AN EMPIRICALANALYSIS OF GROUNDWATER DEPLETION IN THE HIGH PLAINS-OGALLALA AQUIFER REGION

by

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Abstract

Depletion of the Ogallala Aquifer is a significant concern for many communities in the High Plains region and, indeed, the global food system. Using data from 181 counties in the High Plains region, the STIRPAT model is used to identify the social drivers of groundwater depletion. The ordinary least squares regression analysis indicates that the scale of irrigation, value of agricultural commodities, and farm income each increase depletion levels, while county per capita income is negatively associated with depletion. Results from a path analysis reveal that government subsidies indirectly drive groundwater depletion by supporting farm incomes and the value of commodities. Groundwater depletion in the High Plains region is ultimately a policy decision − one that has generated a positive feedback loop linking farm incomes to groundwater withdrawals.

Keywords: Environment, Agriculture, Water, IPAT, Ogallala, STIRPAT

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Dedication

This thesis is dedicated to my husband and best friend, Aaron Hughes. Thank you for preparing meals, keeping my water glass full, and reminding me to take my vitamins every time I became overly obsessed with the data analysis for this thesis. Thank you for encouraging me when I felt too tired to work and for helping me maintain a good sense of humor during the more stressful times. Words cannot express how much I appreciate all that you do.

Chapter 1 - Introduction

The recent media attention to the water crisis in California has increased the level of awareness of water shortage and droughts in other affected areas in United States. One such area to receive increased levels of media attention is the Great Plains region, which is highly dependent on agricultural production and is home to the largest aquifer in North America, the Ogallala Aquifer. A July 2015 issue of *Bloomberg Businessweek* referred to the Ogallala Aquifer's dwindling water supply as "the Great Plain's looming water crisis" and reported that the "depletion of the giant aquifer threatens vital U.S. farmland" (Bjerga, 2015), as the aquifer is the area's main water source for agriculture. During the same month, *The Kansas City Star* also reported that the "days of irrigation for western Kansas seem numbered" and referred to the crisis as "a drying shame", since groundwater pumping for irrigation continues to threaten the life of the aquifer (Wise, 2015). Increasingly, the Ogallala Aquifer is drawing concerns of policy makers and scientists. In order to address groundwater depletion, it is imperative to first understand the social influences driving depletion. Such is the goal of this study.

The Ogallala Aquifer was formed over twenty million years ago through the development of unconsolidated sedimentary layers formed by gravel and sand washed down from the Rocky Mountains. Water from rain and melted snow seeped into storage in the sediments and has been held in the aquifer for millions of years (Guru & Horne, 2000; Hornbeck, 2012; Macfarlane, Misga, Buddemeier, 2000). The aquifer underlies 174,000 square miles across eight states: Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (Hornbeck, 2012; McGuire, 2014; Rosenberg, Epstein, Wang, Vail, Srinivasan, & Arnold, 1999). This region of the country is often referred to as the "breadbasket of America", due to the high level of agricultural production from this region, despite the semi-arid climate that the area typically experiences. The population of the Great Plains, which relies predominantly on groundwater as its main source of water (Guru, 2000), has in recent decades become concerned with the rate of fresh groundwater withdrawals that the aquifer is experiencing. This concern is quite justified as agriculture in this area is the primary source of income to many of the area's residents and contributes billions of dollars a year toward to the global economy (Hornbeck & Keskin, 2010). Wheat, corn, sorghum, and alfalfa are the major commodities that are produced in this area and must be heavily irrigated to result in high levels of production (Benson, 2007). In total, the aquifer supplies 30% of the nation's groundwater for irrigation and over the last 50 years, contemporaneous to the increase in agricultural production, the aquifer has experienced rapidly declining water levels (Steward et al, 2013). The available empirical literature argues that the increased production of agricultural goods are largely attributed to technological advances which have allowed for unsustainable rates of water extraction from the aquifer, resulting in rates of withdrawal that have exceeded the rate of recharge (Beattie, 1981; Bell & Morrison, 1978; Benson, 2007; Clement, 2010; Guru & Horne, 2000; Steward et al., 2013;Warren, Mapp, Ray, Kletke, & Wang, 1982). Recent studies report predictions of highly problematic aquifer depletion levels by 2070, which could have a dramatic effect on the nation's food supply (Steward et al, 2013) and could affect the global economy, making this an area that requires more research to determine how to remedy this issue.

McGuire's (2014) U.S. Geological Survey report describes water-level changes in the High Plains Ogallala aquifer from predevelopment (1950) to 2013 and from 2011-2013, in addition to changes in water storage in the same periods. Area-weighted water level samples were taken across all eight states underlying the aquifer and a range in changes from a rise of 85 feet to a decline of 256 feet was found in the period of predevelopment to 2013. Water-level changes from 2011-2013 ranged from a rise of 19 feet to a decline of 44 feet, averaging a decline of 15.4 feet across the entire aquifer from predevelopment to 2013 and a 2.1 feet decline from 2011-2013 (McGuire, 2014). Across each state, Texas and Kansas have had the most dramatic levels of depletion (-41.2 and -25.5 feet) and Nebraska has had the least (-.03 feet) in the predevelopment to 2013 time period; on a weighted average, all states show overall depletion levels during both time periods (McGuire, 2014). Water storage in the aquifer also has declined in all states, except for South Dakota (McGuire, 2014).

The vast majority of research on groundwater depletion in this region focuses on an apparent proximate cause of groundwater depletion: farmers' individual-level decisions to pump groundwater from the aquifer because their living standards depend on agricultural production. Yet, depletion has continued for over 40 years – a generation – despite a plethora of research. This raises critical questions about whether groundwater depletion could be more effectively explained at a higher level of analysis – one that places farmers' decisions in a social context. From this perspective, the following questions emerge: **What are the social drivers of groundwater consumption? Are groundwater withdrawals driven more by local-level or extra-local factors?** These questions have been given much less attention, but they open up new possibilities for stemming depletion.

To address these questions, this study develops and empirically tests hypotheses from an analytical framework comprised of insights from structural human ecology (the IPAT and STIRPAT models) (Dietz & Rosa, 1994; Rosa et al, 2004; York et al, 2003) and the treadmill of production (Schnaiberg 1980). Below, I review prior research, which includes environmental and sociological work, in order to construct an analytical framework and develop hypotheses for the study. Next, I describe the data and methods I use to test the hypotheses. The last two chapters describe the results of the empirical models, and discuss the findings and implications of the results.

Chapter 2 - Literature Review

Introduction

Across the globe, concerns about environmental degradation are growing (Falkenmark, 2008). Understanding the fundamental structural factors driving environmental degradation is vital for developing policies and interventions that encourage more sustainable human-environmental relations. Toward this end, the development of an analytical model to assess these factors has been a focus of much research, dating back to the 1960s (Dietz, Rosa, & York, 2009).

Development and applications of STIRPAT

Ecologists Paul Ehrlich and John Holdren developed the earliest approach: the IPAT equation, which models environmental impact (I) as the product of population (P), affluence (A), and technology (T). The IPAT model has proven to be a useful conceptual tool, and it has been further refined since its initial formulation. Developed in 1971 just after the beginning of the environmental movement, the initial purpose of the IPAT equation was to quantify predictors of negative environmental impacts from human causes, particularly population, which Ehrlich and Holdren argued is the main contributor of environmental degradation (Chertow, 2001; Kates, 2000; York, Rosa, & Dietz, 2003). The formula has since been reinterpreted to measure possible solutions for sustainability (Chertow, 2001). Although the formula has been refined, the IPAT equation continues to be used as a foundational formula due to its simplicity and practicality in assessing interactions among population, affluence, and technological development (Chertow, 2001; Dietz & Rosa, 1994, 1997; Duarte, Pinilla, & Serrana, 2011; Rosa et al, 2004; York et al., 2003).

Although the IPAT formula has proven to be a valuable contribution, it has received criticism due to its aggregate structure, especially when focusing on how population and affluence may interact to determine technological development (Chertow, 2001; Dietz & Rosa, 1994, 1997; Rosa, et al, 2004; York et al., 2003). For instance, researchers using the equation to assess anthropogenic impact on the environment have struggled with how to quantify (T) *technological development.* Dietz and Rosa (1994, 1997) argue that the *T* term must not only capture "technology" as it is generally conceived, but must also capture all other social driving forces not included in the formula, such as "attitudes, values, institutional arrangements etc. of the population". Through this rationale, multiple variables are likely to be included in the representation of technology development, which IPAT's aggregate structure does not allow. To remedy this issue, Dietz and Rosa (1994) argued for the disaggregation of the formula. To disaggregate the population, affluence, and technology terms from the original IPAT formula, Dietz and Rosa (1994) developed the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) (Dietz & Rosa, 1994, 1997; Chertow, 2001; Rosa, et al., 2004). The STIRPAT model is expressed as:

$$I = aP^b A^c T^d e$$

In this formula, *I* still represents environmental impact, *P* represents population, *A* represents affluence, and *T* may be modeled as a residual term (Dietz & Rosa, 1997). The residual *T* term allows for the inclusion of multiple factors that can be quantified to better assess the social driving forces behind environmental impact. By including the coefficients − *a* as the constant term, *b, c, d* as exponential terms, and *e* as the error term − the STIRPAT formula may be statistically tested as a linear regression model (Chunfu, Chen, Hayat, Alsaedi, & Ahmad, 2014; Dietz & Rosa, 1997).

To test this idea, the creators of the STIRPAT formula have been involved in numerous studies in which they have either applied the formula or have made attempts to strengthen it. In one such study, York, Rosa, and Dietz (2003) discussed the relationship between the STIRPAT, IPAT, and ImPACT models and developed the analytic tool, ecological elasticity (EE), to refine the interpretation of STIRPAT's coefficients. The authors applied these tools to measure cross-national carbon dioxide emissions and the energy footprint. In the refined STIRPAT model, the authors incorporated EE as a way to measure plasticity, the responsiveness of one variable to change in another, to derive an accurate interpretation of the effects of anthropogenic driving forces. With the use of these analytic tools in their analysis of carbon dioxide emission and the energy footprint, the authors found that population has an effect on CO_2 emissions and the energy footprint; affluence increases both variables (York, Rosa, & Dietz, 2003). In a more recent study, Dietz et al. (2015) utilized the STIRPAT formula to assess how demographic and economic forces influence CO_2 emissions. The study found that, as in previous studies, population and affluence are key drivers in CO_2 emissions. In addition, the authors found that pro-environmental ideology might assist in mediating the level of greenhouse gases produced, indicating that elected politicians that advocate for environmentalism may play an important role in the overall reduction of environmental impacts (Dietz et al., 2015).

While STIRPAT has proven useful in measuring environmental impact, researchers have continued to assess water consumption with a number of other measurement tools. For instance, one study utilizing the foundational IPAT formula attempted to measure the past and current use trends to call attention to the impending problem of fresh water depletion and pollution. Duarte, Pinilla, and Serrana (2011) measured water use from 1900 to 2000 on a global level, which was divided into seven regional areas, to determine the level of increased use of fresh water withdrawals for agricultural, industry, and urban use throughout the twentieth century. In addition to the examination of the listed variables, the study also attempted to find the global drivers responsible for the water withdrawals, since, the authors argue, policy and institutions may play a vital role in withdrawal rates (Duarte et al., 2011). The results of the study showed that, over the period of the twentieth century, there was a seven-fold increase in water withdrawals, with the largest increases occurring after 1950 throughout North America, Europe, and Oceania, which, the authors argue, are considered the "developed" regions of the world (Duarte et al., 2011). Moreover, Duarte et al. found that the most important variable to explain fresh water withdrawals was the steady increase of per capita income, which showed a positive correlation. The increase began to occur in the 1950s, continued until leveling off during the 1980s, and then returned to small increases between 1990 and 2000 (Duarte et al., 2011).

Similar to the findings in Duarte et al (2011), another study assessed how population and per capita income contribute to the rise in water consumption. This was explored through the measurement of the Global Biomass Optimization Model (GLOBIOM), an irrigation model that measures the energy and labor requirement used in an irrigated area, and the regional projections of per capita caloric intake and populations (Sauer, Schneider, Schmid, Kinderman, & Obersteiner, 2010). The authors, consistent with previous literature, argue that agriculture plays a critical role in the increased strain on the global water supply. Moreover, agriculture accounts for more than 70% of the anthropogenic water withdrawals and 20% of arable cropland that is under irrigation (Sauer et al., 2010). Additionally, the authors of this study argue that as water scarcities increase, the price of water will also increase, leading to continued technological efforts that will assist in more sustainable methods for water use. Although this study did not utilize the IPAT formula, Sauer (2010) did find a positive relationship between per capita income and water use, but in contrast to the other studies, found that as efficiency of water use increases, consumption of water may level off, despite the level of population increase. This suggests that an increased efficiency of management of water appears to be an inevitable consequence of an increasing population (Sauer et al., 2010).

Another study that examined water consumption focused on the projections of U.S. fresh water withdrawals. Brown (2000) assessed water use trends in population, income, electric energy production, and irrigated acreage in the United States from 1960-1995. The author divided the data for the the country into six regions and analyzed water use for livestock, domestic and public use, industrial and commercial use, and mining use. Brown (2000) found that, depending on the region of the country, water consumption is estimated to rise between 0% and 27% over the next 40 years. Interestingly, the outcome of his measurements indicated that the largest increases are expected to be in both of the eastern regions, with a 9% increase in the northeast and 27% increase in the southeast (Brown, 2000). He attributed the increase in the northeast to public and domestic use, while in the southeast he attributed the expected rise in water use to an increase in agriculture (Brown, 2000). Additionally, Brown (2000) predicted increases in water consumption throughout the Great Plains, Texas Gulf, and the southwest regions, predominately from domestic and public use.

A more recent study by Rockström, Falkenmark, and Karlberg (2012), measured future water use on a global level and focused predominantly on water used for food production. Rockström et al. (2012) argued that one of the primary drivers of water consumption is agriculture. Therefore they examined per capita food demand, the animal feed component, and water productivity, which was measured through per capita food intake using a current annual water intake benchmark. The study found that, at the current rate of demand, coupled with a growing population and technological advances, overall water consumption will more than double by 2050, with water withdrawal levels causing significant ecological risks (Rockström et al., 2012).

Applying the theory of human ecology tradition, which examines the interdependent relationship between humans and environment, Longo and York (2009) investigated the forces that influence freshwater consumption on a global scale, examining both environmental and societal factors. Global estimates from a previous study on freshwater withdrawals for agricultural and non-agricultural use were used in Longo and York's (2009) study. In an attempt to determine the social forces influencing water withdrawal, the researchers measured population, percentage of GDP from the industrial sector, and urbanization. The study found that agricultural water use, GDP per capita and trade are significantly correlated and that the amount of water used in agriculture is positively associated with amount of non-agricultural use, which suggests that the two are synergistic, rather than competing (Longo & York, 2009). The authors argue that these findings suggest that modernization and globalization play a significant role in non-agricultural water use and that "connection to the global economy is a key influence" (Longo & York, 2009). A more recent study focused on the water usage from the Ogallala Aquifer in the state of Kansas. The study also found that human activity, particularly through agriculture, had a significant impact on the pumping practices to withdraw water from the aquifer (Steward et al, 2013). Steward et al (2013), interestingly, found that by reducing pumping by 20%, the aquifer could continue to support agricultural production beyond the year 2070. In addition, the authors show how 40% and 60-80% reductions could affect future agricultural development in the region. These findings provide a foundation for reevaluating water policies and implications for future sustainability

Although multiple studies examining the drivers behind water consumption have explored the interactions between population and economic growth to assess water consumption, few have applied the STIRPAT computation to this crucial issue. One study that did apply STIRPAT assessed the water footprint of the Chinese agricultural sector by evaluating the diet structure in China to analyze its relation to population and affluence (Chunfu et al, 2014). Applying STIRPAT to their study, the authors explored interactions among population, China's growth domestic product (GDP), urbanization, and the proportion of calories from meat products to determine the water footprint change influenced by agriculture products. The results indicated that all of the variables applied to the regression equation had a direct influence on the water footprint, with population showing the strongest influence. Affluence was determined to have the second largest influence, followed by diet structure and urbanization level (Chunfu et al, 2014). Similarly, Clement (2010) explored the sociological drivers that may influence water use in the U.S. by applying STIRPAT. The author of this study applied the model to the problematic impact of water depletion from the Ogallala Aquifer in the state of Texas. Clement (2010) examined the data of 254 Texas counties, a state that historically consumes uniquely high quantities of water, when compared to other states in the United States. Recognizing that the counties within Texas consumed water at highly unequal rates, Clement (2010) applied STIRPAT to the variables related to agricultural water uses, such as crop irrigation and water for livestock, and non-agricultural demands from the commercial, residential, and institutional sectors to determine which human activities were likely to yield higher rates of water consumption. The analysis found that, when tested with "agricultural water use", the geographic proximity to the aquifer (where the county was geographically located compared to the aquifer), acres of irrigated land, and population density were significant in their relationship to the amount of water withdrawals from the aquifer. With "non-agricultural water use", the amount of precipitation, population density, earnings per capita, and the urban population significantly correlated with water usage. These findings support Clement's (2010) hypothesis, that population and affluence, in addition to urbanization, have impacts on water consumption.

Very few studies focus on water consumption or depletion with the application of STIRPAT. As described above, only one such study examined the relationships between water population, affluence, and water depletion from the Ogallala Aquifer. The author of that study concentrated on counties from only one state and, while he did consider water consumed for agricultural purposes, he did not include measures to determine the institutional arrangements that may be indirectly driving depletion of the aquifer through agriculture.

The present study expands on Clement's (2010) study by assessing water depletion from the Ogallala Aquifer across six states, consisting of 181 counties most dependent on this water. Additionally, the present study includes sociological factors in the form of institutional arrangements to represent the *T* residual term in the STIRPAT computation.

As described in numerous studies, population has been found to be one of the main predictors of water depletion through the increased need for agriculture production (Brown, 2000; Chunfu et al, 2014; Clement, 2010; Duarte et al, 2011; Longo & York, 2009; Sauer et al, 2010). This makes theoretical sense, since an in increase in population would naturally result in an increased need for water consumption. But in the Ogallala region a large portion of the water from the aquifer is dedicated to agricultural production (Clement, 2010), so population in the area should not be directly related to an increased need for water. Compared to previous studies that have applied IPAT or STIRPAT, the present study examined water consumption on a much smaller scale, therefore it is expected that population will not be related to water consumption in the area. Therefore, it is hypothesized that:

H1: Population will not be significantly associated with water withdrawals for agriculture use from the Ogallala Aquifer.

Affluence, in the form of economic growth, is also found to be positively related with water consumption in multiple studies (Brown, 2000; Chunfu et al, 2014; Clement, 2010; Duarte et al, 2011; Longo & York, 2009; Sauer et al, 2010). Because farmers are only able to continue agriculture production if they are profitable, it is important to assess the role that farm income and per capita income each have on water consumption in the area. Additionally, because continued use of groundwater highly depends on the amount of commodities and profit that a farm derives, it is hypothesized that:

H2: Farm income will be positively associated with groundwater withdrawals for agriculture use from the Ogallala Aquifer.

As farm income in the area increases, spending in the area should also increase. Additionally, prior studies have consistently found positive links between per capita income and water consumption (Brown, 2000; Chunfu et al, 2014; Clement, 2010; Duarte et al, 2011; Longo & York, 2009; Sauer et al, 2010). But the agricultural income generated from this area may not necessarily lead to a "spillover" in the non-agricultural sector. A 2012 study compared the generated income from 1920 to 2002 in counties that overly the Ogallala ("Ogallala counties) and near by counties (non-Ogallala counties). Hornbeck (2012) measured the income to assess the economic benefits occurring in the agricultural sector and whether they positively economically impact the non-agricultural business sector. The non-agricultural business sector included local sales and service businesses and the local housing market. Horonbeck (2012) found that while there were substantial economic gains in the agriculture sector, there were no long-term economic spillover benefits to the non-agriculture business sector. Additionally, Hornbeck (2012) found that there might be some “crowding-out” by agricultural businesses. In other words, as agricultural businesses become the predominant type of business in an area, other businesses leave the area due to loss of income (Hornbeck, 2012). Therefore it is hypothesized that:

H3: Per capita income will be negatively associated with groundwater withdrawals for agriculture use from the Ogallala Aquifer.

Technological development for this area appears in many forms and was thoroughly explored for the development of the STIRPAT model in the present study. As previously discussed, the ability to include multiple factors to represent the *T* term is one of the key contributions in the development of the STIRPAT computation. This is especially important when assessing water depletion from the aquifer, as these factors may address policies linked to economic production in the region. Clement (2010) found water consumption to have a deterministic role in agricultural production, both in the form of crop irrigation and water used for livestock production. This is problematic, since agriculture has increasingly become more global through the domination of food production by multinational corporations (Busch & Juska, 1997). Globalization theorists, particularly those who explore societal issues through the political economy perspective, often attribute “environmental exploitation to the structure of market economies, the institute of modernity, and the relentless commitment to growth inherent in modern production systems” (York, 2003). In this perspective, capitalists are criticized for their part in the expansion of agriculture, through the irrational overdevelopment of technological advances, which are meant to counter negative environmental impact, but ultimately only lead to greater impacts on natural resources (Schnaiberg, Pellowm, & Weinberg, 2002). This concept is referred to as the "treadmill of production" and has been widely used by both ecologists and sociologists who study social impacts on the environment. In the ecological sense, the "treadmill" refers to the idea that the increased efficiencies of technologies lead to an increase in profits, which allows capitalists to invest in even more productive technologies, resulting in greater stress on natural resources (Schnaiberg, et al., 2002). In the sociological sense, an increase of technological efficiencies related to the intensity of labor performed by human workers results in the removal of the worker from the production process (Schnaiberg et al, 2002). While some workers are able to adapt to the technological advances through the acquisition of technical skills, others, typically in larger numbers, are not. This leads to an increase of unemployment and limitations on spending as workers are displaced to further expand production (York, 2003). Schnaiberg et al (2002) argue that this is a contradiction in the capitalist model, since capitalism is dependent on a balance of production and consumption. One way in which the imbalance of spending and production may be remedied is through the expansion of more production, which is unrealistic since natural resources are ultimately finite (York, 2003).

The treadmill of production is clearly exhibited within contemporary food systems, particularly in the Great Plains, as rates of crop and livestock production push water constraints to the limit in the pursuit of profits, or capital accumulation. In testing for the treadmill of production concept, a cyclical relationship between farm income and water withdrawals is expected.

Accumulation of wealth through the sales of their goods is not the only way that farmers add to their income. Farmers also accumulate wealth with the help of government subsidies paid to them based on their commodity production, and other programs like those for soil protection. One form of government subsidy, as defined by the 2008 Farm Bill[1], was direct payments made to farmers based on the level of production. As the quantity of crops that a farm is able to produce increases, so do the amount of the payments. Over the last two decades, the total direct payments have continued to increase, from $7.3 billion dollars in 1996 to $12.3 billion dollars in 2009 and peaking to $24.4 billion dollars pre-recession in 2005 (White and Hoppe, 2012). In 2009 farms earning $89,540 or more received half of the payouts, farms earning over $209,000 received 25% of the payouts, and farms earning over $425,000 received 10% of the payouts (White and Hoppe, 2012). More importantly and relevant to the present study, not all farms were eligible for direct payments; only farms producing "program crops", such as corn for grain, soybeans, sorghum, wheat, and cotton, are eligible to receive payments, while farms producing only fruits and vegetables are not (White and Hoppe, 2012). As indicated in the 2008 Farm Bill, it was the type of crop produced as well as the level of sales class that determined whether a farm receives direct payments. For instance, in 2005 99% of cash grain and cotton farms with sales over $250,000 received government payments (White and Hoppe, 2012). This is problematic since most of the eligible "program crops" are the predominant crops that are being produced in the Ogallala Region. Moreover, these types of crops rely most heavily on the aquifer's water supply (Benson, 2007).

Federal crop insurance is another type of government subsidy that supports farmers. Federal crop insurance reduces the farmers' risks in years that commodity prices drop below a certain price point or during particularly high drought years. Crop insurance payments have also

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[1] In 2014 the Farm Bill was revised to eliminate direct payments. Rather than direct payments, the new bill places a focus on crop insurance. Because the groundwater consumption assessed for this study dates prior to the change, statistics derived from the 2008 Farm Bill will be taken into consideration.

continued to increase from $955 million in 1991 to $5.2 billion in 2009, with higher earning farms receiving a larger bulk of the payments (White and Hoppe, 2012). To qualify for the Federal crop insurance payment program, a farm must be able to pay the high premium costs, which are more easily afforded by larger farms with high profit margins. Farms must also produce the program crops that are required to qualify for direct payments to be eligible for crop insurance payments.

The statistics related to subsidy payouts are crucially relevant when attempting to assess the drivers behind water consumption in the Ogallala Aquifer region. Understanding why only some farms received government subsidies and why the size of the farm matters, allows for a clearer sense of who consumes the most water and how production, with the aid of government subsidies, may drive consumption. Given that the level of crop production determined the amount of subsidies paid by the government, it is understandable as to why the aquifer's water withdrawals continued over the last few decades. Aw-Hassan et al (2013) found that when offered subsidies, farmers will utilize much more water than is actually needed to ensure that they maximize their crop yields and therefore, maximize their profits, despite water shortages.

Attempting to measure a direct relationship between subsidies and water depletion from the Ogallala Aquifer may prove to be challenging. In analyzing a direct relationship with statistical testing, it is expected that a significant direct relationship is not likely to be found, since the relationships between overall farm income and agricultural farm income makes most theoretical sense and government subsidy payouts are determined by a number of factors. Instead, government subsidies are more likely to be linked to water withdrawals indirectly. As described above, a portion of farmers' income has in the past been derived from government subsidies. Government subsidies were determined by the level and value of commodities that farmers produce, which also contributed toward farm income. As Clement (2010) showed, the amount of water consumed is directly related to the number of acres requiring irrigation. This indicates that larger farms, which are expected to own more land and produce more crops, will receive larger subsidies, consume more water, and have higher rates of agricultural production.

Understanding the various structural levels that are connected to the Ogallala region will assist in understanding how water-pumping practices may be tied to profits aided by government subsidies. One way that these relationships may be tested is through the use of a path analysis within a structural model. A path model allows for the inclusion of observable variables to be measured within a structural model (Kline, 2011). The value of a structural path model is two-fold. First, in disentangling the determining factors of water withdrawal, the magnitude of the relationships between these factors may be assessed. Understanding the strength of the relationships between observable variables is particularly valuable when assessing the interactions between population, economic growth, and technological development in this area. Second, structural path models allow for the testing of indirect, or mediating, relationships that may contribute to environmental impact, particularly water consumption. Mediating effects are especially important when exploring the relationship between subsidies and water depletion from the Ogallala Aquifer.

Exploring the direct relationships that may have been influenced water depletion from the aquifer may contribute to the development of a solution to the impending crisis. Population, per capita income, and farm income will be tested to represent the *P* and *A* terms of the STIRPAT formula. Government subsidies, value of commodities, and number of acres irrigated will be explored as factors to represent the *T* residual term. The U.S. states that the aquifer underlies will also be included in the *T* term, but will only be tested for direct relationships with groundwater withdrawals. Additionally, precipitation will be controlled for within the analyses, as it is expected that areas with higher levels of precipitation will have lower needs for groundwater from the aquifer. Based on the available literature and consideration of variables to include within the *T* term, it is hypothesized that:

H4: The number of acres requiring irrigation will be positively associated to groundwater withdrawals for agriculture use from the Ogallala Aquifer.

H5: Value of commodities will be positively associated to groundwater withdrawals for agriculture use from the Ogallala Aquifer.

H6: Government subsidies will be positively, but indirectly, associated with fresh groundwater withdrawals for agriculture use from the Ogallala Aquifer

H7: Precipitation will be negatively associated with groundwater withdrawals for agriculture use from the Ogallala Aquifer.

Chapter 3 - Data and Methods

Data

Data for this study were collected from multiple sources, since no known dataset exists which includes data for all of the variables included in this study (Table 1). Water withdrawal measurements collected by the U.S. Geological Survey in 2010 provided the data for total water pumped from the Ogallala Aquifer. These withdrawal measurements were made public in 2014 and are the most current measures available to date. All water levels are measured in millions of gallons per day. Per capita income for 2010 was collected from the United States Bureau of Economic Analysis, a federal agency that collects economic data based on mandated employer reporting. Population figures were obtained from the 2010 United States Census. Farm income, commodity values, and government subsidy figures were collected from the United States Department of Agricultural (USDA) 2007 Census of Agriculture. The Census of Agriculture is conducted every five years and collects data from surveys that are completed by registered farm owners. These variables are all measured in U.S. dollars. Measures for average yearly precipitation were collected from Oregon State University's PRISM Climate Group. This group gathers climate data from a wide range of monitoring networks and these data are frequently used in government-funded studies due to their high level of accuracy. Precipitation data from the National Centers for Environmental Information was considered, but due to the unavailability of data for many of the counties, data from the PRISM group was used. All data collected will be analyzed at the U.S. county level.

Table 1. Variables

Variable	Description	Source
Dependent		
Agricultural water use	Acre feet of water used by irrigation and livestock, 2010	US Geological Survey
Independent		
Population density	Total resident population divided by square miles, 2010	US Census Bureau
Per capita income	Earnings per capita, 2010	US Bureau of Economics
Average Farm income	Total farm income divided by total farms by county, 2007	USDA Census of Ag
Acres irrigated	Total fresh ground water used to irrigate acres by county, 2010	US Geological Survey
Government subsidies	Total government subsidies divided by total farms by county, 2007	USDA Census of Ag.
Value of commodities	Total market value of commodities divided by total farms, 2010	USDA Census of Ag.
Precipitation	Total annual precipitation, 2010	PRISM Climate Group
States	CO, KS, NE, NM, OK, TX	

Dependent Variable

The main dependent variable is the **total fresh groundwater withdrawals for *agricultural use***. Agriculture water use represents the "impact" (I) variable that has been included in previous environmental studies applying the STIRPAT formula (Clement, 2010; Dietz and Rosa, Dietz et al, 2015; 1994; York et al, 2003). *Total fresh groundwater used for crop irrigation* and *total fresh groundwater used for livestock* were added to obtain the total *agricultural use* variable. All water amounts are measured in millions of gallons used per day (Mgal/d).

Independent Variables

Population density. Population density serves as a predictor variable that represents the "population" (P) variable in the STIRPAT model. *Population density* is a measurement of the number of human inhabitants per square mile. *Population density* is calculated by dividing the total human inhabitants by the total square miles in each represented county and is therefore measured as number of humans per square mile. As previous studies have found, population is a crucial factor when assessing environmental impacts of human activities; therefore, it is an important variable in this study.

Per capita income and average farm income. Average income per county and farm income will serve as predictor variables that represent the "affluence" (A) variable in the STIRPAT model. The *average per capita income* is calculated by dividing the total income in each represented county and divided by the total population in that county. The data for *average farm income* is calculated by dividing the total farm income in each represented county and divided by the total farms in that county. The two types of income were separated to assess how each type of income relates to water consumption in the area..

Number of acres irrigated. Total *number of acres irrigated* serves as the first of three predictor variables to represent the "technology" (T) variable in the STIRPAT model. The *number of acres irrigated* is defined as the total number of acres in each county that are irrigated with groundwater from the aquifer. Previous studies have found positive relationships between the number of acres irrigated and the amount of water withdrawn from the Ogallala Aquifer (Clement, 2010). Moreover, this relationship, if confirmed, will lend support to the theory of the treadmill of production.

Value of commodities. The *average value of commodities* produced in this region serves as the second predictor to represent the "technology" (T) variable in the STIRPAT model. The average value of commodities per farm is calculated by dividing the total value of commodities produced on all farms in each county and divided by the total number of farms. This variable was included to assess how total profits produced may contribute to the water used in this area since government payments are linked to the level of sales class. For instance, in 2005 almost all cash grains and cotton farms with sales over $250,000 received government payments (White and Hoppe, 2012). The *value* is measured in U.S. dollars for 2007. Due to the little variance in the consumer price index between 2007 and 2010, these values were not adjusted for inflation.

Government subsidies. The average amount of *government subsidies* awarded to each farm operation serves as the third predictor to represent the "technology" (T) variable in the STIRPAT model. Government subsidies are direct payments as defined by the 2008 Farm Bill and are awarded based on the level of commodity production. In other words, the government subsidizes farmers with direct cash payments based on their levels of productions, so the more that a farm produces, the higher the government payment. This incentive was developed to assist farmers who would otherwise be unable to produce enough to keep their farms running. Government subsidies is not included in the reported farm income, but in this study it is believed that subsidies will influence the level of commodities that a farmer can produce, and therefore, the amount of farm income and water used for agriculture.

Six U.S. states. *Six U.S. states* serve as the fourth independent variable to represent "technology" (T). Water appropriation policies vary among U.S. states; therefore to account for the difference in policy, the states are included in the model to assess the how each state may be related to agricultural water usage. The states include Colorado, Kansas, Nebraska, New Mexico, Oklahoma, and Texas. The six states encompass the 181 counties that most heavily rely on the Ogallala's groundwater.

Control Variables

Precipitation. The *precipitation* variable serves as a control variable, because the amount of precipitation affects the amount of additional water required to sustain crop production.

Precipitation is the average level of precipitation in each county over a 1 calendar year period in 2010. Calculating the total precipitation in one calendar year and dividing the total by 365 calendar days provided the daily average precipitation in inches.

Method

A total of 181 counties, located within six U.S. states are included in the analysis for this study. Ordinary Least Squared (OLS) regression analysis was used to develop the multiple regression models to compute the unadjusted and adjusted coefficient of determination. Additionally, the beta weights for each independent variable were calculated, and partial regression residual plots were generated to show the joint distribution of partial values of the dependent variable and each independent variable. *STATA* Version 13.1 (STATACorp LP, 2013) was used in the OLS regression statistical analyses.

As an extension of the OLS regression analysis, a second statistical method was used to illuminate the relationships among the independent variables. Path analysis was used to assess the estimates of the magnitude and significance of causal connections between the predictors of agricultural water use by computing the unadjusted and adjusted coefficient for each independent variable. A path diagram was developed to test the model within a structural equation modeling (SEM) framework that allows for the estimation of the mediating variables within the models. Full Information Maximum Likelihood (FIML) estimation was used to handle missing data. This method estimates a likelihood function for each unit based on the variables that are present so that all data are used. *SPSS* Version 21 and *Mplus* Version 7.31 (Muthen & Muthen, 2013) were used in the path analysis.

Chapter 4 - Results

Introduction

To understand the underlying social causes of pumping groundwater from the Ogallala Aquifer, multiple steps were applied to assess the relationships between the dependent variable and independent variables. Frequency tables were generated and examined. Univariate statistics were generated for each variable to assess for minimum and maximum values, mean, standard deviation, skewness, and kurtosis (Table 2).

Table 2. Descriptive statistics for variables.

Variable	N	Lowest	Highest	Mean	Std. Dev.	Skewness	Kurtosis
Agricultural water use	181	0.03	345.74	66.75	72.43	1.62	5.57
Population density	181	0.10	311.30	14.11	32.28	5.94	46.40
Per capita income	181	17,504	62,032	37,513	6,383	0.60	4.57
Average Farm income	178	6,470	73,213	21,009	9,802	1.65	0.38
Govt. Subsidies	181	3,604	43,804	17,021	7,391	1.16	4.65
Acres irrigated	181	0	327.72	87.14	82.9	0.92	2.84
Value of commodities	181	737	5,400,414	580,709	716,854	3.55	19.62
Precipitation	181	11.29	36.02	23.69	5.94	0.08	2.02

As shown in Table 2, the minimum amount of fresh groundwater withdrawal for *agricultural use* is 0.03 millions of gallons of water per day and the maximum amount is 345.74 million gallons per day. The mean value is 66.75, with a standard deviation of 72.43. The skewness, which measures the asymmetry of the distribution, is 1.62 and the kurtosis is 5.57.

Analyses

Regression Analysis

A correlation matrix was created and analyzed to investigate the dependence between the variables through the assessment of the correlation coefficients between each variables (Table 3).

Next, preliminary multivariate regression analysis was used to assess how each of the seven independent variables contributed to the regression model as a whole to predict the agricultural water use (Table 4). The results of the multivariate regression gave a solution to the equation as:

$$Y = 49.59 + -0.138 + -0.001 + 0.001 + 0.695 + 0.000 + 0.000 + -1.292 + 15.082 + -21.561 + 38.752 + 12.670 + -1.508$$

Table 3. Correlations of fresh groundwater variables, population variable, affluence variable, technology variable, precipitation variable.

Variables	Ag Use	Pop Den	Income	Farm Inc	Acres Ir	Comm	Subsidies	Precip
Agricultural water use	1.0000							
Population density	0.0166	1.0000						
Per capita income	0.0234	-0.0692	1.0000					
Average Farm income	0.4651	0.1368	0.0495	1.0000				
Acres irrigated	0.8319	0.0628	0.0960	0.2977	1.0000			
Gvnmt subsidies	0.4099	0.2362	0.1032	0.6564	0.2721	1.0000		
Value of commodities	0.4875	0.0202	0.1367	0.2347	0.4568	0.1203	1.0000	
Precipitation	-0.1386	0.1283	-0.1058	-0.1692	0.1215	-0.2706	-0.0878	1.0000

Table 4. OLS Regression for Agriculture Water Use (prior to assumptions testing).

Variables	b	S.E.	β
Population density	-0.138	0.074	-0.062
Per capita income	-0.001	0.000	-0.084
Average Farm income	0.001**	0.000	0.112**
Acres irrigated	0.695***	0.036	0.794***
Government subsidies	0.000	0.001	0.027
Value of commodities	0.000***	3.860	0.159***
Precipitation	-1.292*	0.509	-0.106*
Colorado	-15.083	10.900	-0.050
Nebraska	-21.561**	8.203	-0.144**
New Mexico	38.752**	13.808	0.097**
Oklahoma	12.670	11.624	0.043
Texas	-1.508	7.941	-0.010
Constant	49.590	20.368	
n = 178 R^2 = 0.8277			

*p < .05; **p < .01; ***p < .001

The F-test showed statistical significance at the 0.001 level (F = 105.32, p < 0.001) and the adjusted coefficient of determination ($Adj\ R^2$ = 0.8277) suggests that the overall model may explain 82.8% of the variance in the use of millions of gallons of groundwater used for agricultural purpose. The regression analysis results from the two-tailed tests used to test the null hypothesis that the coefficient is 0. Using an alpha of 0.05, the results show that the coefficient for the population variable is not statistically significant (t = -1.88, p = 0.62). The coefficients for average per capita income*, average farm income, average value of commodities*, and *number of acres irrigated* per county are statistically significant (t = -2.57, p < 0.01; t = 2.6, p < 0.05; t = 4.14, p <.001; and t = 19.62, p < 0.001, respectively). The coefficient for the average amount of *government subsidies* was not statistically significant (t = 0.51, p = 0.51). Using Ogallala counties in the state of Kansas as the reference group, the coefficient for Nebraska was significant (t = -2.63, p = 0.01) and the coefficient for *New Mexico* was significant (t = 2.81, p = 0.01). The coefficients for *Oklahoma*, *Colorado*, and *Texas* were not significant (t = -1.54, p = 0.13; t = -1.38, p = 0.13; and t = -0.19, p = 0.85). Lastly, the coefficient for the average amount of *precipitation* was significant (t = -2.54, p <.05).

Linearity Tests

The independent variables were next assessed for the assumption of no specification error to determine accurate linearity with the dependent variable, *agricultural use.* The initial multivariate regression was generated to assess fit, which produced an R^2 of 0.8394. Partial regression residual and component plus residual plots were generated to visually inspect for evidence of possible non-linearity. The results for each are described below.

Residual plots were generated and visually inspected for linearity. Based on the visual inspection, *per capita income* was tested for a suspected non-monotonic, cubic relationship. A new variable was generated through the use of power polynomial test and squaring the original variable. This resulted in a decreased R^2 of 0.8377 and a statistically insignificant t-test (p = 0.18). The available literature and theoretical argument does not support a non-linear relationship, therefore a non-linear relationship was ruled out for this variable and it was determined that a linear relationship is a better fit.

The *acres irrigated* variable was tested for a suspected non-monotonic, quadratic relationship. A new variable was generated through the use of the power polynomial test by taking the square root of the original variable. This resulted in a decreased R^2 (0.8133) and statistically significant t-test (t = 17.55, p > 0.001). The slopes were confirmed to be in the correct direction. Although the test met the criteria for the possibility of a non-linear relationship, the available literature and theoretical argument do not support a non-linear relationship, therefore the non-linear relationship was ruled out for this variable and it was determined that a linear relationship is a better fit. Therefore, the remaining linearity tests were performed to assess for other possible reasons for the statistically significant result.

Through the assessment of the assumption of no specification error and the theoretical arguments tested and provided in the available literature, it was determined that the independent variables best fit a linear relationship with the dependent variable *agricultural water use*.

Correction for Skewness and Kurtosis

Univariate analyses were conducted for each variable to assess descriptive statistics, which included the assessment of the skewness and kurtosis for each variable (see Table 1 above). The dependent variable, *agricultural groundwater use*, has a skewness of 1.62 and kurtosis of 5.57. Skewness determines the symmetry, or distribution, of the data, while kurtosis determined whether the data are heavy or light-tailed (McClendon, 1994). This is within the allowable range, therefore adjustment through power transformation was not performed. The skewness and kurtosis for the independent variables: *per capita income* (0.60, 4.57), *farm income* (1.65, 8.38), *and acres irrigated* (0.92, 2.84), were all within the allowable measure requirements (McClendon, 1994). *Population density* initially had a skewness of 5.94 and kurtosis of 46.40 (outside of the allowable range); therefore power transformation also was applied to this variable. The ladder program in *STATA* was used to determine the appropriate formula to apply. The logarithm of the original variable was used to correct skewness to 0.24 and kurtosis to 3.80. The variable *value of commodities* initially had a skewness of 3.55 and kurtosis of 19.62, which is outside of the allowable range, therefore power transformation was applied to this variable. The ladder program in *STATA* was used to determine the appropriate formula to apply. The logarithm of the original variable was used to correct to the skewness to -1.07 and kurtosis to 7.09.

Multicollinearity

A test for multicollinearity, to see if two or more of the independent variables are highly linearly related, was conducted by generating the variance inflation factor (VIF) coefficients for each independent variable. The test resulted in a VIF of less than 4.0, which is within the recommended range for the test. The mean VIF for the model is 1.80 (Table 5).

Table 5. VIF for variables under consideration.

Variable	VIF	1/VIF
NE	3.03	0.329740
TX	2.84	0.352369
gvtprgmsop~n	2.69	0.371109
FarmInc	2.01	0.497788
Precip	1.74	0.574470
IRIrTot	1.64	0.608335
AvgCommln	1.55	0.646011
OK	1.43	0.698885
CO	1.34	0.745370
NM	1.23	0.813671
PerCapInc	1.09	0.920975
PopDenln	1.06	0.945360
Mean VIF	1.80	

Sub-regressions

To further ensure that multicollinearity does not exist within the model, sub-regressions were generated to regress each of the independent variables on all of the other independent variables (Tables 6-12). Sub-regressions are generated to assess for high R^2 values. An R^2 value of more than 0.75 indicates multicollinearity between two or more of the variables (McClendon, 1994). When the variables were regressed against the *population density* variable, all of the variables resulted in statistically non-significant t-tests. An R^2 of 0.0546 was the result. The sub-regression for the *per capita income* variable showed statistical significance for the state of *New Mexico* ($t = -1.98$, $p < .05$) An R^2 of 0.0790 was the result of this sub-regression. The sub-regression for *farm income* resulted in statistical significance for *value of commodities* and *government subsidies* and had an R^2 of 0.5022. The sub-regression of *value of commodities* showed statistical significance for *farm income* ($t = 2.42$, $p < 0.17$), *acres irrigated* ($t = 4.99$, $p < 0.001$), and the state of *Texas* ($t = -4.60$, $p < 0.001$) and an R^2 of 0.3540. The sub-regression for *government subsidies* resulted in statistical significance for *farm income* ($t = 5.70$, $p < 0.001$), *acres irrigated* ($t = 4.02$, $p < 0.001$), the state of *Nebraska* ($t = -2.36$, $p < 0.05$), and the state of *Texas* ($t = 4.50$, $p < 0.001$). The R^2 for this sub-regression was 0.6301. The sub-regression for total acres irrigated resulted in positive statistical significance average value of commodities ($t = 5.42$, $p < 0.001$), government subsidies ($t = 4.01$, $p < 0.001$), and the state of *Nebraska* ($t = 4.38$, $p < 0.001$) and an R^2 of 0.366. The sub-regression for the control variable *precipitation* resulted in statistical significance for the state of *Nebraska* ($t = 5.99$, $p < 0.001$) and the state of Texas ($t = 3.61$, $p < 0.001$). The results of these tests indicate that none of the variables are highly correlated with one another.

Table 6. Subregression on population density

Source	SS	df	MS
Model	15.3471211	11	1.39519283
Residual	265.528658	166	1.59957023
Total	280.875779	177	1.58686881

Number of obs	=	178
F(11, 166)	=	0.87
Prob > F	=	0.5687
R-squared	=	0.0546
Adj R-squared	=	-0.0080
Root MSE	=	1.2647

PopDenln	Coef.	Std. Err.	t	P>|t|	Beta
PerCapInc	-2.91e-06	.0000155	-0.19	0.851	-.0148139
FarmInc	-2.08e-06	.0000137	-0.15	0.880	-.0161801
AvgCommln	.0370057	.1037057	0.36	0.722	.0334907
gvtprgmsoprtn	.0000207	.0000209	0.99	0.324	.1220651
IRIrTot	-.000189	.0014713	-0.13	0.898	-.012427
Precip	.0220316	.0210601	1.05	0.297	.1038173
CO	-.4088737	.4549011	-0.90	0.370	-.0783748
NE	.1088833	.3416743	0.32	0.750	.0418673
NM	.4147933	.5814102	0.71	0.477	.0595943
OK	-.0404938	.4924309	-0.08	0.935	-.0074229
TX	.3216176	.3483433	0.92	0.357	.1170754
_cons	.4527132	1.552469	0.29	0.771	.

Table 7. Subregression on per capita income.

Source	SS	df	MS
Model	574342140	11	52212921.8
Residual	6.6936e+09	166	40322608.2
Total	7.2679e+09	177	41061554.3

Number of obs =	178
F(11, 166) =	1.29
Prob > F =	0.2313
R-squared =	0.0790
Adj R-squared =	0.0180
Root MSE =	6350

PerCapInc	Coef.	Std. Err.	t	P>|t|	Beta
PopDenln	-73.41195	389.6478	-0.19	0.851	-.0144318
FarmInc	-.034293	.0689633	-0.50	0.620	-.0524581
AvgCommln	185.182	520.6865	0.36	0.723	.0329463
gvtprgmsoprtn	.1475065	.1047444	1.41	0.161	.1711672
IRIrTot	2.911623	7.384077	0.39	0.694	.0376387
Precip	-66.9612	105.9589	-0.63	0.528	-.0620298
CO	-15.10001	2289.517	-0.01	0.995	-.000569
NE	-1130.111	1713.759	-0.66	0.511	-.0854256
NM	-5719.169	2889.72	-1.98	0.049	-.161532
OK	-3259.495	2459.469	-1.33	0.187	-.1174602
TX	-3219.875	1735.545	-1.86	0.065	-.2304186
_cons	36626.64	7259.889	5.05	0.000	.

Table 8. Subregression on farm income.

Source	SS	df	MS
Model	8.5410e+09	11	776456301
Residual	8.4658e+09	166	50998610.9
Total	1.7007e+10	177	96083552.1

Number of obs =	178
F(11, 166) =	15.23
Prob > F =	0.0000
R-squared =	0.5022
Adj R-squared =	0.4692
Root MSE =	7141.3

FarmInc	Coef.	Std. Err.	t	P>|t|	Beta
PerCapInc	-.0433726	.0872223	-0.50	0.620	-.0283536
PopDenln	-66.29511	438.2214	-0.15	0.880	-.0085198
AvgCommln	1393.94	575.7187	2.42	0.017	.1621232
gvtprgmsoprtn	.5978526	.1090359	5.48	0.000	.4535202
IRIrTot	14.2269	8.234444	1.73	0.086	.1202272
Precip	-44.05625	119.2575	-0.37	0.712	-.0266795
CO	-3824.729	2557.661	-1.50	0.137	-.094218
NE	-2396.218	1920.863	-1.25	0.214	-.1184094
NM	-4062.285	3272.796	-1.24	0.216	-.0750048
OK	-3156.405	2769.743	-1.14	0.256	-.0743577
TX	3002.625	1958.136	1.53	0.127	.1404665
_cons	-4912.888	8759.927	-0.56	0.576	.

Table 9. Subregression on average value of commodities.

Source	SS	df	MS
Model	81.4355914	11	7.40323558
Residual	148.615849	166	.895276199
Total	230.05144	177	1.29972565

Number of obs	= 178
F(11, 166)	= 8.27
Prob > F	= 0.0000
R-squared	= 0.3540
Adj R-squared	= 0.3112
Root MSE	= .94619

AvgCommln	Coef.	Std. Err.	t	P>|t|	Beta
PopDenln	.020712	.0580439	0.36	0.722	.0228858
PerCapInc	4.11e-06	.0000116	0.36	0.723	.02311
FarmInc	.0000245	.0000101	2.42	0.017	.2103979
gvtprgmsoprtn	4.73e-06	.0000157	0.30	0.764	.0308426
IRIrTot	.0051219	.0010265	4.99	0.000	.372155
Precip	-.0184267	.0157427	-1.17	0.243	-.0959437
CO	-.4739241	.3391633	-1.40	0.164	-.1003786
NE	-.2741994	.2548076	-1.08	0.283	-.1164998
NM	-.7568369	.4316579	-1.75	0.081	-.1201489
OK	-.6976656	.3644084	-1.91	0.057	-.1413121
TX	-1.131247	.2460794	-4.60	0.000	-.4550172
_cons	12.49299	.6398766	19.52	0.000	.

Table 10. Subregression on subsidies.

Source	SS	df	MS
Model	6.1665e+09	11	560587483
Residual	3.6200e+09	166	21807453.8
Total	9.7865e+09	177	55290958.4

Number of obs	= 178
F(11, 166)	= 25.71
Prob > F	= 0.0000
R-squared	= 0.6301
Adj R-squared	= 0.6056
Root MSE	= 4669.8

gvtprgmsop~n	Coef.	Std. Err.	t	P>|t|	Beta
PopDenln	284.0775	285.6211	0.99	0.321	.0481261
PerCapInc	.0844698	.0569277	1.48	0.140	.0727935
FarmInc	.2686979	.0471077	5.70	0.000	.3542108
AvgComm	-.0004762	.0005984	-0.80	0.427	-.0461011
IRIrTot	21.0301	5.248511	4.01	0.000	.2342778
Precip	-130.1536	77.59651	-1.68	0.095	-.103902
CO	2187.683	1686.594	1.30	0.196	.071042
NE	-2950.793	1252.119	-2.36	0.020	-.1922189
NM	1057.086	2141.652	0.49	0.622	.0257292
OK	-3084.021	1787.403	-1.73	0.086	-.0957741
TX	5234.97	1164.041	4.50	0.000	.3228371
_cons	8817.378	3087.464	2.86	0.005	.

Table 11. Subregression on total acres irrigated.

Source	SS	df	MS
Model	492691.286	11	44790.1169
Residual	721835.522	166	4348.40676
Total	1214526.81	177	6861.73338

Number of obs	=	178
F(11, 166)	=	10.30
Prob > F	=	0.0000
R-squared	=	0.4057
Adj R-squared	=	0.3663
Root MSE	=	65.942

IRIrTot	Coef.	Std. Err.	t	P>|t|	Beta
PopDenln	.0224124	4.045229	0.01	0.996	.0003408
PerCapInc	.0000412	.0008092	0.05	0.959	.0031908
FarmInc	.0009127	.000724	1.26	0.209	.1080066
AvgComm	.0000423	7.80e-06	5.42	0.000	.3676697
gvtprgmsoprtn	.0041934	.0010466	4.01	0.000	.3764234
Precip	1.510026	1.098746	1.37	0.171	.1082087
CO	32.11441	23.80649	1.35	0.179	.093614
NE	74.54607	17.01771	4.38	0.000	.4359053
NM	21.143	30.21973	0.70	0.485	.0461948
OK	19.69443	25.41915	0.77	0.440	.0549015
TX	-8.955728	17.39601	-0.51	0.607	-.049577
_cons	-93.44854	44.06303	-2.12	0.035	.

Table 12. Subregression on precipitation.

Source	SS	df	MS
Model	2675.40801	11	243.21891
Residual	3561.4087	166	21.4542693
Total	6236.81671	177	35.2362526

Number of obs	=	178
F(11, 166)	=	11.34
Prob > F	=	0.0000
R-squared	=	0.4290
Adj R-squared	=	0.3911
Root MSE	=	4.6319

Precip	Coef.	Std. Err.	t	P>|t|	Beta
PopDenln	.2859031	.2832738	1.01	0.314	.0606729
PerCapInc	-.0000294	.0000568	-0.52	0.606	-.0317064
FarmInc	-9.77e-06	.0000511	-0.19	0.849	-.0161371
AvgComm	-9.11e-07	5.90e-07	-1.54	0.125	-.1104323
gvtprgmsoprtn	-.000128	.0000763	-1.68	0.095	-.1603973
IRIrTot	.0074502	.005421	1.37	0.171	.1039657
CO	-3.141355	1.663564	-1.89	0.061	-.1277851
NE	6.85958	1.144796	5.99	0.000	.5597409
NM	-2.981659	2.113163	-1.41	0.160	-.0909089
OK	3.219576	1.771155	1.82	0.071	.1252454
TX	4.250028	1.177561	3.61	0.000	.3283169
_cons	22.97298	2.58061	8.90	0.000	.

Heteroskedasticity

The final test conducted tests for heteroskedasticity, which occurs when the conditional variance of the error term is not constant (Berry, 1993). Heteroskedasticity can have an effect on the overall regression analysis when the dependent variable is measured with error and the amount of error varies with the independent variables (Berry & Feldman, 1985). While it does not affect the value of the slope, it does affect the standard error of the slope, and can result in a biased estimator. A two-way scatter plot was generated to visually examine for evidence of heteroskedasticity around the regression surface. The pattern of the scatterplot of the studentized residuals suggests that there is a non-constant error of variance and it appears to be non-linear. White's test was used to test for significance and probability of heteroskedasticity. The hypotheses for this test are:

H0: The sample plots for the model will contain constant error variance.

H1: The sample plots for the model will contain non-constant error variance.

The level of the chi-square (95.49) indicated significance at the .05 level; therefore, the null hypothesis must be rejected. In an attempt to correct this, White's corrected standard errors was performed to re-estimate the regression model. The robust standard errors were generated so that the beta weights of the model could be measured. In the initial fit test, *per capita income, farm income, value of commodities, acres irrigated, precipitation, the state of Nebraska, and the state of New Mexico* all resulted in significant t-tests. *Population density*, *government subsidies, the state of Colorado, the state of Oklahoma, and the state of Texas* were not statistically significant.

The results of the White's corrected standard errors showed that, when the variables were regressed with robust betas, the probability changed for some of the variables. The final regression resulted in significant probability levels for the *per capita income*, *farm income, value of commodities*, *acres irrigated, precipitation, the state of Colorado, and the state of Nebraska*. *Population density* and the *state of Texas* became non-significant. *Government subsidies* and the *state of Oklahoma* remained non-significant. This suggests that the model may be affected by heteroskedasticity (Table 13).

Table 13. Regression Estimates for Agricultural Groundwater Use Using Robust Standard Errors.

Variables	b	S.E.	β
Population density	-2.642	1.941	-0.046
Per capita income	-0.001*	0.000	-0.071*
Average Farm income	0.001*	0.000	0.143*
Acres irrigated	0.713***	0.057	0.815***
Government subsidies	-0.000	0.001	0.003
Value of commodities	7.743**	2.562	0.122**
Precipitation	-1.495**	0.466	-0.122**
Colorado	-19.244*	9.707	-0.064*
Nebraska	-24.470***	6.161	-0.163***
New Mexico	38.285*	15.308	0.096*
Oklahoma	14.198	8.408	0.045
Texas	1.525	8.087	0.010
Constant	-37.702	36.275	
n = 178 R^2 = 0.8183			

$*p < .05$; $**p < .01$; $***p < .001$

As observed in the final regression model above, when assessing where water from the Ogallala Aquifer is consumed, six hypotheses were supported in the hypothesized direct association to water withdrawals for nonagriculture use. For instance, H4 hypothesized that the number of *acres irrigated* would be positively associated with increased water withdrawals. *Irrigated acreage* was statistically significant at the .001 level, suggesting that we can be 99.9% confident that there is a positive statistically significant relationship between this variable and the dependent variable (*b* = .71, *t* = 12.53, *p* < 0.001). This indicates that for every one-unit increase in number of acres irrigated, there is a .71 unit increase in water used for agricultural purposes. In other words, for every one acre dependent on freshwater for irrigation increase, we can expect that the amount of water withdrawals from the Ogallala will also increase by .77 millions of gallons per day. This finding supported hypotheses four (H4) and was found to be the strongest predictor of groundwater withdrawals for *agriculture use* in the area.

Farm income supported hypothesis two (H2) and was also found to be statistically significant (*b* = 0.001, t = 3.18, p < .05), and positive. Hypothesis 3 stated that *per capita income* would be negatively associated with water withdrawals. This hypothesis was supported. Consistent with the available literature, particularly with Hornbeck's (2012) study, *per capita income* does play a small, but significant role in the amount of agricultural water used in the region (*b* = -0.001, t = -2.16, p < .05). Not consistent with prior studies applying IPAT or STIRPAT, was that this relationship was negative. In other words, as *per capita income* goes up, the amount of water used for agriculture goes down.

Inconsistent with previous studies, but supporting hypothesis one (H1), which stated that *population* was not statistically associated with water withdrawals; *population* was not statistically significant (*b* = -2.64, t = -1.36, p = .17). This finding was expected as it was argued that profits, rather than *population* may be driving water consumption in the area.

The average *value of commodities* supported hypothesis five (H5), which hypothesized that the *value of commodities* would be positively associated with water withdrawals, was found to be statistically significant and positively related to agriculture groundwater use (*b* = 7.74, t = 3.02, p < .01). The *precipitation* control variable supported hypothesis six (H7), with a statistically significant negative relationship (*b* = -1.49, t = -3.21, p < .01).

Omitting the state of *Kansas* to serve as the reference group, *Colorado* (b = -19.24, t = -1.98, p < .05) and Nebraska (b = -24.47, t = -3.97, p < .001) were both negatively and statically significant. *New Mexico* was positive and statistically significant (b = 38.28, t = 2.50, p < .05), while Oklahoma and Texas were not statistically significant. In other words, compared to *Kansas*, farms residing in *Colorado* and *Nebraska* consume less water for agricultural use, while farms residing in *New Mexico* will consume more water, controlling for the other covariates.

Government subsidies were also not statistically significant (b = -.00002, t = -.05, p = .96) within the regression model. The overall adjusted R-squared (0.8306) indicates that the incorporated variables explain 83.06% of total water used for agriculture in the Ogallala Region.

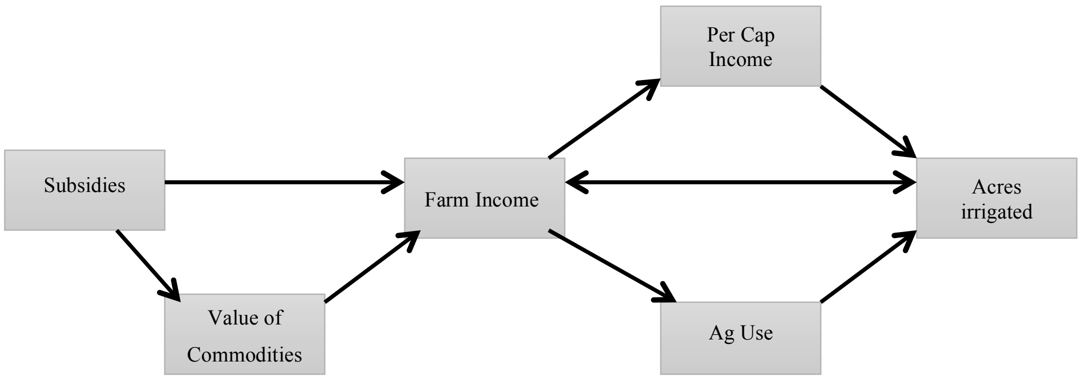
Path Analysis

As previously stated, the STIRPAT formula was initially developed to disentangle the terms included in the early version of IPAT. The intention of the STIRPAT formula was to disaggregate the terms in order to better understand the interactions between population and economic production and how they might influence technological development. Additionally, in disentangling the *T* term, which represents “technological development,” multiple factors may be included in the model for further exploration. To understand the relationships between the variables that represent the *T* term in the present study and how they might influence water pumping practices in the Ogallala region, indirect relationships must be explored through the analysis of a structural path model. While OLS regression analysis provided the coefficients that indicated the correlates between the independent variables and fresh groundwater withdrawal for agricultural use, a structural path analysis will provide the strength of the estimates between independent variables as well as to the dependent variable. Additionally, path analysis will allow for the exploration of indirect, or mediating relationships. To assess the relationships among the variables, multiple structural path models were developed and assessed based on reasoning and theoretical arguments made in the available literature. Identifying the dependent variable, *agricultural water use*, as the outcome variable within the structural model, the independent variables were assessed for direct and indirect relationships. The common argument made by studies that apply either IPAT or STIRPAT state that the focus must be on the technology variable, as this variable may be the only appropriate solution to lessening environmental impact (Chertow, 2001). Therefore, in the current study, the variables included to represent technology must be tested for both direct and indirect predictors of agricultural water use. The variables must also be arranged in the structure to correspond to the literature and hypotheses included in this study. For instance, Dietz and Rosa (1994) argue that when assessing the "technology" variable within sociological studies, "attitudes and institutional arrangements" made within the population must be included. In their recent study, Dietz et al (2015) applied pro-environmental ideology as part of the "technology" variable. The authors found that ideology may serve as a moderator in the production of greenhouse gases through the way that politicians may or may not favor certain environmental policies. In the current study, the variable that was determined to most appropriately represent either "attitudes" or "institutional arrangements" was government subsidies; therefore, this variable was included as a predictor and was the only exogenous variable within the path model structure.

As hypothesized and determined in the OLS regression results, a direct path between *government subsidies* and *agricultural groundwater* use was not found to be statistically significant. This result was expected, as Dietz and Rosa (1997) argued that institutional arrangements should be considered within the *T* term of the STIRPAT model and may have mediating roles within environmental studies (Dietz et al, 2015). Borrowing from a key finding in Dietz et al's (2015) study on pro-environmental values and policy decisions related to the environment by politicians, the government subsidies variable therefore was tested for indirect effects on agriculture water use. Exploring whether government subsidies indirectly contribute to water pumping practices in the Ogallala region is crucial in determining how policy decisions made at the federal level may ultimately be driving these practices. In addition to the findings in Dietz et al (2015) study, Schnaiberg's (1994) treadmill of production theory, which argues that capitalists are driven by profit motives despite environmental impact, was also applied. With the use of these theories, the constructed path for the present study argues that government subsidies awarded to farmers should determine the amount of commodities that are likely to be produced and therefore affect the amount of farm income. Based on this reasoning, farm income, which was found to have a significant positive direct relationship with agricultural water use, was applied as a mediator between government subsidies and water use. Additionally, the commodities variable was applied as a mediator between government subsidies and farm income, as government subsidies were awarded based on level of production and the value of program eligible commodities.

Total *irrigated acres* was found to be the largest direct predictor of agricultural groundwater use within the regression model. This variable was also included in the structural model, but was assessed for a mediating relationship between farm income and agricultural water use. Theoretically, the number of acres that a farmer owns may be related to the amount of potential income earned, since a farmer will have more available land in which he or she may be able to produce commodities. In turn, it is expected that the higher number of owned acres producing the commodities and requiring irrigation, the higher amount of water that will be required. Lastly, per capita income, which had a small effect on agricultural groundwater use within the regression model, was included to be tested for an indirect relationship between farm income and agriculture water use. Previous studies have found positive relationships between increasing water usage and per capita income. Moreover, the population within the Ogallala region depends heavily (although often indirectly) on income based on farming and agriculture. It is therefore expected that farm income will have a direct relationship to per capita income in this area (Figure 1).

Figure 1. Path model. Hypotheses relationships between government subsidies and agricultural water use with mediators (value of commodities, farm income, per capita income, acres irrigated.



Prior to testing the variables in the path model, the data tested for non-linearity were converted into an *SPSS* file, as the *Mplus* software is unable to read data files from the *STATA* software. All additional adjustments that needed to be made to the data prior to obtaining model fit indices were conducted in *SPSS*. One adjustment to the data was the transformation to logarithms of the *agricultural groundwater use* and *subsidies* variables. Additionally, the total *acres irrigated* variable was transformed to its square root. When applying a structural model, *Mplus* is especially sensitive to the level of variance between the variables. *Mplus* detected that the variance in these variables was too large compared to the other variables; therefore, transformation adjustments were required for the model testing to run and terminate normally by the software.

The path analysis showed some consistency and inconsistency with previous studies that have used the STIRPAT measurement and with the regression analysis. The path analysis indicated a good model fit consistent with SEM standards (Kline, 2011): χ^2 (1) = 2.53, p = 0.695; RMSEA = 0.00, CFI = 1.00. Kline (2011) states that a non-significant p-value ($p > 0.05$), RMSEA value of less than 0.05, and a CFI value of larger than 0.95, but no larger than 1.00, is required to indicate a “good” model fit. As shown on Figure 2, multiple direct and indirect paths to water used for agriculture were found. The indirect path from *government subsidies* to average *value of commodities* to farm income was significant ($b = 2.40$ $p < .05$, $\beta = 0.60$), indicating that a one-unit increase in *government subsidies* was indirectly associated with a 2.40 unit increase in farm income, when *value of commodities* serves as a mediator, while controlling for all other predictors in the model. In other words, as the average amount of *government subsidies* increased, *farm income* also increased when the *values of commodities* were included as a mediator. The R^2 for this indirect path was 0.08, indicating that 8.0% of the variance can be explained by this path. The path from the *government subsidies* to average *farm income* ($b = 12.88$ $p < .001$, $\beta = 0.33$) and the path from farm income to *agriculture water use* ($b = 0.01$ $p < .001$, $\beta = 0.21$) were also significant. The indirect path for these variables was also significant ($b = 0.13$ (0.04), $p < .001$, $\beta = .09$) indicating that *government subsidies* are indirectly, through *farm income*, related to an increase in *agriculture water use*. The R^2 for this indirect path was 0.19; therefore, this indirect path can explain 19% of the variance in the model. The overall indirect path farm income to *irrigated acres* to *agricultural groundwater use* was not significant, but the direct path between *irrigated acres* and *agricultural groundwater use* was significant ($b = 0.01$ $p < .001$, $\beta = 0.80$); this indicates that the more acres requiring irrigation, the more water that is used. Neither direct nor indirect paths that included *per capita income* were found to be significant. The total R^2 for the model that includes all indirect paths to predict water used for agriculture was 0.809, indicating that 80.9% of the variance in water usage was explained by the predictors for water used for agricultural purpose.

Figure 2. Path model standardized results for relationship between government subsidies and agricultural water use

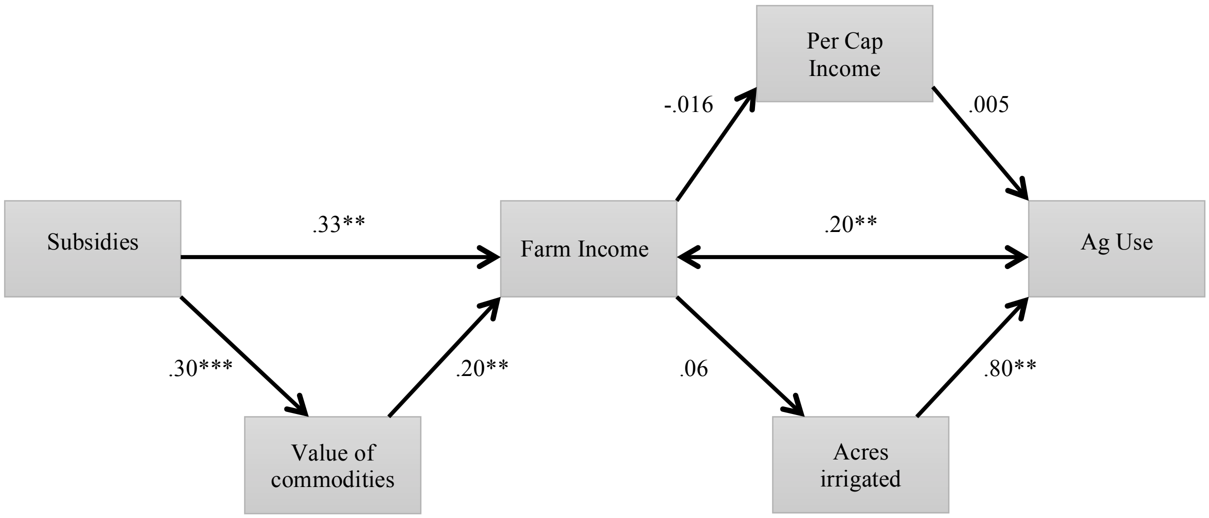


Table 14. Parameter estimates

Parameter Estimate	*Unstandardized*	*Standardized*	*p*
Measurement Model Estimation			
Gov. Subsidies → Farm Income	12.88 (2.78)	.33	.001
Gov. Subsidies → Value of Commodities	0.31 (0.07)	.30	.001
Value of Commodities → Farm Income	7.79 (2.67)	.20	.001
Farm Income → Ag Use	0.01 (0.001)	.20	.001
Farm Income → Acres Irrigated	1.87 (0.01)	.06	.279
Farm income → Per Capita Income	0.03 (0.03)	-.016	.845
Per Capita Income → Ag Use	0.01 (0.003)	.005	.884
Indirect Paths			
Gov. Subsidies → Farm Income → Ag Use	0.13 (0.04)	.09	.001
Gov. Subsidies → Value of Commodities → Farm Income	2.40 (1.01)	.06	.015

*Total model $R^2 = 0.809$

Gov. Subsidies→ Farm Income →Ag Use $R^2 = 0.19$

Gov. Subsidies → Value of Commodities → Farm income $R^2 = 0.08$.

Chapter 5 - Discussion and Conclusion

The water supplies of the largest aquifer in North America are quickly dwindling. The Ogallala Aquifer, located in the highly agricultural area of the Great Plains, formed over twenty million years ago and could take more than 6,000 years to refill if completely drained (Benson, 2007; Guru, 2000). In the latter half of the twentieth century, farmers began to take advantage of the aquifer's bountiful resource in an area of the country that was once thought of as too dry to produce crops. The water reserves from the Ogallala Aquifer gave farmers the opportunity to pump as much water as needed for their crops and livestock, blissfully unaware that rapidly expanding technological advances would eventually pose a critical threat to the aquifer. The aquifer supplies water for 30% of the nation's food supply and provides billions of dollars annually to the global economy (Hornbeck & Keskin, 2010, Steward et al, 2013). This presents a serious dilemma; the aquifer is running out of water. In some areas, water levels are so low that they are no longer economically feasible to pump (McGuire, 2010), but with a growing population, ceasing agriculture production completely is just not logical, nor ideal. In order to determine solutions to this critical dilemma, more focus needs to be brought to not only technological advances, but also to the social factors involved in the depletion of the aquifer's water supply.

The aim of this study was to determine the social motivations for pumping groundwater from the Ogallala Aquifer and whether pumping is driven more from local or extra-local factors. In an attempt to gain a clear understanding of these motivators, multiple steps were taken. First, there was a literature review conducted on previous studies conducted on the anthropogenic impact of environmental degradation. The literature review found multiple studies indicating that the level of population and the level of affluence played strong roles in environmental impact

(Dietz & Rosa, 1994; Duarte et al, 2011; Kischer-Kawalski & Ammann, 2001; Sauer, 2010; York et al, 2003). Two key contributions made to the theoretical framework for this study, based on the extensive literature review, were the concepts of the "treadmill of production" and "IPAT". The treadmill of production argues that the irrational overdevelopment of technological advances that are meant to lessen negative environmental impact instead lead to greater impacts on natural resources through the expansion of agriculture. The concept of IPAT argues that environmental impact is the product of population, affluence, and technology. In other words, population, affluence, and technology are the key factors contributing to human impacts on the environment. Thus, when attempting to determine solutions for stemming negative environmental impacts, such as the depletion of an aquifer, these factors must be taken into account. While the level of population and affluence are easily measured, determining what constitutes "technology" within sociological studies is challenging. Guided by Dietz and Rosa's evolved IPAT version, STIRPAT, and the numerous studies that have applied this concept (Clement, 2010; Dietz & Rosa, 1994, 1997; McGee et al, 2015; Rosa, et al, 2004; York et al, 2003;), multiple variables were assessed to represent the sociological version of "technology" for this study. These variables included the number of total acres irrigated, the average value of commodities produced, the average amount of government subsidies awarded, and the states in which the aquifer lies, which represent the differences in water policies. Additionally, both per capita income and farm income were analyzed separately in the representation of "affluence".

A two-step approach was taken in the statistical analysis of the key variables that were determined to have an influence on water use in the region of the Ogallala Aquifer. First, regression analysis was conducted to assess the direct relationships between the IPAT variables and water usage and to assess the amount of variation explained by these variables. Second, based on the results of the regression analysis and guided by the theoretical argument included in this study, as well as other studies that have applied the STIRPAT formula, a path model was constructed and tested to assess for possible mediators of water use and to assess the magnitude between predictor and outcome variables. After all diagnostic testing was conducted, the final regression analysis, consistent with a previous study (Clement, 2010), found the strongest predictor of water used for agriculture was the number of acres owned that require water for irrigation. This makes logical sense and was not a surprising finding since it is expected that the more water required to irrigate, the more water that will be pumped from the aquifer. Farm income was found to have a small but positive relationship with water used for agriculture. Per capita income, had a small significant negative association with agricultural water usage. All of the reviewed literature applying IPAT or STIRPAT found positive relationships between per capita income and water usage, so this was inconsistent with theses studies. As Hornbeck (2012) found, one possible explanation for this may be that a large portion of the income generated in the area is derived through agricultural activities. This indicates that, while the commodities produced in the area are generating billions of dollars, the bulk of the money generated is not retained in the region, despite the ecological impact to the area. This is problematic because the population in this area not only depends on the water from the aquifer for agriculture, but also for domestic use. Precipitation, as a control variable, did have a significant relationship to water usage. The regression findings indicate that as the amount of precipitation in an area increases, the amount of water usage decreases. This makes logical sense, as it is expected that more water from the aquifer will be required when less precipitation is present.

Another expected finding was that population was not found to be significantly associated with either an increase or a decrease in agricultural groundwater use. This finding was not consistent with all of the available literature in this topic of research and with the IPAT formula itself, which argues that as the number of humans inhabiting the earth increases, the amount of impact on the environment also increases. There are a few reasons previous studies may have found the positive relationship between water use and the population. First, the studies that have tested this relationship typically focused their measures on a global level, whereas the present study only focused on 181 counties within the United States. Second, previous studies focused on longer time spans compared to the present study, which only focused on water usage in 2010. For instance, Duarte et al (2011) measured water use from 1900 to 2000 and this time frame exhibited the fastest rates of population growth in history. It is expected that the population growth would be associated with the level of water usage during this time frame, since an increase in population would naturally require an increase in water to consume. Additionally, the Steward et al (2013) study, which estimated future Ogallala water use, argued that newer technological advances, coupled with responsible pumping, would likely lessen water depletion from the aquifer. But since this does not appear to be the behavior in this area, this finding lends some support to the treadmill of production concept, in which Schainberg and Gould (1994) argue that environmental degradation is driven by profit, not the level of population. In other words, despite the increase in technological development for the conservation of agricultural water use, new technology continues to be pushed to its limits and water consumption continues to increase, further depleting the aquifer.

Government subsidies was also not found to be directly significantly associated with agricultural water use. Based on Dietz and Rosa's (1994) concept that "institutional arrangements and attitudes" may play a role in environmental impacts in an indirect way, the lack of direct relationship to agricultural water use was not completely unexpected. Therefore, it was believed that government subsidies should have a significant indirect relationship when tested within a path model structure. Moreover, this concept is further supported based on the finding that some of the states − Colorado, Nebraska, and New Mexico − displayed significant relationships with water usage for agriculture, since differing water policies within each state vary.

To test the indirect and mediating relationships, the constructed path model was tested and assessed. The path model showed consistent results with previous studies that applied Dietz and Rosa's (1994) evolved STIRPAT formula and Schnaiberg and Gould's (1994) treadmill of production theory. For instance, like Dietz's (2015) recent study that found that pro-environmental ideology moderates environmental policies, government subsidies also were found to have a significant and positive relationship with water used for agriculture, but only indirectly. This was found through two paths. First, government subsidies were found to have a positive indirect relationship to farm income when average value of commodities was included as a mediator. Second, farm income had a significant direct relationship with water used for agriculture. In other words, as government subsidies increased, farm income increased when average value of commodities increase, which led to an increased level of water usage for agriculture. Additionally, the relationship between farm income and agricultural groundwater use was found to be non-recursive, which means that the relationship between the two appears as a positive feedback loop. Hoppe et al (2015) found that only 8 percent of farms, constituting medium to large farms and produce 60 percent of all U.S. agricultural output, indicating that the higher income generating farms are in fact driving agricultural water use, which in turn generates higher profits. This cycle continues, perpetuating the dilemma that the aquifer and the region find itself in today. This finding, coupled with the lack of relationship between population and agriculture water use, supports the treadmill of production theory used to argue the motivation behind water pumping practices in the current study.

When total number of irrigated acres was added as a mediator between farm income and agricultural water use, the relationship between farm income and water use remained significant, but the relationship between farm income and irrigated acreage did not. The relationship between irrigated acres and agricultural water use remained positive, as was expected since this was the biggest predictor of water use for agriculture in the regression model and hypothesized as stated in H4. Lastly, per capita income was not found to be statistically significant within the path model analyses and it was negatively associated with water usage. Moreover, per capita income resulted in a non-significant relationship to agriculture water use when tested as a mediating variable in the path structure. Again this finding supports the notion that, despite the level of environmental impact occurring in the Ogallala region, the area is not reaping any of the benefits and is at risk of losing its greatest source of water.

The findings in this study may lend themselves to important policy implications, but this study was not without limitations. First, the determination of what variables to include in the representation of the "technology variable" was the biggest challenge. Empirical analysis may exhibit some bias in the computing of the values measured, but when attempting to include values that represent "attitudes and institutional arrangements" on a quantifiable basis, the level of bias may increase. Future research should explore other ways in which the technology variable within the STIRPAT formula may be measured on a sociological basis. Second, the lack of inclusion of quantifiable water appropriation policies was another limitation. The unit of analysis in the current study was the county; all variables were measured at the county level. Often water policies differ even within the county level. Because the unit of analyses in this study was at the county level, data for water policies at the city level was not included. Future research should assess this analysis at the city level, which may allow for the inclusion of the water policies. Lastly, the present study only analyzed one year, 2010, which arguably makes it difficult to interpret water usage over time. Because the analyses for this study only included one calendar year, the supporting literature focusing on the Ogallala's water usage described in this study was instead used to make generalizations about the findings and water usage trends. .

While there are some limitations in this study, the results that were found support of the treadmill of production theory with the use of the STIRPAT formula, adding to the available literature in this area. The treadmill of production is evident in the depletion of the Ogallala Aquifer. The production of program crops, supported by subsidies, is associated with decline in the water levels. The findings, in conjunction with this theory, have helped to identify the motivators in pumping fresh groundwater from the Ogallala Aquifer. Agricultural production, derived from pumping water, encouraged by subsidies, significantly drives water use in this semi-arid region of the country.

Prior to 2014, direct payment subsidies were awarded (mostly to large farming corporations) based on the level of commodity production, regardless of income losses or gains (White & Hoppe, 2012). In other words, as the level of commodities produced increased, so did the amount of government subsidies awarded. In an attempt to increase efficiencies, a new Farm Bill was introduced and passed in 2014. The new bill removed direct payments based on level of production (USDA, 2015). The new bill cut funds from the food stamp program to fund the required initial increase in amount spent on subsidies, and now subsidizes farmers mainly through crop insurance. Crop insurance is awarded based on the value of commodities. Through the Price Loss Coverage, which is now a part of the revised version of the Farm Bill's crop insurance, farmers are guaranteed to receive the government set price for their commodities (USDA 2014 Farm Bill). For instance, if during a particular year, the overproduction of a crop, such as corn, leads to a drop in prices through the supply and demand concept, the crop insurance payments are awarded to farmers to cover the loss difference. In other years, when a drought may have occurred and production declines, crop insurance will cover losses for the affected farmers who are enrolled in the program. The new bill has been met with much criticism. One criticism of the new plan is that the government does little to encourage the implementation of measures to be taken in case of drought. Therefore, farmers may continue to overproduce in an attempt to achieve high levels of subsidized program crops without much concern for future droughts. Additionally, the new bill does little to deter the largest farms from receiving the largest subsidies,, since program eligibility is based on paying higher premiums that are difficult for smaller farms to afford. Similarly, when commodity prices fall, larger farms will continue to be the major benefactors of subsidies, as previous studies have found (White and Hoppe, 2012).

The findings from this study were derived from data that were obtained prior to the implementation of the 2014 Farm Bill and during a time period in which direct payments were still in practice. These findings represent aquifer water withdrawals from 2010, and farm income, government subsidies, and value of commodities from 2007, since the 2010 water withdrawal figures are the most available to date. Despite the change in the method of government subsidies disbursements, the findings and the theoretical argument based on the treadmill of production remain relevant, since profits and subsidies, particularly from large agribusinesses, continue to drive water pumping practices in the Ogallala Aquifer region. Additionally, it is expected that higher earning farms will continue to receive a large portion of subsidies through crop insurance, since an eligibility is determined by the approved “program crops”, which are overwhelmingly produced by larger farms.

Application of the STIRPAT formula also proved to be useful in determining the drivers behind water use in the area. Prior studies that have applied and advocated the use of the STIRPAT formula have consistently argued that with the evolvement of the original IPAT formula, more attention and focus must be emphasized on the technology variable, since this variable will ultimately be the solution in decreasing environmental impact. In applying the sociological factors to the “T” variable through examination of number of acres owned and irrigated, value of commodities, government subsidies, and state policies, consistent with previous studies, this study determined that sociological factors do in fact play a major role in the depletion of the largest aquifer in North America. As the availability and access to freshwater from the aquifer is reduced, residents in the area, and consumers in the global food system more broadly, will face the undesirable consequences of over-production by decisions made at the federal level to further a treadmill of production.

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