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Ranchers Adapting to Climate Variability in the Upper Colorado River Basin, Utah

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RANCHERS ADAPTING TO CLIMATE VARIABILITY IN THE UPPER

COLORADO RIVER BASIN, UTAH

by

Hadia Akbar

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ABSTRACT

Ranchers Adapting to Climate Variability in the Upper Colorado River Basin,

Utah

by

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Utah State University, 2019

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Department: Civil Engineering

Climate-temperature & precipitation, streamflow influence agricultural production. Different analytical methods and crop models have been used to study the relationship between climate and agriculture. Prior research indicated that climate has been among the biggest factor in influencing agricultural production. These studies have mostly used analytical models and studied the impact of long-term climate on agriculture. This study uses a two-tiered approach of data mining techniques and interviews to explore how climate variability affects agricultural production in the Utah regions of the Upper Colorado River Basin and how the farmers are adapting their practices to these changes. First, multilinear regression and random forest regression are used to determine the relationship between climate and agricultural production using climate extreme indices and agricultural production data. Second, interviews with farmers and ranchers are used to understand the gaps in the knowledge that cannot be explained by the results of quantitative analysis. The results show that temperature has more impact than precipitation and precipitation does not have any statistically significant relationship with cattle and hay production over a 35-year period. Among non-climatic variables, commodity prices and their regulations by the government are the most important factors that influence year-to-year production. Farmers are well-aware of these impacts and have adapted by changing their irrigation practices and cropping patterns to produce enough forage to maintain the number of cattle on their ranches. Some farmers are also experimenting to produce hybrid cow species that are resilient to hotter temperatures and use a wider variety of forage.

(63 pages)

PUBLIC ABSTRACT

Ranchers Adapting to Climate Variability in the Upper Colorado River Basin, Utah

Hadia Akbar

Changes in climate influence agricultural production. This study looks at the impacts of climate variability in the Utah regions of the Upper Colorado River Basin by combining regression techniques with interview data to explore how climate variability affects agricultural production and how the farmers are adapting their practices to these changes. The results show that climate does not have any significant impact on cattle and hay production in the study area on a decadal scale. However, on an annual basis temperature seems to have more impact than precipitation. Among non-climatic variables, commodity prices and their regulations by the government are the most important factors that influence the year-to-year production. Farmers are well-aware of these impacts and have adapted significantly to the changes that occur on a year-to-year basis.

DEDICATION

I dedicate this work to my loving mother Shagufta and to my invaluable sisters Fazilat and Midhat whose support and encouragement made my journey easier.

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Hadia Akbar

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CHAPTER 1

INTRODUCTION

Agriculture is very sensitive sector to climate variability and change (Adams, Hurd, Lenhart, & Leary, 1998; Hoffmann, 2013; Yohannes, 2015). Climate change impacts global agricultural production where the impacts on crop yield range from -13.4% to +3.4% depending on region (Ray, West, Clark, Prischepov, & Chatterjee, 2019). In Europe, crop yields are expected to decrease by 45% to up to 81% under a future warming climate(Bird et al., 2016; Lehmann, 2011). In India, where wheat and rice are major food crops, 15% and 22% of decrease in rice and wheat production are expected under the ongoing climate change (Birthal, Khan, Negi, & Agarwal, 2014). In China, which supports about 22% of the world's population (with only 7% of the world's arable land), climate change has been associated with decreased crop yields, northward expansion of croplands and expansion of pests. For the corn belt in the US, the corn and soybean yields are predicted to decline drastically (Bhattarai, Secchi, & Schoof, 2017) as much as 31-43% under the lowest warming scenario and 67-79% under the worst-case scenario by the end of the century (Schlenker & Roberts, 2008). About one-third of the variability in the crop yields can be associated with climate variability (Ray, Gerber, Macdonald, & West, 2015; Vogel et al., 2019) and with the increasing intensity of extreme temperatures and precipitation events, the crop yields are most likely to decrease in future (Kang, Khan, & Ma, 2009).

The second aspect of agriculture production is livestock. Climate variability and change have direct and indirect impacts on cattle and other production animals in several ways. Extremely hot and humid climate conditions directly affect impaired growth, health, and immune systems as well as the reproduction rate in animals (Hansen, 2009; Nardone, Ronchi, Lacetera, Ranieri, & Bernabucci, 2010). Increased heat stress in cattle can also increase the mortality rate (Crescio, Forastiere, Maurella, Ingravalle, & Ru, 2010). These combined effects can cost billions of dollars to the beef and dairy industry in the US alone (Key & Sneeringer, 2014; St-Pierre, Cobanov, & Schnitkey, 2003). In addition to these direct impacts, cold and dry climate conditions indirectly affect livestock productions through changes in the quantity and quality of cattle feed, both pastures and forage crops (Henry, Charmley, Eckard, Gaughan, & Hegarty, 2012; Reeves & Bagne, 2016; Rust & Rust, 2013; Thornton, van de Steeg, Notenbaert, & Herrero, 2009; Topp & Doyle, 1996). The changes in quality of feed are associated with changes in nutrient concentration. These changes, linked with water availability and soil characteristics and coupled with heat stress can impact the rumen physiology of cattle (Gauly et al., 2013). Additionally, with predicted future warming, the water demand for livestock is expected to increase by a factor of three(Rojas-Downing, Nejadhashemi, Harrigan, & Woznicki, 2017). Limited water availability will further stress the cattle industry. These changes can adversely impact regional and global economies.

Various studies on the impacts of climate warming on agricultural production conclude that climate warming results in decreased production of agricultural products, such as crops and cattle. Diverse methods (mostly analytical) have been applied to study the relationship between agriculture and climate (Kang et al., 2009). Salvo provides a review of the analytical models that can be used to estimate the effects of climate change on agriculture (Salvo, 2013). Specifically for crop yield changes due to climate, many models have been implemented such as CERES-Maize (Crop Environment Resource Synthesis), CERES-Wheat, SWAP (soil–water–atmosphere–plant), InFoCrop, CropSyst, GLAS, SWAT (Kang et al., 2009) and FAO's Aquacrop model (Bird et al., 2016; Kikoyo & Nobert, 2016). These studies rarely identify or rank the factors that influence production.

Based on the research available, it is hypothesized that the variability in climate has a direct impact on cattle and hay production. This study focuses on investigating how climate has influenced agriculture in Utah regions of UCRB. It identifies the factors that can explain the changes in agricultural production due to climate variability in the study area.

Though different modeling techniques have proven useful for visualizing possible future scenarios of climate change and to help evaluate potential adaptation strategies for farmers to, however, they do not represent the capacity of the farmers to adapt to changes. The modeling approach lacks the ability to identify factors such as farmers' ability to innovate, the availability of resources and labor, and other socio-cultural/environmental/ecological drivers that influence the farmers' decision and strategy to adapt (Bhatta, Aggarwal, Kristjanson, & Shrivastava, 2016; T. A. Crane, Roncoli, & Hoogenboom, 2011). Changes in agricultural productivity and adaptation strategies of farmers to climate change are not solely dependent on climatic parameters, the changes in crop yields considering just the climatic factors can be estimated to be higher than actual (Li, Takahashi, Suzuki, & Kaiser, 2011). The non-climatic variables may either add to or reduce the impacts of climate-related stress. Some studies have identified other factors such as the effects of economic and technology adaptation on crop yields globally, market-related forces and resource issues, government policy, availability of labor, land or water rights, availability of credit or insurance, access to appropriate technology, management capacities, to name but a few (Abid, Schilling, Scheffran, & Zulfiqar, 2016; Arendse & Crane, 2010; Bhatta et al., 2016; Li et al., 2011; Smit & Skinner, 2002; Uddin, Bokelmann, & Entsminger, 2014). This intermix of factors that influences farmers' decision and strategy to adapt is well described by Richards musical analogy, wherein musicians (farmers) must interact with other musicians (social/environmental/ecological processes) in real-time during the performance of a piece (agricultural production process) (Richards, 1993). Regardless of the causes of the changes in climatic patterns or other factors, farmers adapt quickly to avoid yield and income losses and understanding how farmers adapt to the changes in climate is vital in long term planning to mitigate the effects of climate on agriculture (Mendelsohn & Dinar, 1999). Many propositions have been put forward to cope with the threat to agricultural productivity due to climate change. Among these, some of them are the adoption of climate-smart technologies such as conservation agriculture(McCarthy, Lipper, & Branca, 2011), transformational adaptation (Colloff et al., 2017; Rickards & Howden, 2012; Rippke et al., 2016), systematic and targeted diversification of production systems(Howden et al., 2007). Additionally, agricultural practices are different in every region. Depending upon the availability of resources and management options farmers have different adaptation strategies to maintain the overall agricultural production.

The existing research that is reviewed identifies in detail the adaptation capacities and practices of farmers to climate change, whereas farmers' decision to adapt depends on the changes in climate on a year-to-year basis. This study explores how the farmers in the Upper Colorado River Basin (UCRB) in Utah perceive the impacts of climate variability on the production of cattle and hay in the past three decades and how they have adapted to these changes to maintain a sustainable business. Largely, this study aimed to answer the following questions,

- Which variables, including climate variability, affect agricultural production in the region?
- How have farmers adapted to the changes in cattle and hay production?

CHAPTER 2

CASE STUDY – COLORADO RIVER BASIN IN UTAH

Within the Colorado River basin that serves approximately 40 million people, climate impacts on agriculture are expected to be severe. The river is managed by several treaties, regulations, and compacts that are collectively called The Law of the River. Not only does agriculture have the senior water right (due to the law of prior appropriation), but it is also the largest consumer of water in the basin (70%) that contributes to about 15% of the total crop production and about 13% of livestock in the US (Bureau of Reclamation, 2011, 2012). In irrigated agriculture, hay or forage crop, grown primarily as cattle feed, is the largest consumer of water in the basin as approximately 60% of the agricultural land is used to grow forage crops and pastures(Cohen, Christian-Smith, & John, 2013) Most of the basin is arid and receives insufficient rainfall so irrigation is required for 90% of cropland to supplement the water requirement(Cohen et al., 2013).

Typically, calves are born in spring and are a part of the herd for a year. They are raised and fed on ranches where ranchers grow hay as cattle feed. Cattle are also fed on rangelands and pastures in the summer. Most rangelands are under the Bureau of Land Management or the United States Forest Service and the lands are leased to the ranchers yearly. The cattle are rounded up in the fall and fed on individual ranches through the winter. Ranchers use hay and other supplements to feed the cattle during the season. Young cattle are sold in the spring.

The Colorado River Compact (1922) demarcates and apportions the water between the Upper and Lower Colorado River Basin. The Upper Basin includes parts of Colorado, Wyoming, Utah, Arizona, and New Mexico (Figure 1).

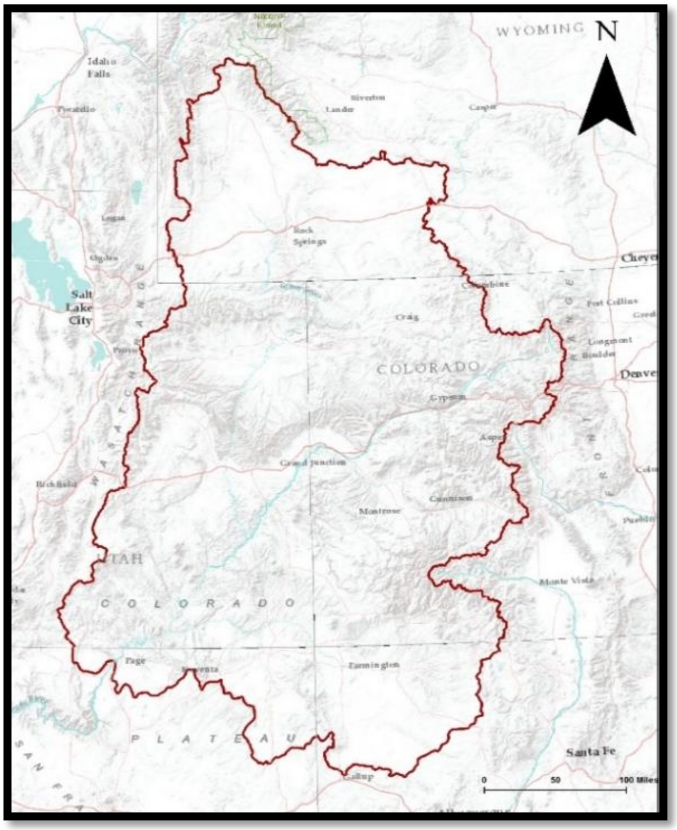

Figure 1: Upper Colorado River Basin (UCRB)

Our study is focused on the Upper Colorado Basin in Utah (Figure 2), where agriculture (primarily hay) is the predominant consumer of water (Bammes, 2015). Utah's share of apportioned water is 10.45% of the Colorado river basin, which is the second-highest allocation in the UCRB. The production agriculture that includes farming, ranching, dairy, and other support industries, is a major economic driver in Utah (Ward & Paul, 2013; Ward & Salisbury, 2016). In 2014 alone, the production agriculture contributed $3.5 billion to the state's economy (Ward & Salisbury, 2016). This study is conducted at the county level. The ten counties of Utah that are included in UCRB are in the southern and eastern part of the state, as shown in red on the map below (Figure 2).

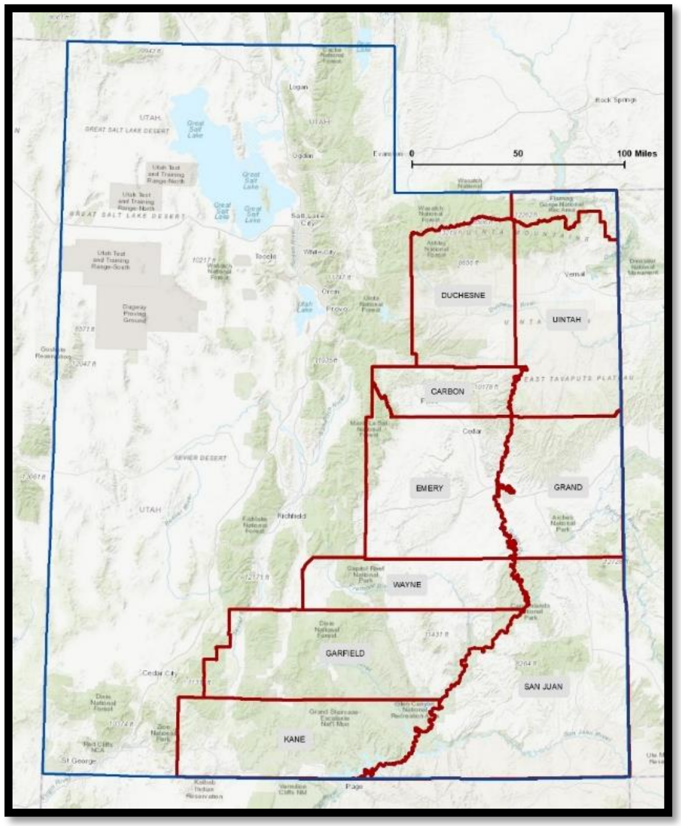

Figure 2: Counties of Utah in Upper Colorado River Basin

Colorado River is one of the most over-allocated rivers in the world (Bureau of Reclamation, 2012; N. S. Christensen, Wood, Voisin, Lettenmaier, & Palmer, 2004), and the Colorado river basin is an area of concern pertaining to water resources (McMurrray, 2012). The water availability in the basin is snowmelt-driven where about 80% of the precipitation in the basin is in the form of snow. Since the last three decades of the 20th century, the snowmelt has shifted 2-3 weeks earlier (Clow, 2010), this phenomenon can be associated with the decreased availability of water during the growing season in the basin (Das, Pierce, Cayan, Vano, & Lettenmaier, 2011). Though discrepancies exist among the researchers based on methodological differences, there is a consensus that this region will face a drastic reduction in water supply in the coming decades (Cayan et al., 2010; N. Christensen & Lettenmaier, 2007; Dawadi & Ahmad, 2012; Hoerling & Jon, 2007; McCabe & Wolock, 2007; McMurrray, 2012; Vano, Das, & Lettenmaier, 2012; Wehner, Arnold, Knutson, Kunkel, & LeGrande, 2017). In Upper Colorado River Basin alone, the river flow has declined by 16.4% in the last century(Xiao, Udall, & Lettenmaier, 2018). The river flow in the entire basin is expected to decline by up to 20% by midcentury and 35% by the end of this century if business-as-usual warming continues (Udall & Overpeck, 2017). These recent trends of early-season snowmelt, decreasing snowpack, runoff shifts, and prolonged droughts can be a forerunner to a drier climate (Bureau of Reclamation, 2011; Seager et al., 2007) and the predicted changes in climate would stress water availability in the future (Belnap & Campbell, 2011; Hamlet, Mote, Clark, & Lettenmaier, 2007). As agriculture is a vital part of the economy in the study region, the reduction in water availability can translate into economic losses for the region. To sustain agriculture in the basin, it is important to understand how climatic variability and other factors affect agricultural production in the region. While much work has been focused on the impact of climate change and variability on water resources in the Colorado River basin, little work has focused on the impacts of changes in climate on agricultural production, that is why this region is chosen for this case study.

CHAPTER 3

METHODS

This study combines quantitative data mining and qualitative interview methods. In the first part data analysis is conducted using trend analysis, correlation test, multilinear regression, and random forest regression to determine the most important variables that affect the cattle and hay production in the study area. The second part of the study conducts interviews with farmers in the study area to understand how they have adapted their ranching practices to cope with climate variability in the region and what impacts the changing climate has had on cattle and hay production. The data used in the quantitative analysis has a large variance which the models cannot fully explain. The interviews fill the gap in information that the quantitative analysis cannot explain.

3.1 Statistical Analysis

3.1.1 Data

The daily temperature and precipitation data were acquired from Parameter-elevation Regressions on Independent Slopes Model (PRISM)(PRISM Climate Group, 2018). The data for natural streamflow was acquired from the Bureau of Reclamation. Natural streamflow is the streamflow that would have existed if there were no reservoir storage on the river and no other consumptive uses were in play (Bureau of Reclamation, 2019). The data for agricultural production (cattle numbers, alfalfa production, alfalfa yield, acres of alfalfa harvested per year) was downloaded from the National Agricultural

Statistics Service (NASS) by the US Department of Agriculture (USDA). All these data were acquired for 1981- 2015. A summary of the data, format, and sources is given in Table 1. All the data analyses were conducted using R version 3.4.2.

Table 1: Sources and format of data

Data	Source	Data format	Spatial scale	Time Step
Precipitation and Temperature	PRISM	Csv files	County	Daily
Natural Streamflow	Bureau of Reclamation	Csv files	Station data	Daily
Agriculture Data	NASS-USDA	Csv files	County	Annual

3.1.2 Climate Extreme Indices

The climate extreme indices proposed by The Expert Team on Sector-specific Climate Indices (ET-SCI) are used in the study to test the relation of climate to the hay and cattle production in our study area. The climate indices provide a better characterization of the climate extremes as well as facilitate the monitoring of the trends and intensity of events that can potentially be responsible for the climatic effects on humans and the environment (Zhang et al., 2011). These indices are derived from daily temperature and precipitation data. Prior to calculating indices, the time series were homogenized by adjusting the series so that the empirical distributions of all segments of the de-trended base series match each other. The homogenization was done using the RHTest_V4 and RHtests_dlyPrcp (Wang, 2008b, 2008a; Wang, Chen, Wu, Feng, & Pu, 2012; Wang & Feng, 2013b, 2013a) for temperature and precipitation time series respectively based on the penalized maximal t-test (Wang, Wen, & Wu, 2007) and the` penalized maximal F test (Wang, 2008b). This is done primarily to remove any trends in the series that occur due to non-climatic factors.

The quality controlled data is used to calculate the climate extreme indices using Climpact2 software (Alexander & Herold, 2016). RHTest software and Climpact2 are based on R. The details of the indices used are given in Table A in Appendix A.

3.1.3 Correlation Test

The first part of this study implements a bottom-up approach where the relationships between climatic variables (precipitation and temperature) and agricultural production are tested by identifying the indices to which cattle and hay production is most sensitive. Prior to implementing the regression models, the correlation of the indices with cattle and hay production numbers and with the indices was tested. The association between cattle production, hay production, and the climate indices is investigated using correlation test. Pearson's correlation coefficient is used as a measure of the strength of the relationship between the two variables. For any two indices that had a correlation coefficient of greater than |0.5|, the index with higher correlation with other indices was removed from the data as it did not add any new information to the model and may have created bias in the regression.

3.1.4 Regression Analyses

Two data mining techniques are used to test the relation of climatic parameters to hay and cattle production in the study area. The hypothesized relation of cattle and hay production to climate is tested using multilinear regression (MLR) and random forest regression (RFR).

a. Multilinear Regression

Multiple linear regression is used to assess if there is a relationship between the response variables (cattle/hay numbers) and explanatory variables (selected climate indices). MLR is used as a standard regression technique to study the relation of a response with many predictors where a linear relation is expected between the response and predictors. Since the units of the variables used are different and vary from tens (for temperature) to a hundred thousand (for cattle numbers), the data were normalized by their standard deviation before implementing MLR. Cattle numbers and hay production (lbs.) per year are used as response variables whereas the climate indices, streamflow, and acreage of hay are used as predictors. Since the indices are correlated with each other, they cannot be used as independent variables for MLR. Two indices for precipitation and temperature are chosen that are not correlated to other indices.

The overall significance or fit of the model is determined by the F statistic, the value shows if the group of the predictors are jointly significant. The other parameter to judge the fitness of the model is the p-value of the F statistic. A value of 0.05 is considered as the threshold where the values less than 0.05 are considered significant. F statistic and p-value are jointly assessed to access with overall fitness of the model. The individual predictors are evaluated based on the t-statistic value and the variance explained by the predictor in the model. Larger the t-statistic value from zero, greater is the relative association between the predictor and the response variable.

b. Random Forest Regression

Random forest regression is chosen as it has shown to be superior in predictive ability to other modeling techniques, such as multiple linear regression, artificial neural network, and support vector machine models. It also performs well for identifying the most important predictors (Grömping, 2009; Hengl et al., 2015; Ok, Akar, & Gungor, 2012; Pal, 2005; Pang, Yue, Zhao, & Xu, 2017) especially for variables that have a nonlinear correlation (Cootes, Ionita, Lindner, & Sauer, 2012). The regression forest is an ensemble of decision trees where many decision trees are combined into a single model. Each tree is built by breaking down the data into random subsets that include homogenous responses and only uses data points from that subset to create the tree (Breiman, 2001). The random subsets are created by bootstrap aggregation (bagging) (Breiman, 1996). Bootstrap sets are created by random sampling with replacement. By doing so, each tree is essentially using different predictors from each other. This process decorrelates the individual trees thus restrict the model from overfitting the data and reduces the variance in prediction. Each decision tree is considered a weak learner and individual predictions might not be very accurate thus the predictions of the individual trees are aggregated to get a single prediction for the model. The predictors in our model are the climate indices for precipitation and temperature, streamflow and hay acreage and the response variable are cattle and hay production.

To build the random forest model for our study, the randomForest package in R was used (Liaw & Wiener, 2002). In the implementation of the model in randomforest in R, two parameters can be changed by the user; the number of trees in a forest (ntree) and the number of variables that can be tested on each split (branch) of a tree (mtry). The model gives the variables that are most important for the prediction of the response variable (here cattle numbers and hay production) as well as ranks them. The best-fit model or forest (R^2 value) for a combination of ntree and mtry is represented by the percentage of variance explained by the model in randomforest in R. Additionally seed function is used to create reproducible results. Due to the nature of our data, changing the values of the three parameters (ntree, mtry and seed) gives results with high variance and different importance ranking for the indices for each run. To account for this variance, a function was created that tries out different combinations of the three parameters from seed values from 1:5000. The models that had positive values for R^2 were kept in the end and the frequency of occurrence the most important variables were calculated. The parameters that occurred as important variables in most of the runs were considered the most important variables for cattle and hay production.

3.2 Qualitative Analysis: Interviews

Farmers from the ten counties of Utah that irrigate from the Colorado River and its tributaries were interviewed. The interviewees were farmers whose focus on agriculture was cattle production, hay production, or both. The farmers interviewed had ranching experience of 15-60 years. The interviewees were contacted by email or phone and depending on the preference, they were either interviewed via phone or were sent the questionnaire by email. The phone interviews took approximately half an hour each. If participants agreed, the interviews were recorded.

The interview protocol was approved by the Utah State University Institutional Review Board (IRB), protocol # 10208. Nine farmers were interviewed in total, 3 from Carbon, 2 from Duchesne and Emery each and 1 from SanJuan and Uintah county. The interviewees were asked questions about their farming practices, whether they have observed any changes in agricultural production in the last three decades and what have been their adaptation practices to cope with the changes. The complete questionnaire is attached as Appendix B. Thematic network analysis (Jennifer, 2001) was used to analyze the interview data.

CHAPTER 4

RESULTS

The first part of this section contains results from trend analysis, correlation test, multilinear regression, and random forest regression that aim to identify the important variables for agricultural production. The second part includes results from the qualitative interview section to investigate the adaptation practices of the ranchers to the climate variability and other factors in the study area.

4.1 Statistical Analysis

From 1981-2015, the mean temperature in the study area has been rising whereas there is no significant change in the trend in total annual precipitation (Figure 3a, 3b). Despite the increasing trend in hay production, there is an overall decrease in cattle production in the thirty-five years studied (Figure 3c, 3d). On some wet years, cattle numbers and hay production is very low and vice versa (Figure 3a, 3c, 3d) which indicates that precipitation alone does not influence agricultural production in the study area. There is a large variance in cattle numbers and hay produced in the region on a wet and dry year. We can find the lower hay production during the extremely low precipitation years of 1989, 2002, and 2012, whereas the extremely high precipitation years, accompany not only higher hay productions in 1997 but also lower or normal productions in 1983, 2010, and 2015. This result suggests that the hay production in UCRB is affected by drought but not during the normal and wet years. In other words, multiple factors including climate and adaptation strategies affect year-to-year variations in hay productions and a number of cattle.

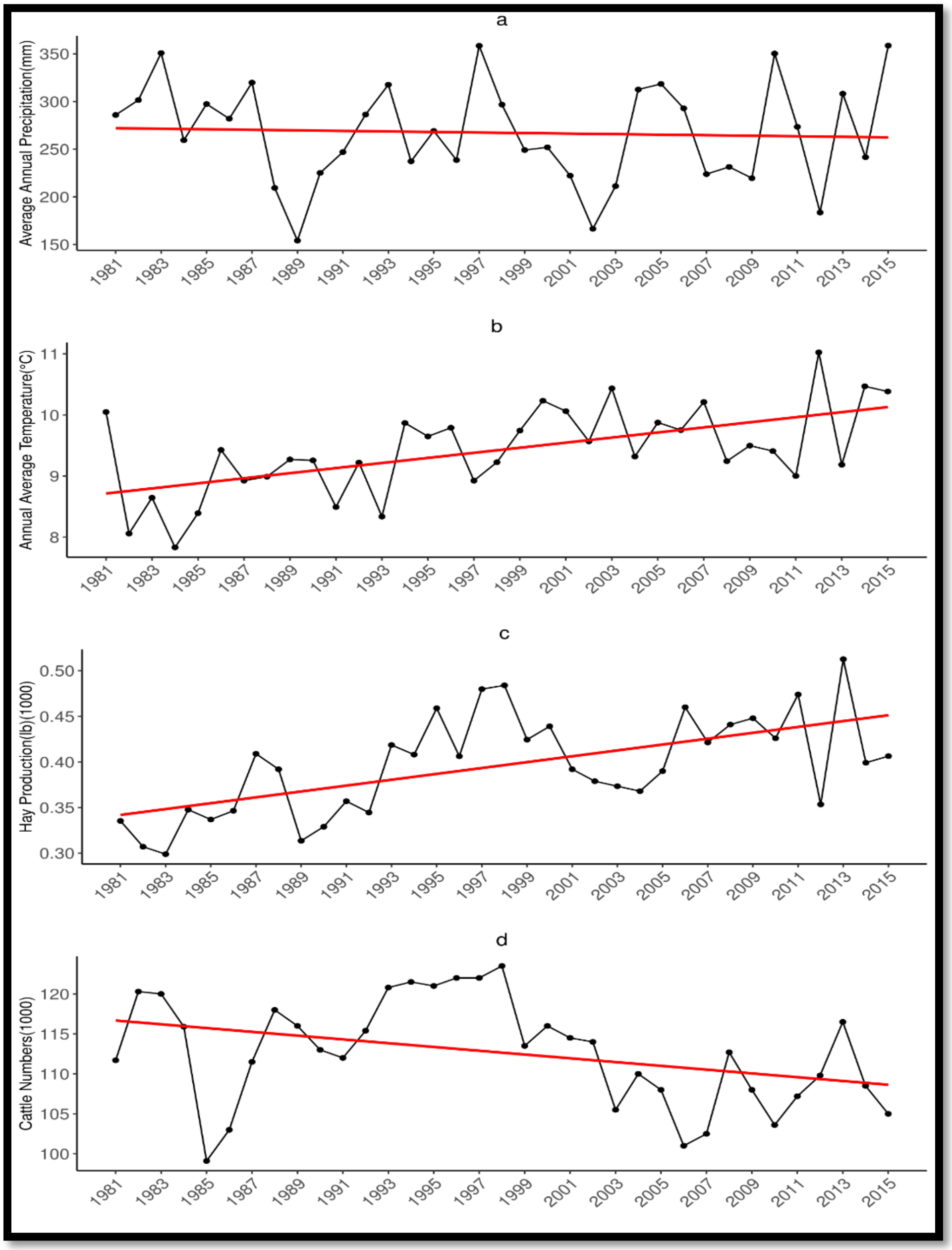

Figure 3: Annual climatic and agricultural production trends in UCRB-Utah region 1981-2015. a) Precipitation b) Mean temperature c) Hay production d) Cattle production

4.1.1 Correlation Test

Overall, hay production shows a weak linear relation with the precipitation whereas cattle production is not influenced by changes in precipitation (Figure 4a, 4c).

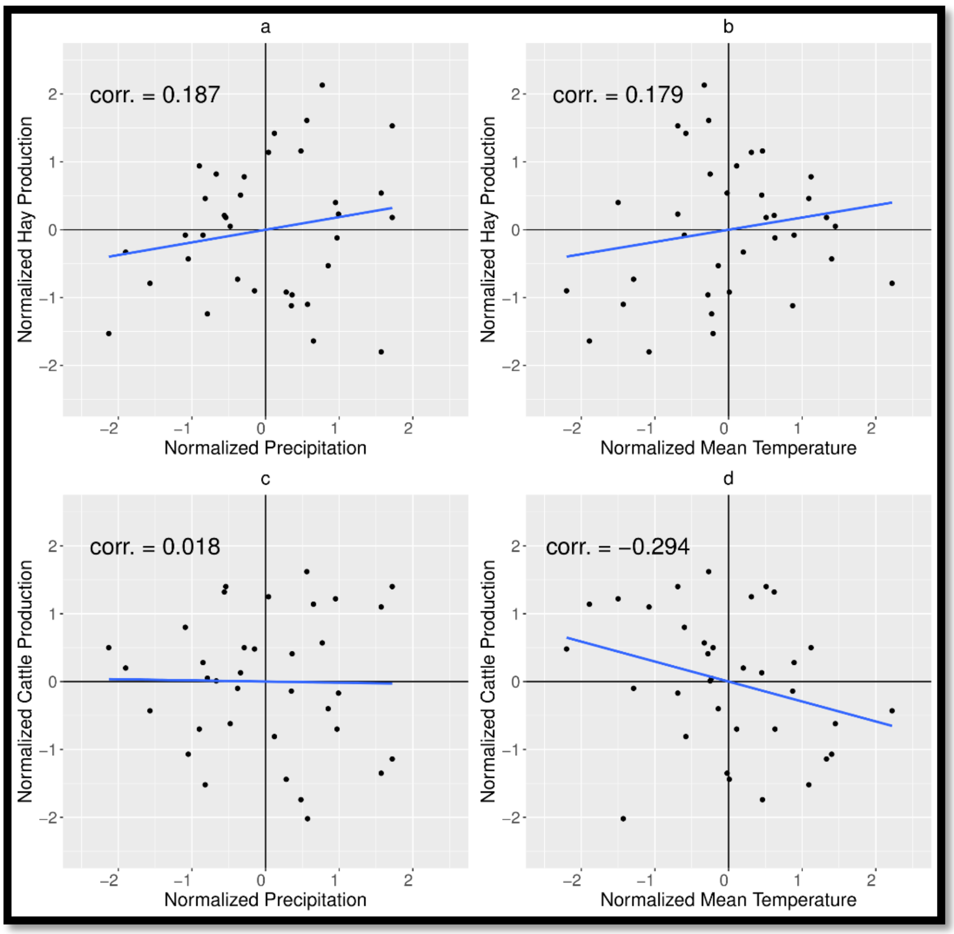

Figure 4: Correlation plots for precipitation and temperature with hay and cattle production with precipitation in UCRB Utah a) Hay production with precipitation b) Hay production with mean temperature c) Cattle production with precipitation d) Cattle production with mean temperature

The mean temperature has a positive linear relation with hay production whereas a negative linear relation with cattle production (Figure 4b, 4d). It means that high temperatures are favorable for hay production, as it provides a longer growing season. Contrary to that, high temperatures correspond to lower cattle numbers. This can be associated with heat stress-induced high mortality rates in cattle.

The results for the Pearson correlation test for the indices and cattle and hay production show that there is a correlation between cattle/ hay production and temperature indices (Figure 5).

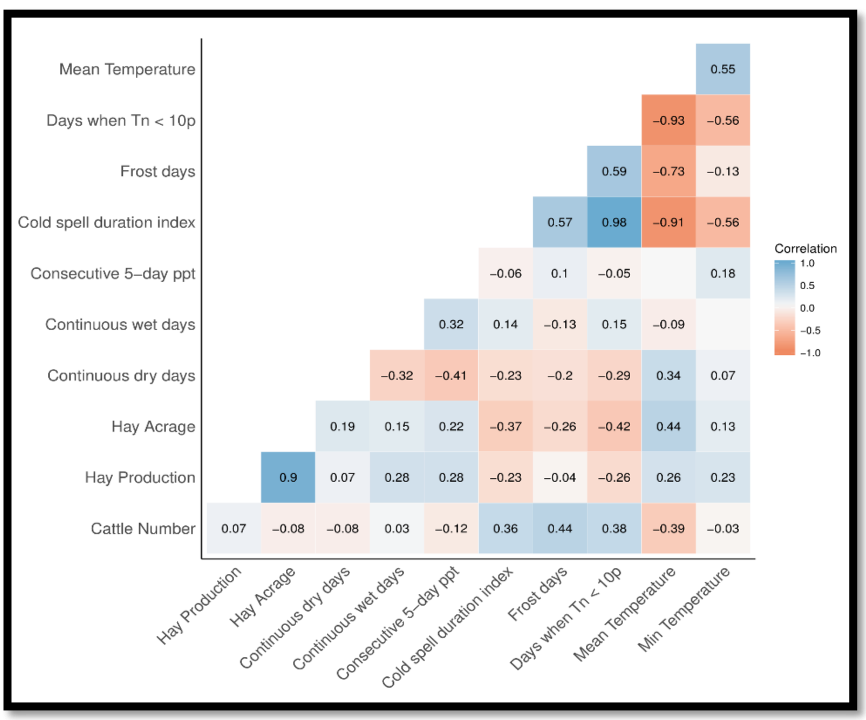

Figure 5: Correlation matrix for climate indices, cattle, and hay

**Correlation coefficient value < 0.01 is not shown in the matrix*

Days with extremely cold temperatures have the strongest positive correlation with cattle production, as shown by the correlation coefficient of 0.44 with frost days (Figure 5). The hay production does not correlate significantly to any temperature or precipitation index but merely on the acreage of hay per year. (Figure 5).

4.1.2 Multilinear Regression

The results from the cattle model suggest that there is no significant relationship between climate indices and cattle production, as indicated by a p-value of 0.08(Table 2). Among the indices used as predictors, frost days are the most important for cattle production (Table 2, Figure 7). For the hay model, the p-value is 6.08e-13 (Table 2), which implies that at least one of the predictor variables is significantly related to hay production. Hay acreage is ranked the most important variable in the hay model as shown by the t-statistic value of 15.019 and 79.74% variance explained (Table 2, Figure 6). This can be explained by the direct relation of the acreage of hay and the overall hay production.

Among the climatic indices, none of the variables are significant for hay production. The accuracy of the model is determined by the R-squared (R^2) value, where the best-fit model would have a value close to 1. Though the hay model has a better fit for linear regression than the cattle model (Table 2), hay acreage alone explains most of the variance in the model. It can be interpreted as that other indices don't contribute to the prediction of the number of cattle.

Table 2: Summary statistics for the results of multilinear regression

Predictor Variables		Hay Model	Cattle Model
		t-statistic	
Hay Production		-	1.12
Hay Acreage		15.019	-1.00
Continuous dry days		-0.28	-0.58
Continuous wet days		2.19	0.84
Frost days		3.11	2.50
Icing days		-2.45	-0.34
Natural Streamflow		0.62	-2.30
Model fit	F statistic	43.67	2.09
	p-value for F statistic	6.08e-13	0.08
Model Accuracy	R^2 value	0.90	0.35
	Adjusted R^2	0.88	0.18

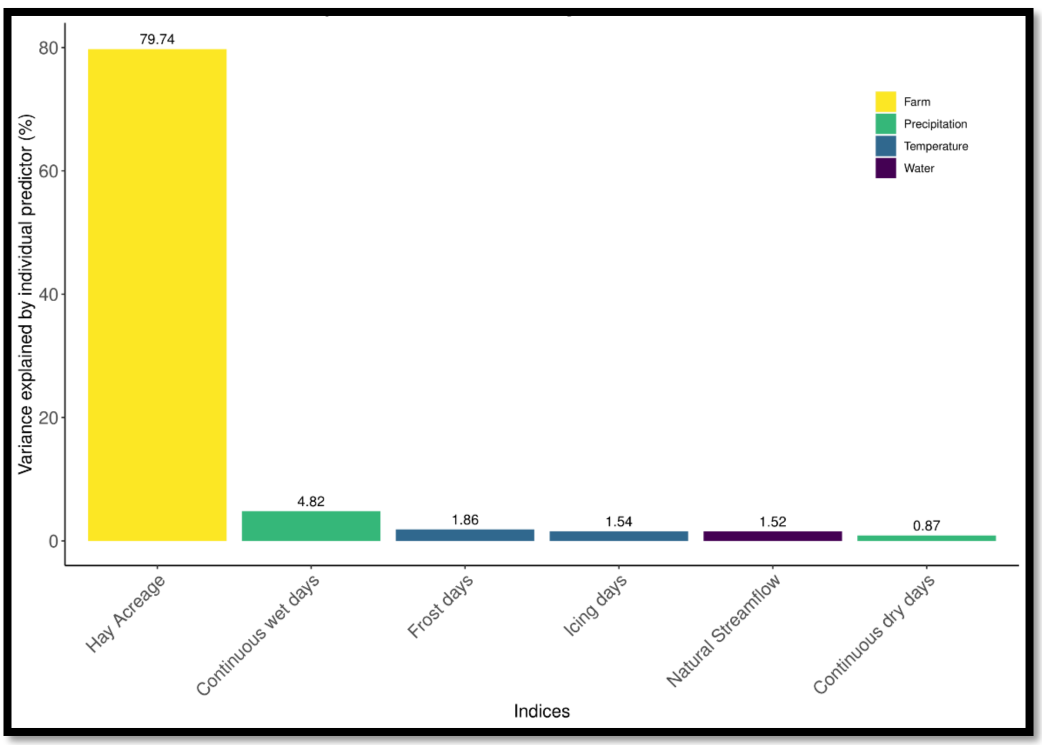

Figure 6: Most Important Climate Indices for Hay Production in UCRB-Utah (MLR)

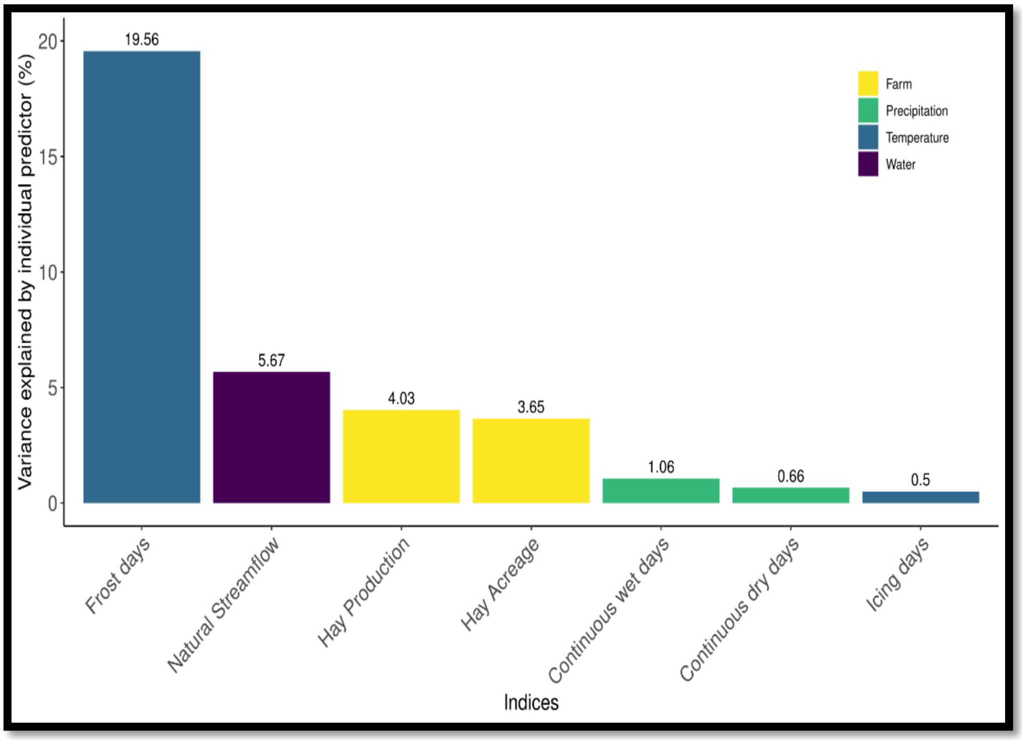

Figure 7: Most Important Climate Indices for Cattle Production in UCRB-Utah (MLR)

4.1.3 Random Forest Regression

The results from the random forest regression show that climatic parameters are more important for hay production than cattle production as the parameters occur more frequently for the model in hay production than for cattle production (Figure 8,9). The index that has the highest frequency of occurrence is considered to have the most influence on cattle or hay production. In the climate indices, the temperature-based indices appear to have more impact on the cattle and hay production in the region (Figure 8,9).

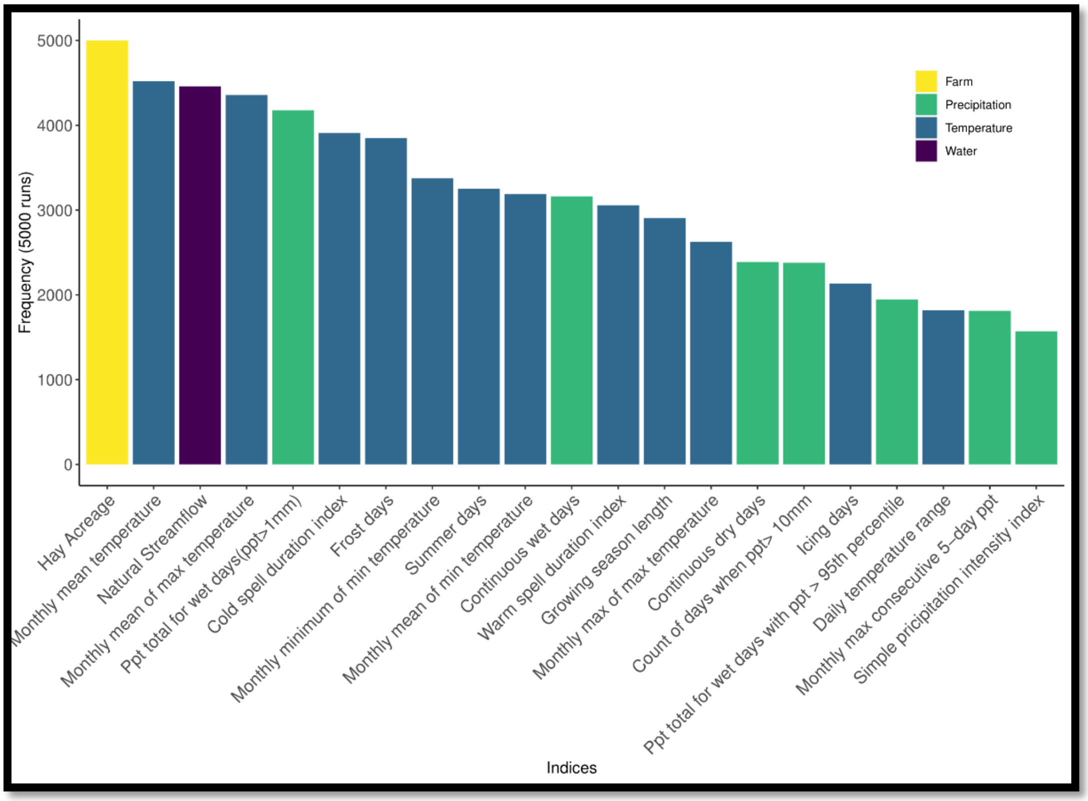

Figure 8: Most Important Climate Indices for Hay Production in UCRB-Utah (RFR)

Apart from the climatic factors, streamflow (water availability) is an important factor in hay production in the region but it is ranked much lower for cattle production (Figure 8,9). This can be explained since cattle production is indirectly related to hay (or crop) production which is directly related to water availability. The acreage of hay does not appear to be important for cattle production (Figure 8,9). We explore this aspect in the interviews to identify other factors in play that can influence cattle production.

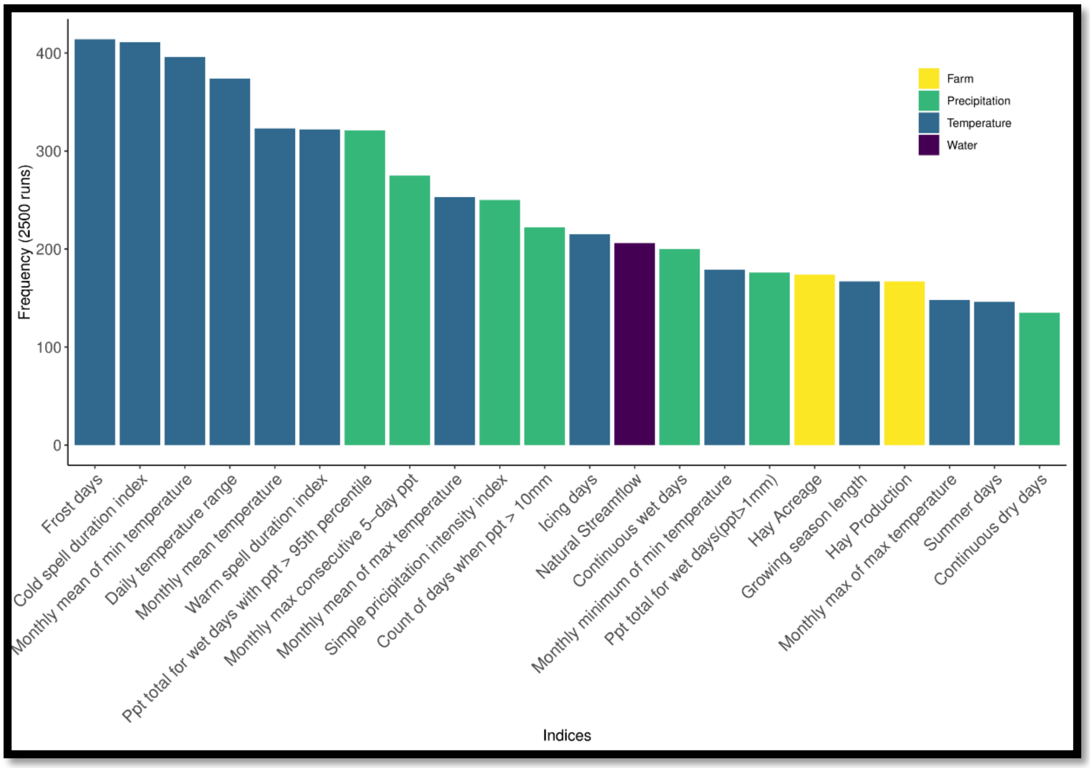

Figure 9: Most Important Climate Indices for Cattle Production in UCRB-Utah (RFR)

4.2 Qualitative Interview Analysis

Thematic analysis identified three organizing themes in the data; the effects of climate variability on cattle and hay production, the most important factors that influence cattle and hay production and the adaptation measures in place and future by the farmers. The network shown below (Figure 10) summarizes the results of the qualitative analysis based on thematic network analysis.

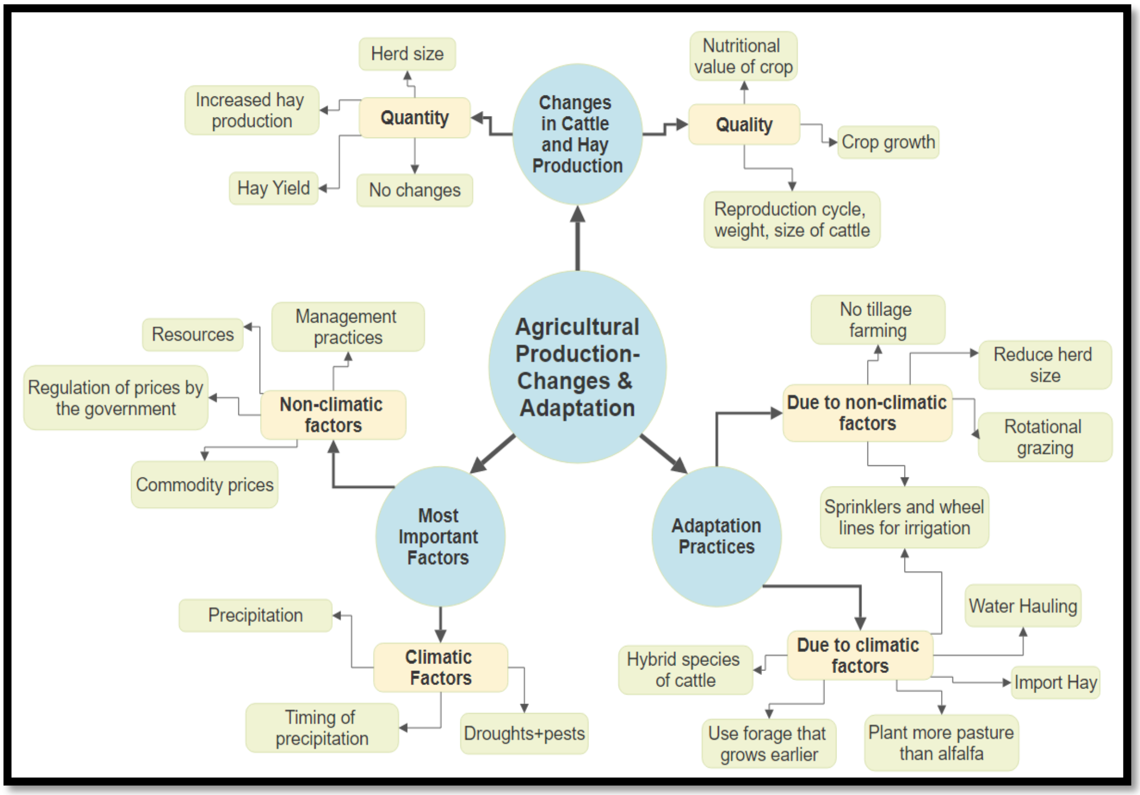

Figure 10: Thematic Network for the interview results with the farmers/ranchers in Upper Colorado River Basin in Utah

4.2.1 Changes in Cattle and Hay Production

This theme summarizes the responses of the farmers where they share their observations on changes in cattle and hay production in the last three decades. Most farmers who we interviewed believe that climate variability has some impact on agricultural production. In terms of forage production, they report that they have seen a decrease in hay amount and yield in dry years in general. The change in yield, apart from climate, is also associated with water supply and restriction on the kind of crop a farmer can irrigate in a year. If the water supply from the reservoir is adequate, even on a dry year, hay crop production is not affected. The quality of forage is also directly tied to the water availability and thus with lack of water with heat stress farmers saw a decreased growth of the hay crop. The water-stressed crop is also prone to pest infestation as farmers note that lack of water reduces the immunity of the plant itself. On wet years (for instance 2019), it is harder to store hay that has been rained on. To avoid this, the farmers would not cut the hay and allow it to grow. As a result, the crop quantity might increase (taller, greener crop) but the nutritional value decreases as there is lesser protein content in the crop. Only one farmer said that the wet or dry year does not affect the quality of hay. A couple of farmers also noted that they have seen an increase in the production of the crop on their farms in the last few decades. This increase in production is mainly due to advancements in methods for farming such as automatic moisture sensors, efficient irrigation systems, fertilizers, mechanization of farms, etc.

The cattle numbers do not change a lot on a wet or dry year, but certain qualitative characteristics change in the cattle. For instance, the reproduction cycle of cattle is affected in dry years. Sometimes the cows are not pregnant in the fall, then the farmer either must sell the cow or feed them through the winter with no expectation of compensation by selling the calves. This is considered an additional burden by the farmers. Though most farmers reported that they have lighter and weaker animals in their herd on dry years as there is not as much forage available for them, a couple of them noted that the cattle adapt to changes more quickly and there are no significant changes.

A farmer who has been in the ranching business for 30 years mentioned that cattle have acclimated to climate changes. This means that since these cattle are born to a mother who was raised on the range, therefore, they have adapted to the changes. When it comes to choosing which animal to keep in the herd, he is biased towards the acclimated cattle and explains this practice because,

"Multi-generation of cattle have an intuition to adapt quicker than the other livestock"

Some farmers believe that although the production of hay and cattle changes year to year depending on whether the year is dry or wet, the overall production in five years or more remains the same. The farmers live from one extreme year to another and hence, do not see a notable change at the decadal scale. A wet year like the water year 2019 (October 2018 – September 2019) makes up for the preceding bad years. They believe it is an ebb and flow as has always existed and cannot be associated with changes in climate.

4.2.2 Most Important Factors

This theme summarizes the responses of farmers where they talk about the most important factors that impact the production on their lands. Most farmers believe that the most important factors that impact the production of hay and cattle in the region are precipitation and the timing of precipitation. In drought years, farmers also have to deal with insect infestations sometimes. In dry years, it is hard for farmers to keep cows on the range for long periods. Moreover, feeding them for around an additional 90 days hurts them financially. However, one farmer notes that climate changes do not have any significant impact on agriculture production on his farm. Changes that occur in the production are normal and inevitable; therefore, they cannot be associated with climate. Changes in the production of hay or cattle can be related to the variability in the water supply on the farms. Most farmers note that the water availability changes year-to-year but for recent decades, the water supply has been less than adequate.

Management practices play a big role in productivity if farmers have the ability to innovate. The farmers who have the resources to maintain a private pasture that can be used in dry years can prioritize which lands need to water based on the water allocation that year. The cattle that are raised on private lands (for the ranchers who have private lands) recover quickly from a dry season. Additionally, if the farmer himself works on the farm instead of hiring labor, he would invest more time and energy into it. Farmers believe that you cannot pay someone enough to care for the crop and cattle the way they do themselves.

Another important aspect of farm operation noted in the interviews is deciding the herd size was that the commodity prices have dropped whereas the overhead costs have increased in the past few years. The regulation in prices by the government does not allow ranchers to get a fair price for their cows and calves. The US imports agricultural imports from other countries like Canada, where the government subsidizes the market. The price of the product (like beef) is much lower which causes the market price of products from the US to be lower thus the farmers must sell the higher quality product at a lower cost than its value. On dry years the calves are lighter, and the farmers get even lower prices per pound. Due to this, it is hard for farmers to maintain viable farm operations. It is also mentioned that free market should be allowed for farmers to get the fair price as the cattle prices set by the government that hurts the local farmer and there is not enough money made on farms in usual years to sustain profitable farm operations; most farmers have a day job to support their families. These changes in prices and not the climatic conditions drive the decision on how many cattle to keep that year.

4.2.3 Adaptation Strategies

The farmers talked about various strategies that they have adopted to maintain their farm operations. Some practices are due to the variability of climate in the region and some of them are due to convenience and other factors that are discussed later in this section. The most quoted practice that has changed over time was using sprinklers and rolling (wheel) lines for irrigation instead of flood irrigation. Although this practice is done primarily due to limited water availability, occasionally it is done because it is more convenient, water-efficient, and reduces labor costs. Hauling water for livestock and buying hay to use as feed were also mentioned as strategies to deal with a shortage of water in dry years. Other practices mentioned in the interviews to preserve land and improve pastures are no-tillage operations and rotational grazing.

To maintain cattle, farmers plant more pasture than alfalfa, so they can bring the cattle to the range earlier. They are also looking into using grain or forage that starts growing earlier. For those who have the resources, they keep the cow on a farm in a dry year and supplement the feed from other sources. In dry years, some farmers keep part of their herd on the private pastures and not on the Bureau of Land Management grazing lands. This strategy is only viable for the farmers with bigger lands and private pastures where they can keep the cattle for at least a season without jeopardizing their health. Most farmers reduce herd size on dry years but do so as a last resort. Farmers also note that they must bring the cattle earlier to the rangelands due to the lack of availability of forage. In addition, they must keep fewer cattle in their herd on a dry year. A farmer with a big ranch in San Juan County noted that they are experimenting with local cattle to get a hybrid breed with Criollo cow that appears to be more adaptable to an arid environment. The hybrid is expected to be smaller cattle that can travel further to water and can use a wider variety of forage. The hybrid is also expected to be more resilient to temperature (than the climatized cattle), however, it would take at least a decade to find out whether the hybrid was a success for Southern Utah landscape and climatic conditions or not.

CHAPTER 5

DISCUSSION AND CONCLUSION

5.1 Discussion

When identifying the relationships between climate and agricultural production, the correlation test found that the climatic parameters and indices tested had correlation coefficient values less than 0.5. This implies that there was not a statistically significant relationship between cattle and hay production and climate. This result is contrary to what was expected and what is presented in previous studies where climatic parameters (temperature and precipitation) have shown a significant impact on the cattle and crop production (Crescio et al., 2010; Henry et al., 2012; Nardone et al., 2010; Ray et al., 2015; Reeves & Bagne, 2016; Rust & Rust, 2013; Vogel et al., 2019). For the 35 years of the analysis, the cattle and hay production in the region does not depend directly on the trends of rainfall and temperature but on the year to the variability of the temperature and precipitation.

The results from the random forest regression show that climatic parameters are more important for hay production than cattle production as the frequency of occurrence of the indices in importance ranking is more for hay production than for cattle production (Figure 8,9). In the climate indices, the temperature-based indices appear to have more impact on the cattle and hay production in the region than precipitation based indices (Figure 8,9). The results also rank streamflow (water availability) high as an important factor in hay production. These results are in parallel to the results of previous studies that in the ongoing post millennium drought, changes in temperature have a more pronounced effect on river flows (hence water availability) (Udall & Overpeck, 2017; Xiao et al., 2018). It implies that temperature changes drive streamflow and by extension the crop production in the region. Streamflow is ranked much lower for cattle which can be explained by the fact that cattle production is related to hay (or crop) production which is directly related to water availability. The acreage of hay does not appear to be important for cattle production (Figure 8,9). We explore this aspect in the interviews to identify other factors in play that can influence cattle production.

The overall hypothesis, that climatic parameters influence hay and cattle production, is shown to be proven wrong as per the quantitative analysis as very few indices seem to have a statistical correlation with agricultural production. The quantitative analysis does not show a distinct pattern or relationship between climate and agriculture on the annual time scale. Due to season-to-season adaptation practices, we do not see any significant changes in cattle and hay numbers at the end of the year. This result was verified by conducting interviews with farmers in the study area. Largely there is a consensus by the farmers that year-to-year variability in temperature and precipitation has a negative impact on the cattle and hay production. Many adaptation techniques were mentioned that included changing irrigation practices and cropping patterns to produce enough forage for the cattle to maintain the number of cattle on the ranches, experimenting to produce hybrid species of cattle, that are resilient to hotter temperature and can use a wider variety of forage. Prior studies show that non-climatic factors are the driving force behind the adaptation and changes in practices for farmers. Many reasons are mentioned for doing so including but not limited to lack of resources, limited market access, (Uddin et al., 2014), local market availability and market prices (Bhatta et al., 2016) and social factors such as social history, social nature of risk management (T. A. Crane et al., 2011; Todd A. Crane et al., 2010). Though the regulation of commodity prices is generally driven by the global market, it has strong impacts on the local economy as farmers indicate. In UCRB in Utah, regulation of prices is one of the biggest factors in affecting farmers' decision to decide on the herd size as well as the kind of crop to plant year by year.

5.2 Limitations and Future Research

The main limitation of this study was data availability. The only source of agricultural data was from NASS, which reports the data on a yearly basis. We were not able to identify at which time of year the NASS surveys are assimilated, this means that the data might be missing for certain parts of the year and the given data may not account for an entire year. The data sets that we could use for all ten counties of Utah in the study were only available for cattle numbers and alfalfa production that is why we used these two parameters for agricultural production. The unpredictability of the random forest model is very high, thus we run the same model for 5000 times to account for the variability in results. More variables that can account for the economic aspect of the agricultural production can be included to bridge the unpredictability.

The impact of the commodity prices on farmers' decision to keep a herd size to a limit should be accounted for as it appears to play a major role in farm operations that can be done using more sophisticated agronomic/economic models. Most farmers and ranchers are well aware of the impact climate has on the production on their farms and ranches but not all of them have the capacity to adapt to the changes. The individual adaptive capacity of a farmer is dependent on many social and economic factors.

5.3 Conclusion

Agriculture is considered as one of the most vulnerable sectors to changes in climate. The warming trends indicate that there would be limited water available in the Colorado River Basin. As agriculture is the biggest consumer of water, it is important to identify and understand how climate affects agricultural practices and how the farmers/ranchers adapt to them. The overall objectives of this study were to understand the different variables that influence agricultural production and how the ranchers in the Upper Colorado River Basin in Utah have been adapting to it. It was hypothesized that variability in climate has a direct impact on cattle and hay production in Utah regions of UCRB. This study used a two-tiered approach in which the relationship between climate and agriculture is investigated using quantitative and qualitative analyses.

Agricultural production is influenced by climatic and non-climatic factors. As shown by the case study of the Upper Colorado river basin in Utah, the variability in climate does impact agricultural production but the farmers have significantly adapted their practices to maintain the productivity on the farms. In the correlations identified, temperature seems to have more influence on cattle and hay production than precipitation. Non- climatic factors have more influence on agricultural production in the study area as compared to climatic parameters studied. Since quantitative analysis does not identify any correlation, trends or influence of climatic indices on cattle and hay production, interviews were conducted to get a deeper insight into the climate-agriculture relationship. The results from interviews were summarized using thematic analysis which explains the gaps in the results of quantitative data analysis. They also give an insight into farmers' perception of the changes in climate, and its effects on their individual farms and ranches. The results also highlight that farmers are well aware of the changes and adaptation to climate and non-climatic influences is not new to the farmers. The most quoted adaptation practices are changing irrigation systems, crop rotation, bringing cattle to pastures earlier and as a last resort; reducing herd size.

DATA AVAILABILITY AND REPRODUCIBLE RESULTS

The data and code for the figures in the quantitative analysis are present in hydroshare repository and can be accessed at http://www.hydroshare.org/resource/b984a0cb5fc34a329240b4eea2402373. The data for the interviews cannot be made available due to the privacy of the interviewed ranchers.

Emily Wilkins (Utah State University) downloaded and ran all the R scripts and reproduced the results in the figures in the quantitative section of this study.

REFERENCES

Abid, M., Schilling, J., Scheffran, J., & Zulfiqar, F. (2016). Climate change vulnerability, adaptation and risk perceptions at farm level in Punjab, Pakistan. *Science of the Total Environment*, *547*, 447–460. https://doi.org/10.1016/j.scitotenv.2015.11.125

Adams, R. M., Hurd, B. H., Lenhart, S., & Leary, N. (1998). Effects of global climate change on agriculture: An interpretative review. *Climate Research*, *11*(1), 19–30.

Alexander, L., & Herold, N. (2016). ClimPACT2-Indices and software, (February), 46.

Arendse, A., & Crane, T. A. (2010). *Impacts of climate change on smallholder farmers in Africa and their adaptation strategies: What are the roles for research? International Symposium and Consultation (29-31 March, 2010, Arusha, Tanzania)*.

Bammes, D. (2015). Hay! One Crop is Utah's Biggest Water Consumer. Retrieved from http://www.utahfoundation.org/2015/05/hay-one-crop-is-utahs-biggest-water-consumer/

Belnap, J., & Campbell, D. H. (2011). Effects of Climate Change and Land Use on Water Resources in the Upper Colorado River Basin. USGS.

Bhatta, G. D., Aggarwal, P. K., Kristjanson, P., & Shrivastava, A. K. (2016). Climatic and non-climatic factors influencing changing agricultural practices across different rainfall regimes in South Asia. *Current Science*, *110*(7), 1272–1281. https://doi.org/10.18520/cs/v110/i7/1272-1281

Bhattarai, M. D., Secchi, S., & Schoof, J. (2017). Projecting corn and soybeans yields under climate change in a Corn Belt watershed. *Agricultural Systems*, *152*, 90–99. https://doi.org/10.1016/j.agsy.2016.12.013

Bird, D. N., Benabdallah, S., Gouda, N., Hummel, F., Koeberl, J., La Jeunesse, I., … Woess-Gallasch, S. (2016). Modelling climate change impacts on and adaptation strategies for agriculture in Sardinia and Tunisia using AquaCrop and value-at-risk. *Science of the Total Environment*, *543*, 1019–1027. https://doi.org/10.1016/j.scitotenv.2015.07.035

Birthal, P. S., Khan, M. T., Negi, D. S., & Agarwal, S. (2014). Impact of Climate Change on Yields of Major Food Crops in India: Implications for Food Security. *Agricultural Economics Research Review*, *27*(2), 145–155. https://doi.org/10.5958/0974-0279.2014.00019.6

Breiman, L. (1996). Bagging predictors. *Machine Learning*, *24*(2), 123–140. https://doi.org/10.1007/BF00058655

Breiman, L. (2001). Random forests. *Machine Learning*, *45*(1), 5–32. https://doi.org/10.1017/CBO9781107415324.004

Bureau of Reclamation. (2011). Colorado River Basin Water Supply and Demand Study. *Colorado River Basin Water Supply and Demand Study*, (June).

Bureau of Reclamation. (2012). Colorado River Basin Water Supply and Demand Study-Executive Summary. *Reclamation: Managing Water in the West*, (December), 34.

Bureau of Reclamation. (2019). Colorado River Basin Natural Flow and Salt Data. Retrieved April 4, 2019, from https://www.usbr.gov/lc/region/g4000/NaturalFlow/

Cayan, D. R., Das, T., Pierce, D. W., Barnett, T. P., Tyree, M., & Gershunov, A. (2010). Future dryness in the southwest US and the hydrology of the early 21st century drought. *Proceedings of the National Academy of Sciences*, *107*(50), 21271–21276. https://doi.org/10.1073/pnas.0912391107

Christensen, N., & Lettenmaier, D. P. (2007). A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. *Hydrology and Earth System Sciences Discussions*, *3*, 3727–3770.

Christensen, N. S., Wood, A. W., Voisin, N., Lettenmaier, D. P., & Palmer, R. N. (2004). The effects of climate change on the hydrology and water resources of the Colorado River basin. *Climatic Change*, *62*(1–3), 337–363. https://doi.org/10.1023/B:CLIM.0000013684.13621.1f

Clow, D. W. (2010). Changes in the timing of snowmelt and streamflow in Colorado: A response to recent warming. *Journal of Climate*, *23*(9), 2293–2306. https://doi.org/10.1175/2009JCLI2951.1

Cohen, M., Christian-Smith, J., & John, B. (2013). *Water Supply to the Land*. Retrieved from http://water.usgs.gov/watercensus/colorado.html

Colloff, M. J., Martín-López, B., Lavorel, S., Locatelli, B., Gorddard, R., Longaretti, P. Y., … Murphy, H. T. (2017). An integrative research framework for enabling transformative adaptation. *Environmental Science and Policy*, *68*, 87–96. https://doi.org/10.1016/j.envsci.2016.11.007

Cootes, T. F., Ionita, M. C., Lindner, C., & Sauer, P. (2012). Robust and accurate shape model fitting using random forest regression voting. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *7578 LNCS*(PART 7), 278–291. https://doi.org/10.1007/978-3-642-33786-4_21

Crane, T. A., Roncoli, C., & Hoogenboom, G. (2011). Adaptation to climate change and climate variability: The importance of understanding agriculture as performance. *NJAS - Wageningen Journal of Life Sciences*, *57*(3–4), 179–185. https://doi.org/10.1016/j.njas.2010.11.002

Crane, Todd A., Roncoli, C., Paz, J., Breuer, N., Broad, K., Ingram, K. T., & Hoogenboom, G. (2010). Forecast skill and farmers' skills: Seasonal climate forecasts and agricultural risk management in the southeastern United States. *Weather, Climate, and Society*, *2*(1), 44–59. https://doi.org/10.1175/2009WCAS1006.1

Crescio, M. I., Forastiere, F., Maurella, C., Ingravalle, F., & Ru, G. (2010). Heat-related mortality in dairy cattle: A case crossover study. *Preventive Veterinary Medicine*, *97*(3–4), 191–197. https://doi.org/10.1016/j.prevetmed.2010.09.004

Das, T., Pierce, D. W., Cayan, D. R., Vano, J. A., & Lettenmaier, D. P. (2011). The importance of warm season warming to western U.S. streamflow changes. *Geophysical Research Letters*, *38*(23), 1–5. https://doi.org/10.1029/2011GL049660

Dawadi, S., & Ahmad, S. (2012). Changing climatic conditions in the Colorado River Basin: Implications for water resources management. *Journal of Hydrology*, *430–431*, 127–141. https://doi.org/10.1016/j.jhydrol.2012.02.010

Gauly, M., Bollwein, H., Breves, G., Brügemann, K., Dänicke, S., Daş, G., … Wrenzycki, C. (2013). Future consequences and challenges for dairy cow production systems arising from climate change in Central Europe - A review. *Animal*, *7*(5), 843–859. https://doi.org/10.1017/S1751731112002352

Grömping, U. (2009). Variable importance assessment in regression: Linear regression versus random forest. *American Statistician*, *63*(4), 308–319. https://doi.org/10.1198/tast.2009.08199

Hamlet, A. F., Mote, P. W., Clark, M. P., & Lettenmaier, D. P. (2007). Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States. *Journal of Climate*, *20*(8), 1468–1486. https://doi.org/10.1175/JCLI4051.1

Hansen, P. J. (2009). Effects of heat stress on mammalian reproduction. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1534), 3341–3350. https://doi.org/10.1098/rstb.2009.0131

Hengl, T., Heuvelink, G. B. M., Kempen, B., Leenaars, J. G. B., Walsh, M. G., Shepherd, K. D., … Tondoh, J. E. (2015). Mapping soil properties of Africa at 250 m resolution: Random forests significantly improve current predictions. *PLoS ONE*, *10*(6), 1–26. https://doi.org/10.1371/journal.pone.0125814

Henry, B., Charmley, E., Eckard, R., Gaughan, J. B., & Hegarty, R. (2012). Livestock production in a changing climate: adaptation and mitigation research in Australia. *Crop & Pasture Science*, *63*(3), 191–202. https://doi.org/Doi 10.1071/Cp11169

Hoerling, M., & Jon, E. (2007). Past Peak Water in Southweast. *Southwest Hydrology*, *4*.

Hoffmann, U. (2013). Section B: Agriculture: a key driver and a major victim of global warming. In *Key Development Challenges of a Fundamental Transformation of Agriculture* (pp. 3–5).

Howden, S. M., Soussana, J.-F. J.-F., Tubiello, F. N., Chhetri, N., Dunlop, M., & Meinke, H. (2007). Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences*, *104*(50), 19691 LP – 19696. https://doi.org/10.1073/pnas.0701890104

Jennifer, A.-S. (2001). Thematic networks: an analytic tool for qualitative research. *Qualitative Research*, *1*(3), 385–405. https://doi.org/10.1039/C5EN00171D

Kang, Y., Khan, S., & Ma, X. (2009). Climate change impacts on crop yield, crop water productivity and food security - A review. *Progress in Natural Science*, *19*(12), 1665–1674. https://doi.org/10.1016/j.pnsc.2009.08.001

Key, N., & Sneeringer, S. (2014). Potential effects of climate change on the productivity of U.S. dairies. *American Journal of Agricultural Economics*, *96*(4), 1136–1156. https://doi.org/10.1093/ajae/aau002

Kikoyo, D. A., & Nobert, J. (2016). Assessment of impact of climate change and adaptation strategies on maize production in Uganda. *Physics and Chemistry of the Earth*, *93*, 37–45. https://doi.org/10.1016/j.pce.2015.09.005

Lehmann, N. (2011). Regional Crop Modeling: How Future Climate May Impact Crop Yields in Switzerland. *YSA*, 269–291.

Li, X., Takahashi, T., Suzuki, N., & Kaiser, H. M. (2011). The impact of climate change on maize yields in the United States and China. *Agricultural Systems*, *104*(4), 348–353. https://doi.org/10.1016/j.agsy.2010.12.006

Liaw, A., & Wiener, M. (2002). Classification and Regression by randomForest. *R News*, *2*(December), 18–22. https://doi.org/10.1177/154405910408300516

McCabe, G. J., & Wolock, D. M. (2007). Warming may create substantial water supply shortages in the Colorado River basin. *Geophysical Research Letters*, *34*(22), 1–5. https://doi.org/10.1029/2007GL031764

McCarthy, N., Lipper, L., & Branca, G. (2011). *Climate-Smart Agriculture : Smallholder*

Adoption and Implications for Climate Change Adaptation and Mitigation. *Mitigation of Climate Change in Agriculture Working Paper 3*.

McMurrray, C. (2012). *The Colorado River Basin and Climate : Perfect Storm for the Twenty-First Century ?*

Mendelsohn, R., & Dinar, A. (1999). Climate change, agriculture, and developing countries: Does adaptation matter? *World Bank Research Observer*, *14*(2), 277–293. https://doi.org/10.1093/wbro/14.2.277

Nardone, A., Ronchi, B., Lacetera, N., Ranieri, M. S., & Bernabucci, U. (2010). Effects of climate changes on animal production and sustainability of livestock systems. *Livestock Science*, *130*(1–3), 57–69. https://doi.org/10.1016/j.livsci.2010.02.011

Ok, A. O., Akar, O., & Gungor, O. (2012). Evaluation of random forest method for agricultural crop classification. *European Journal of Remote Sensing*, *45*(1), 421–432. https://doi.org/10.5721/EuJRS20124535

Pal, M. (2005). Random forest classifier for remote sensing classification. *International Journal of Remote Sensing*, *26*(1), 217–222. https://doi.org/10.1080/01431160412331269698

Pang, B., Yue, J., Zhao, G., & Xu, Z. (2017). Statistical Downscaling of Temperature with the Random Forest Model. *Advances in Meteorology*, *2017*.

PRISM Climate Group. (2018). Parameter-elevation Regressions on Independent Slopes Model. Retrieved from http://www.prism.oregonstate.edu/recent/

Ray, D. K., Gerber, J. S., Macdonald, G. K., & West, P. C. (2015). Climate variation explains a third of global crop yield variability. *Nature Communications*, *6*, 1–9. https://doi.org/10.1038/ncomms6989

Ray, D. K., West, P. C., Clark, M., Prischepov, A. V., & Chatterjee, S. (2019). Climate change has likely already affected global food production. *PLoS ONE*, *14*(5). https://doi.org/10.1038/ncomms6989

Reeves, M. C., & Bagne, K. E. (2016). Vulnerability of cattle production to climate change on U.S. rangelands, (May), 39.

Richards, P. (1993). Cultivation : knowledge or performance ? In *An anthropological critique of development: the growth of ignorance.* (pp. 61–78).

Rickards, L., & Howden, S. M. (2012). Transformational adaptation: Agriculture and climate change. *Crop and Pasture Science*, *63*(3), 240–250. https://doi.org/10.1071/CP11172

Rippke, U., Ramirez-Villegas, J., Jarvis, A., Vermeulen, S. J., Parker, L., Mer, F., … Howden, M. (2016). Timescales of transformational climate change adaptation in sub-Saharan African agriculture. *Nature Climate Change*, *6*, 605. Retrieved from https://doi.org/10.1038/nclimate2947

Rojas-Downing, M. M., Nejadhashemi, A. P., Harrigan, T., & Woznicki, S. A. (2017). Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, *16*, 145–163. https://doi.org/10.1016/j.crm.2017.02.001

Rust, J., & Rust, T. (2013). Climate change and livestock production: A review with emphasis on Africa. *South African Journal of Animal Science*, *43*(3), 255. https://doi.org/10.4314/sajas.v43i3.3

Salvo, D. (2013). Measuring the effect of climate change on agriculture: A literature review of analytical models. *Journal of Development and Agricultural Economics*, *5*(12), 499–509. https://doi.org/10.5897/JDAE2013.0519

Schlenker, W., & Roberts, M. J. (2008). *Estimating the Impact of Climate Change on Crop Yields : The importance of nonlinear temperature effects*. *NBER Working Paper Series*.

Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., … Naik, N. (2007). Model projections of an imminent transition to a more arid climate in southwesterna North America. *Science*, *316*(May), 1181–1184.

Smit, B., & Skinner, M. W. (2002). Adaptation options in agriculture to climate change: A typology. *Mitigation and Adaptation Strategies for Global Change*, *7*(1), 85–114. https://doi.org/10.1023/A:1015862228270

St-Pierre, N. R., Cobanov, B., & Schnitkey, G. (2003). Economic Losses from Heat Stress by US Livestock Industries. *Journal of Dairy Science*, *86*(31), E52–E77. https://doi.org/10.3168/jds.S0022-0302(03)74040-5

Thornton, P. K., van de Steeg, J., Notenbaert, A., & Herrero, M. (2009). The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agricultural Systems*, *101*(3), 113–127. https://doi.org/10.1016/j.agsy.2009.05.002

Topp, C. F. E., & Doyle, C. J. (1996). Simulating the impact of global warming on milk and forage production in Scotland: 1. The effects on dry-matter yield of grass and grass-white clover swards. *Agricultural Systems*, *52*(2–3), 213–242. https://doi.org/10.1016/0308-521X(96)00010-8

Udall, B., & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research*, *53*(3), 2404–2418.

https://doi.org/10.1002/2016WR019638

Uddin, M. N., Bokelmann, W., & Entsminger, J. S. (2014). Factors Affecting Farmers' Adaptation Strategies to Environmental Degradation and Climate Change Effects: A Farm Level Study in Bangladesh. *Climate*, *2*(4), 223–241. https://doi.org/10.3390/cli2040223

USDA. (2018). National Agricultural Statistics Service. Retrieved from https://quickstats.nass.usda.gov/

Vano, J. A., Das, T., & Lettenmaier, D. P. (2012). Hydrologic Sensitivities of Colorado River Runoff to Changes in Precipitation and Temperature*. *Journal of Hydrometeorology*, *13*(3), 932–949. https://doi.org/10.1175/JHM-D-11-069.1

Vogel, E., Donat, M. G., Alexander, L. V, Meinshausen, M., Ray, D. K., Karoly, D., … Frieler, K. (2019). The effects of climate extremes on global agricultural yields. *Environmental Research Letters*, *14*(5), 054010.

Wang, X. L. (2008a). Accounting for autocorrelation in detecting mean shifts in climate data series using the penalized maximal t or F test. *Journal of Applied Meteorology and Climatology*, *47*(9), 2423–2444. https://doi.org/10.1175/2008JAMC1741.1

Wang, X. L. (2008b). Penalized maximal F test for detecting undocumented mean shift without trend change. *Journal of Atmospheric and Oceanic Technology*, *25*(3), 368–384. https://doi.org/10.1175/2007JTECHA982.1

Wang, X. L., Chen, H., Wu, Y., Feng, Y., & Pu, Q. (2012). New techniques for detection and adjustment of shifts in daily precipitation data series. *Journal of Applied Meteorology and Climatology*, *4*(12), 1–51. https://doi.org/10.1175/2010JAMC2376.1

Wang, X. L., & Feng, Y. (2013a). RHtests_dlyPrcp User Manual. Climate Research Division, Atmospheric Science and Technology Directorate, Science and Technology Branch, Environment Canada. Retrieved from http://etccdi.pacificclimate.org/software.shtml

Wang, X. L., & Feng, Y. (2013b). RHtestsV4 User Manual. Climate Research Division, Atmospheric Science and Technology Directorate, Science and Technology Branch, Environment Canad. Retrieved from http://etccdi.pacificclimate.org/software.shtm

Wang, X. L., Wen, Q. H., & Wu, Y. (2007). Penalized maximal t test for detecting undocumented mean change in climate data series. *Journal of Applied Meteorology and Climatology*, *46*(6), 916–931. https://doi.org/10.1175/JAM2504.1

Ward, R. A., & Paul, M. J. (2013). The Economic Contribution of Agriculture to the Utah

Economy in 2011, (October), 1–10. Retrieved from http://www.ag.utah/documents/Economic Contribution of Agriculture to the Utah Economy 2014.pdf

Ward, R. A., & Salisbury, K. (2016). The Economic Contribution of Agriculture to the Utah Economy in 2014, (October), 1–10. Retrieved from http://www.ag.utah/documents/Economic Contribution of Agriclture to the Utah Economy 2014.pdf

Wehner, M. F., Arnold, J. R., Knutson, T., Kunkel, K. E., & LeGrande, A. N. (2017). Droughts, floods, and wildfires. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)] (pp. 231–256). https://doi.org/10.7930/J0CJ8BNN

Xiao, M., Udall, B., & Lettenmaier, D. P. (2018). On the causes of declining Colorado River streamflows. *Water Resources Research*, *2*, 1–18. https://doi.org/10.1029/2018WR023153

Yohannes, H. (2015). A Review on Relationship between Climate Change and Agriculture. *Journal of Earth Science & Climatic Change*, *07*(02). https://doi.org/10.4172/2157-7617.1000335

Zhang, X., Alexander, L., Hegerl, G. C., Jones, P., Tank, A. K., Peterson, T. C., … Zwiers, F. W. (2011). Indices for monitoring changes in extremes based on daily temperature and precipitation data. *Wiley Interdisciplinary Reviews: Climate Change*, *2*(6), 851–870. https://doi.org/10.1002/wcc.147

APPENDICES

APPENDIX A. LIST OF CLIMATE INDICES

Table A: List of Climate Indices

Variables	Unit	Name	Definition
Harvest	Acres	Acreage of Hay planted/year	Number of acres of hay planted each year
Prod	Lb	Annual production of hay (lbs.)	The total amount of hay produced each year
Cattle	Number	Number of cattle produced annually	Total number of cattle kept on farm/ranches each year
Cdd	Days	Continuous dry days	The maximum length of dry spell: maximum number of consecutive days with precipitation < 1mm
Csdi	Days	Cold spell duration index	The annual count of days with at least 6 consecutive days when TN < 10th percentile
Cwd	Days	Continuous wet days	The maximum length of wet spell: maximum number of consecutive days with precipitation > 1mm
Dtr	⁰C	Daily temperature range	Monthly mean of the difference between daily max temperature (Tx) and daily min temperature (Tn)
Fd	Days	Frost Days	The annual count of days when Tn (daily minimum temperature) < 0°C.
SFlow	m^3/sec	Natural streamflow	Streamflow in absence of reservoir storage on the river but all the other consumptive uses being met
Gsl	Days	Growing season length	Count between the first span of at least 6 days with daily mean temperature >5°C and first span after July 1st (Jan 1st in SH) of 6 days with <5°C.
Id	Days	Number of icing days	The annual count of days when Tx (daily maximum temperature) < 0°C.
Ppt	mm	Annual total precipitation in wet days (ppt > 1mm)	Total annual precipitation for the days where precipitation exceeds 1 mm.
r5day	mm	Monthly maximum of consecutive 5-day precipitation	Monthly maximum of consecutive 5-day precipitation total
r10	Days	The annual count of days when ppt ≥ 10mm	Extremely wet days: The annual count of days when precipitation is greater than or equal to 10 mm.

Variables	Unit	Name	Definition
r95p	mm	Annual total ppt when ppt > 95p	Annual total precipitation of days when precipitation is more than 95 percentile.
Sdii	mm/day	Simple precipitation intensity index	The intensity of the rainfall in wet days (Sum of ppt on wet days/number of wet days)
Su	Days	Number of summer days	The annual count of days when TX (daily maximum temperature) > 25ºC.
Tmm	ºC	The monthly mean value of daily mean temperature	The monthly mean value of daily mean temperature
Tnm	ºC	The monthly minimum value of daily mean temperature	The monthly minimum value of daily mean temperature
Tnn	ºC	The monthly minimum value of daily minimum temperature	The monthly minimum value of daily minimum temperature
Txm	ºC	The monthly maximum value of daily mean temperature	The monthly maximum value of daily mean temperature
Txx	ºC	The monthly maximum value of daily maximum temperature	The monthly maximum value of daily maximum temperature:
Wsdi	Days	Warm spell duration index	The annual count of days with at least 6 consecutive days when Tx > 90th percentile

APPENDIX B. QUESTIONNAIRE FOR INTERVIEWS

IMPACTS OF CLIMATE VARIABILITY ON AGRICULTURE IN UTAH

LIST OF QUESTIONS FOR INTERVIEW

This interview is a part of research to understand the impacts of changes in climate on agriculture in Utah. It has been observed that over the past three-decade temperature in Utah has risen with a decrease in precipitation. We are exploring how these changes have influenced the agricultural production in Utah and how ranchers have adapted to these changes.

A. Background

1. Please state your name and the county of Utah in which you have your farm/ranch
2. How long have you been associated with agriculture?
3. For the purposes of our research, we are interested in irrigated forage and cattle production in agriculture. What is the primary focus of your agriculture among the two?
4. What is the source of your irrigation water (direct streamflow, storage, and/or groundwater)?
5. Is your land situated at the main stem or a tributary of Colorado River, Green River or San Juan River?

B. Agricultural Production

1. What changes have you observed in agricultural production over the years?
2. In your opinion, what are the most important factors that impact agricultural production?
3. [If not mentioned previously].
   In your observation, how do annual temperature and precipitation variability influence your agricultural production?

4. How does your farm irrigation water supply change in a wet, dry, hotter, or cooler year?

5. [If not mentioned previously].
Do differences in precipitation and temperature affect the health, weight, reproduction rate of your livestock?

6. Do you change your herd size based on a wet or dry year?

7. [If not mentioned previously].
Do differences in precipitation and temperature affect the quality of the irrigated forage?

8. Does the irrigated forage yield change in a dry and wet year?

9. How have you changed your practices overtime to maintain the productivity of agriculture at your land?

C. Concluding

1. Would you like to be identified in the research?

2. Would you be able to provide details of another farmer who might be interested to participate?