TRENDS IN ALFALFA GROWTH AND GROUNDWATER LEVELS IN ARIZONA

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Abstract:

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The federal government has been providing significant subsidies to the dairy industry since 1933. These subsidies are important to farmers and to the industry as a whole because they keep incomes steady during fluctuations in market prices. However, federal policies can also incentivize dairy production which increases agricultural production which has negative impacts on water resources. Here, we explore the impacts of dairy subsidies on groundwater storage in Arizona. On one hand, the dry climate, abundant sunshine, and good soil make Arizona an attractive location for alfalfa farms, and alfalfa is a major source of feed for the dairy cow population. However, Arizona has very limited surface water supplies, and irrigated agriculture often relies on groundwater. Groundwater use is unregulated in many rural parts of the state, which creates the potential for unsustainable pumping to support water-intensive crops like alfalfa. We present a retrospective analysis of alfalfa and dairy expansion across the state using datasets from CropScape, which uses satellites to determine ground cover, and the United States Department of Agriculture (USDA, 2021). Using data from the Arizona Department of Water Resources (ADWR), we explored how much alfalfa is being irrigated by renewable versus-nonrenewable sources. Finally, we explored connections between alfalfa and groundwater levels.

Preliminary results show a correlation between increased alfalfa growth and declining water levels in areas where groundwater is alfalfa's main irrigation source. Future work will explore spatial patterns in alfalfa expansion and groundwater declines relative to different regulatory frameworks across the state.

Introduction

How have changing groundwater levels and use affected agricultural decisions on crop choices, irrigated acreage, irrigation intensities and energy consumption inside versus outside Active Management Areas (AMAs). Groundwater is an important water supply for irrigated crops. Crop irrigation accounts for 43% of water use worldwide and 53% in North America (Siebert et al. 2010). As surface water supplies decrease, farmers will increasingly rely on groundwater supplies to irrigate crops. Decreasing groundwater levels could threaten drinking water supplies, food supplies, and energy systems.

In the mid-1900s, significant advancements in groundwater pumping technology allowed pumps to reach greater aquifer depths and rapidly pump large volumes of water. Currently, groundwater comprises 50% of the source water for irrigation (Dieter et al. 2018). The energy demand required to pump groundwater for irrigation is usually larger than delivering surface water. Farmers consume large amounts of water and energy but have relatively small contributions to support jobs and economic growth (Nesheim et al. 2015).

Groundwater usage rates are only sometimes monitored in agricultural use therefore, finding reliable well and pumping data outside the AMAs can be challenging. In the United States only 7.5% of crop acreage is irrigated, but irrigated crops account for 55% of all crop sales (U.S. Department of Agriculture, 2014). These data suggest that high-value crops are mainly grown in large areas of irrigated farmland, especially in the Desert Southwest. Water and energy use in irrigated farmland largely occur in the western United States where energy demand is already strained and water supply is low (Hitaj & Suttles, 2016). Assessing the energy cost at which farmers start to shift from low-value crops to high-value crops could be crucial in predicting future crop shifts and how those shifts could affect the economics, food supply, and water supply in a given area.

The independent variables include changing groundwater levels over a set period of time, and the stakeholder use of that groundwater (e.g. municipal, agricultural, industrial, etc.). The dependent variables include crop choices, irrigated acreage, irrigation intensities, and energy consumption.

I hypothesize that decreasing groundwater levels lead to an increase in the amount of energy required to pump the same volume of water, which in turn will cause a shift from staple crops to non-staple crops. A staple crop is one which sells for low monetary value and is a standard portion of a person's everyday diet. I believe irrigated acreage and irrigation intensities will vary from low to high depending on the specific crops' water needs and acreage requirements. I suspect a larger increase in irrigated acreage will have occurred outside the AMAs where there is little to no groundwater regulation, compared with inside AMAs, where regulations are strictly followed. The scope of this project will be on the Phoenix, Pinal, Tucson, Santa Cruz AMAs as well as southwestern Arizona, which is not part of any AMA. All areas are located within the state of Arizona in the United States.

Definitions

Groundwater- Water that is found and stored beneath the earth's surface in small pore spaces between sand, soil and rocks.
Surface Water - Water that collects on the earth's surface such as in lakes, rivers, reservoirs, etc.
AMA- Active Management Areas. These are five watersheds the with strict groundwater regulations and conservation programs to reduce groundwater withdrawals. The goal, as stipulated by Arizona's Groundwater Management Act of 1980, is for each AMA to achieve "safe yield" (i.e. groundwater withdrawals ≤ groundwater recharge) by 2025.
Staple crops- Crops that sell for low monetary values and are a standard portion of a person's everyday diet. Some examples include: cereals, legumes, tubers and root crops.
Non-staple crops- Crops that sell for large monetary values such as vegetables, fruits, flowers, condiments and spices.

Literature Review

Numerous researchers (e.g. Harou & Lund, 2008; USDA, 2014; Dieter et al., 2018) have studied changing (i.e. dropping) groundwater levels and how this has affected farmers’ crop choices, irrigated acreage, irrigation intensities, and energy consumption. Harou & Lund (2008) studied groundwater overdrafts in Tulare basin in California, where there is also sparse groundwater management or regulation. They observed that groundwater overdraft can have large system-wide consequences on the aquifer and sometimes has the potential to make water withdrawals economically impossible. To minimize groundwater overdraft, Harou & Lund (2008) described various solutions, including: increasing runoff capture and infiltration; taxes and fees; water conservation policies; relocation of high-water-use crops; using or importing other water sources; and land cycling. Land cycling is a strategy to optimize a specific crops’ water needs by mimicking the natural precipitation patterns of the region. Farmers can inexpensively pump water out of the ground but at some point the groundwater will be too deep and it will become too expensive to pump (i.e. when groundwater pumping costs exceed crop sale prices). Farmers use many methods to combat this such as water trading, smart irrigation, etc., which have been extremely successful in certain areas when managed correctly. Groundwater over-drafting in this area of California could cost farmers around $31 million annually in extra groundwater pumping costs. In 2014, the USDA reported that sprinkler systems were the most common irrigation method, followed by gravity fed systems, and then drip irrigators. Dieter et al. (2018) also showed that irrigated lands in the USA have become more efficient, with a 10% increase in sprinkler use and 11% decrease in flood irrigation, meaning there is less water lost to evaporation. New technologies and infrastructure will hopefully buffer the continued overdrafting of the system.

Howitt et al. (2015) discuss how to minimize economic losses during drought. Some processes they suggest are groundwater substitution for surface water use. Drought can potentially cause fallowed land, crops losses, and job losses. Howitt et al. (2015) showed that economic hardships were not equally distributed over their study area and that areas with limited groundwater resources experience the largest economic impact during drought. Groundwater use on crops in the California central valley is more expensive than delivering surface water, but this can slightly be offset by increasing crop sale prices at harvest time. They estimated that the surface water shortage was 48% less than in a normal water year. This led to a 72% increase in groundwater pumping with a total net water shortage of around 10%. The amount of idle land was 45% greater than during a normal water year (Howitt et al. 2015).

Groundwater pumping costs increased by 75% in response to the drought. The most fascinating thing associated with this study were these statistics. One might expect crop losses to be large, but crop revenue losses accounted for only 2.6%. These minimized revenue losses are the result of the success of water trading that typically takes place with municipal water companies, which are less subsided than farm water. In fact, farms can make more money by trading their water to municipalities than growing crops.

Siebert et al. (2010) discussed how groundwater use in irrigation is becoming a more widely-used practice worldwide. It accounts now for 43% of total irrigation water and around 545 (km3). The three largest groundwater users are India, China, and the USA. Irrigation water accounts for 70% of global freshwater withdrawals, and 90% of total global water use is for irrigation. Worldwide only about 38% of cropland can be irrigated with groundwater, for many reasons. Dieter et al. (2018) discussed the history of water use for irrigation in the United States, starting with groundwater pumping for irrigation, which steadily increased from 1950-1980, at which point it peaked at 150 bgal/day. From 1980 to 2005, irrigation withdrawals remained steady at 127 bgal/day, and has decreased to 116-118 bgal/day) today. The source of irrigation has shifted: surface water deliveries have decreased by 14% and groundwater withdrawals were 13% greater than in 2010 than in the 1980s. Withdrawals for irrigation were 37% of the total water withdrawals, and 17 states west of the continental divide accounted for 81% of total irrigated lands in the USA (Dieter et al, 2018). Increased reliance on groundwater for irrigation will cause groundwater tables to drop, and negatively impact the cost of pumping.

Scanlon et al. (2012) addressed groundwater depletion and sustainability of irrigation in the central versus western areas of the USA. In particular, they compared the High Plains aquifer in the Midwest with the Central Valley aquifer in central California, which are the two largest aquifers used for irrigation in the USA. Pumping for irrigation has caused a 36% and 15% decline in groundwater levels in these two aquifers, respectively. Scanlon et al. (2012) showed that depletion varies spatially: the northern regions of each aquifer had increases in groundwater table levels, in contrast to the southern regions, where pumping was dominant, and thus had groundwater declines. Modeling in the same area of the High Plains aquifer was conducted by Condon & Maxwell (2014), and included the interaction of surface water and groundwater over a simulated (hypothetical) 20-year period which was chosen because it would contain climate variability.

The model ran simulations where crops are irrigated using groundwater only, and also a constant pump model was analyzed to simulate irrigation against a base scenario where model results showed exactly what one would expect: groundwater pumping affects the temporal dynamics of water table depth by causing it to continue to drop over time rather than remaining relatively static. These modeling results were important because they confirmed that natural recharge cannot replenish the groundwater quickly enough to compensate for large-scale agricultural withdrawal. Irrigation makes groundwater systems highly variable, which makes them vulnerable, especially in times of drought when recharge to the system is low. Another interesting conclusion is that the water table in recharge areas is relatively stable, and doesn't experience a large water table decline that is common in pumping areas.

Castle et al. (2014) analyzed surface and groundwater depletion in the Colorado River basin from 2004 to 2013. Approximately 77% of all surface and groundwater water lost to evapotranspiration and consumptive use throughout the Colorado River basin is groundwater. During the 10-year period of study, the basin experienced moderate to severe drought in which surface water levels dropped only slightly at 0.9 km3/yr while groundwater levels dropped sharply at 5.6 km3/yr. This decline is concerning because there are strict usage requirements on surface water and far fewer regulations on groundwater use. Fewer regulations make groundwater more appealing to farmers, and the result is the depletion of the aquifer faster than it can replenish itself, and this has potentially severe consequences for all stakeholders who rely on the aquifer.

The goal of the current project is to explore how changing groundwater levels within and outside regulated areas have affected agricultural choices and to determine if groundwater regulations are driving crop choices and spatial distribution throughout Arizona. This information will be useful in future groundwater modeling to accurately predict drawdown due to agricultural pumping in southwestern Arizona. Groundwater level changes were analyzed throughout the state of Arizona using data from the Arizona Department of Water Resources (ADWR). Crop selection and locations were analyzed using the United States Department of Agriculture CropScape (USDA, 2021) and agricultural statistics survey (United States Department of Agriculture, 2019).

Site Description

The domain of my research project is the southwestern part of the state of Arizona and includes the counties of La Paz, Yuma, Maricopa, Pinal, and Pima, all shown in red in Figure 1. Arizona has a diverse range of physical features. The northeast corner consists of the Colorado Plateau (5,000-11,000 ft above mean sea level (AMSL)) which is mostly high desert with small areas of forests. The southwestern portion of the state contains basin and range provinces with multiple valleys in between several small mountain ranges. The desert regions have high daytime temperatures and cooler overnight temperatures and receive low amounts of rainfall (e.g. 12"/yr) compared to the higher elevation locations (e.g. 20"/yr). The transition zone between low and high desert runs from southeast to northwest and contains both desert and mountainous terrain. Figure two is a topographic map of Arizona that illustrates the transition zone, with low desert located in the southwest part of the state, depicted in deepening shades of green with increasing elevation, and high desert (950 to >3750 m AMSL) depicted in shades of light orange to red with increasing elevation. The large range of physical features in Arizona make it a fascinating location for this project.

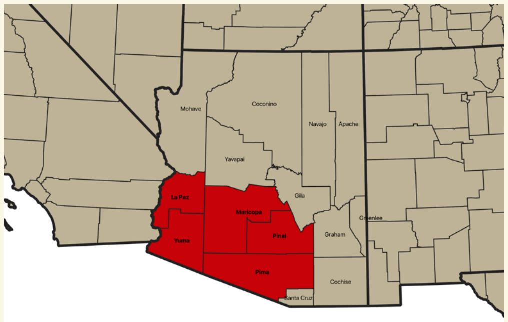

Figure 1: Arizona county map highlighting the southwestern region

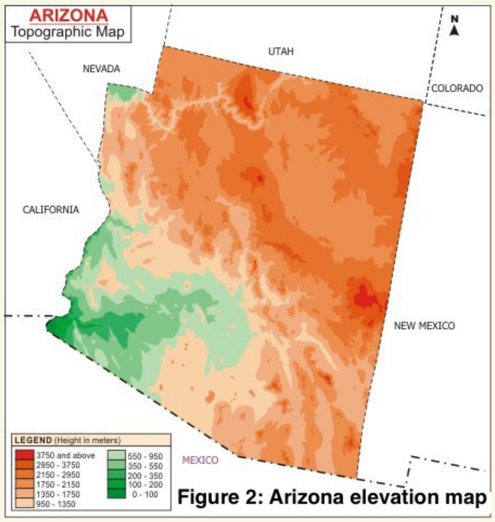

Figure 2: Arizona elevation map

I have focused much of my research on the Phoenix and Pinal AMAs, La Paz County, and the Harquahala irrigation non-expansion area (INA) (see Figure 3). Areas outside of AMAs such as Yuma and La Paz counties (see Figure 1) were also part of this study, and are important because they are the location of Arizona's largest agricultural regions outside the regulated groundwater areas of AMAs.

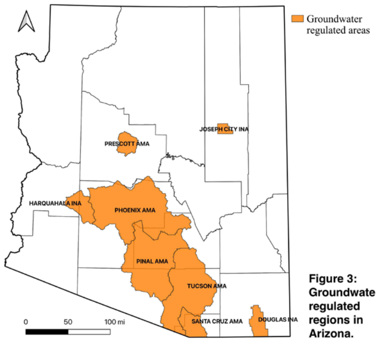

Figure 3: Groundwater regulated regions in Arizona.

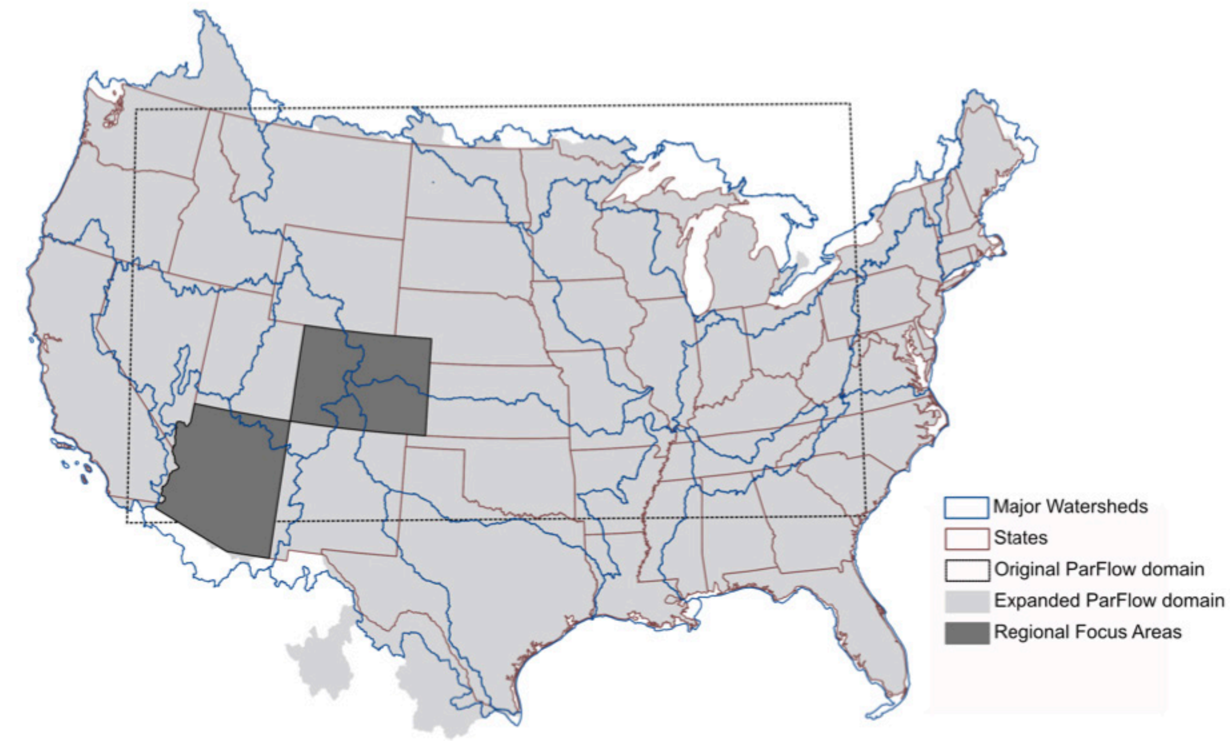

Figure 4: Map of the continental United States highlighting Arizona & Colorado

Yuma County is especially important because it is also a large agricultural region that continues to grow, with over 120,000 irrigated areas of farmland in 2010 (Yuma County Agriculture Water Coalition, 2015). The project is likely to expand into other states such as Colorado for my master's thesis (see Figure 4).

The abundant sunshine in Arizona makes it a very favorable location for growing crops. The annual precipitation in the driest parts of the state (e.g. near Yuma) is often less than 4 inches per year, which is insufficient to support most crops, and therefore crops must be irrigated using surface water or groundwater. There are two separate rainfall seasons in the Sonoran Desert region. In the winter months, steady light to moderate frontal storms passes through the area from the Pacific Ocean. Rain is the dominant precipitation type in the valleys but snow commonly occurs in locations above 4,000 ft above sea level. The other rainfall period is during the summer monsoon. During the monsoon, there is a seasonal shift in wind patterns, and moisture from the Gulf of Mexico, Gulf of California, and the Pacific Ocean are blown over state. Uneven summer heating of the land causes the moist air to rise and condense, which causes intense and violent thunderstorms that can drop inches of rain in short time periods. All other months are generally very dry and rain seldom occurs.

Materials & Methods

The objective of this research was to investigate how changing groundwater levels and use affect agricultural decisions on crop choices, irrigated acreage, irrigation intensities and energy consumption within versus outside AMAs. Data showing groundwater levels and pumping rates in Arizona were obtained from the Arizona Department of Water Resources known as the ADWR, which is a government agency dedicated to protecting and enhancing state water supplies. Groundwater levels from about 45,000 wells in Arizona were procured from the ADWR database. This study focused on depth-to-water measurements from 1910-2020 in four groundwater subbasins: Gila Bend (GIL), East Salt River Valley (ESR), Eloy (ELO), and Maricopa-Stanfield (MST) (Figure 5). This is a fairly comprehensive history of wells drilled in Arizona going back to the 1800s. Most of these wells do not have water level measurements associated with them, and were thus not relevant to this particular study. A group of 1000 index wells were selected for use in this study. Index wells have been measured at least yearly since 1984 by ADWR personnel. There is also a small group of wells that have pressure transducers in them. These transducers are automated devices that measure the water level in wells at specified intervals – in this case every 15 minutes – and record the time and associated water level in a data logger. The data from the logger is then downloaded onto a computer or wirelessly updated to the ADWR database. Water level and pumping data were downloaded and linked to each well's identification number and put into a QGIS file for a visual representation before they were analyzed.

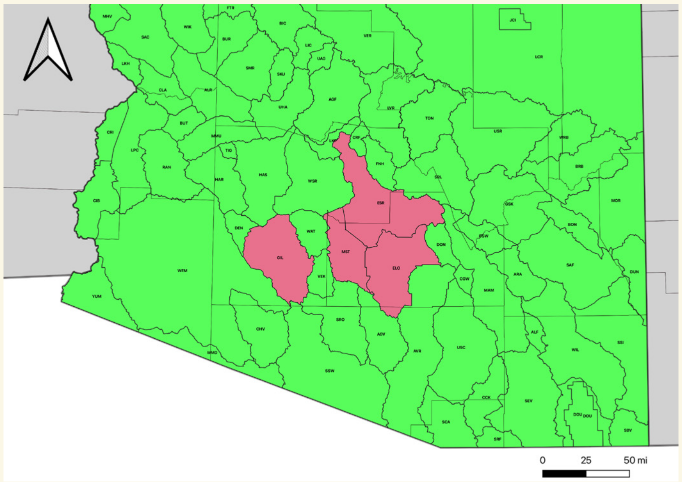

Figure 5:

Depth-to-water measurements were obtained from ADWR's Groundwater Site Inventory (GWSI) online database for the groundwater subbasins (highlighted in red).

As mentioned previously, the domain of this research project is the state of Arizona with the possibility of expanding into other states for my master's thesis research. I have focused on the Phoenix, Pinal, AMAs, and the Harquahala irrigation non-expansion area (INA), as well as Yuma and La Paz counties, which are neither part of an AMAs nor an INA. Areas outside of AMAs and INAs are especially important because they are the location of Arizona's largest agricultural regions outside the regulated groundwater areas of AMAs. In unregulated areas, reporting the quantity of water pumped is voluntary and therefore limited. The water level data in Arizona dates back to the late 1800s and continues through today but pumping data are available only from1984 to - the present. Water level measurements from the late 1800s and early 1900s were taken so infrequently that the data for this time period are not useful for this study. Therefore, the period of study was from 1984 to the present.

Our research team determined that the Arizona Department of Water Resources (ADWR) and the United States Geological Survey (USGS) would be able to provide the largest and most accurate public-domain datasets. These datasets were chosen because of a large temporal and spatial range, and both government agencies have a history of strict quality control procedures when collecting data measurements. Data showing groundwater levels and pumping rates inside Arizona were obtained from ADWR and USGS. Groundwater levels from all wells inside of Arizona were taken from Wells 55, which is a database of approximately 45,000 wells drilled between 1800-2020. A smaller group of 1,450 strategically-selected wells make up the Groundwater Site Inventory (GWSI) index wells which have been measured at least yearly by ADWR since 1984. Agricultural data for Arizona were gathered from the USDA Agricultural Statistics Survey (United States Department of Agriculture, 2019), which is completed every five years. While the complete ADWR dataset ranges from 1840-2017, our main focus was 1930- 2017 since government dairy subsidies started in the 1930s. Satellite data were acquired from CropScape to identify alfalfa field locations in Arizona; this dataset ranges from 2009-2020 (U.S. Department of Agriculture, 2021). After the data were obtained, they were input into spatial software QGIS to better visualize the spatial distribution of the data. The data were then uploaded into a data analysis package in Python called the Geospatial Data Abstraction Library (GDAL), which allowed the data to be sorted, manipulated, and graphed to analyze and better understand the patterns and trends.

Preliminary Results & Discussion

Preliminary results show a correlation between an increasing number of dairy cows and an increase in alfalfa acreage in Arizona (Figure 6). Alfalfa is a dairy cow's main food source. In 1983, the Dairy Production Stabilization Act was enacted by the United States federal government and authorized direct payments to farmers to reduce their milk production. The problem with this program was the government had strict regulations qualifying farmers for the program and direct payments were lower than dairy prices at the time. By the early 1990's most farmers decided not to participate. Figure 6 shows how dairy production increased significantly with the increase in dairy cow populations and the corresponding increase in alfalfa production.

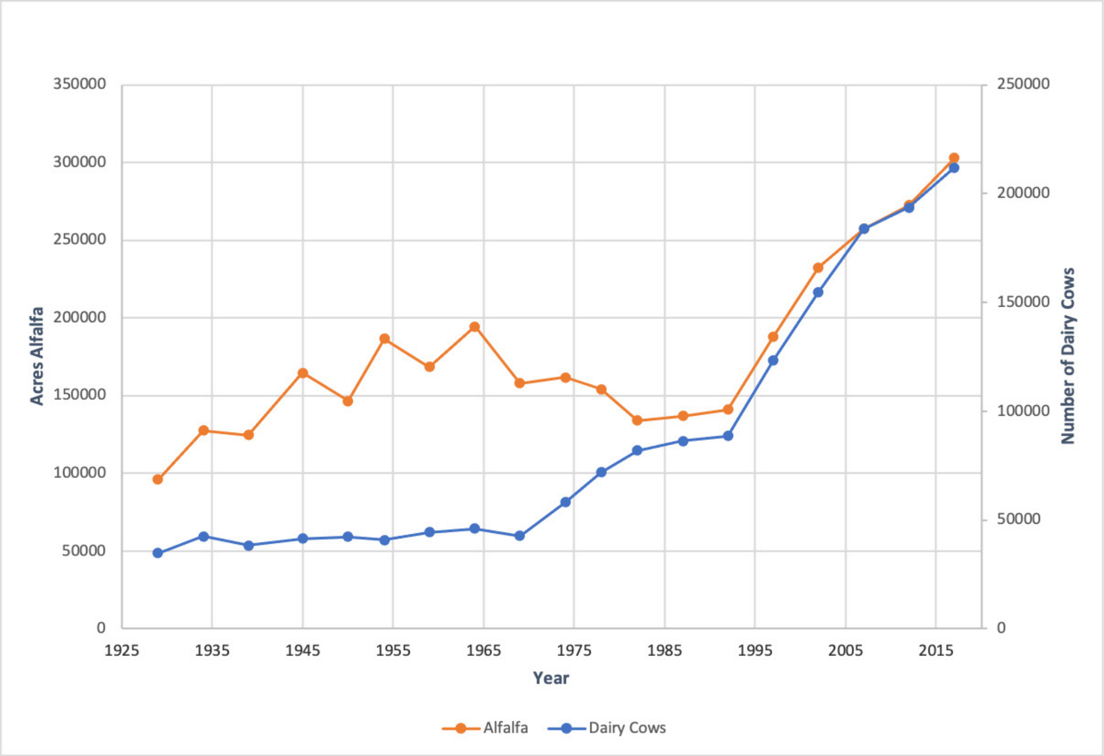

Figure 6: The dairy cow population and alfalfa acreage in Arizona from 1925-2017.

The earliest data on the spatial distribution of alfalfa in Arizona only dates back to 2008 in the CropScape database. Figure 7 is a map of southern Arizona that illustrates the increase in alfalfa acreage in the state. The new alfalfa acreage in 2020 is shown in light blue, while the acreage from previous years (2015, 2010, and 2008) is shown in increasingly darker shades of blue.

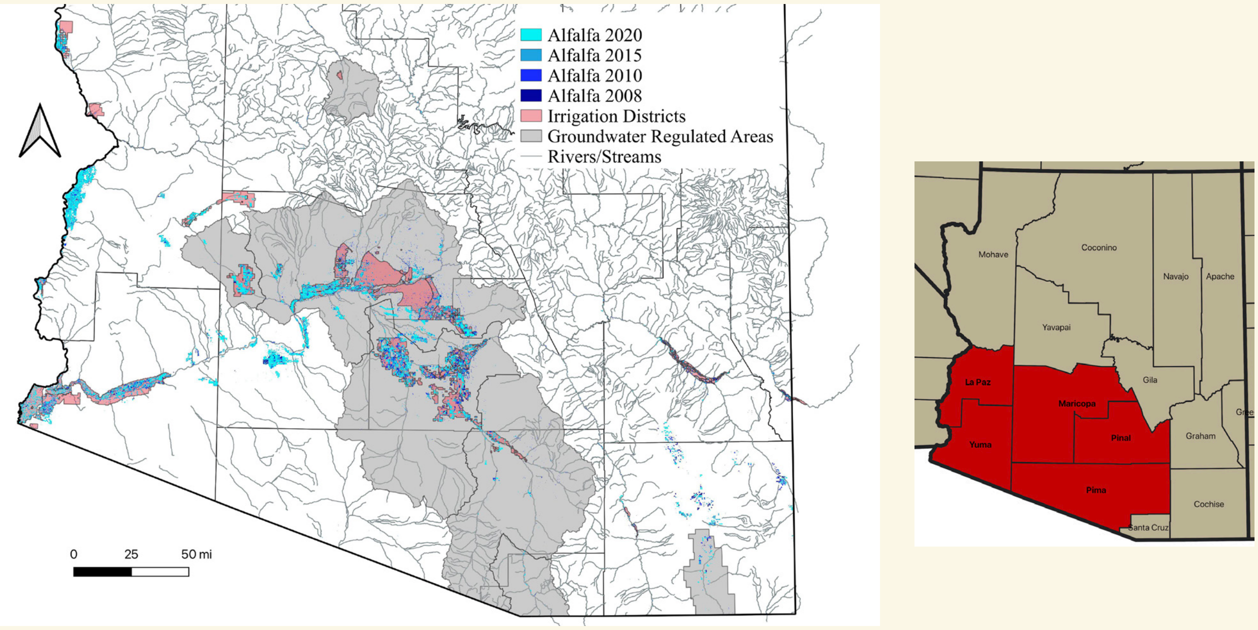

Figure 7: Spatial distribution of alfalfa in Arizona 2008-2020.

The largest increases in alfalfa acreage are evident in Maricopa County which has groundwater regulations (the gray shaded areas in Figure 7) in some but not all parts of the county. The large increase in alfalfa in this county most likely has been attributed to the fact that over 60% of the total state population lives in Maricopa County (United States Census Bureau, 2020). Dairy farms tend to be located relatively close to urban areas so that their products are trucked shorter distances to local markets, therefore reducing transportation costs to the farmers. Figure 7 also shows that alfalfa is grown within and outside irrigation districts.

Figure 8 shows the change in alfalfa acreage between 2008 and 2020. In the Figure 8, irrigation wells are shown as green dots, alfalfa acreage in 2020 is shown in light blue versus dark blue in 2008, and rivers shown in gray. This figure also shows the connection that irrigation wells are commonly found near natural waterways where shallow groundwater is. This shallow groundwater allows farmers to reduce pumping costs because pumps only have to lift groundwater a short distance to the surface. Alfalfa is commonly grown near streams and irrigation wells to provide sufficient irrigation water due to its high water requirements. Commonly near streams, the depth to water is usually significantly more shallow than in areas further from natural waterways. Streams can be one of two types; the first type is a losing stream which is more common in the desert southwest. In a losing stream, water infiltrates to the groundwater table, which causes a reduction in surface water flow.

A gaining stream is the opposite: the stream gains water from the groundwater table which thus feeds surface water flow. Alfalfa and other crops are commonly grown close to natural waterways where groundwater is shallow because this allows farmers to minimize pumping costs. It costs farmers less money to withdraw shallow groundwater versus deeper groundwater. Shallow groundwater wells are also much cheaper to drill compared with deep groundwater wells, since drillers tend to charge by the foot. Overall, growing alfalfa and other crops close to natural waterways can make it more economically friendly for farmers to withdraw groundwater.

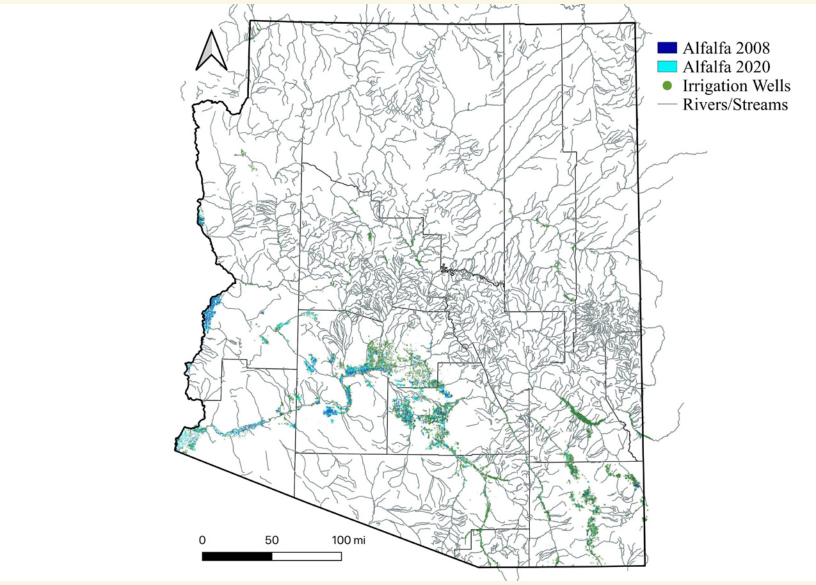

Figure 8: Spatial distribution of irrigation wells, rivers, and alfalfa locations in Arizona in 2020.

Depth to water from 1910-2020 is shown in Figure 9 for four groundwater subbasins: Gila Bend (GIL), East Salt River Valley (ESR), Eloy (ELO), and Maricopa-Stanfield (MST). These four subbasins were chosen because three of the subbasins (ESR, ELO, and MST) are located in areas where there are groundwater regulations, and the GIL subbasin provides an example of groundwater conditions where few if any regulations exist. An especially important characteristic of all four subbasins is that they collectively contain 157,530 acres of alfalfa which is 52% of Arizona's total. Since these irrigated alfalfa acres are too far from natural waterways to be irrigated by surface water their primary irrigation source must be groundwater, it can be concluded that increased alfalfa production in these areas has had a negative impact on the groundwater levels. Figure 9 shows that since 1980, groundwater levels have stayed steady or even had some recovery in the three regulated subbasins. The steady and/or recovering groundwater levels can be explained by the enactment of the Groundwater Management Act of 1980 in Arizona which created AMAs and INAs and charged the AMAs with the goal of safe yield by 2025.

Safe yield means the amount of groundwater being withdrawn is less than or equal to the amount of groundwater recharge to an aquifer. In the GIL subbasin where regulations are lacking, there is a continuing groundwater decline even after 1980. Figure 9 shows that in all four subbasins, groundwater levels have steadily declined from the early 1900s through today. Alfalfa grown in areas where groundwater is the primary irrigation source have had negative impacts on groundwater locally in those areas.

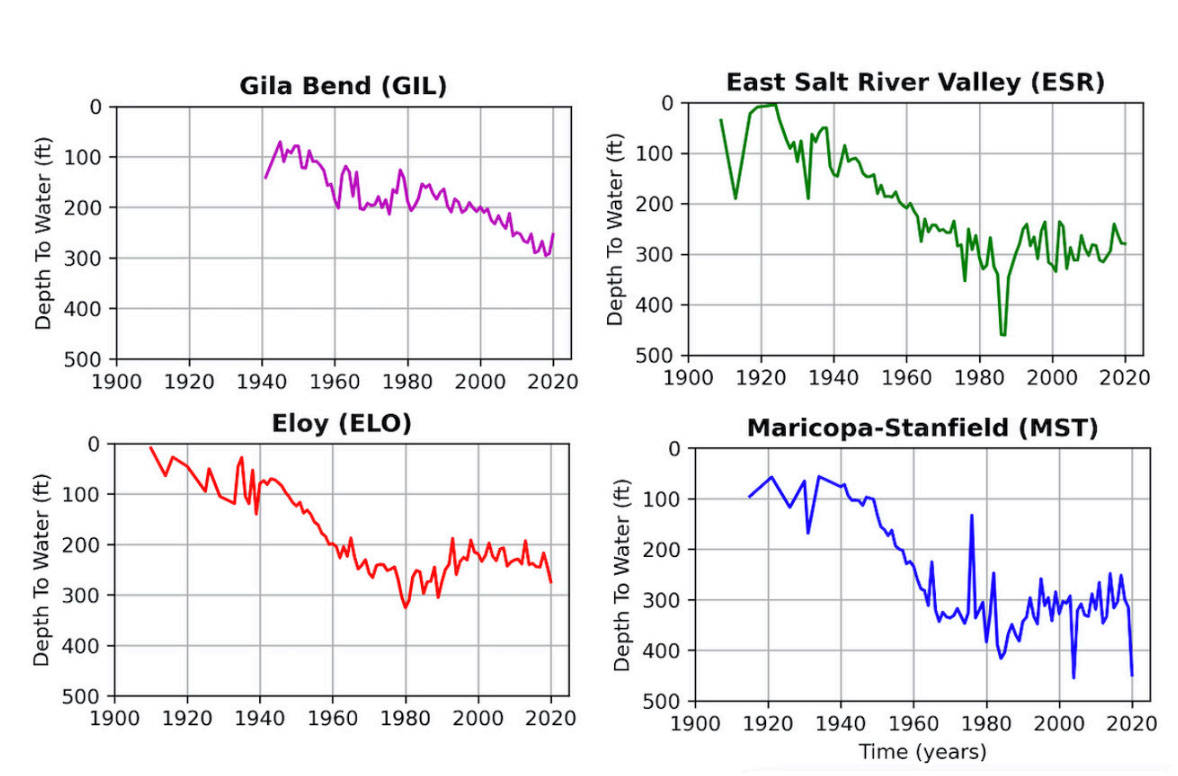

Figure 9: Time series of depth to water in four selected subbasins.

Future Research

The next step in this research is to investigate the connection between alfalfa expansion and new groundwater regulation in CA. In 2014, California signed the Sustainable Groundwater Management Act (SGMA), hoping to attain sustainable groundwater yield within the next 20 years. The goal of the SGMA is to stop groundwater overdraft in California, and reach balanced levels of pumping and recharge within the next 20 years of implementation (State Water Resources Control Board, 2020).

It is possible that after the introduction of SGMA in 2014, California farmers have moved to Arizona to take advantage of the lack of regulations outside the AMAs. I intend to explore spatial patterns in alfalfa expansion and groundwater declines relative to different groundwater regulation areas in AZ. Regulations differ slightly in AMAs compared to INAs and I will investigate how these differences in regulations affect groundwater declines. Third, I will explore discrepancies between the USDA Agricultural Statistics Service and CropScape values for alfalfa acreage (see Figure 10). CropScape estimates alfalfa acreage using Landsat imaging while the USDA Agricultural Statistics Service sequesters farmers records. For 2006-2012, CropScape estimated ~100,000 more acres of alfalfa than the USDA, and the difference has been increasing since ~2013. I hypothesize that the value generated by the USDA data is underestimated due to varying crop rotations involving alfalfa, which causes large amounts of under sampling. Lastly, I will analyze how dairy subsidies affect dairy in Arizona compared with data at the national level. A preliminary investigation (Murphree, 2018) shows that dairy cow populations have stayed constant nationally but increased in Arizona. This can be explained by the fact that milk yields per cow are higher because Arizona has more favorable environmental factors such as dry climate, abundant sunshine, and warm temperatures(Murphree, 2018). This could be an additional explanation for farmers moving to Arizona to obtain higher milk yields per cow rather than just the lack of groundwater regulations.

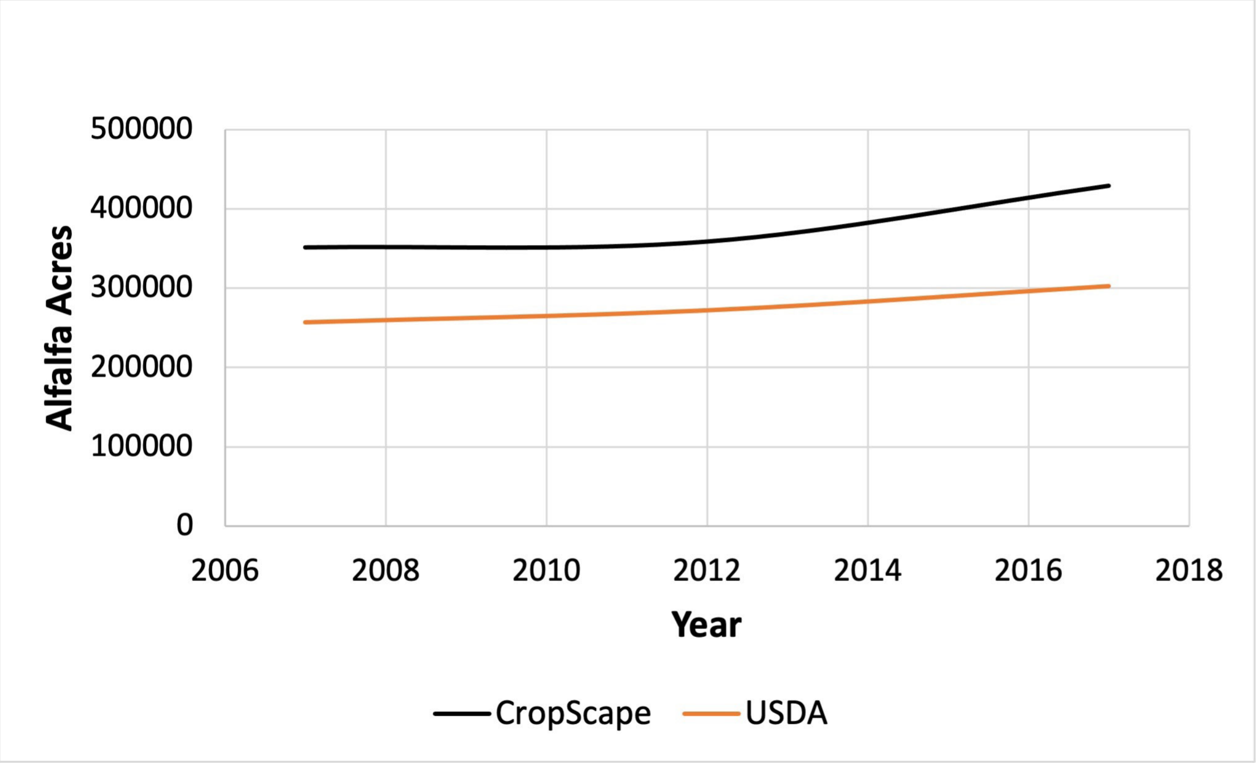

Figure 10: Alfalfa acreage CropScape vs. USDA Agricultural Statistics Service

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