

Principles of place-based education are perhaps the most difficult to implement in the traditional framework of science courses. Content coverage is often prioritized in science courses due to institutional standards (credit hours, course sequencing), tradition, and professional and student expectations (Barr & Tagg, 1995; Luckie et al., 2012; Petersen et al., 2020). Place-based education devotes time to topics that are beyond the traditional scope of these classes, but investing in place-based methodologies is worthwhile to engage students from underrepresented backgrounds and to inspire interdisciplinarity and critical thinking. When a field trip is not possible, focusing on the area around the campus is a sound strategy, as the campus is familiar to students and allows them to link their everyday activities with scientific inquiry and processes. When working with remote data, activities can be imbued with a sense of place by including historical and contemporary photographs and narrative stories by residents or scientists (Figure 6.2). For example, in a geomorphology course in Fall 2020, I [author JJ] used the example of the Mississippi River flood of 2011 to examine the geomorphic consequences of flooding as well as the complex social and political dimensions of rivers through the case of Pinhook, Missouri, which was destroyed during the flood. The unit included work with aerial imagery, geomorphic change detection, and hydraulic model outputs, as well as a podcast, a short documentary, and an excerpt from an ethnography written about the residents of Pinhook

(Center for Investigative Reporting 2018; Goodwell et al., 2014; Lawrence & Lawless, 2014, 2018; Luke et al., 2015). Though I sacrificed a lecture to a non-scientific podcast, the discussions about the case were rich and students thought critically about how to connect science to real-world issues, a valuable skill for those who go on to careers in science.



Concept	Field	Classroom
Active Learning	Students work in groups to measure fracture spacing on outcrops, share findings with the whole class	Students work in groups to measure fracture spacing on outcrops in ImageJ, share findings with the whole class
Knowledge Co-Production	Students & instructor set up a wetland litterbag experiment to test a detritivore contribution question	Students & instructor gather aquatic litterbag data / literature, analyze for a detritivore contribution question
Place-Based Learning	Field trip led or accompanied by local residents, knowledge holders, or field guides	Students listen to and reflect on interview / podcast with residents or knowledge holders in area of study
Feedback	Students share data collected in the morning during lunch and instructor provides guidance about next steps	Instructor pauses at halfway point and asks students to record one question or comment each, then responds to one or more

Figure 6.2. Field trips can incorporate four main pedagogical attributes: active learning, knowledge co-production or co-construction, feedback (between peers and between the instructor and the students), and place-based learning. These four attributes are transferable to classroom activities when field trips are not possible.

Putting these attributes together, a multi-faceted activity arises. Students should learn about the environment and history of a place, work with data from that place, brainstorm an answerable question about that place’s ecology/geology/etc., and work with the instructor and peers to answer the question. Throughout the process, students give and receive feedback to guide learning and promote growth. Ideally, this structure can be implemented throughout a course by using backwards design, where assignments are devised to align with specific course objectives. For example, instructors should consider these attributes when designing course objectives and outcomes, within course modules, as the capstone of a course or multi-week exploration of a topic, as well as in a singular lab, class activity, or assignment. These types of projects can introduce students to working in different facets of a discipline, helping them discover a specialization or area to improve. Giving students the opportunity to engage in field-inspired activities may facilitate a sense of belonging and contribution to the discipline, demonstrating that they can pursue careers in the natural sciences.

Faculty are notably constrained by time and resources, which can prevent them from implementing innovative teaching strategies (Hovey et al., 2019; Shadle et al., 2017). However, instructors are motivated by improvements to student engagement (Hovey et al., 2019; Shadle et al., 2017). The pedagogies that we outline above have clear benefits for students that can serve as motivation for instructors. Research also suggests that building upon current practices, such as iterating on activities from existing field trips, makes innovation more manageable (Hovey et al., 2019; Shadle et al., 2017). Additionally, institutional training about learner-centered teaching and ongoing teaching support can improve adoption of new teaching strategies (Andrews & Lemons, 2015; Ebert-May et al., 2015). These teaching changes could make the difference for student success in science. Positive undergraduate experiences and supportive instructors can be key to retention of underrepresented students in the natural sciences (Sherman-Morris & McNeal, 2016).

Implications for Virtual Field Trips

As virtual field trips (VFTs) become increasingly common, there are more published assessments of their effectiveness. While VFTs have been shown to increase appreciation for the environment and natural sciences (Bursztyn et al., 2017; Markowitz et al., 2018), student enthusiasm for novel technology (Pringle, 2013), and provide important introductions or preparation for traditional field trips (Burden et al., 2017; Jolley et al., 2018), there are few studies comparing the effectiveness of a VFT to a traditional field trip. Current research on these comparisons has yielded mixed results, with a couple instances where traditional field trips were better (by author metrics of student performance or appreciation) than VFTs (Kolivras et al., 2012; Seifan et al., 2020), and many instances where there was no difference between traditional field trips and VFTs (Garner & Gallo, 2005; Klippel et al., 2020; Ruberto, 2018; Shinneman et al., 2020; Stumpf et al., 2008). We did not find any instances where a VFT was better than a traditional field trip. Importantly, there are many instances where having a traditional field trip, or a VFT, is better than not incorporating one (Bowler et al., 1999; Elkins & Elkins, 2007; Houser et al., 2011; Jolley et al., 2018; Kern & Carpenter, 1986).

Although VFTs can be highly effective teaching tools, several shortcomings of VFTs have emerged. These include a lack of immersion (Lei, 2015), reliance on instructor direction (Mead et al., 2019), difficulty with higher-order questions (Friess et al., 2016; Kolivras et al., 2012), technological difficulties (Jolley et al., 2018), lack of flexibility once an activity is created (Lei, 2015), demanding preparation (Pringle, 2013), and a lack of classmate interaction (Klippel et al., 2020). The four concepts that we outline above (active learning, co-production of knowledge, place-based learning, and feedback) may address the shortcomings noted in the VFT literature.

Most VFTs use active learning, as students are required to navigate through activities at their own pace and zoom in and out of images to make measurements and observations. VFTs are place-based in that they focus on specific locations, but often do not incorporate multiple interpretations of place. Adding this element (e.g. via video or audio interviews) might help students feel more engaged with the material and might lessen the abstraction of working virtually. Feedback between class members is difficult in a virtual reality setting, unless everyone is in the same virtual space. Making VFTs group-oriented could provide opportunities for feedback. Further, VFT programs with adaptive feedback settings can respond instantaneously to student actions and enhance interactivity, and has been linked to instances of marked student learning gains within a VFT (Mead et al., 2019). Co-production of knowledge might be most difficult because VFTs are pre-made, thus cannot promote unexplored territory. While VFTs have shown to be valuable educationally, they cannot offer the same full-body experience and novel research opportunities as a field trip. We recommend that instructors plan field trips when possible, and arrange a VFT or other activity based on pedagogies of field trips for instances when field trips are not possible.

Conclusion

Field trips are widely regarded as formative experiences in the natural sciences that are integral to student learning. We find that learning on field trips stems from the pedagogy embedded in them- including active learning, co-creation of knowledge, peer-instructor feedback, and strong sense of place. Due to their numerous benefits, we need to promote the continuation of field trips, provided instructors consider the experience of underrepresented groups during planning. As field trips become more difficult to conduct due to institutional barriers, transitioning field trip pedagogies to the classroom may be a way to promote higher-order learning, academic skills, and personal development. Using pedagogies inherent to field trips, indoor activities will hopefully impart the knowledge gains of a traditional field trip and continue to inspire natural science aspirations in undergraduate students.

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Chapter 7. Conclusions, and Earth science through the lens of science and technology studies

The diverse set of chapters in this dissertation illustrate the multifaceted ways in which humans intersect with the Earth that we inhabit. Those intersections can be unidirectional – human impacts on climate, land cover, and hydrologic pathways significantly influences streamflow (which will in turn have feedbacks on humans in the form of flooding and degraded ecosystem services). The feedbacks can be multidirectional, as humans alter stream systems and enjoy unequal benefits and hazards as a result. And the practice of doing Earth science – including considerations about which humans have access to the tools and agency to ask and address questions – influences what we know and what we deem as valuable knowledge. All these processes affect the Earth and the way that we understand it.

Scholars from several critical fields have turned towards the geosciences in recent years to investigate these complex interactions, including critical Black theory (e.g., Yusoff, 2018), feminist theory (e.g., Carey et al., 2016), and critical physical geography (e.g., Lave et al., 2014). The field of Science and Technology Studies is often applied in environmental systems, and provides another lens to consider the multifaceted connections between humans and the geologic Earth. Science and technology studies (STS) is predicated on the notion that all aspects of science and technology can be studied and understood as constructed – science and technology are made by particular people with particular aims, operating in specific contexts, and using certain materials (Sismondo, 2010). As a result, science is not an objective reflection of nature, rather it is a description of the world that is filtered through the values, beliefs, and practices of scientists (Lave, 2016; Tadaki et al., 2015). Though a full analysis of Earth science through the lens of STS is beyond the scope of this conclusion section, analyzing the Earth sciences through this lens forces us to consider its broader context– the history, actors, aims, and cultural norms of the discipline – and how they influence the type of science that was practiced historically and is still practiced today.

There has been limited explicit application of STS to the Earth sciences, though Pico's recent feminist critique of field geology provides a detailed example (2022). Pico traces the origin of geology as a colonial science and focuses on John Wesley Powell and Louis Agassiz as prominent figures who conducted race-based research in addition to their geological work. She illustrates that racial science and colonial geology were intimately intertwined, as the logic that informed exploration of the geologic world was deeply tied to notions of superiority, primitiveness, and nature. This allowed scientists, governments, and militaries to exploit people and places for resource extraction and production (e.g., Goffe, 2019; Nyblade & McDonald, 2021; Pico, 2022). In modern-day textbooks, Aggasiz and Powell are praised for their brilliance, ruggedness, and adventurousness, while their race science is largely ignored (Pico, 2022). Many of the same traits that were praised in Powell and Agassiz continue to be upheld and valued in the geosciences, leading to a (literal) textbook conception of a geologist as a heroic scientist – rugged, able-bodied, adventurous, and typically, white and male (Bush & Mattox, 2020; Pico, 2022).

In addition to this idealized identity that has been constructed, the history of the geosciences influences the actual practice of doing science. The field sites that researchers investigate, the research questions they choose to ask, and the way that they parameterize landscapes are all informed by the history of the discipline and the composition of the workforce. These attributes are true in the field of geomorphology, where there is a paucity of studies on urban streams and agricultural watersheds (Urban, 2018). Arguably, only three of the 13 AGU Leopold Award winners (the early career researcher award in Earth and Planetary Surface Processes) conducted research at the intersection of humans and landscapes at the time of their award. Inasmuch as awards communicate what is seen as valuable and exemplary, the recent history of awards in EPSP signifies that fundamental science is valued more than science at the intersection of humans and geomorphology. While this is not inherently good or bad, focusing our collective energy on fundamental science (particularly if it is at the expense of human-landscape studies) limits our ability to understand human-landscape interactions (Brown et al., 2017; Chin et al., 2014; Harden, 2014; Lazarus & Goldstein, 2019; Schell et al., 2020; Slaymaker et al., 2021; Wohl, 2019). A greater integration of humans into our understanding of Earth science will be increasingly important as humans combat the greatest challenges of climate change.

Through this short analysis, we begin to see the ways that the history and practice of geoscience creates and reinforces the existing culture of the discipline – one which is disproportionately white, male, and able-bodied. Ultimately, a narrow conception of the discipline limits our ability to understand the Earth, which should be our ultimate aim as Earth scientists. Part of the challenge, then, for Earth science in the 21st Century, is to confront and undue the scientific and logistical practices that limit our ability to understand the Earth. I suggest that through a deeper engagement with the multifaceted human dimensions of the Earth sciences – including continued investigation of the ways that humans impact geologic processes, justice-informed studies of the ways that geologic processes impact human livelihoods, and challenging existing notions about scientific validity – we have the power to transform the cultural norms of our discipline. Cultural change is always resisted by those who hold power, and that is already proving true in the Earth sciences as well (Ali et al., 2021; Burton et al., 2023; Gillette and Gillette, 1972). However, if we truly want to transform our discipline to meet the challenges of the 21st Century, we need to recognize and actualize the notion that Humans are Earth Too.

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