Understanding the Impact of Natural and Built Environments on COVID-19 Outcomes in Wyoming

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Project Summary: Environmental conditions are inextricably linked to human health outcomes. One Health is a transdisciplinary approach employed by the CDC that aims to optimize health outcomes by recognizing the connections between people, animals, and plants, and their shared environment at the local, regional, national, and global levels. In the spirit of One Health, our proposed work will evaluate multiple components of the shared environment with the goal of optimizing health outcomes at the county, state, and national levels. Human disease transmission occurs within a complex environment that encompasses human and nonhuman factors. The EPA refers to the anthropogenic components as the built environment, and non-human components as the natural environment. Components of the built environment that we will evaluate include human mobility, and anthropogenic pollution such as air pollutants and mining contamination. Components of the natural environment that we will evaluate include elevation and wind speed. These factors are known to impact infectious disease and therefore, it is important to understand their impact on COVID-19. It is understood that the built and natural environments are interconnected. For example, human mobility gives rise to air pollution through carbon emissions, and wind speed influences the dispersal of airborne pollutants and viral particles. Our multifaceted approach will allow us to further elucidate connections between a variety of variables and will contribute to a holistic understanding of the spread of COVID-19.

The understudied state of Wyoming will be an impactful study site to characterize due to its rurality, and heterogeneity in terms of both built and natural environmental factors. Comparing and contrasting each Wyoming county will allow us to identify the connections between the factors examined in our study. Our findings will be used to create interactive public health information that will detail county-specific COVID-19 prevalence and connections to environmental factors. We will create interactive data visualizations, including mapping for the Wyoming Public Health Laboratory (WPHL) website. We will also produce a mobile app that provides this same interactive public health information in a format that is more convenient for the public. The interactive reporting on both the mobile app and WPHL website will be consistently updated to provide current information. We hypothesize that our selected built and natural environmental variables will be directly correlated with county-specific variations in COVID-19 outcomes. We will use structural equation modeling to communicate the directionality of correlations among built and natural environmental variables.

Intellectual merit: The findings of this work will add to a growing understanding of the influence of human mobility, pollution, and climate on disease transmission. In our globalized world, understanding these environmental factors with respect to disease networks is of paramount importance for both this pandemic as well as future disease outbreaks. By studying these relationships we will strengthen the understanding of environmental health in the rural and understudied state of Wyoming.

Broader impacts: The resources we will produce will help inform the COVID-19 related decision making of Wyoming residents, out-of-state visitors, and Wyoming policy makers. We will share our findings with kindergarten through 12th grade (K-12) students and community organizations in high impact areas of Wyoming through outreach education events with the LAMP roadshow. This outreach will expose community members to computational and epidemiological methods, and also help them better understand the COVID-19 crisis that has been affecting their community. By making our findings interactive, publicly available, and understandable for a public audience, and then presenting our findings to Wyoming K-12 students, we will help bridge a gap between academic research and the general public.

Table of Contents

Project Description

Statement of Problem and Significance

Certain environmental factors have been shown to have adverse effects on human health. Contamination of food, water, and air has been linked with increased susceptibility to disease (Li 2017). Systematic damages to the environment, such as climate change, have been shown to increase the probability of novel disease emergence (Li 2017). Numerous aspects of the built environment, especially pollution, have been demonstrated to negatively impact lung and heart health (Pope III et al. 2002). This existing problem has become amplified by the COVID-19 pandemic, as lung and heart conditions are major risk factors for COVID-19 outcomes ("COVID-19: Who's At Higher Risk Of Serious Symptoms?" 2020). We suspect that these environmentally imposed health impacts disproportionately impact residents that are unable to relocate to a safer environment. However, much of this research and public health messaging has focused on areas with high population density, with much less attention given to rural communities (Chen 2019).

While Wyoming is extremely rural, it is also home to some of the most heavily visited natural environments in the nation ("Visitation Numbers" 2020). In 2019, Yellowstone National Park (YNP) and Grand Teton National Park (GTNP) received 4 and 3.4 million visitors respectively ("Visitation Numbers" 2020). With a residential population of just 578,759, these National Park visitation numbers are roughly eight times the state's residential population ("Quick facts: Wyoming" 2020). In order to get to and from these National Parks, visitors often travel throughout the state of Wyoming ("Traffic Data" 2020). This visitation and mobility creates a sort of collision of the built and natural environments, in which large, dense groups of humans are imported into rural communities and pristine natural environments. The movement of large groups of humans clearly has potential to alter both built and natural environmental factors. These impacts may build over time, resulting in considerable changes to air quality, environmental health, and disease transmission (Pinter-Wollman, Jelić and Wells 2018; Cohen 1978).

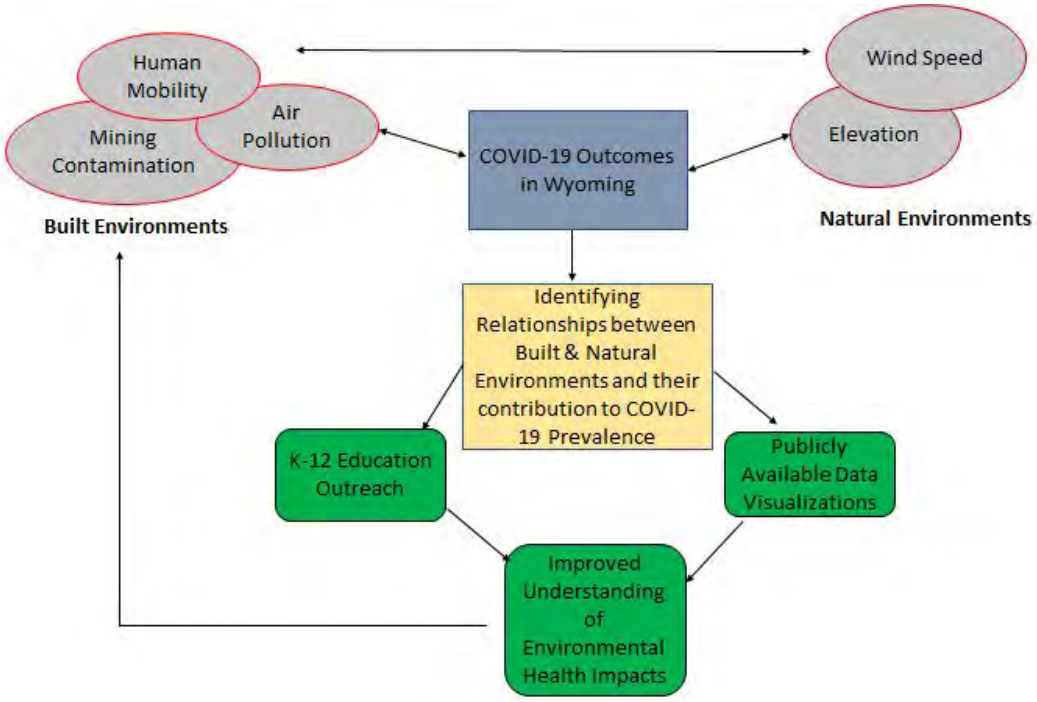
The COVID-19 pandemic, and its associated business closures and travel bans, has dramatically altered human mobility patterns (United Nations World Tourism Organization, Sustainable Development of Tourism Department 2020; Badr et al. 2020). Public health agencies are advising citizens to avoid indoor gatherings and are proposing outdoor recreation as a safe alternative ("Stay Safe, Have Fun During The COVID-19 Pandemic" 2020). These factors are likely driving observed increases in travel to rural areas, and outdoor destinations (Xingyu 2020). One such area that has seen a surge in tourism, greater than 2019 levels, is Jackson, Wyoming and the Greater Yellowstone Area (GYA) (Pope 2020). Many visitors seem unaware that SARS-CoV-2 exists in rural areas like Wyoming, and others still seem completely unmotivated to protect locals from potential transmission (Pope 2020). This interface with visitors is likely to disproportionately infect service industry employees and other frontline workers that are among the community's most vulnerable members. In light of these potentially harmful impacts of tourism, there is a need for data-driven public messaging that will inform visitors of the current level of travel-related infections in Wyoming, and the predicted impact that they will have on their chosen destination. The findings of this research may go on to inform future travel bans and other tourism related policies as the current pandemic progresses and later on, when the next disease outbreak arises.

The COVID-19 pandemic has created a more pressing concern for understanding the individual variables contributing to environmental injustices and their effects on human health. In particular, studying environmental factors across the state of Wyoming with respect to COVID-19 outcomes is of pivotal importance to community health. Factors such as air pollution, altitude, wind speed, and mining contamination are each important to understanding the impact of the environment on infectious disease spread.

Justification of Approach

By gathering built and natural environmental data from a variety of sources, and then analyzing these data with respect to COVID-19 testing data, we will be able to draw novel insights from a robust data set. Data acquisition and analysis will occur *in silico*. This will enable us to fully execute our proposed research while maintaining social distance during the pandemic. Our proposed computational methods, especially statistical analysis in R, are widely used among researchers in a number of fields. We, therefore, gain a dual advantage as early career researchers by learning these computational methods, and then applying them to perform meaningful research. R is also free, opensource, and reproducible, which enables the work done in R to be readily shared with colleagues and the general public (www.r-project.org/). Shiny is an R package that will enable us to convert our R data visualizations directly to an interactive web app (shiny.rstudio.com). CircleCI is a mobile app development platform that will allow us to distribute our data visualizations to smartphone users in a convenient format (circleci.com). By sharing our findings via interactive web and mobile apps, we hope to provide digestible and useful information to a broad, public audience. This multifaceted approach will allow for a greater, holistic understanding of how environmental injustices are impacting COVID-19 rates within the state of Wyoming.

Conceptual Model



Preliminary Data

Preliminary mobility data shows that the GYA has been experiencing increased visitation and mobility during the summer of 2020. During this time, Park County displayed a 95% increase in retail and recreation associated mobility compared to the historical baseline ("COVID-19 Community Mobility Report" 2020). Teton County has experienced a 48% increase in retail and recreation associated mobility, and a 2% increase in transit station visitation from baseline levels ("COVID-19 Community Mobility Report" 2020). YNP is reporting 2.09% and 7.70% increases in total recreation for July and August respectively ("Visitor Use Statistics" 2020). GTNP is reporting a 2.58% decrease in total recreation during July, and a 1.16% increase in total recreation during August ("Visitor Use Statistics" 2020). The recreation totals for National Park Service units are reported above in terms of percent change from the same month last year ("Visitor Use Statistics" 2020).

Visitation and mobility trends for Devils Tower National Monument (DETO) located in Crook County, Wyoming are less clear than those for the GYA, but still indicate an increase in visitation during the summer 2020 tourist season. In July, DETO experienced a 4.46% drop in total recreation compared to the same month last year. However, August and September of 2020 experienced 13.36 and 10.02 percent increases in total recreation from the same respective months of the previous year ("Visitor Use Statistics" 2020). Unfortunately, there is no Google Mobility data that meets quality and privacy thresholds for Crook County ("COVID-19 Community Mobility Report" 2020).

The Wyoming Public Health Lab (WPHL) is responsible for 60% of Wyoming's COVID-19 testing. Preliminary data gathered from the WPHL identifies Freemont, Albany, Laramie, Natrona, and Teton County as having the highest number of cases of COVID-19 ("COVID-19 Map And Statistics - Wyoming Department Of Health" 2020). We attribute the spike in COVID-19 cases in Albany County to the start of the fall semester at the University of Wyoming, where the population increases in size as students move into this county. As a whole, the state of Wyoming has the highest average wind speed in the country, maintaining an annual average wind speed of 12.9mph ("Wind Products At The Wyoming State Climate Office And Water Resources Data System" 2020). Preliminary data suggests significant differences in wind speeds between these four counties of interest ("Wind Products At The Wyoming State Climate Office And Water Resources Data System" 2020). Furthermore, Campbell, Lincoln, and Sweetwater counties were found to contain the largest coal production in the state ("USGS.Gov | Science For A Changing World" 2020). We expect these higher rates of pollution to be accompanied by higher COVID-19 cases. However, the lack of overlap between the primary coal producing counties (Campbell, Lincoln, and Sweetwater) and the highest COVID-19 prevalence counties (Freemon, Albany, Laramie, Natrona, and Teton) warrants further investigation.

Relevant Literature

Approaches, such as the CDC's One Health, that recognize the intricate connections between environmental health and human health, have been gaining traction in the US ("One Health Basics | One Health | CDC" 2020). Environmental contamination and communicable disease are two among many issues identified by One Health ("One Health Basics | One Health | CDC" 2020). Therefore, the One Health framework will guide our discussion of literature relating to COVID-19 and environmental health.

Given that the SARS-CoV-2 remains infectious in the air, different air-related environmental factors have the potential to impact the spread of the virus (Rendana 2020). One such factor is wind speed. A recent study analyzed the relation between wind speed and COVID-19 and found a strong correlation between low wind speed and increased COVID-19 cases (Rendana 2020). However, this study did not find a strong correlation between high wind speeds and COVID-19 cases, suggesting a need for further evaluation of the impact of wind speed on the spread of COVID-19 (Rendana 2020).

Air quality is a major risk factor for respiratory diseases and infections (Pope III et al. 2002). Areas polluted with airborne particulates have been shown to decrease human health by increasing the risk of inhaling microorganisms and particles that negatively impact the body's immunity (Cao et al. 2020). In particular, strong positive correlations were found between increased COVID-19 cases and four types of air pollutants- particles with diameters $\leq 2.5_{\mu m}$ (PM2.5), particles with diameters $\leq 10_{\mu m}$ (PM10), nitrogen dioxide (NO_2), and ozone (O_3) (Yongjian et. al 2020). Researchers studying Canada's, China's, and Latin America's air quality found similar results, suggesting that air pollution contributing to higher risk of COVID-19 incidence is of global concern (Bolaño-Ortiz et al. 2020; Stieb et al. 2020; Yongjian et al. 2020).

Mining contamination is a built environmental factor with potential to influence air quality, water quality and ultimately, human health ("Basic Information About The Built Environment | US EPA" 2020; Neamtiu et al. 2017). These risks are indicated by higher rates of coronary heart

disease and heart attack morbidity in regions with close proximity to mining activity (Hendryx et al. 2009). Provided that these communities are already battling detrimental health impacts from their proximity to mining contamination, understanding how an infectious disease, such as COVID-19, impacts these communities could lead to enhanced understanding of environmental risks on human health.

Human mobility has potential to interact with air quality and disease transmission (Bao, Rui and Zhang 2020; Badr et al. 2020). The levels of various forms of travel vary by county in Wyoming ("COVID-19 Community Mobility Report" 2020). These various types of travel include retail and recreation, residential, and workplace related travel ("COVID-19 Community Mobility Report" 2020). Investigation into the influence of travel on COVID-19 transmission has been underway since the onset of the pandemic. Early in the outbreak, Zhao et al. set out to quantify an association between domestic travel and the exportation of COVID-19 cases from Wuhan, China (2020). They found a significant, positive association between passengers departing Wuhan multiplied by local infectivity in Wuhan, and the number of cases reported outside of Wuhan. Once the outbreak reached Europe, tourism-related travel was found to be elevating COVID-19 cases detected at a university hospital in northwestern Germany, where 36 out of 90 COVID patients were recent visitors of a popular ski town in Austria (Correa-Martinez et al. 2020). The association between travel and COVID-19 transmission was also identified during the initial weeks of the outbreak in the United States (Badr et al. 2020). This was accomplished by transforming cellphone mobility data and county-specific COVID-19 testing data into mobility ratios (MR) and growth ratios (GR), respectively. These researchers found a strong, positive correlation between MR and GR. All these findings have clear implications for tourist destinations in Wyoming, such as the GYA, that experienced visitation levels during the summer of 2020 that were greater than the preceding year (Pope 2020).

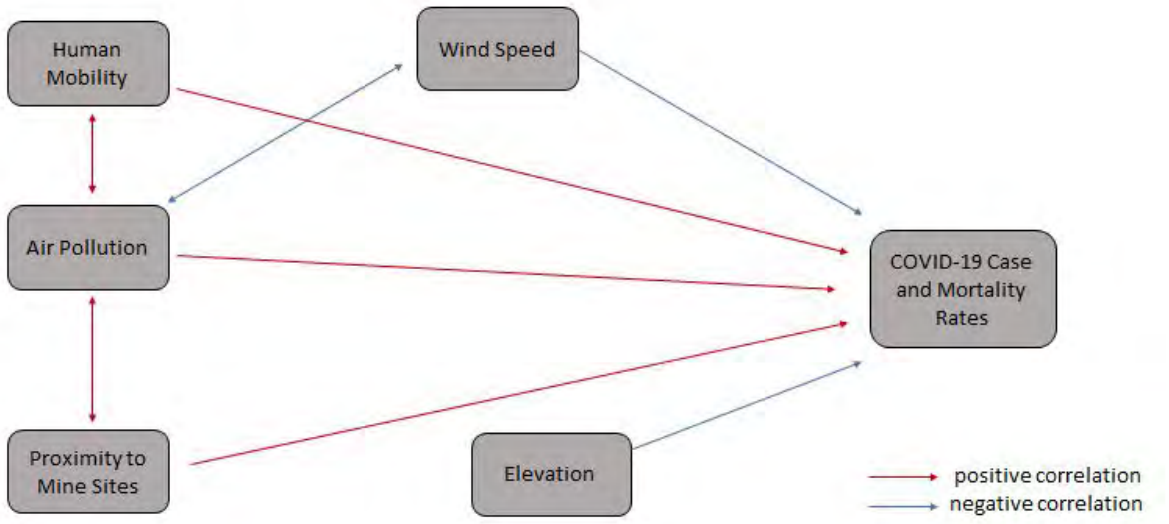
Altitude is a relevant environmental variable in the mountainous state of Wyoming, and has potential to impact COVID-19 outcomes (Arieas-Reyes et. al 2020; Huamaní et al. 2020; Segovia-Juarez, Castagnetto and Gonzales 2020). A recent study has shown that high altitudes are associated with a reduction in COVID-19 infection rates, but not a significant decrease in case-fatality rate (Segovia-Juarez, Castagnetto and Gonzales 2020). SARS-CoV-2 requires interaction with the human angiotensin converting enzyme 2 (ACE2) receptor for entry. Individuals with high ACE2 expression levels have increased susceptibility to infection (Duijf 2020). Gene expression with low ACE2 activity is found with high frequency in high altitude areas, which may be contributing to the low rate of infection (Segovia-Juarez, Castagnetto and Gonzales 2020). This clear example of environmental impacts on human health illustrates the validity of One Health.

Research Plan

Objectives

- To evaluate the impact of visitation and mobility on Wyoming statewide and county-specific COVID-19 prevalence and infection rates
- To create data-driven, interactive, public health information that communicates the Wyoming county-specific levels of COVID-19 prevalence and mobility, both in real-time and historically
- To determine if environmental contamination from mining areas and air pollution have an impact on the prevalence of COVID-19 outcomes in the state of Wyoming.
- To determine if factors such as wind speed and high altitude impact the rates of COVID-19.
- To clearly communicate the association between factors of natural and built environments and COVID-19 outcomes to the public
- To educate Wyoming K-12 students about our findings.
- To create and share useful information with the general public about health risks due to environmental factors.

Hypotheses



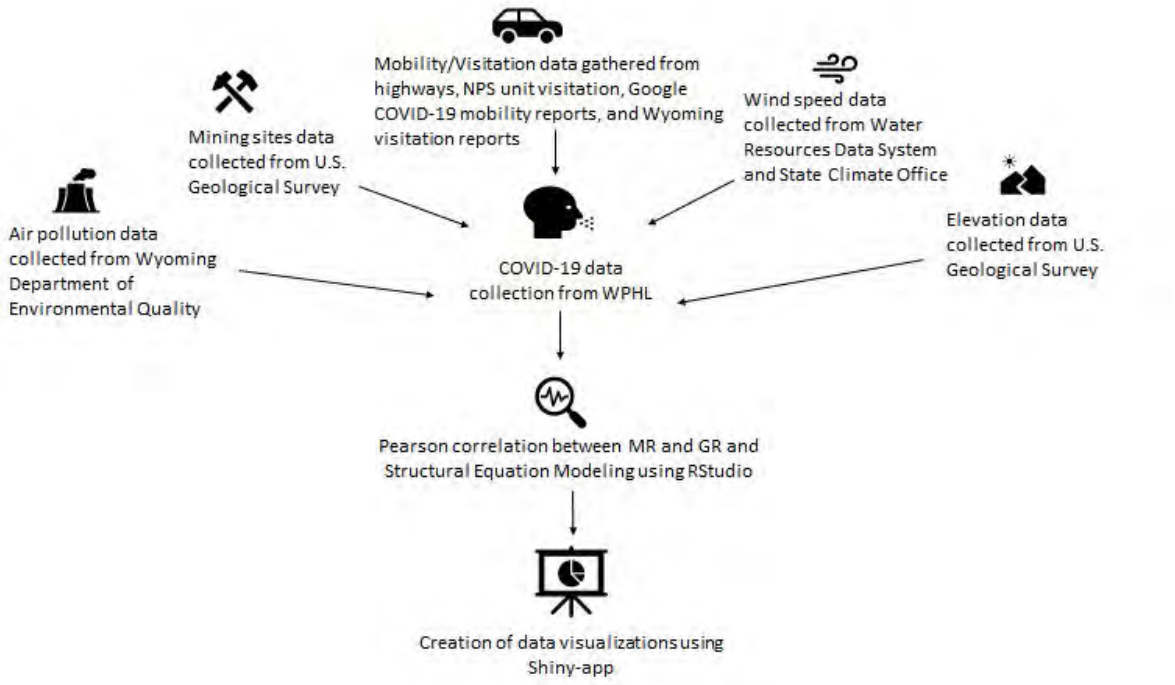
Specific Aims

- To determine the strength of correlation between COVID-19 incidence rates and four types of air pollutants: particles with a diameter less than $2.5_{\mu m}$, particles with diameters less than $10_{\mu m}$, nitrogen dioxide, and ozone using data from the Wyoming Department of Environmental Quality and United States Environmental Protection Agency

- To determine the strength of the correlation between COVID-19 incidence rates to counties that are in close proximity to mining sites, using data from the U.S. Geological Survey
- To determine the strength of the correlation of COVID-19 incidence rates with varying levels of wind speed using data from the Water Resources Data System and State Climate Office
- To determine the strength of the correlation between COVID-19 incidence rates with areas of high-altitude using data from the U.S. Geological Survey
- Combine all environmental factors studied to create an overall assessment of environmental risks impacting COVID-19 rates in each county of Wyoming
- To acquire visitation and mobility data from National Park Service Units in Wyoming, Wyoming tourism reports, Wyoming highways, and COVID-19 Community Mobility Reports (Google)
- To acquire COVID-19 testing data from the WPHL and Johns Hopkins Coronavirus Resource Center
    - To transform these data into growth ratios (GR) using the methods of Badr et al. (2020)
- Using statistical analysis, directly compare Wyoming counties with similar populations and locations but varying levels of visitation and mobility, in order to evaluate differences in COVID-19 prevalence that may be associated with differences in visitation/mobility
- To create interactive data visualizations through Shiny-App and CircleCI that use visitation/mobility and COVID-19 prevalence data to inform travelers of the COVID-19 related risks and impacts for a given Wyoming county

Project Timeline

Research Design



Methods and Materials

Data Acquisition for air pollution: Air pollution data sets will be gathered from the Wyoming Department of Environmental Quality and United States Environmental Protection Agency ("Wyoming Air Quality Monitoring Network 2020"). County wide levels of four different types of air pollutants will be collected: particles with a diameter less than $2.5_{\mu m}$, particles with diameters less than $10_{\mu m}$, nitrogen dioxide, and ozone.

Data Acquisition for mine site proximity: Mining site information will be gathered from the U.S. Geological Survey ("USGS.Gov | Science For A Changing World" 2020). This dataset will enable us to analyze community proximity to mining sites and comparisons at a county-wide level.

Data Acquisition for mobility: Visitation data will be acquired from the Wyoming National Park Services Visitor Use Statistics Reports ("Visitor Use Statistics" 2020), and Wyoming Tourism Reports ("Monthly Reports" 2020). Mobility data will be acquired from Wyoming Department of Transportation traffic data ("Traffic Data" 2020) and Google's COVID-19 Community Mobility Reports ("COVID-19 Community Mobility Report" 2020). These visitation and mobility data will be transformed into mobility ratios (MR) using the methods of Badr et al. (2020).

Data Acquisition for wind speed: Wyoming wind speed data will be collected from the Water Resources Data System and State Climate Office ("Wind Products at The Wyoming State Climate Office And Water Resources Data System" 2020).

Data Acquisition for elevation: Wyoming county elevation data will be gathered from the U.S. Geological Survey ("USGS.Gov | Science For A Changing World" 2020).

Data Acquisition for COVID-19: Data for COVID-19 prevalence and mortality rate will be gathered from the WPHL as well as Johns Hopkins Coronavirus Resource Center ("Cssegisanddata/COVID-19" 2020). Associated zip code data with COVID-19 cases across the state of Wyoming will be utilized to provide an accurate model of locations of high COVID-19 prevalence. This data will be used to analyze potential correlations between COVID-19 and each variable mentioned above.

Data sets will be read into RStudio. Structural equation modeling will be used for analysis allowing for correlations to be found between the environmental variables and COVID-19 data, as well as correlations to be found between the different environmental factors. We will create multiple forms of data visualizations displaying our results using the R Shiny-app. We will create graphs displaying individual correlations between each environmental variable and COVID-19 trends across the state. More specific information regarding the statistics will be available interactively on these graphs. Similar graphs showing county comparisons of each variable will also be made. Maps displaying the strength of correlations found across the entire state of Wyoming will also be produced. These interactive data visualizations will be shared on the WPHL website. We will use the software program CircleCI to convert these visualizations into a mobile app to enhance accessibility of our findings.

Our collaboration with community partners at the WPHL will enable us to acquire COVID-19 data and consult experts in the field of infectious disease. Our partners at the WPHL, Dr. Noah Hull and Dr. Heather Talbott, have extensive backgrounds in infectious disease epidemiology, molecular diagnostics, and public health. Along with their team at the WPHL, they are leading Wyoming's state-wide COVID-19 testing program. These community partners will graciously be sharing their expertise and data during the execution of our proposed research. Our advisor, Rachel Watson, is an expert and active researcher working to address environmental injustices. Dr. Christine Porter and Erin Burman, experts actively engaged in environmental justice research, are contributing their expertise on these aspects of our proposed research. Sierra Jech, PhD student in CU Boulder's Ecology and Evolutionary Biology Department and expert in interdisciplinary quantitative biology is an advisor to our team. Ella DeWolf, MS student in Botany at the University of Wyoming, will provide expertise in R, RStudio and data visualization. Our combined expertise in statistics, computational analysis, data visualization, epidemiology, and environmental justice will enable us to execute the proposed objectives and specific aims.

Analysis and Expected Results

Analysis of statistical significance between COVID-19 rates and each environmental variable mentioned above will be completed using structural equation modeling through RStudio. We

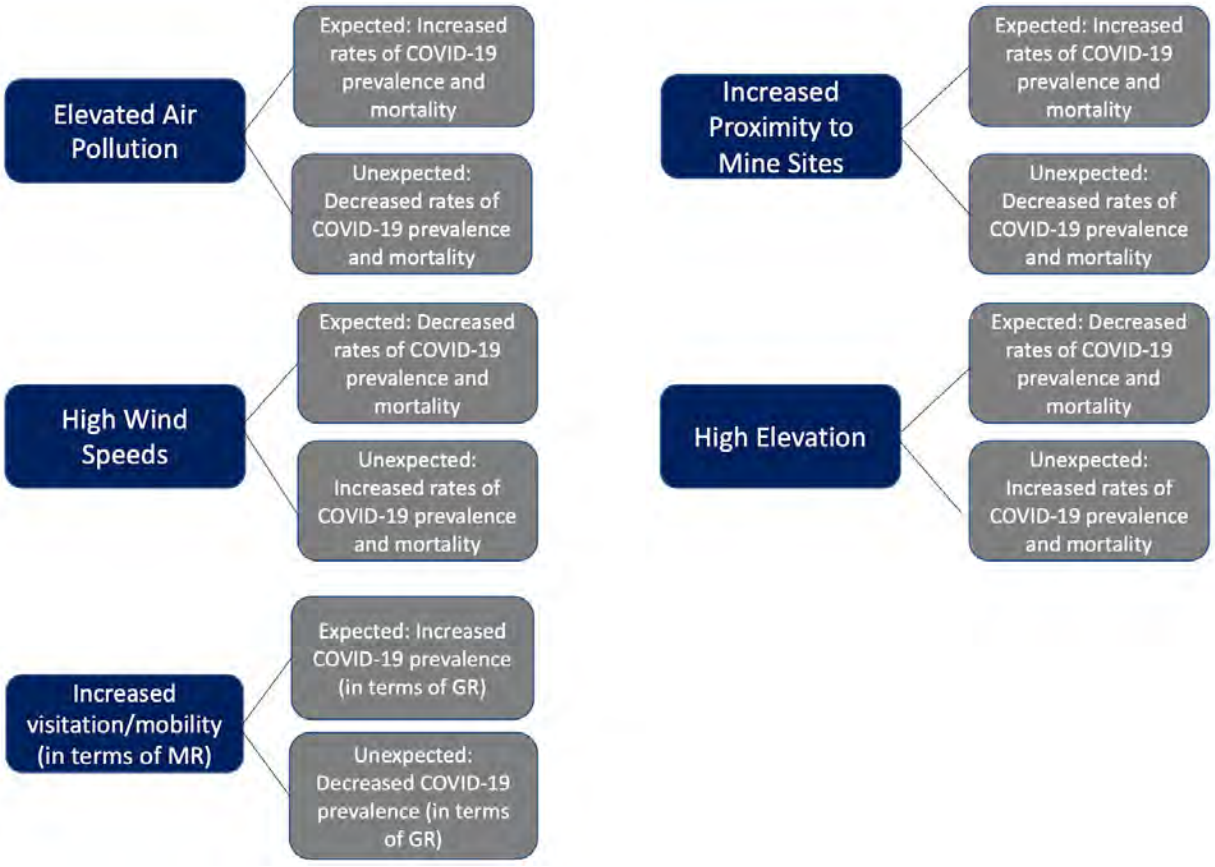
expect to find higher rates of COVID-19 cases with increases of environmental pollutants such as air pollution and mining contamination. We expect to find a negative correlation between COVID-19 rates and average wind speed. We also expect to find a negative correlation between COVID-19 rates and elevation. We expect to find that the correlations found with COVID-19 prevalence rates will mirror correlations found with COVID-19 mortality rates. Potential unexpected results may be correlations between climate variables (wind speed and elevation) and our measurements of pollution. By using a structural equation model for our analysis, identification of unexpected results will remain possible.

At varying temporal and spatial scales, MR and GR will be tested for correlation. Correlation between MR and GR will be tested in one- to three- week windows throughout the historical and incoming data. These correlation tests will be performed both at the county and state levels. An alternate time frame that will be used to test correlation between MR and GR will be the summer tourist season, as determined from the NPS and Wyoming Tourism data ("Visitor Use Statistics" 2020; “Monthly Reports" 2020). County-to-county comparisons of MR and GR will be performed to identify high and low MR and GR counties.

We expect to find significant, positive correlations between MR and GR at both statewide and county levels. We expect these correlations to be most significant within a one- to three-week window, that allows for lag time between disease transmission and case detection. These results are expected in light of an assumption that travel necessarily involves person-to-person interfaces, and these interfaces enable COVID-19 transmission. Support for this assumption and the expected results are based on the work of Badr et al. (2020) and Zhao et al. (2020).

An alternate, but foreseeable result, is that MR and GR are not significantly correlated in our data. This could arise due to the effectiveness of social distancing measures (e.g. mask wearing), the low population density of Wyoming communities (compared to communities examined by Badr et al. 2020), and/or the outdoor nature of Wyoming tourist destinations. We do not expect to find a significant negative correlation between MR, and GR, as this would contradict our understanding of disease transmission, and previous research by Badr et al. (2020) and Zhao et al. (2020).

Using RStudio, Shiny app, and CircleCI all environmental, visitation, mobility, and COVID-19 testing data and metrics will be transformed into an interactive Wyoming map. Data and findings will be presented through a publicly available Shiny App, a mobile app, and archived in a GitHub repository.


Elevated Air Pollution
Expected: Increased rates of COVID-19 prevalence and mortality
Unexpected: Decreased rates of COVID-19 prevalence and mortality
Increased Proximity to Mine Sites
Expected: Increased rates of COVID-19 prevalence and mortality
Unexpected: Decreased rates of COVID-19 prevalence and mortality
High Wind Speeds
Expected: Decreased rates of COVID-19 prevalence and mortality
Unexpected: Increased rates of COVID-19 prevalence and mortality
High Elevation
Expected: Decreased rates of COVID-19 prevalence and mortality
Unexpected: Increased rates of COVID-19 prevalence and mortality
Increased visitation/mobility (in terms of MR)
Expected: Increased COVID-19 prevalence (in terms of GR)
Unexpected: Decreased COVID-19 prevalence (in terms of GR)

References

Arias-Reyes, C., Zubieta-DeUrioste, N., Poma-Machicao, L., Aliaga-Raudan, F., Carvajal-Rodriguez, F., Dutschmann, M., Schneider-Gasser, E., Zubieta-Calleja, G. and Soliz, J., 2020. Does the pathogenesis of SAR-CoV-2 virus decrease at high-altitude?. *Respiratory Physiology & Neurobiology*, p.103443.

This study was presented to us by our professor, Rachel Watson. This study found less susceptibility to COVID-19 in high-altitude areas. We will use this to better understand the methods in creating correlations between COVID-19 cases and environmental variables.

Badr, Hamada S, Hongru Du, Maximilian Marshall, Ensheng Dong, Marietta M Squire, and Lauren M Gardner. 2020. "Association Between Mobility Patterns And COVID-19 Transmission In The USA: A Mathematical Modelling Study". The Lancet Infectious Diseases. doi:10.1016/s1473-3099(20)30553-3.

This study was brought to our attention by our colleague, Liam Guille. This was one of the first studies to examine mobility and COVID-19 transmission in the US by using cellphone mobility data. The methods of this work have directly shaped the methods we are proposing for further work to build on the understanding of mobility and COVID-19 transmission in the US.

Bao, Rui, and Acheng Zhang. 2020. "Does Lockdown Reduce Air Pollution? Evidence From 44 Cities In Northern China". *Science Of The Total Environment* 731: 139052. doi:10.1016/j.scitotenv.2020.139052.

This study was accessed through NCBI. This research makes connections between mobility, air pollution and COVID-19 related lockdowns. These connections are crucial for justifying connections between our proposed variables of study, especially mobility and air pollution.

"Basic Information About The Built Environment | US EPA". 2020. *US EPA*. https://www.epa.gov/smm/basic-information-about-built-environment.

The EPA's definitions of the built and natural environment are a guiding framework for our project. This framework was brought to our attention by Rachel Watson. This EPA webpage helps ground our stated definition of the built environment.

Bolaño-Ortiz, T.R., Camargo-Caicedo, Y., Puliafito, S.E., Ruggeri, M.F., Bolaño-Diaz, S., Pascual-Flores, R., Saturno, J., Ibarra-Espinosa, S., Mayol-Bracero, O.L., Torres-Delgado, E. and Cereceda-Balic, F., 2020. Spread of SARS-CoV-2 through Latin America and the Caribbean region: A look from its economic conditions, climate and air pollution indicators. *Environmental research*, *191*, p.109938.

Accessed through NCBI database, this article describes correlations found between air pollution and the spread of COVID-10 rates. Understanding which air pollutants are shown to have a strong correlation with COVID-19 will help us choose which air pollutants to gather data for.

Cao, C., Jiang, W., Wang, B., Fang, J., Lang, J., Tian, G., Jiang, J. and Zhu, T.F., 2014. Inhalable microorganisms in Beijing's PM2. 5 and PM10 pollutants during a severe smog event. *Environmental science & technology*, *48*(3), pp.1499-1507.

This article was presented to us by our professor, Rachel Watson. It discusses how potential health damage could occur through increased interaction with microorganisms present in severe air pollution. This will be useful in understanding the potential, unknown consequences of increased levels of air pollution.

Chen, X., Orom, H., Hay, J.L., Waters, E.A., Schofield, E., Li, Y. and Kiviniemi, M.T., 2019. Differences in rural and urban health information access and use. *The Journal of Rural Health*, *35*(3), pp.405-417.

Accessed through the NCBI database, this article discusses the lack of accessible health information provided to rural communities. We will use this resource to better understand the need for using Wyoming as a study site.

Cohen, Erik. 1978. "The Impact Of Tourism On The Physical Environment". *Annals Of Tourism Research* 5 (2): 215-237. doi:10.1016/0160-7383(78)90221-9.

This source is used to support our significance statement, that tourism has a cumulative impact on the environment.

"COVID-19 Community Mobility Report". 2020. COVID-19 Community Mobility Report. https://www.google.com/covid19/mobility/.

Google has been performing mobile-data based analysis of community mobility during the COVID-19 pandemic. This analysis is county-specific, and therefore, prime for integration into our MR calculations. These data are publicly available, providing a major advantage over for-purchase cellphone mobility data sets. This resource was discovered through a Google search for "cellphone mobility data".

Correa-Martinez, Carlos, Stefanie Kampmeier, Philipp Kumpers, Vera Schwierzeck, Marc Hennies, Hafezi Wali, Joachim Kuhn, Hermann Paenstadt, Stephan Ludwig, and Alexander Mellmann. 2020. "A Pandemic in Times of Global Tourism: Superspreading and Exportation of COVID-19 Cases from a Ski Area in Austria," n.d.

This article was accessed through an NCBI search using "COVID-19 tourism" as the query. The connection between the skiing/tourism community outbreak in Austria reported in this article, and a similar skiing/tourism community outbreak in Jackson could prove useful in analyzing the findings of our proposed research.

"Cssegisanddata/COVID-19". 2020. Github. https://github.com/CSSEGISandData/COVID-19.

This GitHub repository contains the COVID-19 data repository by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University. This repository is frequently updated with incoming testing data from across the US. This powerful, nationwide data set will be used to bolster our own Wyoming testing data, and to contextualize our Wyoming-specific data within the national data.

"COVID-19: Who's At Higher Risk Of Serious Symptoms?". 2020. *Mayo Clinic*. https://www.mayoclinic.org/diseases-conditions/coronavirus/in-depth/coronavirus-who-is-at-risk/art-20483301.

A resource detailing risk factors that can lead to higher susceptibility of COVID-19.

Duijf, P.H., 2020. Baseline pulmonary levels of CD8+ T cells and NK cells inversely correlate with expression of the SARS-CoV-2 entry receptor ACE2. *bioRxiv*.

Accessed through NCBI database. This article describes the expression of ACE2 receptor used for SARS-CoV-2 entry. This will help determine why certain high elevation areas are prone to less expression of ACE2 receptors and how this correlates to a decrease in COVID-19 rates.

Hendryx, M. and Zullig, K.J., 2009. Higher coronary heart disease and heart attack morbidity in Appalachian coal mining regions. *Preventive medicine*, *49*(5), pp.355-359.

Accessed through the NCBI database, this article shows the detrimental health impacts from proximity to coal mining sites. This will be helpful in creating a model to compare health impacts from COVID-19 to community locations to active mine sites.

Huamaní, C., Velásquez, L., Montes, S. and Miranda-Solis, F., 2020. Propagation by COVID-19 at high altitude: Cusco case. *Respiratory Physiology & Neurobiology*, *279*, p.103448.

Accessed through the NCBI database. This study found conflicting evidence of the impact altitude has on COVID-19 susceptibility. The presentation of multiple variables impacting COVID-19 will be useful in creating our own methods section.

Li, A. M. 2017. Ecological determinants of health: food and environment on human health. *Environmental Science and Pollution Research*, *24*(10), 9002-9015.

Accessed through the NCBI database. This resource describes the complexity of human health and disease through a variety of factors. The article mentions the importance of One Health and will be useful in understanding how multiple variables can impact human health.

"Monthly Reports". 2020. Travel Wyoming. https://travelwyoming.com/industry/research/monthly-reports.

These monthly data on welcome center visitation and sales and lodging tax will be used in conjunction with NPS visitation data to quantify visitation over time. We were directed to this resource by Dr. Jennifer Newton, a social scientist at Grand Teton National Park.

Neamtiu, I.A., Al-Abed, S.R., McKernan, J.L., Baciu, C.L., Gurzau, E.S., Pogacean, A.O. and Bessler, S.M., 2017. Metal contamination in environmental media in residential areas around Romanian mining sites. *Reviews on Environmental Health*, *32*(1-2), pp.215-220.

Accessed through the NCBI database, this publication describes the pollution of water and air near metal mining sites, and the possible impact it has on human health. This will be helpful in understanding the risks that mining communities face.

"One Health Basics | One Health | CDC". 2020. *Cdc.Gov*. https://www.cdc.gov/onehealth/basics/index.html.

This summary of One Health, accessed through the CDC website provides the source material for our discussion of One Health.

Pinter-Wollman, Noa, Andrea Jelić, and Nancy M. Wells. 2018. "The Impact Of The Built Environment On Health Behaviours And Disease Transmission In Social Systems". *Philosophical Transactions Of The Royal Society B: Biological Sciences* 373 (1753): 20170245. doi:10.1098/rstb.2017.0245.

Rachel Watson directed us to this source. It is a review on health and behavioral impacts of the built environment. The most germane section of this review for our work is on built environmental influence on disease transmission.

Pope, Kristen. 2020. "Surging Tourism Is Straining This Yellowstone Gateway Town". Nationalgeographic.Com.https://www.nationalgeographic.com/travel/2020/07/jackson-hole-yellowstone-grand-teton-struggle-with-record-breaking-coronavirus-tourism/#close.

This article was recommended by our colleague, Benjamin Romanjenko. It is extremely germane, as it focuses on Jackson, Wyoming, with interviews from affected community members and descriptions of the current tourism levels and social dynamics. This article serves as the direct link from rural tourism in general to rural tourism in Wyoming's GYA.

Pope Iii, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K. and Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Jama*, *287*(9), pp.1132-1141.

This article was found through the NCBI database. It discusses a positive correlation found between lung cancer and exposure to air pollution. We will use this to better understand the relation between pollution and health impacts.

"Quick Facts: Wyoming". 2020. *Census.Gov*. https://www.census.gov/glossary/#term_Populationestimates.

This Census data was accessed in order to cite the total population of Wyoming.

Rendana, M., 2020. Impact of the wind conditions on COVID-19 pandemic: A new insight for direction of the spread of the virus. *Urban climate*, *34*, p.100680.

Accessed through NCBI database. This article describes correlations found between low wind speed and higher rates of COVID-19 cases. This will be helpful in understanding how to use and quantify wind speeds in correlations to COVID-19 rates.

Segovia-Juarez, J., Castagnetto, J.M. and Gonzales, G.F., 2020. High altitude reduces infection rate of COVID-19 but not case-fatality rate. *Respiratory Physiology & Neurobiology*, *281*, p.103494.

Accessed through the NCBI database, this article describes the findings of decreases in COVID-19 cases in high altitude communities. However, the case-fatality rate does not appear to change with changes in altitude. This article will be helpful in referencing methods to study COVID-19 outcomes beyond the number of cases.

"Stay Safe, Have Fun During The COVID-19 Pandemic". 2020. Mayo Clinic. https://www.mayoclinic.org/diseases-conditions/coronavirus/in-depth/safe-activities-during-covid19/art-20489385.

This article was accessed through a Google search for public health advisories during the COVID-19 pandemic. The Mayo Clinic is a reputable public health information source. Their advisory to engage in outdoor recreation will be useful in explaining the rise in rural tourism. Interestingly, the Mayo Clinic advises against out of state travel for outdoor recreation.

Stieb, D.M., Evans, G.J., To, T.M., Brook, J.R. and Burnett, R.T., 2020. An ecological analysis of long-term exposure to PM2. 5 and incidence of COVID-19 in Canadian health regions. *Environmental research*, *191*, p.110052.

Accessed through NCBI database, this article compares air pollution exposure to COVID-19 rates. This will help us create a study that explores data collected from long time periods.

"Traffic Data". 2020. Dot.State.Wy.Us http://www.dot.state.wy.us/home/planning_projects/Traffic_Data.html.

This Wyoming highway traffic data will be essential for calculating MR. This publicly available data set was discovered through a Google search for "Wyoming highway data".

Ullman, J.B., 2006. Reviewing the basics and moving forward. *J Pers Assess,* 87, pp.35-50.

Accessed through ResearchGate, this article describes the validity of structural equation modeling. This will be helpful to understand the methodology when doing our analyses.

United Nations World Tourism Organization, Sustainable Development of Tourism Department. 2020. "COVID-10 Related Travel Restrictions A Global Review For Tourism."

This review was cited by Xingyu 2020. The UN is a high impact source for global travel information. This article is slightly dated, as it came out in April of 2020. This report on global travel bans will help establish the background from which high tourism to rural areas arose.

"USGS.Gov | Science For A Changing World". 2020. *Usgs.Gov*. https://www.usgs.gov/.

This resource will be used to gather data for elevation per county in Wyoming and data on mine sites across Wyoming.

"Visitation Numbers". 2020. *Nps.Gov*. https://www.nps.gov/aboutus/visitation-numbers.htm.

This page from the National Park Service has total annual visitation numbers for our NPS units of interest. This page was accessed through a general web search to find the most visited wilderness areas in the US. The purpose of using these statistics in the proposal is to demonstrate the immense visitation of Wyoming National Parks.

"Visitor Use Statistics". 2020. Irma.Nps.Gov. https://irma.nps.gov/STATS/.

These visitor use statistics from the National Park Service (NPS) serve as a crucial data set for our analysis of visitation to Wyoming NPS units. We were directed to this resource by Dr. Jennifer Newton, a social scientist at Grand Teton National Park.

Xingyu, Cui. 2020. "Travel In The Post-Pandemic Era: Rural Tours On The Rise". News.Cgtn.Com.https://news.cgtn.com/news/2020-06-05/Travel-in-the-Post-Pandemic-Era-Rural-tours-on-the-rise-R4MJI8tPk4/index.html.

This article was accessed through a Google search for 'tourism during the COVID-19 Pandemic'. While this periodical article is germane, it does lack academic rigor. The article discusses surges in rural tourism in China. It will be useful to compare the dynamics in China to those in Wyoming.

Yongjian, Z., Jingu, X., Fengming, H. and Liqing, C., 2020. Association between short-term exposure to air pollution and COVID-19 infection: Evidence from China. *Science of the total environment,* p.138704.

Accessed through NCBI database, this article describes short-term exposure of air pollution and COVID-19 prevalence. This will be helpful in funneling which air pollutants we should be studying.

"Wind Products At The Wyoming State Climate Office And Water Resources Data System". 2020. *Wrds.Uwyo.Edu*. http://www.wrds.uwyo.edu/PaD-Wind.html.

This resource will allow us to gather data sets containing wind speed averages throughout Wyoming counties.

"Wyoming Air Quality Monitoring Network". 2020. *Wyvisnet.Com*. http://www.wyvisnet.com/Data/PlotRecentData.aspx.

We will use this source to gather datasets that display the four air pollutants across counties in Wyoming.

Zhao, Shi, Zian Zhuang, Peihua Cao, Jinjun Ran, Daozhou Gao, Yijun Lou, and Lin Yang.,

2020. "Quantifying The Association Between Domestic Travel And The Exportation Of Novel Coronavirus (2019-Ncov) Cases From Wuhan, China In 2020: A Correlational Analysis". Journal Of Travel Medicine 27 (2). doi:10.1093/jtm/taaa022.

This study, conducted early in the Wuhan outbreak, found a significant, positive association between travel out of Wuhan, and the number of cases reported outside of Wuhan. Badr et al. (2020) cited this work in agreement with their own findings. The Badr et al. citation was the source of our discovery of Zhao et al.'s research.