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EXPLORING THE RELATIONSHIP BETWEEN DROUGHT AND POPULATION CHANGE ON THE NORTH AMERICAN GREAT PLAINS, 1970-2010

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by

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Abstract

Through the second half of the 20th century, the North American Great Plains saw widespread rural out-migration, a continuation of trends that began with the Dust Bowl crisis during the Great Depression of the 1930s. As part of a wider academic focus on the roles climate and environmental changes have on migration, this research project sought to understand the relationship between drought conditions and rural population decline on the Great Plains. In this explorative research, census population data for Canada and the US from 1970-2010 were analyzed along with temperature, precipitation, and Palmer Drought Severity Index data for the same period using a variety of regression to seek out possible association between drought conditions and population loss at local scales. As part of this process, a novel index for identifying drought likelihood was also developed and tested. Results indicate that the significance and direction of the relationship between drought and rural population loss is spatially heterogenous. Geographically weighted regression models are demonstrated to have better predictive power than traditional regression methods, although that predictive power deteriorates through the decades in the study period. Small clusters of counties were detected where the drought-population loss is relatively strong in certain decades, but generally the results suggest that non-climatic factors were the primary drivers of population loss across the Great Plains. The modelling results are discussed in the context of a case study of Lincoln County, Colorado, a dryland county visited as part of field research for this project.

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1.0 Introduction

What is drought? In the western world, the first instinct might be to think of the Dust Bowl crisis of the 1930s, with mental images of dust storms and failed crops. The destruction caused by droughts are easily identifiable but much of a drought, such as a measuring of its severity or the duration of a dry period are inconclusive. Droughts are not to be confused with deserts or aridity - drought is a temporary state. Droughts are common to most all ecoregions around the world and are influenced by anomalies in temperature, precipitation, wind strength, relative humidity, and the seasonality of each (Mishra & Singh, 2010). Droughts can persist for weeks, months, or years, and the impacts of drought can have wide-ranging socio-economic impacts. Drought is particularly troublesome in regions where rain-fed agricultural operations are dominant (Wilhite, 2016). Crop failures triggered due to land and soil degradation in the absence of moisture caused by seasonal or multi-year droughts can generate food insecurity. Drought appears when water supply falls below demand and remains a concern until the deficit alleviates (Sen, 2010). As demand can vary based on climate and need, the thresholds for drought conditions can vary over space and time. A drought's duration is more complex than a simple measurement of the time between rains, as the replenishment of soil moisture, plants, and subsurface reservoirs and time.

Since the 1980s, increasing attention has been given to the role environmental conditions have had on migration patterns around the world (Neumann et al., 2015). Much of this growth in academic interest is tied to the predicted rise of climate refugees and climate-induced migrations in the 21st century as a result of anthropogenic climate change. There are identified literature gaps in both the analyses of human responses to drought conditions and of migration in response to climate change in high income countries (Rosenberg, 1979, Maxwell & Soule, 2011, Curtis & Schneider, 2011). Climate is naturally a much harder variable to isolate on its own as it is naturally unpredictable and not human-induced (Maxwell & Soule, 2011). Environmentally induced migration is especially hard to tease out of migration data as it is often understood as a "last resort" after all other possible adaptation possibilities have been exhausted. Amidst growing global urbanization, over 2 billion people still live in dryland environments, and over 40% of global land cover can be classified as arid or semi-arid (McLeman & Ploeger, 2012, Neumann et al., 2015). Periods of water scarcity created by drought on agriculture is the clearest way in which climate influences economic outcomes, and these periods have shown to be a significant push factor to migration in drylands (Neumann et al., 2015). Field crops are most sensitive to temperatures early in the growth cycle, and rainfall can be damaging if it falls in a few heavy storms rather than steady across a growing season (Carleton & Hsiang, 2016).

These same landscapes and potential climate vulnerabilities also exist in the first world -- notably the Great Plains ecoregion of the central United States and Canada. The Great Plains are a vast semi-arid grassland that stretches from the Rio Grande to the Canadian Shield, where the dominant land use since late 1800s settlement has been agriculture (Hudson, 2011). While the Great Plains region generates hundreds of millions of dollars annually through corn, sorghum, wheat, and livestock production, it has been said, only somewhat in jest, that its most consistent export for the past century has been emigrants (Boyles, 2006). In contrast to urban intensification in other regions to the east and west, large areas of the Great Plains reached their population peak in the first half of the 20th century and have steadily lost population in subsequent decades (Gutmann et al., 2005, Parton et al., 2007). Population losses commenced with the Dust Bowl disaster of the 1930s and have not stopped despite drought conditions relenting in the following decades. Most counties in the central Plains states of North Dakota, South Dakota, Nebraska, and Kansas were at their largest in the pre-Dust Bowl decades and today's populations make up fractions of those totals (Johnson & Lichter, 2019). The Dust Bowl was the largest and most notorious example of environmental disaster- a combination of severe drought coincided with devalued commodity prices and a global economic crisis, leading to the outmigration of hundreds of thousands from the Plains (McLeman, 2013, McLeman et al., 2010). There have been documented periods of drought across the Great Plains both before and after the Dust Bowl, but curiously the droughts in the late-20th century have been observed without accompanying mass emigrations like those prior (McLeman et al., 2021, Warrick, 1980, Cook et al., 2007).

A "lessening hypothesis" has been put forth in social science circles that technological developments and adaptation to recurring climatic events of similar magnitudes at both the household and community level have helped build resilience to that climatic event over time. If drought is substituted in as the climatic event, then it stands reasoning that advances in irrigation and seed technology amongst other adaptations have reduced farmers vulnerability to migration as a solution to recurring drought. Increases in off-farm employment opportunities in the Great Plains have also worked to increase those whose livelihood is not greatly influenced by agricultural productivity. (McLeman & Ploeger, 2012).

Studying drought impacts on the Great Plains is also important in understanding the longer-term prospects for the economic and social landscapes of the region, where agriculture continues to be the dominant land-use. The causes of prolonged wet and dry periods in the Great Plains are not well understood leading to precipitation deficit forecasts carrying a large degree of uncertainty (Hudson, 2019). The impacts of precipitation deficits are better known. Drought conditions can be harmful to not only those who live in the Great Plains but anyone that relies on the agricultural outputs grown throughout the region (Basara et al., 2013). Even short durations of dry conditions can stress groundwater capacity for irrigation, reduce soil quality, and strain farm finances. Drought has the potential to damage both crop yields and livestock production as many herders operate simultaneous croplands for winter feed. Unirrigated farms have a higher vulnerability to dry conditions and may be forced to increase operational expenditures to obtain water and/or animal feed when drought strikes (McLeman, 2013). Forecasts of more severe droughts and increases in temperature create greater concern for the future viability of both cropping farms and grazing operators on the Great Plains (Basara et al., 2013).

The vulnerability of residents of the Great Plains to future climatic events is changing. Developments in center-pivot irrigation technology have allowed farm operators access to deep groundwater reservoirs, such as the High Plains (or Ogallala) Aquifer to offset deficits in precipitation. At its current extent (Figure 1), the aquifer underlies 450,000 sq km of the High Plains, but only 14% of the total land area of the Great Plains (Aistrup et al., 2017). Farming operations away from the aquifer must rely on either smaller groundwater reserves or rainfall capture to provide the necessary irrigation to overcome dry periods. Excessive extraction of groundwater from the aquifer has created a tragedy of the commons and overuse of the aquifer has gone mostly unregulated (Hornbeck & Keskin, 2014). The Ogallala is a closed aquifer that only receives an inch of annual recharge. While the irrigation water has boosted the value of agricultural crops at the surface, the estimated value of the groundwater in the aquifer has diminished to a third of what it was in the 1970s (Hornbeck & Keskin, 2014, Hornbeck & Keskin, 2015, Wienhold et al., 2017).

Figure 1 - The Great Plains Study Area and Ogallala Aquifer Boundary (2010)

This project explored a variety of ways to model the relationship between drought conditions and rural population change across the Great Plains of the United States and Canada for the period 1970-2010. One of the unique features of my project is that I sought to understand this relationship using an ecological delineation of the Great Plains rather than a political one that has been oft used in Great Plains migration literature. (see McLeman & Ploeger, 2012 for an example of Canadian prairie studies, Gutmann et al., 2005, Maxwell & Soule, 2011 or Golding, 2014 for studies exclusive to the American Plains). These types of transnational studies has often been neglected due to laborious data integration and the overall smaller population of the Canadian Prairies (the Great Plains are culturally referred to as the Prairies in Canada) relative to the American Great Plains. To this end, I established the following research questions:

1. Are population changes in the Great Plains significantly associated with measures of drought?
2. How has changing conditions of the past 40 years influenced the landscape of agriculture in the Great Plains and their relative resilience to drought? Is the lessening theory continuing to cloud the drought-migration relationship?

To answer these questions, I collected data for rural population change in the Canadian and US parts of the Great Plains from 1970 to 2010 and data for temperature, precipitation, and the Palmer Drought Severity Index (PDSI) for the same region and period. These three conditions that capture both current and preceding climatic conditions were combined into a unique and novel "Drought Potential Index" to explore whether particular combinations of these independent variables might be more strongly associated with population loss than any of these three variables on their own. A geographically weighted regression (GWR) analysis was then conducted to assess whether rural population losses at local scales may have been associated with a combination of extreme summer temperatures, low precipitation levels and PDSI scores. Determinants of migration, of which environmental conditions are just one, vary across spatial scales and would be poorly defined by traditional aspatial regression approaches. Further, there is heterogeneity across the Plains in the observed rainfall deficit, agricultural land use, ease in access to groundwater for irrigation, and off-farm employment in drought-proof industries. All of these factors influence the ability of drought to stimulate a migration- yet would not be considered in more simplistic linear regression work. With the Drought Potential Index, we expect to see an inverse relationship between drought likelihood and population change with specific emphasis on the relationship in regions of the Great Plains that experience population decline. Environmental factors such as drought are considered a "push" factor towards migration and less often as "pull" factors. Migrants often do not value the climate as strong as other socio-economic factors when choosing a migration destination. It is the initial assumption that areas with a significantly positive relationship are noise and are assumed to be gaining in population due to other socio-economic reasons. Lastly, we enter this study with the hypothesis that the lessening theory will reduce the strength of any relationship between population and drought over time due to the building of resiliency. Resiliency in the Great Plains is mentioned throughout this report and can include disaster relief funds made available by government agencies, technological developments in either the conservation of water for irrigation or seed biology, or expansion in non-farm employment sectors. Increases in resilience to drought only increases the drought severity and duration to increases for which emigration would occur.

The remainder of this thesis describes in detail my methodological approach and findings. I also provide a brief case study of Lincoln County, Colorado, an area where my the GWR models suggest that rural population change may have been influenced by drought over the study period. First, I provide a more detailed review of the literature relevant to this project.

2.0 Literature Review

2.1 Defining and Measuring Drought

A fundamental issue among research dealing with drought and human migration is the intellectual disagreement over definitions for both of those terms. There are inexact thresholds of migration, such as the distance traveled where a relocation becomes a migration, or the impetus for a migration, which could be any one of for economic opportunities, discretionary income, family reunifications, destination amenities or in response to the environmental changes among other reasons. (Gutmann et al., 2005, McLeman & Ploeger, 2012). A further difficulty with specific environmentally induced migration is the individual magnitude and duration to drought that residents can withstand before needing to migrate. A reasonable pathway to the occurrence of drought migration would be for conditions of drought persisting long enough to overcome stored water capacity, operator reserves, and disaster relief funds. If one of those supports is enough to overcome the drought then it could be concluded that migration is unlikely. In other drylands around the world the same support may be more expensive or unavailable, which increases an individual's vulnerability. Furthermore, an agricultural worker forced out of work due to climatic circumstances could always retrain into a non-agricultural field locally without necessitating a migration if such positions are available.

Drought at its simplest definition is a period where precipitation received is significantly diminished from historical norms (Mishra & Singh, 2010). There are numerous drought indexes used for representing drought (Tian et al., 2008 identify 150 such drought indices, Zargar et al., 2011 review and classify many of them). Each has utilized a variety of input variables to represent one or more of the four different classifications of drought, classified by (Sen, 2015) as:

- **Meteorological drought**, a period with extremely low precipitation recordings compared to historical averages and trends
- **Hydrological drought**, a delayed onset drought where there are marked decreases in surface streamflow or groundwater storage
- **Agricultural drought,** which considers declines in soil moisture quality as well for the purpose of growing and harvesting seasonal crops successfully
- **Socio-economic Drought**, which considers the social and economic ramifications from any one of the first three environmental droughts. These kinds of droughts are seen when water shortages force demand for a product (most commonly food or hydro-electric power) to exceed supply.

These four forms of drought are not mutually exclusive but are best understood as a natural progression. Most droughts begin as meteorological droughts, however there is a temporal lag before those prolonged periods of low precipitation begin to influence water availability (hydrological drought) in reservoirs, streams, or groundwater basins. As hydrological drought conditions emerge, soil moisture levels and the irrigative water reserves typically begin to dwindle. A return of precipitation to within the seasonal variation at would immediately resolve meteorological droughts, but that rainfall would have to first filter through the surface or subsurface environments before easing the latter forms of drought. Socio-economic droughts that involve annual crop growing could take years to recover after the meteorological drought ends.

Two of the most common drought indices are the Palmer Drought Severity Index (PDSI), developed by Palmer (1965), and the Standardized Precipitation Index

(SPI), developed by McKee et al. (1993). The PDSI is designed for meteorological drought monitoring in the United States and is one of the most commonly used drought indices. The PDSI includes observed precipitation, evapotranspiration rates, and surface run-off in an algorithm modelling the cumulative departure in surface water balance from historical averages (Dai, 2012, Chelton & Risien, 2020). The SPI is a less computationally intensive index that uses purely a summation of recorded precipitation during a user-customized time span in its comparison to historical precipitation.

Modifications have been made to both the SPI and PDSI in more recent research. Specific metrics have been made to capture shorter (Palmer Z index) and longer (Palmer Hydrological Drought Index) time frames than the original PDSI. National real-time drought monitoring services are provided by both the Canadian and American federal governments. The Canadian Drought Monitor aggregates various individual indexes such as soil moisture, PDSI and NDVI satellite imagery into one five-class classification ranging from “abnormal” to “exceptional” drought (Government of Canada, n.d.). The American Drought Monitor uses six indicators - including the PDSI and SPI - in their identical five-class classification, published weekly.

2.2 Historical Settlement and Migration Patterns

European settlement of the Great Plains grew rapidly in the second half of the 19th century and the first three decades of the 20th century (Smith & McAlister, 2015), the first settlements appearing during the California Gold Rush of 1849 as rest areas for those bound for the west coast (Sylvester et al., 2006, Hudson, 2019). Initially, lands were used primarily for ranching cattle, but this was replaced in subsequent decades by government initiatives in the US and Canada to encourage family farming. The Homestead Act of 1860 promised free land in the American Plains to those willing to construct a home and maintain the land for five years (Burger & Combs, 2009). Homestead planning was conducted with little concern for site topography, and plots were assigned in strict square units that are still recognizable on the landscape today. Townships were six miles long by six miles wide, and each homestead was assigned one quarter of the 36 one-mile plots within the township (Sylvester et al., 2006, Conzen, 2010, Smith & McAlister, 2015). Small Plains towns ended up looking quite similar to each other. They sprouted up as stations along trans-continental railway lines to serve as transfer points for farmers to ship their crops and cattle to distant markets, and gradually added shops and services to support area farmers. The design of these towns adhere to fairly strict grid layouts dominated by a wider Main Street running perpendicular to the rail line (Conzen, 2010). Crowley (1996) identifies three classes of Plains towns: *sutlands, grainlands*, and *ranchlands*. Sutlands are railway towns and commerce centres typically in fertile regions along river valleys. *Grainland* towns are identifiable by a large grain elevator and water tower dominating the skyline. Grainland towns are found off of major transportation routes. *Ranchland* towns are contemporarily dying towns isolated away from transportation networks. Many ranchland towns have little population or are fully deserted. Some ranchland towns only maintain population based on being a county seat. While this classification was based on a study of Montana towns, it is a framework applicable to the urban landscape throughout the Great Plains.

The first half of the twentieth century saw a population influx in areas with strong agricultural activity, as immigrants from Europe and migrants from eastern North America sought to establish family farms in the west. To that point, farming was still very labour intensive, which led to much higher rural population densities than those in decades after the large-scale mechanization of agriculture decoupled the close association of agricultural outputs and the size of the farm workforce (White, 2008). Despite some farm closures and initial emigration, primarily by early settlers who struggled with farming in the highly variable climate, populations grew substantially in counties where land and/or agricultural work was available (Smith & McAlister, 2015). Most counties in the Plains reached their peak populations in the pre-Dust Bowl period of 1900-1930 (Johnson & Lichter, n.d.). The “Dust Bowl” years of the 1930s saw wide-scale migration and abandonment of farms in the Plains as multi-year droughts coincided with the economic crisis of the Great Depression. (Gutmann et al., 2005, Basara et al., 2013). Many of those who left the Plains in the 1930s were young families in search of work, never to return when the drought receded (McLeman, 2013). This resulted in a reversal of population patterns on the Plains, with rural areas subsequently experiencing a decades-long decline in population and the number of farms (White, 2008).

The technological advances made during the Second World War impacted farming too. The development of the tractor in 1940 was the first in a wave of mechanical advances that reduced the reliance on manual labour. The increase in individual productivity meant farmers were not as persuaded to rehire those returning from war (White, 2008). Off-farm employment grew in importance in the post-war period. White (2008) identified that counties with high emigration saw a dwindling of non-agricultural business counts, as much of these operations were reliant on agricultural employees with discretionary income as their clientele. The spatial separation of agricultural and non-agricultural businesses only reinforced the population outmigration of the pre-war years into the post-war: those out of on-farm work had nowhere else to turn. A continuation of technological advances and periodic droughts in the latter half of the twentieth century further strained finances and trimmed the job prospects in agriculture (McLeman, 2013a). Despite nationwide trends of population growth in non-metropolitan counties in the 1970s, Albrecht (1986) illustrated how agriculturally reliant counties on the Plains still were as likely to see population decline from Census to Census as they were in the decades before 1970. Migration out of the region resulted in a loss of roughly three million people since the onset of the Depression by 1990 (Gutmann et al., 2005).

2.3 The Great Plains Today & Future Challenges

Today, agriculture in less-arid parts of the Great Plains is dominated by large-scale crop farming operations, featuring corn and soybeans in eastern areas, where precipitation is sufficient), and sorghum (referred to colloquially as milo), wheat, and alfalfa in drier areas (Aistrup et al., 2017). These crop choices reflect prevailing climate conditions and variations across the region. Average daily temperatures increase from the Canadian prairies south to Texas, but extreme high temperatures (i.e., where the daily high temperature exceeds 30°C/86°F) that place stress on crops may be experienced throughout the Great Plains in the summer months. Average annual precipitation increases on an east-west gradient with the highest average rainfall received in Iowa and Minnesota and the least in New Mexico and west Texas. The combination of high summer temperatures and low precipitation creates a gradient for potential evapotranspiration (PET) that increases from the northeast to southwest. PET levels exceed precipitation many months of the year, making precipitation management important to farm operations that do not have access to irrigation (Peterson & Westfall, 2003). The IPCC projects that agricultural drought will expand in central North America due to increasing evapotranspiration rates (IPCC, 2021). These droughts will be related to high confidence projections of increasing mean temperatures and annual precipitation for much of the continent. These anticipated changes in weather patterns could provide some initial benefit to the productivity of some opportunistic Plains farms, especially in the northern Plains. A greater number of warmer months and increases in precipitation could expand the growing season and reduce farm reliance on expensive irrigation to meet the water needs of more profitable water intensive crops (Wienhold et al., 2017, Nawrotzki et al., 2017). It is a delicate balance however, as cumulative exposure to heat and drought will meet a natural threshold where further warming or precipitation becomes detrimental to future yields.

Sorghum is a relatively drought tolerant crop that is used in the production of bread, livestock feed and ethanol, making it suitable for growth in drier regions of the Plains (McLeman, 2013). When presented with the option, growers are more likely to turn away from sorghum to plant more irrigative-intensive wheat or corn due to potential higher market return and a higher production per acre (McLeman, 2013a). Previously offered governmental price supports made wheat the most prominent crop, but the elimination of those supports have since removed the more stable financial return (Gunprecht, 1998). When those supports were phased out, and programs were instituted to phase out unprofitable fields, wheat acreage declined steadily from 7 million square acres in 1970 to 4 million square acres in 2015 (Cotterman et al., 2017).

Modern day wheat farms have adjusted their growing seasons as an adaptation strategy to deal with the potential of damaging hot summer droughts. Contemporary wheat agriculture often adheres to one planting per 24-month cycle with the land sitting fallow for the remainder of the time. While fallow, the land is routinely tilled in aim of collecting as much precipitation as possible to reuse as irrigation in the growing period (Peterson & Westfall, 2003). This strategy is designed to minimize crop loss if drought conditions arise during the growth season, but the extended periods of tilled fallow can accelerate soil erosion. Unlike other dryland environments around the world, most precipitation in the Great Plains coincides with the warmest temperatures in the summer season when the potential for losses to evaporation are at their highest. A second adaptation strategy available to wheat farmers in the central and southern Great Plains is to remain on a 12-month cycle but use the winter season for planting and growing when the average daily temperature is lower. In the northern Plains, a spring wheat planting is an option to avoid exposing the crops to the potentially dangerous conditions of the summer heat. Both situations require a reserve of irrigation water as non-summer precipitation is relatively low. Growing corn and other crops out of the traditional summer season is rare (USDA, 2010), but technological improvements in seed genetics and irrigation capacity have allowed for improved yields in the summer months.

Crop insurance does provide a safety net for farm operators from any environmentally caused damages, but any combination of soil degradation, wind erosion, or decrease in water availability can have lingering impacts in subsequent growing seasons. Some farms leverage their access to compensation programs to make unsuitable crop decisions, but the aforementioned self-reinforcing nature of droughts makes this a risky fallback option (McLeman, 2013).

Grazing covers the most acreage and is primarily found in the northwestern and southwestern areas of the Plains, where soil moisture is limited (Crowley, 1996, White, 2008). Cattle herding in the Great Plains is an industry worth tens of billions annually (Briske et al., 2020), and home to approximately half of American cattle herds. Briske et al., (2020) provide a comprehensive overview of the current ranching industry in the Great Plains. They document a northward migration of cattle herds from southern states (Texas) to the central and northern Plains (Dakotas and Nebraska) in the 2010s, and a dearth of studies that focus on how future climate pattern changes will impact the cattle raising industry specifically. Cattle raising is a fundamentally different process than growing seasonal crops, which take only 3-6 months from planting to harvest. Cattle raising is a year-round process where feed and access to water are required, and it can take three years for individual cattle to mature.

The Great Plains is projected to see an increase in average temperature over the next century, ranging from 3°C (5°F) in the northern Plains to as much as 5°C (9°F) in the southern Plains by 2100 (Briske et al., 2020). The IPCC’s 2021 Sixth Assessment Review projections for North America (Ranasinghe et al., 2021) predict with medium confidence increasing aridity with expansion in agricultural droughts for the Great Plains. Droughts will become more common in the northern and eastern regions of the Great Plains despite projected increases in precipitation, counteracting a Plains-wide increase in air temperatures intensifying evaporative demand and reducing soil moisture. The panel's report concludes that increases in air temperatures will lead to similar increases in growing degree-days, elongate the growing season, and introducing an additional month of extreme heat days (defined as days where the air temperature exceeds 35°C / 95°F) in the southern Plains by the middle of the 21st century. While temperatures rise, the IPCC's models predict increases in precipitation in the northern and Central Great Plains, especially in the winter and spring months, but increasing dryness in the southern Great Plains.

Beyond the IPCC assessment review, there are many projections of drought conditions and severity in the Great Plains that either agree with the findings or counter with more optimistic outlooks. Much of the deviation in outlooks revolve around the drought index used in the modelling work (Hoerling et al., 2012). The prediction of anthropogenically-caused increases in air temperatures can bias the calculation of the PDSI due to the relationship between potential evapotranspiration and air temperature in its formula (Wehner et al., 2011). Palmer Drought Severity Indexes that use the Thornthwaite equation of calculating PET often create rather dire outlooks of drought in the late 21st century in the Great Plains as the equation is so sensitive to temperature changes (Feng et al., 2017). Projections that rely on soil moisture models, or the Penman-Monteith formula of PET estimation are more conservative in their forecast of the surface water balance. They indicate that soil moisture levels will remain relatively similar to the present conditions, as increases in potential evapotranspiration caused by temperature increase will be offset by the rise in mean precipitation (Hoerling et al., 2012). Drought frequency remains similar to its present risk in these models, although the seasonal distribution and severity of the increasing precipitation could be troublesome to farmers.

3.0 Methods

3.1. Study Area

An outline of the Study Area is provided in Figure 1. The Great Plains is defined environmentally, using the boundary file produced by the United States Environmental Protection Agency. The EPA classifies the entire North American continent (Canada, continental USA, and Mexico) into 12 mutually exclusive eco-regions, of which the Great Plains is one. The eco-regions are classified based on a range of geophysical and biophysical criteria including landforms, climate, flora and fauna and topography (Tollerud et al., 2018). The extent of the Great Plains stretches from central Alberta down into northeastern Mexico; however the Mexican region was not included in this research.

3.2 Population data for this project

The population unit of analysis in the United States is the county and in Canada the census subdivision. County-level population data is reported in 10-year increments in the United States Census in years ending in zero. US counties on the Plains had stable boundaries during the study period. The only boundary adjustment was the establishment of Broomfield County in suburban Denver, Colorado in 2001. This adjustment only affects population analysis in the 2000s decade, and its suburban characteristics meant that it was subsequently removed from my dataset. In all, there were 911 counties that overlapped with at least some of the EPA Great Plains boundary file. Canada does not have an equivalent unit of analysis with a reporting consistency and similar size to an American county. The best spatial unit for population comparison is the Consolidated Census Subdivision (referred to as ‘census subdivisions’ from here on). Census subdivisions are an aggregated class of municipalities and other equivalent-sized units in rural areas. In the Canadian Great Plains, the most common type of census subdivisions are rural municipalities (in Saskatchewan and Manitoba) or municipal districts (in Alberta). These agglomerations of smaller units have no bureaucratic or cultural significance beyond Census tabulation. The borders of these census subdivisions fluctuate from Census to Census and do not provide historical consistency for comparative analysis. A multi-week georeferencing project was undertaken to standardize the census boundaries and population counts to a workable form. 385 Canadian census subdivisions were selected to fill out the Canadian component of the study region by virtue of overlapping the same EPA delineation of the Great Plains.

A few large urban centres are scattered across the Great Plains, with both populations magnitudes larger than rural counties, and economies that contain very low to zero agricultural activity. In these counties, it can be logically concluded that drought conditions would not generate any population emigration, as so few people rely on agriculture for employment. These large cities within the Great Plains include Houston, Dallas, Denver, Kansas City, Edmonton, Calgary, Oklahoma City, Winnipeg, and Minneapolis. The Rural-Urban Continuum from the US Department of Agriculture was utilized to filter these cities and their suburban sprawl out of the analyses. The continuum is a nine-class classification of American counties based on their urban populations and their proximity to defined metropolitan areas. This scale allows for the removal of urban counties across the Plains, and their adjacent counties that serve as suburban bedroom communities. The continuum was first published in 1974 and has been subsequently updated in each decade. To be included in our regression analyses, a county must be classified in one of the rural categories (classes 4 to 9) for a given decade. A Canadian equivalent of the Continuum does not exist, so a methodical approach was adopted to remove census subdivisions within larger Census Metropolitan Areas and adjacent sub-divisions that contained a density greater than 400 persons per square kilometre.

Population counts were obtained from the IPUMS National Historic Geographic Information System (NHGIS) database maintained by the University of Minnesota (Manson et al, 2020). The NHGIS contains historic Census-derived population data for the United States back to the 18th century. I obtained population counts from the 1970, 1980, 1990, 2000, 2010, and from the Canadian censuses of 1971, 1981, 1991, 2001, and 2011. For ease of comparison, the one-year difference in census dates was assumed to be equal. Canadian census data came from Statistics Canada.

3.3 Climate data used for this project

In the small number of studies that have attempted to identify associations between drought and rural population change, the most common climatic data used have been monthly PDSI values (Gutmann et al., 2005, Parton et al., 2007) and extreme temperature and precipitation data calibrated to the growing season (McLeman et al., 2010, McLeman and Ploeger, 2013). The combination of existing drought indices or climatological data into *hybrid* or *composite* indexes to get a more comprehensive overview of dry periods is getting more attention, and hybrid models such as the US Drought Monitor have led the way in this regard (Zargar et al., 2011).

For this study, I collected the following three sets of climatic data to utilize as my independent variables for modeling:

1. Extreme heat conditions, determined as the count of days in the Plains growing season (defined as April 1 to August 30) when the maximum daily temperature eclipsed 30°C (86°F).
2. Growing season precipitation, measured in millimeters of observed rainfall, in the same April 1 to August 30 period. Rather than annual precipitation, rainfall during the traditional growing season is most relevant to the likelihood of a successful yield. Water scarcity in the growing season requires farmers to begin to find irrigation water from elsewhere.
3. The average Palmer Drought Severity Index (a monthly estimate at the climate division scale). The PDSI is a standardized scale that incorporates recent temperature and precipitation records to estimate relative dryness or wetness. The index is standardized with a score of 0 indicating an intermediate between positive values (wetness) and negative values (dryness). Absolute values of 4 or greater indicate signs of extreme conditions (Palmer, 1965). The PDSI is historically shown to be an excellent proxy indicator of Great Plains soil moisture (Hoerling et al., 2012). The Palmer Drought Index has been used in similar past modelling of the drought-population relationship, including Gutmann et al., 2005 and Parton et al., 2007.

In the United States, temperature and precipitation data was extrapolated from the 341 stations within the United States Historical Climatology Network (USHCN) that lie within the Great Plains. The USHCN is a historical database of precipitation and temperature data from a collection of legacy weather stations across the United States. Temperature and precipitation data for Canada was taken from the gridded NRCANmet climatology dataset (Hutchinson et al., 2009). American Palmer Drought scores were obtained from the NOAA’s National Center for Environmental Information as discrete monthly estimates for American climate divisions, and Canadian information came from TerraClim as continuous surfaces.

These three datasets were combined to form a novel unique index that I call a Drought Potential Index, to explore whether a combination of the other three sets of data might show a stronger association with observed population change than any other three variables on their own. The Drought Potential Index is designed to serve as an explorative tool aggregating observed temperature and precipitation data for the 1970s to the present, rather than applied exclusively to periods of known drought. Without constraining our study area and time frame to regions and years where known droughts occurred, we intend to monitor overall population trends for the region as a whole with the goal of identifying regional or individual counties where the drought index returns alarming results. This project is unique in that its scope is investigative rather than reactive. Widespread droughts that caused financial and environmental devastation are well documented, especially the Dust Bowl of the 1930s, but droughts in subsequent decades have been limited to smaller regions of the Great Plains or into neighbouring eco-regions.

In the past, the PDSI has been criticized in literature for its applicability to regional studies. Some of the criticisms include the index's sensitivity to mountainous regions or where the topography is unstable, the feasibility of using the index in climates outside of the continental USA, and its inability to account for snow precipitation that has a delayed entry into the local water system (Sen, 2010). These criticisms are avoided in this research by the Great Plains' iconic flat topography and the procedural decision to only include raw precipitation measurements from summer months. Using pure precipitation or temperature data as a proxy for drought is also historically problematic as it ignores antecedent conditions

3.4 Climate data acquisition and preparation

The point-level US precipitation and temperature weather station data was converted to a continuous raster surface via an Inverse Distance Weighting (IDW) interpolation in the R program. In IDW interpolations, an unsampled point is calculated as the weighted average of known values with weights assigned based on Euclidean distance between the known points and the unsampled points. IDW interpolations are simple and intuitive but are often criticized for their geographical simplifications that ignore the influence of large bodies of water or changes in elevation. The method could be problematic for continental interpolations but is suitable for the homogenous and featureless landscape of the Plains. Weather stations in regions just beyond the borders of the Great Plains were not included in the interpolations which causes some edge effects to counties on the outer margins of the Great Plains. IDW interpolations use weighted averages, therefore the maximum and minimum interpolated value can not exceed the maximum and minimum known values. The existing temperature and precipitation gradients make it reasonable to assume that some regions might see conditions above or below the range of observed conditions, however the density of weather stations, and the eventual spatial averaging to the county/census subdivision level, it was determined that the loss of data specificity would not greatly alter the interpolated values. Utilizing those proximate weather stations beyond the Great Plains in interpolations would invite the influence of other weather patterns and uneven elevations into the calculations of our Plains drought index.

One raster surface was created for both precipitation and temperature data for each of the 40 years from 1970 to 2010, inclusive at a 10km-by-10km output cell size. The PDSI data obtained was vectorized and reported at the climate division level, a spatial unit that is part-way in size between the state and county level. In a majority of cases the climate division is an aggregate of counties sharing the same boundaries. To account for the locations where county and climate divisions do not align, these values were also converted to an identical 10km by 10km raster surface as precipitation and temperature data.

Canadian temperature and precipitation records were obtained from the gridded NRCANmet climatology dataset (Hutchinson et al., 2009). These surfaces were treated using thin-plated ANUSPLIN splines and have an identical $10km^2$ resolution to the processed American data. No further steps were needed to prepare the data. TerraClim's derived PDSI scores were reported at a grid size or 1/24th of a degree (~$4km^2$).

3.5 Additional steps to create the DPI

Once all three input variables for the DPI were in a gridded form, a rescaling function was applied to create a 10 point scale outlining the potential of drought conditions. This rescaling operation was completed using the DMwR package in the R environment. For growing season precipitation and summer days with extreme temperatures, the cell values for all years were sorted into deciles with scores of 1 indicating low probability of agricultural drought (high precipitation or low extreme temperature days) and scores of 10 indicating a high probability of agricultural drought (low precipitation, high extreme temperature days). Seasonal shifts in the growing season precipitation necessitated the rescaling operation to be done once for all grid cells regardless of year observed to ensure that equal precipitation measurements in separate years were scored in the same decile. The upper and lower limits of the rescaling were set by the maximum and minimum interpolated values that were entered in the operation. For example, the lowest recorded cell in any of the annual extreme temperature days was 0, observed in Clearwater County, Minnesota in 2009.

The annual Drought Potential Index was then assembled by adding together the rescaled value for each of the three input variables. The addition of current season precipitation and temperature measurements and the antecedent conditions captured in the PDSI measurement overall creates an explorative weighted average of current growing season stress with the existing dry or wet conditions. The resulting annual Drought Potential Index is then a scale ranging from 3 (a value of 1 for all three variables) to 30 (a value of 10 for all three). Decadal sums, adding up the annual scores for 10 year periods that match population counts, are similarly in a 30 to 300 range. determining our estimation for the potential of agricultural drought given the observed climate conditions. The decadal sums used in regression analysis are displayed in Figure 3.

3.6 Modelling methods used: Regression Approaches and Geographically Weighted Regression

The reliance on global models is often problematic with spatial data, as they assume that the magnitude and directionality of the relationship is stable for the entire region from which data is collected. The traditional linear regression is expressed as;

Equation 1 - Expression of a traditional OLS linear regression

$$y_i = \beta_0 + \beta_1 X_1 + \ldots \beta_n X_n \ + \epsilon$$

where y is the regression estimate, $\beta_0$is the estimated intercept, $\beta_1 \ldots \beta_n$are the global estimated slope coefficients for the n independent variables, and ϵ is a random error term. The static parameters in global models act as spatial averages of regional parameter estimates, and as such can be potentially unrepresentative of anywhere in the study region. When local parameter estimates go undetermined, as they are in an OLS model, much information regarding the spatial patterns and range of parameter estimations go unknown.

An improved regression approach that accounts for variation in the dependent and independent variable across the study area is geographic weighted regression, a method first proposed by Fotheringham, Brunsdon & Charlton (2002). Geographically weighted regression considers that modelled phenomena are rarely consistent across geographic areas, and that spatial data are rarely independent. Instead of a single model fitted to the entirety of the study region, GWR calibrates a separate regression equation for every observation point or input location in the study area. The individual regression at each of the points subsequently weights known observations based on their Euclidean distances to the regression point. Closer observations are given a greater weight than distant observations. Along with individual parameters, goodness-of-fit metrics can also be produced for every point to display similar variations in model performance, complete with new parameters and goodness-of-fit assessments for each point. GWR exists as a method of exploring spatial heterogeneity in datasets and has the ability to reveal information not captured by a global regression. It's formula expands on the common OLS model and can be expressed as:

Equation 2 - Expression for a geographic weighted regression

$$y_i = \beta_0(u_i, v_i) + \sum_{z=1}^{n} \beta_z(u_i, v_i)x_{iz} + \epsilon_i$$

where again y_i represents the regression estimate but this time is value-specific to regression location *i*. The coordinates of i are noted by the Cartesian grid coordinates u_i, v_i. The intercept coefficient β_0 and the parameter estimates for all zth explanatory variables are each calculated independently for the location. Assigning the spatial weighting scheme for individual regression points can be done using either a fixed or adaptive kernel configuration. Fixed kernels set a constant geographic extent across all regression points and are recommended in models where there is a homogeneous distribution of known points (Ha, 2016). Adaptive kernels control for the density of data points and assign weights based on the adjacency of the nearest neighbours rather than absolute distance (Fotheringham et al., 2002). Adaptive kernels use larger bandwidths in areas where data points are sparse and smaller bandwidths in more denser regions of the study area. Bandwidth settings on the kernel further allow to control the number of points included in the calculation of a regression point (Nagoya et al., 2016). Bi-square bandwidths have defined ranges (either distance or k-nearest neighbours depending on the kernel selection) where the weights are non-zero. Gaussian bandwidths assign non-zero weights to all data points. The weighting structure in this report uses a Gaussian kernel function due to the steady size in counties across the Great Plains.

GWR is a multidisciplinary approach that can be useful for any discipline that works with spatial data sets. Matthews & Yang (2012) list an extensive review of its usages including health care policy, poverty distributions, religious studies and voting patterns. A frequent example of the added insight a geographically weighted regression can provide are hedonic price models used to model real estate values based on a wide assortment of amenities. Using a linear regression to predict housing prices based on various features would ignore the influence of neighbourhood effects of certain household amenities. The presence of multicollinearity in multivariate linear models are a frequent criticism of the GWR approach (Wheeler & Tiefelsdorf, 2005, Griffith, 2008, Wheeler & Waller, 2009), and correlations between independent variables has the ability to bias the local coefficient estimates. My research avoids the issue of multicollinearity by dealing exclusively with single regressor models, but future multiple regression analyses can use developed tools such as variance inflation factors (VIF) or a correlation matrix to explore individual collinearity between independent variables and make the proper adjustments to the model inputs.

All GWR analysis was done using the GWR4.09 release of the GWR4 for Windows application (Nakaya et al., 2016). Compared to other programs that include GWR capabilities, the GWR4 software maintains an interactive and helpful GUI that lets users develop and refine their models without programming expertise. One of the added capabilities of GWR4 are initial spatial non-stationarity tests designed to determine if the independent variables are better represented as a global (fixed) term or as a local (spatially varying) term. In a model with a single predictor variable such as this, this is a simple comparison to see if there is an improvement in the Akaike Information Criterion (AIC). The AIC operates on a belief that a “true model” can logically exist but is unverifiable. The AIC can be used to compare models built with the same input data to measure which is closest to a true model (Fotheringham et al., 2002). AIC is more than a goodness-of-fit metric as it also includes model complexity through degrees of freedom in calculations. In more complex GWR models that utilize multiple predictor variables, the spatial non-stationarity test is run iteratively through *k* local-varying predictor variables, computing a comparative model where the *k*th variable is computed as a global term. The comparative model is run with identical bandwidth, kernel selections, and other predictor variables in the same specification as the original. If the AIC in the comparative model has an improved predictive power (an AIC of two points or more below the original is considered a significant improvement), then it is recommended that the *k*th term be expressed as a global indicator in a semi-parametric GWR. Semi-parametric GWR models are hybrid compositions that allow both global and local variables to be included in the same GWR analysis. With only one independent variable in each model in this project, semi-parametric models were not necessary and AIC results demonstrated that all DVI decadal scores were best expressed as spatially varying.

Regression results are heavily influenced by the neighbourhood selection and spatial weighting scheme choice. GWR4 offers an automatic iterative process to identify the optimal bandwidth size that maximizes the predictive power of the GWR. The golden section search iterates through bandwidths in search of the output that minimizes the residual sum of squares (Nilsson, 2014). GWR4 also allows a user to create a custom range of bandwidths that the program will perform a similar issue, or a specific bandwidth. All models below used the golden section search to identify the optimal bandwidth, and those results are listed with model results. Bandwidths were kept variable from decade-to-decade due to both modest changes in the counties included in the rural classification and to use the variance in bandwidths as added insight as to the scope of drought-induced population migration. GWR4 is designed to work with point data, so county and census subdivisions polygons were converted to points using their geometric centroids. Point-based data removes uncertainty when calculating distances to be used in the weighting scheme as all counties are assigned a fixed Cartesian coordinate position.

4.0 Results

Figure 2 displays the observed population change (dependent variable) across the rural Great Plains in each of the four decades and highlights the predominant decline in rural population that has occurred since the 1970s. Accompanying it are maps displaying the absolute population counts (Figure 2.2) and a histogram outlining the distribution of the absolute counts (Figure 2.3). The most notable areas of steady intensification are around the city of Denver, Colorado, while consistent population declines can be spotted in the High Plains of western Nebraska and Kansas. The widespread growth in non-metropolitan counties in the 1970s is consistent with non-metropolitan growth seen across the United States and represents a marked deviation from decades both before and after it (Frey & Speare, 1992). Population decline in the Great Plains has been attributed to increasing mechanization making agricultural workers expendable, and overall declines in profitability of agriculture (Gutmann et al., 2005). Economic hardships in the 1980s stunted the decade of growth and steady declines in the region returned for the next three decades. Figure 2.2 notes the stark contrast in population size between the census subdivision subunits in rural Canada compared to the counties in the rural United States. Despite the depopulation, counties in the Great Plains still maintain populations in the thousands, while a strong majority of Canadian census subdivisions have less than 1000 residents. The histogram (Figure 2.3) notes that units with less than 1000 residents are the most common of the units in the analysis.

Figure 2.1 - Observed population change for time periods 1970s (left) to 2000s (right) among rural Great Plains counties and census subdivisions

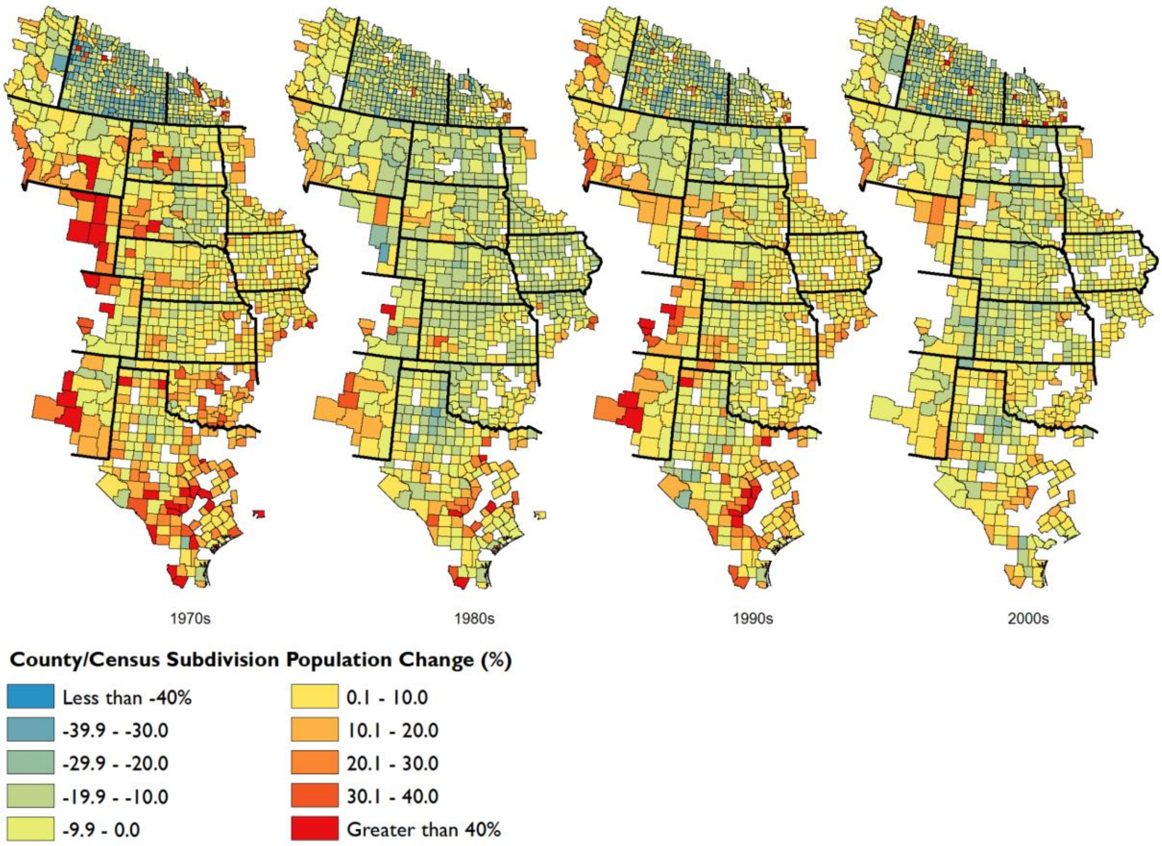


Figure 2.2 - Total Population Counts of Great Plains Counties and Census Subdivisions for each of the 5 Census samples.

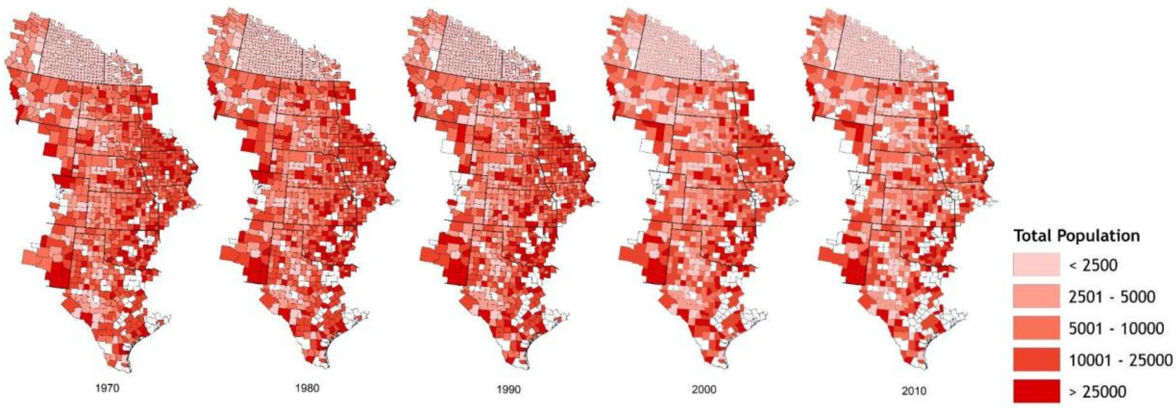
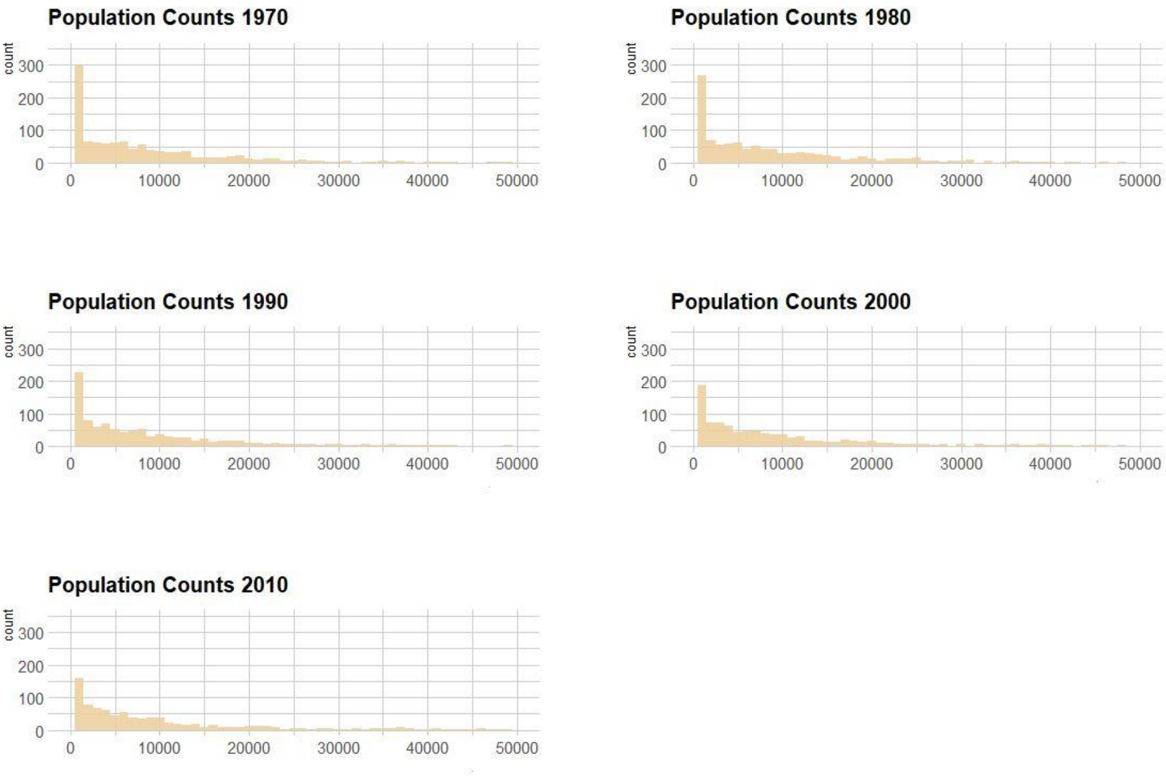
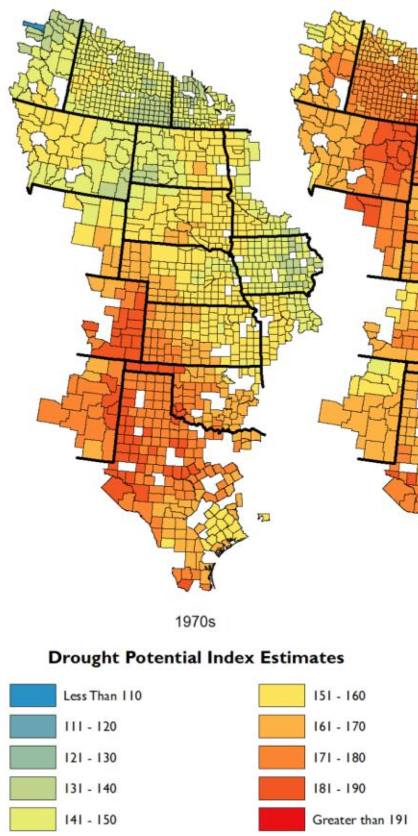


Figure 2.3 - Histogram of Population Counts for each of the 5 Census samples



The summed annual Drought Potential Index - my independent variable - is displayed in Figure 3. The annual DPI estimates were cumulatively summed in identical 10 year intervals to match the intervals in Census population recordings. The images in Figure 3 indicate that the 1980s were the decade where drought conditions were most likely, with an average DPI score in the Great Plains of 162.93, and the 1990s were the least threatening (DPI average 140.29). The fifteen highest DPI scores of the study period were all observed in the 2000s. Big Horn County, Wyoming had the highest DPI estimate of any county for the entire four decade period at 203.91 in the 2000s. The lowest observed decadal DPI score was seen in Freeborn County, Minnesota in the 1990s (103.41). The record high drought conditions in the west in the 2000s are offset by wetter and cooler conditions in the eastern Plains. In Iowa, Minnesota, and eastern North Dakota, the Drought Potential Index declined from the 1970s through the 2010s. These results fall in line with the existing precipitation east-west and north-south PET gradients. Drought conditions should theoretically be more likely in the southwestern semi-arid Plains of Wyoming, Colorado, New Mexico, and west Texas and relatively less likely in the temperate Prairies of Iowa, Minnesota and Saskatchewan if expected conditions are observed.

Figure 3 – Drought Potential Index Estimates (Independent Variable)

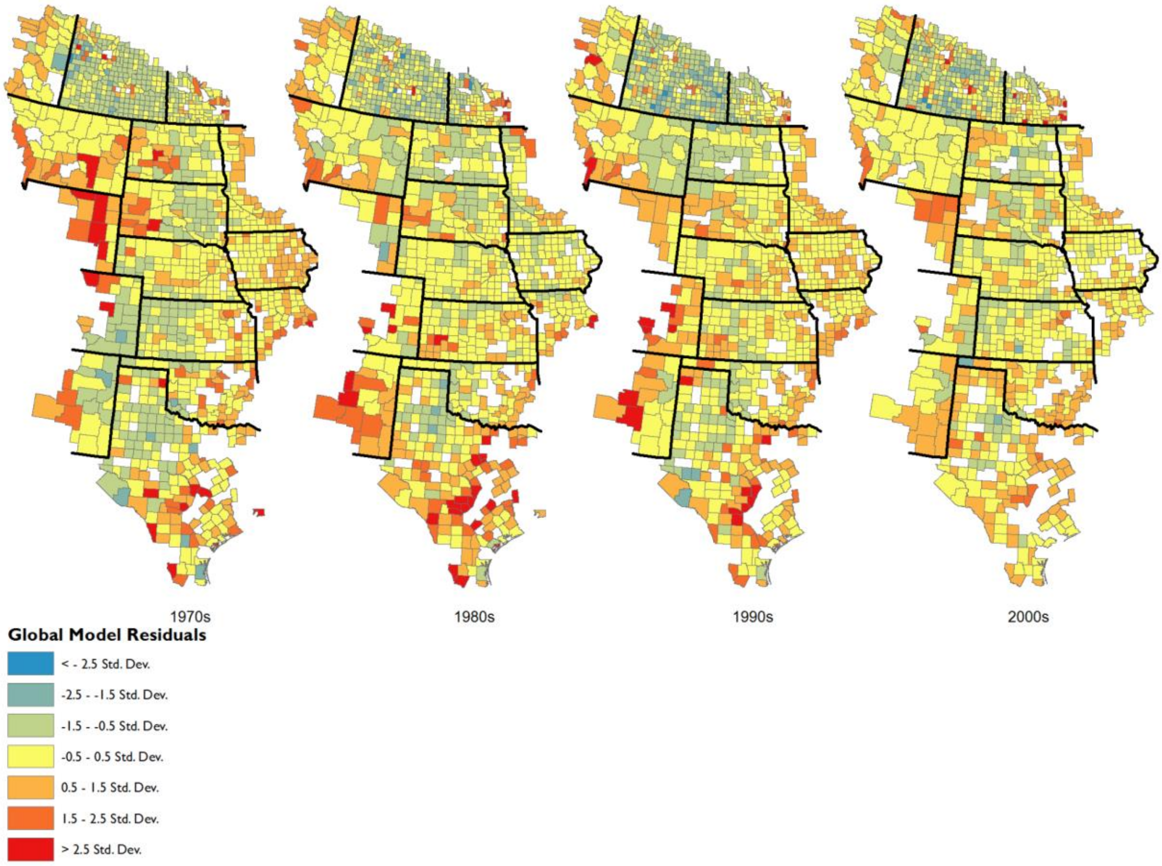


A brief summary of results from the global OLS models is included in Table 1. These initial global models reveal conflicting findings for the directionality and significance of a relationship between the DPI and population change. Only in the 1970s (t-score =14.228) and 1990s (t-score =4.435) are the relationships confirmed at significance level $\alpha \leq .05$. Both DPI estimates in the significant OLS models have a positive sign – contradictory to my initial hypothesis that counties with drier conditions would be more likely to see stronger population decline. The anticipated inverse relationship between the DPI and observed population change is only observed in the 1980s, albeit in a decade where any association is inconclusive at the global level. The OLS estimates indicate that population decline would exist in all four decades for a theoretical county that received the minimum DPI decadal score of 30. Furthermore, the slope is strong enough that all three global models with a modelled positive relationship predict to see population growth in the most drought-prone counties/census subdivisions. As expected, our linear models do a noticeably poor job of explaining the variability in population change, with R^2 values of 0.145, 0, 0.017, and 0 respectively for each of the four decades. Moran's I tests of model residuals reveal significant positive spatial clustering. The positive association in the OLS residuals indicate that population trends are similar among proximate counties than distant one. The significance in the association highlights that other extenuating influential processes of population migration are unaccounted for by this univariable model. The residuals are displayed in Figure 5.

Table 1 - Parameter estimates for the global models (*Significant at 99.9%)

	Intercept		Drought Potential Index		r-squared	Classic AIC	Moran's I of Residuals
	Estimate	t-value	Estimate	t-value			
1970s	-93.81	-14.355*	0.604	14.228*	0.145	10202.40	0.288*
1980s	-6.75	-1.227	-0.003	-0.087	0.000	9186.39	0.307*
1990s	-18.62	-4.897*	0.120	4.435*	0.017	9499.06	0.451*
2000s	-6.25	-1.745	0.009	0.389	0.000	8961.17	0.188*

Figure 5 - Model Residuals of the Global Model



The poor performance of linear models when utilized for capturing spatial phenomena is not new. As seen from our input climate data, the conditions across the Plains are not homogenous and agriculture must adapt to local weather patterns and economic conditions. Regional differences in temperature, precipitation, elevation, population density, economic focuses, crop decisions and groundwater/irrigation availability all influence the forms of agricultural resiliency and subsequently, the level of environmental stress required to create population displacement. Some regionally specific calibrations of the OLS were attempted, including splits based on nationality, states/provinces, and along with finer-scale eco-region classifications from the EPA, and each did not greatly enhance the ability to describe a drought-migration relationship. Comparing census subdivisions in southern Alberta with counties in northern Texas, where seasonal patterns and economic landscapes are much different, and expecting climate to have a constant effect in all places in between seems fool hardy in explanation, but that is exactly the assumptions made in an OLS model. A more regional approach, such as a GWR, is better suited as it accounts for spatial heterogeneity in our study area by allowing the relationships between population change and the drought index to vary.

Model results greatly improve when a geographic weighted regression approach is adopted. Fixed Gaussian kernels repeatedly returned the best goodness-of-fit results compared to other kernel types in GWR4. Individual bandwidths in the fixed Gaussian models varied from decade-to-decade, with optimal distances selected by the golden selection search in the software of 57, 60, 65, and 125km chronologically. Fixed Gaussian kernels were the optimal preferred for the first three decades of the model, but the GWR with an adaptive bi-square kernel had the best predictability in the 2000s. Tables 2 and 3 summarize the parameter estimates for our four GWR models as well as offer an overview of the improvement in predictivity when going from the OLS to GWR technique. Table 2 reports the median coefficient value for in the 1970s is 0.14, meaning a one-unit gain in the DPI would result in an expected 0.14% growth in population (or lesser decline when dealing with negative values). The range of coefficient values in all four models emphasize the heterogeneity of drought's influence on population across the Plains. The Moran's I test for spatial autocorrelation reveals that the degree of autocorrelation diminished compared to the strong positive associations in the OLS model but remained significant in the first three decades at $\alpha=0.05$ and all four decades at $\alpha=0.1$. Table 3 lists the differences in the residual sum of squares, degrees of freedom and r-squared for the GWR models in comparison with the same values for the corresponding OLS model. For the first three decades, the residual sum of squares is decreased by over 60% when changing to a spatially weighted regression approach. In the 2000s decade the improvement is a more modest 20%. Similarly, the r-squared values have increased by over 50% for the three decades with a lesser improvement of 21% for the 2000s decade. The F-test for all decades confirms that the spatial non-stationarity in the dataset is significant enough that the GWR model is a more appropriate fit. The model residuals of the GWR model are demonstrated in Figure 6.

Table 2 - Parameter Estimates for GWR analyses

	Min	Mean	Median	Max
1970s (Moran's I = 0.022, z= -3.07, p=0.0022)				
Intercept	-1016.05	-18.85	-24.99	2668.70
DPI	-15.19	0.14	0.14	6.66
1980s (Moran's I -0.023, z= -3.29, p=0.00099)				
Intercept	-757.47	-6.73	-6.39	881.57
DPI	-5.26	-0.08	-0.11	5.04
1990s (Moran's I = -0.020, z= -2.21, p=0.027)				
Intercept	-566.71	18.85	13.72	1493.70
DPI	-9.61	-0.14	-0.12	3.43
2000s (Moran's I = 0.013, z=1.77, p=0.076)				
Intercept	-216.03	3.56	-2.53	301.23
DPI	-1.86	-0.07	-0.02	1.21

Table 3 - Summarize of Model Improvements from OLS to GWR

	Sum of Squares	Degrees of Freedom	R^2	F
1970s				
OLS	362050.71	1190	0.145	
GWR	135766.28	885.25	0.680	**4.842**
Improvement	226284.43	304.75	0.535	
1980s				
OLS	163392.69	1180	0.000	
GWR	61723.66	907.33	0.622	**5.481**
Improvement	101669.03	272.66	0.622	
1990s				
OLS	235896.78	1163	0.017	
GWR	83114.62	933.46	0.653	**7.475**
Improvement	152782.16	229.54	0.636	
2000s				
OLS	205993.21	1109	0.000	
GWR	162411.79	1035.02	0.212	**3.754**
Improvement	43581.41	73.98	0.212	

Figure 6 – Model Residuals from the Geographically Weighted Regression

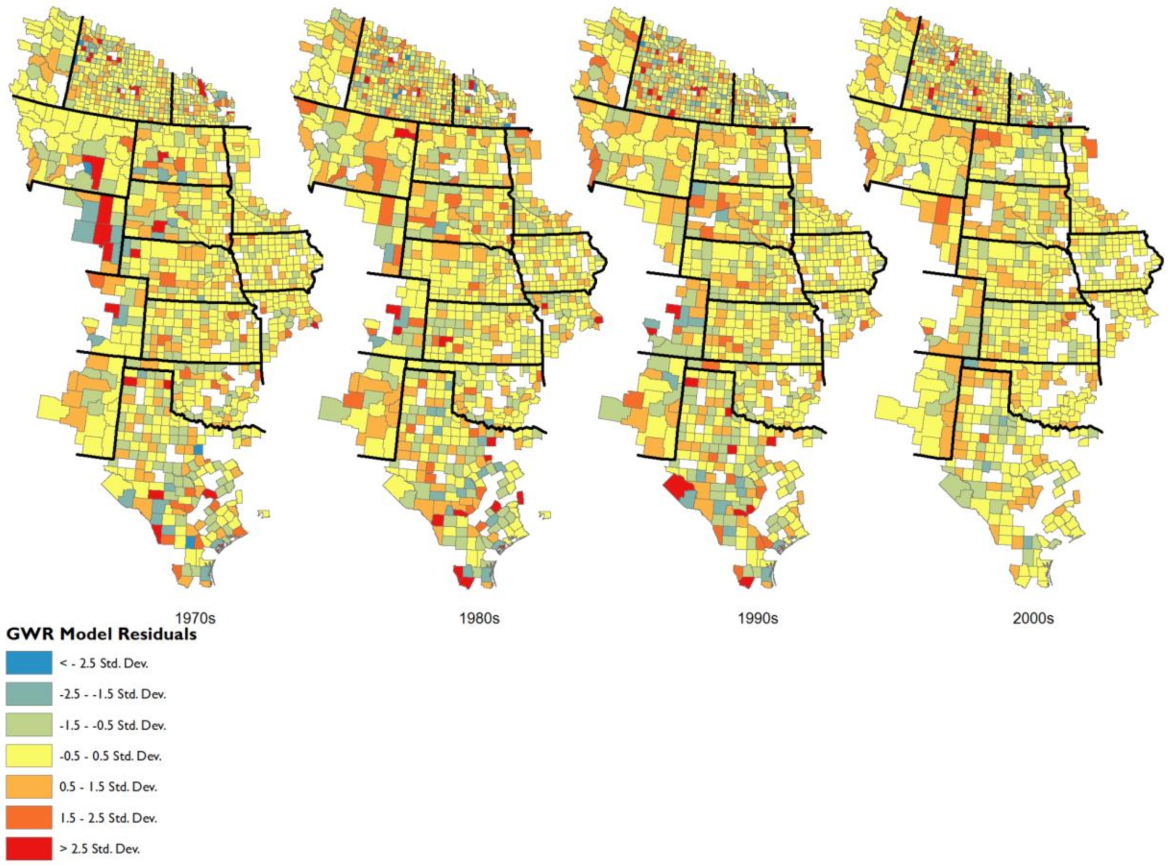
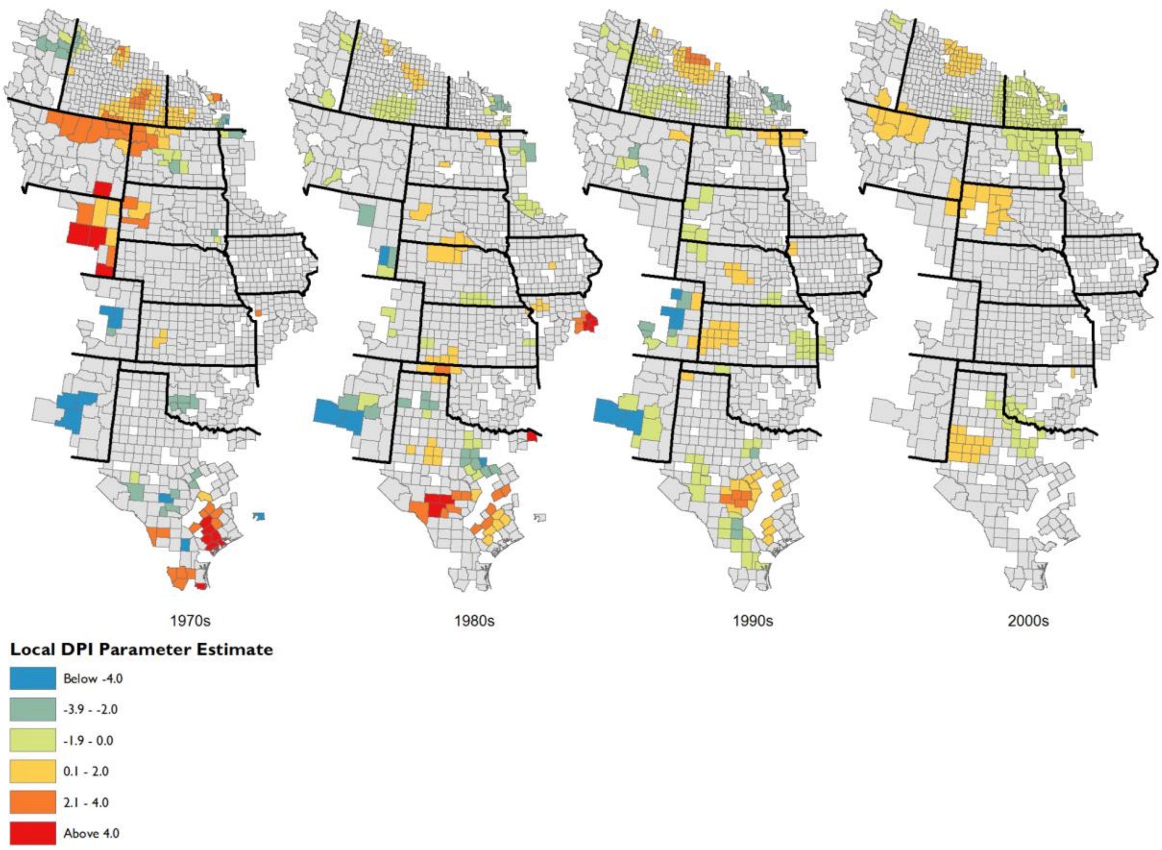


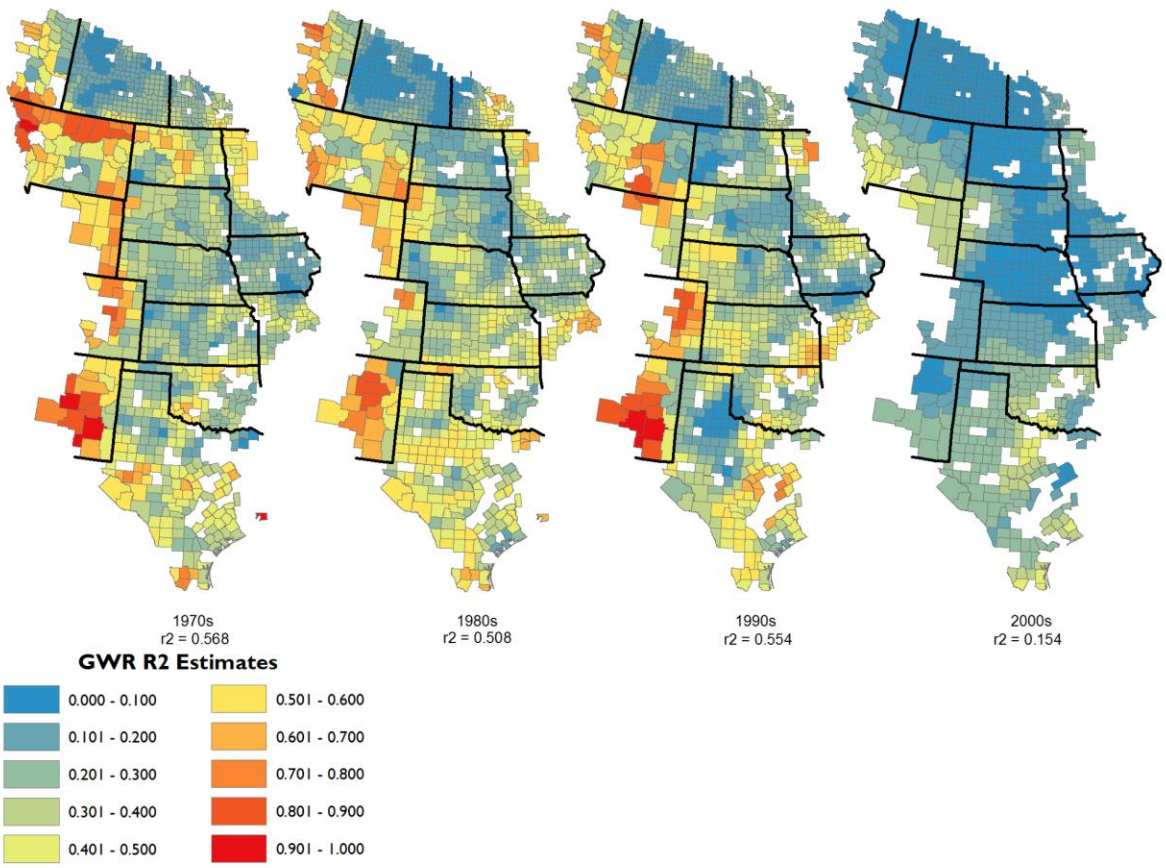
Figure 4 is a compilation of bivariate choropleth maps representing the local regression coefficients for the DPI generated by the GWR, filtered to only show the parameters in the counties or census subdivisions where a significant relationship (α=.05, t≥ 1.96 or t≤ -1.96) was detected. These maps were created in ArcGIS 10.7 utilizing the GWR4 results, using transparency features and a bivariate colour scheme that distinguishes the significant positive t-scores from the significant negative t-scores. Counties and census subdivisions displayed in green or blue values indicate a t-score < -1.96 (or a significant negative relationship) and areas in orange and red indicate t-scores > 1.96 (a significant positive relationship). The maps reveal clusters of counties/census subdivisions for which the DPI is a significant predictor of population changes. In the 1970s model, the largest significant clusters are positive clusters along the Texas gulf coast, and in the predominant ranch lands of eastern Wyoming, northeastern Montana and north into central Saskatchewan. In the 1980s, a significant negative cluster appeared in southern Saskatchewan with many isolated or very small groupings displayed across the Plains. In the 1990s, the southwestern semi-arid plains were highlighted, with negative clusters appearing in western Kansas, eastern Colorado, and New Mexico. Finally in the 2000s the cleanest groupings emerged. A cluster of significant negative association appears in the northeastern Great Plains of Manitoba, eastern North Dakota, and northwestern Minnesota, along with other clusters in South Dakota, Montana, and west Texas. Unlike previous decades, there are no isolated counties with significance spread across the Great Plains.

Figure 4 - DPI parameter estimates for the time periods 1970s (left) to 2000’s (right)



A map of the spatial variation of the local r-squared results for the GWR models is displayed in Figure 7. The location-specific adjusted r-squared values are overall quite high compared to previous studies estimating environmental factors in first-world population migration patterns. Previous estimates have reported that climatic factors have low explanatory power (Guttman et al., 2005); my models have highlighted the non-stationarity of those estimates. In these analyses, the r-squared can range anywhere from single digit percentages to over 90%. Much of the still unexplained variation can be assumed to be in social, economic, and non-farm circumstances that go uncaptured in our single predictor model. In the 1970s, 1980s, and 1990s decades, the highest r-squared values are seen in lands with high amounts of pasture and grazeland, and the model has a relatively poorer performance in the Corn Belt and farmland-intensive counties of the eastern Plains.

Figure 7 - Local r-squared results from GWR models



5.0 Case Study - Dryland environments and adaptation strategies in Lincoln County, Colorado

5.1 Background

Much of the earlier discussion above has considered a macro-level discussion of migration in the Great Plains, with the underlying assumption that local environmental conditions would determine the extent of agricultural activity or outmigration if none was practical. This case study of Lincoln County, Colorado will focus more tangibly on how the environment is influencing population mobility, the development of drought-resilient technology in agriculture, and the role of agriculture in the local economic system.

Lincoln County, Colorado is a rural county found in east-central Colorado towards the western edge of the Great Plains. About an hour's drive east of the capital city of Denver, the terrain in Lincoln County (over 2500 square miles/6500 sq km) resembles more of the flat dryland of the High Plains than the picturesque mountain scenery of the western regions of the state. The observed precipitation gradient on the Great Plains results in the western and southwestern regions of the Plains seeing the least annual precipitation, necessitating secondary water sources to ensure a productive annual harvest. Lincoln County is in the same agricultural predicament that many other dryland communities across the Great Plains find themselves in in the present day. Just like all of its High Plains neighbouring counties, Lincoln County sees some of the lowest annual precipitation totals of the Plains, with most years only recording a total of 10-15 inches of rainfall according to our USHCN interpolations. A critical missing element of the landscape in Lincoln County compared to its neighbouring counties to the east in western Kansas and the Oklahoma panhandle is the presence of subsurface and groundwater sources to overcome the significant annual rainfall deficit in these regions. Estimates from the decadal Census of Agriculture report that only 5-8% of farmland in the county has access to irrigation since 1970. Farms located in these eastern and southern adjacent counties often tap into the vast Ogallala Aquifer to overcome the existing drought conditions, but the aquifer's extent does not reach Lincoln County boundaries. In the 2007 Census of Agriculture, nearly 50% of all agricultural land was reported as irrigated to the immediate south in Crowley County, and further to the south in Otero County nearly 75% of agricultural land was irrigated. The increased availability of irrigation water allows Otero County farming operators to grow corn and other vegetables in a greater abundance in lieu of crops that can tolerate drier conditions such as wheat.

5.2 Demographic characteristics

The population of Lincoln County resides primarily in one of two communities: Hugo, the county seat found in the centre of the county, and Limon, in the north. By Crowley's (1996) classification, Limon is a sutland town, located along a historical river valley and serves as a service centre to travellers on the Interstate 70 corridor. The economy of Limon is focused on transportation with a range of gas stations, hotels, and chain restaurants directed towards travellers and truck drivers. These amenities are not located in the traditional downtown but are immediately adjacent to the Interstate interchanges on the eastern and western edges of the town. Hugo is unlike many other county seats in the Great Plains as it is not the largest community in the county. Hugo is best described as a grainland county seat, as it features a large grain elevator along the rail line. 67% of the county's adult residents are male, weighted by the over-representation of men in the criminal justice system (these and all forthcoming statistics from the American Community Survey, 2019). 89% of people are white, and 90.3% report speaking only English. 54% of workers in the county do not have more than a high school diploma, more than double the Colorado state average. Educated youth are in short supply in the county, only 20% of the population is 21 years of age or younger and in 2019 only 44 residents reported a current enrollment at a post-secondary institution.

The available labour market in Lincoln County is aging. The median worker in 2019 was listed at 47 years of age, and over half of the 1500 households in the county contained a family member over the age of 60. The workforce is also local, 86.9% of residents work within Lincoln County, and only 9% commute over an hour to employment (most likely to the Denver metro area along Interstate 70). A unique characteristic of the county is the low unemployment rate – just 2.7%. Despite the active workforce, a growing percentage of the population requires social assistance annually – 14.8% of residents were reported as being below the poverty line in 2019 and enrollment in the Supplemental Nutrition Assistance Program (SNAP) has risen nearly 40% this decade despite the shrinking number of households and population. Overall, the steady decline in population trend of past decades is continuing with steady declines in total population, school enrollments, households, labour force population all declining in ACS results from 2010 to 2019, with another census taking place in 2020.

The pattern of modest population decline in Lincoln County is quite consistent with the pattern seen across the Great Plains in terms of both absolute numbers and percentages. 4836 residents were identified in the 1970 census, a population base that shrunk marginally over the following four decades: -3.58% in the 1970s, -2.87% in the 1980s, -11.34% in the 2000s. These patterns parallel the slight declines in neighbouring Kit Carson County to the east, Crowley County to the south, as well as the rural Plains in general (-1.11% decline in the rural Plains in the 1970s, -7.22% in the 1980s, -4.86% in the 2000s). Using migration flow data from the United States Census Bureau for the late 2000s and early 2010s, the primary destination for migrants leaving Lincoln County were other eastern Colorado counties, predominantly those closer to metropolitan Denver. There were very few relative migrations to other states and most of the observed out-of-state migrations remained within the Great Plains. This data is not available for previous decades. Running contrary to this slow decline was a boom decade in the 1990s, where the reported population grew by a third (+34.40%). This growth can be attributed to the opening of the penitentiary in Limon, as incarcerated populations are included in census populations. In absolute counts, much of the growth in the county (+1558 residents) can be explained by the 960-unit correctional facility and the staff required for its operation. The facility remains a large employer in the county, and close to 40% of Lincoln County residents in 2010 reported working in social assistance, public administration, education, and social services.

5.3 Climate

Lincoln County lies in the driest of both environmental gradients that exist across the Great Plains. On the western edges of the Plains, it sees roughly half of the annual rainfall that counties in the eastern Plains receive. Additionally, its location in the southern Plains results in higher PET rates than the northern Great Plains. Both of these conditions provide challenges to the production potential of the soils of Lincoln County (Hanson et al., 2012). 75% of the annual precipitation in eastern Colorado falls in the typical growing season of April to September, but the summer heat and low relative humidity mean much precipitation can be lost to evaporation (Peterson & Westfall, 2003).

The Drought Potential Index indicates that the 1970s and 2000s were particularly dry in southeastern Colorado. Lincoln County's estimates registered in the highest 10^{th} percentile of observed Great Plains counties for dry conditions in both of those decades. The index reported that 2002 was the individual year where drought conditions were the worst. In that summer, Lincoln County recorded its lowest growing season precipitation total of our forty-year study period and received over 100mm less than they had the summer before. In the ten summers immediately before the 2002 drought, Lincoln County had averaged 325mm (12.8 inches) of summer rain to aid in agriculture, but in 2002 our interpolations estimated that only 199.43mm (7.85 inches) fell in total for the growing season. As a result of the large precipitation deficit, the Palmer Drought Index, which is perceptive to dry conditions that persist for at least 12 consecutive months, reported extremely dry conditions for the summer months of 2002. The 2002 drought was not a particularly hot drought, only 44 days were estimated to have seen temperatures reach the 30°C (86°F) threshold, just slightly above the average count of days in Lincoln County when the maximum air temperature exceeds conditions of optimal crop growth. More conducive conditions returned in the summer of 2003 – summer rainfall (256.09mm/10.1 inches) returned closer to seasonal norms but the stresses caused by the previous summer still led to an environment of moderate drought, by the PDSI classification.

There are other environmental hazards to both the residents and agriculture industry in Lincoln County beyond stress-inducing conditions. Severe summer thunderstorms can bring damaging hail and tornadoes are not unfamiliar to the region. These single day events still can pack enough punch to damage both facilities, houses, crops, and livestock. Four tornadoes of at least an F2 ranking on the Fujita scale have been observed in Lincoln County since 1970. The most notable was on June 6, 1990, when an F3 tornado tore through Limon itself, leaving 14 injured and much of the downtown core flattened. The tornado was on the ground for 16 miles before reaching the town, leaving a trail of crops and farm equipment damage. In terms of agricultural operations, tornado impacts are constrained to smaller paths than regional droughts but can be just as devastating to the farms they hit. Along with damage to farm equipment and soil contamination from the vicious wind cycle, debris in grazing lands that is consumed by livestock could have deadly consequences (Hirsch, 2013). Minimal precipitation events and the efforts to preserve as much groundwater for any agricultural or community purposes mean that the river mesa at the heart of Limon, the Big Sandy Creek, is predominantly dry and no perennially flowing creeks or rivers can be found throughout the county.

Agriculture is the predominant land-use type in Lincoln County. The lack of soil moisture prohibits many of the economically richer crops such as corn that are more abundant to the east in counties with greater irrigation capacity. Farmers in these dry counties are tasked with difficult decisions – use available farmland to harvest crops with lesser water demands, such as winter wheat or sorghum, or convert the land to grazing for cattle ranching. The result has been dueling strategies, roughly 50% of the economic output of agriculture in the county in the most recent Census of Agriculture was generated by crop farming (53%) while the remainder was made by beef cattle raising. Many wheat farmers choose to plant during the winter season to minimize the heat stress.

5.4 Model Results for Lincoln County

In my GWR analysis, the Drought Potential Index was identified as a significant determinant of population changes in the 1970s and 1990s for Lincoln County. The relationship was insignificant for the other two decades. A summary of the local GWR results for Lincoln County are provided in Table D.

Table D - Model results for geographically weighted regression models performed for Lincoln County, CO

Decade	Intercept			Drought Potential Index			Local R-squared
	Estimate	Standard Error	t-score	Estimate	Standard Error	t-score	
1970s	762.491	165.011	**4.621**	-4.238	0.920	**-4.605**	0.798
1980s	129.660	77.293	1.677	-0.743	0.464	-1.600	0.442
1990s	949.095	134.243	**7.070**	-6.080	0.881	**-6.903**	0.817
2000s	-63.007	46.435	-1.356	0.314	0.264	1.188	0.174

Both the 1970s and 1990s (as well as the insignificant 1980s) models project that as the potential for drought conditions begin to increase, decreases in population gains will continue until a threshold DPI score of 179.91 is reached, when expected population changes become losses. In the 1990s, the DPI threshold for population decline to occur was 156. The observed DPI outcomes in Lincoln County were 176.54 for the 1970s and 148.55 in the 1990s and resulted in negative residuals in both situations. Both significantly associated decades also have local r-squared values 20% more than the average r-squared for the entire GWR. As previously stated, much of the population growth in the 1990s in the county can be explained by the opening of the Limon correctional facility. Despite this very obvious growth in population that is unrelated to agriculture, the drought index still explains over 81% of the variance (R^2= 0.817) in population growth when weighted for Lincoln County, influenced by the high drought potential and observed double digit decline in population percentage in adjacent counties.

Predictive power for the 2000s decade was overall much poorer for the rural Great Plains as a whole and Lincoln County is no different. With a local r-squared far below the other three models (only 17.4% of variation explained), the GWR for the 2000s indicated a reversal relationship where increases in the drought potential index would lead to lesser population decline and predicted growth. The associated t-value of 1.188 indicates that the relationship can't be confirmed as non-zero at any critical value. In the parameters provided, a county would have to have a decadal DPI of 201 when no population. Only one of the 1111 counties and census subdivisions recorded a DPI score that high in the 2000s. Any relation is deemed insignificant.

5.5 Drought adaptation in Lincoln County

There is a significant correlation between the DPI and population change in two nonsequential decades of the four in my study period, yet the driest period identified of 2002 was in one of the two insignificant decades. This may reflect socio-economic changes and agricultural adaptations that have emerged in recent decades. The percentage of Lincoln County's workforce employed in agriculture has stayed consistent amidst the slow depopulation, which suggests that the agricultural industry in the county is relatively resilient to the climate difficulties they have confronted.

In counties such as Lincoln with scarce water availability and where irrigation is not an option, agricultural operations must get creative to salvage available water and soil quality. Crops better suited for drier climates such as winter wheat and sorghum are the crops of choice in the county. In more recent decades, technological advancements in wheat harvesting have produced newer varieties that are more tolerant of dry conditions and can flourish with less water consumption (McLeman, 2019). These newer cultivars of drought-tolerant wheat are still not as economically profitable as irrigated wheat or other water-intensive crops. The combination of lower cash-per-acre-planted yields from dryland crops and required fixed cost investments (such as tractors, harvesters, fertilizer, and pesticides) has led to a widespread growth in farm size as an economy of scale. The average farm size has grown in the Great Plains since the Dust Bowl era to over 3,000 acres in Lincoln County today (Census of Agriculture, 2017). Acreage growth has been associated in the past to times of drought as an adaptation strategy in the pre-deep well irrigation era (Baltensperger, 1993). In 2017, the average farm size in Lincoln County was estimated at over 3,000 acres with 60% of total farmland estimated as pastureland

and 39% as cropland. Conversely, in rural Iowa, where precipitation rates are far greater and PET rates lower, the average farm size in the most recent census was 355 acres.

Livestock herding and production are more often reserved for regions that experience water scarcity (Hanson et al., 2012), but grazing is not an industry that is immune from drought-related stresses. With increasing variability in temperatures and precipitation conditions, years with forage plant deficits are expected to occur more often in the southern Great Plains in the coming decades (Briske et al., 2020). As many cattle operations maintain simultaneous hay production to be used as winter feed, summer droughts that limit production can have lasting impacts. In Lincoln County, farmers have had to offset drinking water shortages and crop failures by having additional water and hay shipped into use for cattle raising (McLeman, 2019). These added shipping costs to livestock production are irretrievable as raising the price of their stock would make the farm uncompetitive in the market to other operations who did not have the same challenges.

Financial support systems exist to aid farmers who have been negatively impacted by drought, although supports differ for croplands and ranchlands. Crop insurance availability is a factor of recent yields, so applicants who have suffered from drought in consecutive years will find themselves in a precarious position. Drought-related supports from the federal government is so abundant that there are dedicated pages on the drought.gov portal listing supports, from Disaster Support funds from the US Department of Agriculture to economic disaster aid from the US Department for Small Business.

Our GWR model detected Lincoln County as being part of a cluster of counties on the western edge of the Great Plains where the drought-population change relationship is significantly negative. The cluster of counties in southeastern Colorado all have experienced similar trajectories in recent decades, a modest depopulation decade over decade, a consolidation in agriculture amongst remaining farm enterprises (using average farm size as a proxy), and a greater reliance on non-farm employment. Unlike its neighbouring counties to the north (Washington County) and south (Crowley and Kiowa Counties), Lincoln County has the geographical benefit of the Interstate as a way of generating off-farm employment and less of a reliance on agricultural activity. The abundance of fast-food and hotel jobs are not particularly lucrative work, but the supplemental employment is an advantage of the transportation network not afforded to other rural Colorado counties. In the border counties away from the interstate, off-farm employment is reduced to county administration or social services, with those unfit to fill those roles moving to larger towns, such as Limon or Denver.

The use of the Ogallala Aquifer to the east of Lincoln County to irrigate crops is itself an adaptation strategy used by farmers to overcome similar rainfall deficits to those experienced in eastern Colorado. Farmers above the aquifer's basin have used post-war developments in technology to extract water for irrigation at unsustainable levels. As a result, the Ogallala Aquifer's range and volume has diminished considerably since the mid-1970s and the geographic extent of farms with access to deep-level irrigation is contracting. Future challenges regarding its accessibility, coupled with expected temperature-based increases in PET will create more dryland environments similar to those currently in Lincoln County. Lincoln County has functionally adapted to their water-scarce landscape by converting to livestock grazing, planting drought-resistant crops such as winter wheat, and maximizing economies of scale with larger farm sizes to make up the difference in revenue between irrigative-intensive crops grown in other counties. There will be future challenges. Any increases in average summer temperature will add further stress to the already fragile balance agriculture operates in. Prolonged periods of dangerous temperature or high evapotranspiration rates will continue to create water shortages and threaten crop and livestock production. The vitality of livestock in the region is dependent on the ability to provide nourishment to the herd at an economical rate – a concern still not fully addressed. Many of these challenges will involve the role of actors outside the county– including state, and federal bodies to provide relief funds, and international bodies to collaborate on environmental policies that combat climate change and prevent the Lincoln County story from replicating in dryland prairies across North America and beyond.

6.0 Discussion

This study has taken a novel approach of assessing climatic influences on migration in the first world. Past research into environmentally induced human migration patterns have focused primarily on low-income countries and subsistence-based cultures where community adaptive capacity is far less. Identifying the drought-agricultural relationship in drylands of high-income countries has previously been shown to be much more difficult and reflective of the advances in technology, land maintenance techniques, and other financial, social, or infrastructural circumstances that make Great Plains farmers less vulnerable to droughts. Further, the economy of the Plains is more diversified than the agrarian-dominant societies of the third world, which means households in the Great Plains each have different exposures and vulnerabilities to drought forces. As the percentage of the workforce involved in the agricultural production sector declines, the cumulative exposure of the region diminishes. A second key difference in the methodology of this study was ignoring the well-documented history of droughts in the Great Plains from the Dust Bowl-era to the present day. Much research into agricultural developments in the Great Plains have been focused on the aftermath of documented dry periods (Cook et al., 2007, McLeman et al., 2010). Our broad-based exploratory research was designed intentionally to detect broader trends that could be caused by wider-scale climatic change. In the Great Plains, climate change will create new realities for growing seasons and conditions for economically desirable crops if projections become reality. Damaging droughts remain a threat to the food system of the United States.

Many previous studies that have sought out the influence of environmental factors on migration have returned similar conclusions to my work here - it depends. (Hunter et al., 2015). It depends on spatial location, which is revealed by the local parameter estimates of the geographically weighted regression. The four GWR models add much needed spatial context to the inconclusive OLS results regarding the significance of the relationship between the Drought Potential Index and observed population change in each of the four decades. Both the geographical variability tests and the f-value from the GWR ANOVA analysis confirm that the DPI is best expressed as a spatially varying term rather than as a fixed global term. The GWR model allows for the creation of significance maps for each predictor variable which filters parameters to only display units where the statistical relationship is significant. The significance maps in Figure 4 reveal there are many Plains counties and census subdivisions in the 1970s and 1990s where the DPI is incapable of predicting population changes, despite a significant relationship determination at the global level. Inversely, there are clusters of counties in the 1980s and 2000s decades where significant associations were detected, but the global model for that period failed to identify a correlation for the Great Plains overall.

The DPI served as a reasonable proxy of drought potential when compared against known drought events in the Great Plains during the late 20th century. Using selected known droughts in South Dakota in 1976 (McLeman et al., 2021), Montana, Saskatchewan, and the Dakotas in 1988 (Arndt, n.d.), and Oklahoma in 1998 (Arndt, n.d.), all return DPI scores greater than the rest of the Great Plains in those given years. For all counties and census subdivisions collectively, the highest mean DPI score were in notoriously dry years of 1980 and 1989. Counties in the southern Plains in Texas and New Mexico tended to receive the highest average annual DPI due to the frequency of higher temperatures and lower summer precipitation totals.

The DPI does a serviceable job as the climate variable but is an experimental index created for my models and can still be refined. The current construction of the DPI equally weights the conditions in the PDSI with the current season's extreme temperatures and observed rainfall, however the inclusion of antecedent temperature and precipitation in the PDSI's monthly calculation does introduce some collinearity to the input variables. The DPI, which inverts the scale of the PDSI, and the PDSI itself correlate annually in a range between -0.65 and -0.9 for the 40-year study period. A future research assessment of the DPI that involves running the same GWR analysis using PDSI as the independent climate variable to assess the differences in the models would be informative. The PDSI does weigh the input conditions temporally with greater emphasis on more recent observations, so exploratory work to compare the indices would help to understand further the utility of the DPI.

Along with visualizing the variation in local parameters that are uncaptured by the OLS, we can also chart the counties and census subdivisions that run contradictory to our hypothesis of a negative association. In Figure 4, these contradictory areas are represented by the warmer colours (yellow, orange, red). No clear spatial trends emerge from the location of these contradictory clusters. I am hesitant to conclude that areas of significant positive association with the index confirm that population gains are the result of drier conditions, as environmental conditions are considered a push factor for migration rather than a pull factor. When choosing a migration destination other factor such as economic factors, the availability of affordable housing, or personal familiarity are often weighted more heavily. The significance maps reveal a striking number of transparent counties or census subdivisions - representative of there being no significant relationship in those units between the DPI and population change. From a methodological perspective, the vast areas of “white space” in each decade showcase the trouble of some traditional studies that analyze output local parameter surfaces without considering the local t-scores (Mennis, 2006). A large number of inconclusive counties is also reasonable with the regional nature of drought and the expectation that more counties experience “normal” conditions compared to excessively wet or dry conditions. The decreases in community exposure and agricultural vulnerability in the first world also allows drought adaptations that do not result in relocations.

Some areas where it would be quite logical to conclude that the drought index would not have a large and direct influence on migration would include areas with large non-farm employment industries. There are a plethora of communities that are dominated by other industries such as the railway communities of North Platte, Nebraska or Belen, New Mexico, or counties with extensive oil extraction such as much of the Texas panhandle. Alternatively, counties above the Ogallala Aquifer in the High Plains of western Kansas, Oklahoma, and north Texas have had an abundance of irrigation water that has allowed them to plant, irrigate, and harvest almost independently of environmental conditions. Some counties above the Ogallala Aquifer appear in positive association throughout the first three decades, likely due to the relocation of the meatpacking industry to be proximate to the abundant feedlots and cornfields of the High Plains. Jobs in the meatpacking industry are often precarious, low-skill, and low-paying roles that many residents did not wish to fill. As a result, much of the workforce was recruited from southeast Asian and Hispanic cultures that were indifferent to those job characteristics (Broadway, 1990). An influx of migrants to Garden City, Kansas in the 1970s to fill the job vacancies of opening processing plants is represented by a small grouping of positively associated counties in southwest Kansas.

The spatial variation of clusters from decade to decade also creates individual counties that appear as both significant positive and significant negative in different decades. A noticeable example of these temporally diverging counties appears in south-central Saskatchewan. These census-subdivisions appeared as positive in the 1970s before shifting to negative associations in the following two decades. The occurrence of diverging counties in the model is not unexpected, after all shifting climate patterns over the Plains are the impetus for this research and drought is by its nature an anomaly in recorded climate patterns rather than a historical constant. A likely cause of the conflicting associations here is an inherent data issue with using census subdivisions. The badlands of southwestern Saskatchewan are sparsely populated and the smaller size of the census sub-division compared to the county means there are some census subdivisions that report less than 100 people in each Census. As such, modest absolute gains or losses in population from decade-to-decade could create outlier data when converted to percentages. At the base of the Oklahoma panhandle sits Beaver County, where the DPI is positively associated with population change in the 1980s, and a negative associated in the 1990s. The county saw an 8% increase in population during the 1970s as oil and gas exploration intensified before steady declines followed in subsequent decades. Census of Agriculture data for the county reveal consistency in the total farms, acres, irrigated acres, primary crops, and operators over the last 50 years. Further research would be needed to understand if much of the decline in Beaver and surrounding counties was caused by the mechanization of gas and oil production, if the county's location on the fringes of the shrinking Ogallala Aquifer made irrigation difficult, or other extenuating factors are involved.

R-squared values represent the variability of data points relative to the fitted regression line so values can be assessed regardless of the local significance in the drought/population relationship. The maps displayed in Figure 7 show that when accounting for spatial heterogeneity, the DPI can explain a greater percentage of observed population change in the ranch land and pasture-intensive environments. The ability of the DPI to explain roughly 50% of population migration overall and greater than 70% in select regions is itself an advancement from previous works that have highlighted the difficulty of identifying drought-related migration through a variety of lenses (McLeman & Ploeger, 2012).The strongest local r-squared results were seen in the western Plains, specifically in Montana and New Mexico, where low precipitation combines with poor irrigative capacity to make cash cropping difficult and cattle grazing is the predominant agriculture activity and use of land. The GWR results were relatively poor in the “Corn Belt” of Iowa and eastern Nebraska, where growing season precipitation is much higher. Regardless of location, the DPI has a far greater explanatory power of population change than in a GWR model compared to the global OLS models. When compared to crop farms, ranchland farms have fewer avenues to financial support and debt recovery after times of drought (McLeman, 2019). If severe drought strikes a ranching community and causes damage, their capacity to withstand those impacts is likely less than what a cropland farmer could sustain.

Conversely, the DPI does a relatively poor explanatory job of explaining population change in south central Saskatchewan along the international border. The grouping is again likely the result of a small change in absolute population creating large percentage changes for a decade. To confirm, an outlier analysis using Cook’s Distance (d) statistic identifies that many of the largest outliers can be found in Saskatchewan in the 2000s. Along with greater precipitation, other resiliency mechanisms such as irrigation water availability and non-farm employment are more abundant towards the eastern edges of our study area and are represented as such in the poorer predictive power.

The second of my research hypotheses was that the drought/population relationship would deteriorate with time in line with the “lessening hypothesis”. The relationship between climate and agriculture is an “adaptational paradigm” where the historical aridity has guided agriculture towards environmentally suitable activities (Riebsame, 1991). Despite constant changes in the economy, environment, and technology, the Plains has adapted and innovated to maintain the same usage that it has since it was settled. Farmers continue to reduce vulnerability by developing infrastructure that shelters their operations from adverse drought conditions, and as a result increasing mechanization of farm work lessens the workforce in agriculture. This theory of lessening is displayed in the predictive power of both the GWR and OLS models. The most accurate of our four OLS models was the chronologically earliest model with an r-squared of 0.145. The following decades were all incapable of explaining any of the variation in population change. Similarly, the GWR model for the 2000s was by far the least predictive model of the four locally varying models, explaining just 21.2% of population changes, a number far less than the previous three decades. Beyond the regional-wide decline in our 2000s model, there was no sequential lessening at the local level for the parameters for Lincoln County as the two significant decades were not chronological. Researchers have been following the decline in agricultural employment as far back as the 1970s as an influence on demographic patterns (Albrecht, 1986, Gutman et al., 2005). For migration to truly be influenced by dry conditions, there must remain a large enough population employed directly in farming or in the immediate processing of crops or livestock, and as the non-agricultural workforce expands there exists a greater percentage of the population that are sensitive to dry conditions.

The stark decline in predictive power for the GWR models between drought and population change in the 2000s is another finding worthy of discussion. The plot in Figure 7 demonstrates that the r-squared values for the 2000s are much lower than they are for other decades, and the overall r-squared for the model is approximately one third of the models for the other decades. Further, the 2000s decade was the only decade where the use of an adaptive bi-square spatial kernel produced a better description of the drought-population relationship than the fixed Gaussian model. The difference between the fixed Gaussian and adaptive bi-square outputs (the adaptive bi-square r-squared was 0.335) were not great enough to add the complexity to this project of introducing a second spatial weighting scheme, however the poorer predictive power and a different optimal kernel were noteworthy.

There could be a diverse array of hypotheses created regarding why the DPI has a relative collapse in predictive power for the 2000s. Drought conditions detected by the DPI were not anomalous to the decades prior. Could we be seeing further advancements in technology that enhance adaptive capacity to insulate from drought events? Are those same advancements in technology further reducing the number of workers directly in agriculture? Or are there simply much larger non-environmental factors at play in the 2000s compared to the three decades before it? The 2008 global financial recession may be a partial explainer of the poor model performance, especially as the Census was taken only 18 months after the recession began. This economic crisis was not coupled with widespread agricultural drought like the Great Depression of the 1930s but had significant influences on many in the Plains who were forced to move for financial purposes. Amidst the recession, the Great Plains has been on an economic upswing. Much of the exports are agricultural products, but there was also significant growth in non-farm manufacturing sectors beginning around 2000 (Scott, 2017). Off-farm employment, especially in high-wage positions, has grown in the Plains., and many of the states with the highest rates of employment in 21 were in the Great Plains. Kotkin (2010), discussing North Dakota, emphasizes the growth in natural gas and energy jobs in the state, with note on the high percentage of residents 25-34 with college degrees. Much of this economic specialization is rooted in urban areas such as Fargo that are excluded from our work here, but the increasing diversification of the Plains economy is worthy of future consideration for the now completed 2010s decade, and again in the future with 2020 data soon to be published. One academic argument as to the changing landscape in the 2000s is that the continued progression in conservationist agricultural practices, such as tilling practices, planting cycles, and other ecologically based farming systems have created a “sustainable equilibrium” that is relatively shielded from drought conditions (Riebsame, 1991, Martens et al., 2013). This argument is akin to an “endgame” for the lessening hypothesis where drought has no significant influence on migration.

Another considerable shift in the 21st century is a rethinking of historical migration flows in the Great Plains. Technology developments that are now ubiquitous in daily life such as broadband Internet, cell phones have made rural life more accommodating. The growing work-from-home population further reduces the influence of workplace location in a relocation. An increasing academic focus on “amenity-based” migration follows influxes of people not from the traditional rural-to-urban regions but towards areas with added amenities, be it natural features such as lakes and beaches, or areas with increased services such as specialized health care services for seniors (Lewis, 1977, Gutmann et al., 2005, Golding, 2014). Gutmann et al., (2005) find that Great Plains counties with more recreational water features saw higher in-migration consistently from the Great Depression through the 1980s. The demographic shifts amongst farming families has also been advanced as a reason for declining populations in agricultural-dominant rural counties and the deteriorating climate-migration relationship. Overall fertility rates have declined, and those children are more likely to move away in pursuit of post-secondary education than they are to take over control of the farm from their parents (Maxwell & Soule, 2011). The documented “brain drain” is a result of educated youth eschewing their hometowns post-graduation in search of other lines of work, typically non-agricultural elsewhere and has profound impacts on the demographics of counties (White, 1993, Gutmann et al., 2005). Migration has always been a dynamic and complex process and each of these social and demographic developments in the Great Plains should be considered in future work in the same vein as this.

To build a stronger population model of the Great Plains, consideration to variables outside of environmental factors are required. An extensive and diverse set of nearly 50 independent variables that are considered to explain in some regard the livability of the rural Great Plains was collected during a field visit to northern Kansas and southern Nebraska in 2018. The list was developed based on first-hand observations and insights provided by long-time residents regarding the changes they had seen in recent decades. Data points recommended include the availability of education for adolescents (both high schools and post-secondary institutions), the availability of agricultural irrigation, locations of crop or livestock processing facilities such as meatpacking or ethanol plants, and locations of Dollar General, the low-cost discount retail chain that is ubiquitous in the rural Great Plains. All these variables are readily available in the present day, but many lack historical consistency unless significant research was undertaken. Further, the significant lag between the most recent population estimates (2010) and the time of this data collection (in 2018 and 2019) was determined to be too large a time to be considered representative. There is an abundance of future research opportunities in utilizing this wealth of variables to build a larger comprehensive population model that couples both the environmental and economic landscapes of the Great Plains.

In terms of agriculture resiliency, Lincoln County provides many insights into the dynamic relationship between agricultural operations and environmental conditions in the Great Plains. Much of these strategies involve preserving precipitation to use as supplemental irrigation during the growing season. Farmers have taken to unorthodox growing seasons, especially with the drought-tolerant wheat cultivars predominant in Lincoln County, to reduce the stress on crops from the increasingly hot summer conditions. An advantage in Lincoln County, and much of the Great Plains is the dominance of clay-based alfisol soils that are absorptive and conducive to agriculture. There is a diversification of the county economy beyond farm employment in the county and despite the Limon service industry or penitentiary not creating a wave of white-collar jobs, these are all industries that will not be influenced by dry periods.

The lessons of dryland adaptation will need to be heeded by counties currently utilizing the Ogallala aquifer for intensive irrigation. 90% of aquifer extracts are currently used for agriculture and the heavy reliance on groundwater to overcome precipitation shortfalls results in a surface landscape that looks much different than the dryland environments surrounding the aquifer (Chaudhuri & Ale, 2014). The abundant center-pivot irrigation heads, rows of corn, and clustering of feedlots and large meat processing plants are all a result of the different choices allowed to the industry by having such bountiful groundwater available (White, 1994). There is an array of projections as to when the day of reckoning for irrigation-reliant farmers will come but at current rates corn production will decline by 65% by the end of the century if extraction rates continue at the current pace (Cottermann et al., 2017). Irrigated agriculture is the economic base for the High Plains and decline in the aquifer to reduced or unusable levels will have an enormous effect on both agriculture operations, and the high employment industries that process agricultural products, such as the aforementioned feedlots and meat processing plants but also includes ethanol plants and the transport industry that connects these locations.

6.1 Challenges and Next Steps

For as generalized as this research was there are multiple data shortcomings that had to be considered. Creating any specific drought index is a difficult task and the climate data chosen to model drought can change from researcher to researcher. Our search for agricultural drought seeks to identify periods of high temperature and low precipitation, a methodology which would ignore occurrences of cool droughts or wet spells in areas of high PET that hide harmful conditions. The decadal American censuses provide trustworthy and consistent population measurements, but the ten-year period hinders the ability to capture immediate responses to dry periods that occur early in the decade. In recent years, annual county population estimates are released by the Census Bureau. Future research updating this methodology for the now-completed 2010s decade to analyze finer-scale movements could provide insight that our decadal estimates overlook. A broader generalization brought on by the ten-year gaps between Censuses is the assumption that all migration that occurred in the decade where drought and population change experienced a significant association, is environmentally induced migration. Movements for non-farm employment, family reunification, or other commonly observed migration push and pull factors still can influence absolute counts of people in terms of drought. Net migration databases from the University of Wisconsin and the Census Flow Mapper available on the United States Census Bureau website add extra insight into the “landing spots” of those that left a given county in a ten-year period, if their destination spot was still within the United States’ borders. No equivalent program exists from Statistics Canada to track intra-Canadian migrations in the same capacity.

Geographically weighted regression is at its core an explorative data technique and the fundamental regression cliché that “correlation does not imply causation” must always be considered during regression analysis. The isolated counties that express a significant relationship in the Plains should be considered in this regard. Droughts are regional in nature but not small enough to be restricted to an individual county or census-subdivision. Individual counties that share significance with none of their adjacent neighbours are likely a result of influences not captured by our model (such as emigration caused by a factory closing, or years when high temperatures and low precipitation were observed, but rarely in the same season). GWR is an evaluation tool of spatial non-stationarity and not a definitive determinant of causation (Ha, 2019).

7. Conclusion

This research adds to the literature on environmentally induced population migration by utilizing an example of a first world study region with reliable data sources. As migration influences can vary from the micro- to the macro-levels, this study accounts for spatial non-stationarity in climate/population interactions in attempts to identify smaller subregions where the relationship is more pronounced. We developed an index designed to detect agricultural drought and observed that it was able to predict a greater percentage of the variation in population change than global ordinary least squares models and other previous research suggested. A geographical weighted regression revealed that observed drought conditions have a spatially varying influence on population changes in the agriculturally dominated Great Plains. In primarily ranch lands of the western Great Plains, increases in the Drought Potential Index had the strongest associations with population declines, evident that support systems for cattle raising operations are not as beneficial as adaptation strategies for crop farmers. Drought has a diverse set of influences It is self-evident that numerous other social, economic, or demographic factors shape migration and deserve inclusion in a population change model, but this report concludes that accounting for spatial variation greatly enhances our understanding of the drought-population dynamic in first world drylands.

8. References

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