

Article

Historical Trends in New Mexico Forage Crop Production in Relation to Climate, Energy, and Rangelands

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Abstract: This study was conducted within the context of providing an improved understanding of New Mexico's food, energy, water systems (FEWS) and their behavior under variable climate and socioeconomic conditions. The goal of this paper was to characterize the relationships between production and prices of some forage crops (hay, grain sorghum, and corn) that can be used as feed supplements for beef cattle production and the potential impacts from a changing climate (precipitation, temperature) and energy inputs (crude oil production and prices). The analysis was based on 60 years of data (1958–2017) using generalized autoregressive conditional heteroscedasticity models. Hay production showed a declining trend since 2000 and in 2017, it dropped by ~33% compared to that of 2000. Crude oil production ($R^2 = 0.83$) and beef cattle population ($R^2 = 0.85$) were negatively correlated with hay production. A moderate declining trend in mean annual hay prices was also observed. Mean annual range conditions ($R^2 = 0.60$) was negatively correlated with mean annual hay prices, whereas mean annual crude oil prices ($R^2 = 0.48$) showed a positive relationship. Grain sorghum production showed a consistent declining trend since 1971 and in 2017, it dropped by ~91% compared to that of 1971. Mean annual temperature ($R^2 = 0.58$) was negatively correlated with grain sorghum production, while beef cattle population ($R^2 = 0.61$) and range conditions ($R^2 = 0.51$) showed positive linear relationships. Mean annual grain sorghum prices decreased since the peak of 1974 and in 2017, they dropped by ~77% compared to those of 1974. Crude oil prices ($R^2 = 0.72$) and beef cattle population ($R^2 = 0.73$) were positively correlated with mean annual grain sorghum prices. Corn production in 2017 dropped by ~61% compared to the peak that occurred in 1999. Crude oil production ($R^2 = 0.85$) and beef cattle population ($R^2 = 0.86$) were negatively correlated with corn production. Mean annual corn prices showed a declining trend since 1974 and in 2017, they dropped by ~75% compared to those of 1974. Mean annual corn prices were positively correlated with mean annual precipitation ($R^2 = 0.83$) and negatively correlated with crude oil production ($R^2 = 0.84$). These findings can particularly help in developing a more holistic model that integrates FEWS components to explain their response to internal (i.e., management practices) and external (i.e., environmental) stressors. Such holistic modeling can further inform the development and adoption of more sustainable production and resource use practices.

Keywords: hay; corn; and grain sorghum; crude oil production and prices; precipitation and temperature; beef cattle production and prices; New Mexico

1. Introduction

World rangelands and pasturelands play an important role in meeting food needs of an increasing human population [1]. It is expected that the world human population, now at 7.7 billion, will reach nine to ten billion by 2050 [2,3]. Most of the growth in human population over the next 30 years will occur in African countries. About 16% of human food needs are provided by rangelands and pasturelands, while 77% are provided by farmlands and 7% by the oceans [1,2]. Rangelands, as defined by [4], comprise ~70% of the world's land area and include natural grasslands, deserts, temperate forests, and tropical forests. Roughly rangelands and pasturelands provide about 80% to 85% of the feed needs of domestic livestock worldwide. In African countries, rangelands provide over 85% of the feed needs of domestic livestock, while in the United States (US), their contribution is about 50% to 65% [1,4]. We note that based on data from the National Oceanic Atmospheric Administration (NOAA), the National Aeronautics Space Administration (NASA), and the World Meteorological Organization (WMO) that climate change is accelerating and that the 2010's were the hottest decade on record [5]. The last five years of the 2010's stand out as much warmer than anything previously documented. Consequently, concerns are growing that climate change will adversely impact world food production through heat waves, massive droughts, loss of mountain glaciers that are the sources of major rivers, and increased crop losses to diseases and insects [2,6,7]. Evidently, the US is not so different when it comes to these global concerns [8]. Recent studies from New Mexico (NM) (~92% rangeland [9,10]) in the southwestern US, indicate that climate change may have reduced rangeland carrying capacity by as much as 30% over the last 30 years [11,12]. New Mexico, because of its mid-latitude position and diversity of rangeland types, is considered a good indicator for what may happen on arid and semi-arid rangelands in many other parts of the world [11]. Although direct loss of grazing capacity is a major climate change threat to rangeland livestock production, impacts on livestock feed supplements based on forage crops is also of concern as they play a key role in supporting livestock production systems.

Generally, in New Mexico and other regions with similar climate, nutritional deficiency for grazing animals usually occur when rangeland plants are under dormancy during winter and early spring months. This deficiency can also occur during drought events [4]. The importance of feed supplements arise from the fact that such lack of suitable rangeland forage makes their use necessary in order to meet animals' nutritional requirements and improve productivity [4]. Specifically, beef and dairy cattle feed on rangeland forage, supplemental feeds, or both to meet their daily rations (i.e., required nutrients). Beef cattle feed almost equally (50% of the time) on pasture (irrigated or rainfed) and in feedlots (using feed supplements) during the different stages of animal growth [4,13]. Dairy cattle feed almost all the time in feedlots. Hence, cattle feed supplements provide more than 50% of beef and dairy cattle collectively [4,13–15]. This highlight, in general, the importance of feed supplements in cattle production systems. Cattle feed ration consists mostly of protein and energy, which make up about 80%–90% of the daily nutritional requirements, as well as small amounts of minerals and vitamins. Protein and energy components in feed supplements come from variety of forage crops and byproducts which can be provided as a mixture of hay (roughage), corn (gluten feed, distillers), sorghum grain (as a replacement of corn), among others [4,13]. Notably, hay, grain sorghum, and corn represent the majority of feed supplement components used in NM [4,16,17]. There is no specific combination to follow in using these forage crops as their production can vary regionally. Depending on their availability and animal nutritional and need conditions, these forage crops supplements can be used in a variety of ways. Hence, the availability of forage crops plays a significant role in the production systems of beef and dairy cattle and generally NM's food production systems.

This study was conducted within the context of identifying and providing an improved understanding of the linkages between NM's food, energy, and water (FEW) systems under a project funded by the US National Science Foundation [18]. A major challenge that faces NM's FEW systems is the sustainability of these systems during variable environmental and socioeconomic conditions [19]. Within this context, the goal of this study was mainly to evaluate how the production of the above-mentioned forage crops is affected by these conditions and in turn, how their production affects livestock (specifically rangeland beef cattle) production systems. In this regard, some recent studies indicated in a more general sense that the production of forage crops has been increasingly affected by climate change [20] and rising energy prices (e.g., crude oil) [21,22]. However, information is lacking about, and thus there is a need to conduct a more detailed evaluation of, the effects of these variables on the long-term sustainability of NM's forage crops and beef cattle production systems.

Generally, NM's agricultural and food processing sector is one of the most important sectors for the state's economy. This sector, in 2012, accounted for ~12.3% of the state's gross state product (GSP) of \$ 87.6 billion and the livestock production accounted for ~3.4% [23]. NM's livestock feed needs are supported by a combination of rangelands and forage crop production. It should be noted that ~92% of NM's land can be considered as rangelands suitable for grazing [9,10]. Thus, NM's rangelands provide a significant source of low-cost forage supply for livestock. On the other hand, in 2012, the production expenses of all livestock feed supplements were the largest as indicated by the NM Department of Agriculture (NMDA) and this pattern continued to be the case during the past few years [24]. At the farm and ranch level, recent ranch budget analysis suggested that the cost of supplemental feeds can be up to 1/3rd of the total cost of operation for a medium ranch in southeastern NM [25]. Moreover, in 2012, approximately 5.6% of NM's total agricultural receipts was generated by livestock feed crops. This contribution to the state's economy in 2012 consisted of 20%, 5.8%, and 0.7% of hay, corn, and sorghum with total planted areas of ~115,000; 51,000; and 36,000 hectares, respectively [23,26]. The sustainability and hence the economic contribution of forage crops and beef cattle production systems in the state have shown a variable behavior in response to some environmental changes such as drought, limited water supply, and rising temperature. These environmental changes collectively can negatively impact New Mexican's livelihood, and thus there is a need to further evaluate their effects [1,11,22,25,27].

Evidently, drought and high temperatures can affect the production of forage crops [28–34]. Specifically, droughts can result in a reduced water supply, and thus limiting the amount of water needed for irrigation to support forage crop production [32]. Furthermore, high temperatures can increase soil evaporation, reduce soil moisture availability to support plant growth, and increase transpiration rates from plants [33,34]. Increased temperature can result in a significant increase in plants' water requirements for a healthy growth without suffering water stress conditions [28,29,33]. Additionally, variable precipitation patterns can affect the production of non-irrigated crops like sorghum, which accounts for 80% of the total US production of all non-irrigated crops [35]. Moreover, increased temperature and water stress conditions due to drought can affect the reproductive ability of grain crops by delaying or inhibiting flowering processes [28,29]; negatively affect plants metabolism which can result in precocious termination of grain filling [30,31]; and reduce plants' ability to produce vegetative materials (e.g., can result in reduced hay production). For instance, when the drought of 2012 occurred in the southwestern US region, the production of hay decreased by about 42% compared to that of 2011 [36]. Previous studies suggested that in the US, unfavorable climate was one of most important environmental factors that contributed to a decrease in forage crops production with estimated losses of 71% [35].

High demand for feed supplements during drought periods can result in increased prices of hay and grains [36,37]. It is known that the demand for forage crops to feed rangeland livestock is usually high during the winter and early spring period (3–5 months) [38]. Forage crops are also considered as the main feed for backgrounding operations and fattening animals in feedlots [39]. This demand becomes even higher during droughts. It should be noted that, in the southwestern US, droughts can also result in a reduced rangeland forage production by more than 50% [40,41]. This reduction can

affect (i.e., limits) rangelands' ability to meet the nutritional requirements for forage by animals which can cause calves to be weaned early, make them spend more time in backgrounding and feedlots, increase the need to use (i.e., demand) additional feed supplements, and increase the prices of feed supplement. As a specific example, because of the 1996 drought, grain prices were approximately two-fold higher than those of 1995 [37].

Increased pressure on water, land use change, and increased production expenses that coincide with a decline in farmers' income are common challenges in New Mexico [42]. NM is one of the driest states in the US [43]. Therefore, planting crops mainly depends on irrigation water that is withdrawn from surface (54.46%) and groundwater (45.54%) [44] sources as their use can vary from year to year. NM's groundwater aquifers and surface water supply are supported by precipitation and complex interconnected surface-groundwater systems in some areas. The lack of precipitation and cyclic drought events can limit water supplies [45,46]. Such variable water supply can negatively impact the production of these irrigated forage crops (i.e., hay, grain sorghum, and corn). To make the production process of these food components more challenging, NM's maximum temperatures, which can reach up to 40.6 °C during summer months, can result in high rates of evapotranspiration (ET) that can potentially exceed 250 mm yearly [33]. Such high ET rates can also impact the production of non-irrigated (i.e., rainfed) forage crops like grain sorghum. In addition, high costs of energy and fluctuations in farmers' income have resulted in financial losses. In New Mexico, the number of farms who suffered from net economic losses rose more than 80% between 2002–2012 [42]. All these factors have resulted, in recent years, in conversion of agricultural land to other uses such as crude oil extraction to reduce economic impacts (i.e., losses) and improve the livelihood of NM's farmers and ranchers [42].

Previous studies suggested that increased energy prices (represented here by crude oil) can result in increased forage crops prices [22,47]. In the US, energy is widely utilized for synthesizing nitrogenous fertilizers and powering agricultural machineries [48]. The combined effect of increased use of energy and its rising prices can result in increased production expenses of agricultural commodities [49]. Increased production expenses can be considered one of the main reasons for increased crop prices [21]. For example, in the US, crude oil price rose from \$ 27.9 in 1985 to \$ 50 per barrel in 2017 [50], while the total production expenses of fertilizers increased from \$ 8.6 billion to \$ 22 billion during the same period [26]. It was indicated that this increase in crude oil prices influenced and resulted in a significant increase in hay prices to about 72% during the same period [26].

Recent technological advances in the crude oil industry have resulted in the development of new and effective methods of crude oil extraction [51]. It was indicated that the emergence of these new extraction methods coincided with a significant increase in production to meet the increased demand for this product. However, this increase in crude oil production was also correlated with the loss of cropland areas and increased pressure on water [51]. During 2000–2015, about 50,000 new wells were drilled in North America [51]. This increase in crude oil extraction activities required conversion of lands to crude oil pads, roads, and other supporting infrastructures [51]. It has been estimated that three million hectares have been lost because of crude oil extraction between 2000 and 2012 [51]. Furthermore, the well drilling process leads to an increased pressure on water resources as each crude oil production well requires a considerable amount of water that ranges from 1000 to 7,00,000 m³ [52].

The study was motivated by the need to provide an improved understanding of NM's FEW systems and their response to different environmental and socioeconomic stressors. Thus, due to these stressors, NM is struggling to sustain the production of some of the major forage crops (i.e., hay, corn, and grain sorghum) that play an important role in supporting beef cattle production systems in the state. The goal is to provide an improved understanding of the impacts of these stressors on the production of these forage crops. Such understanding is critical and can help in developing enhanced management practices for sustainable production. The objective of this study was to investigate the linkages between the production and prices of these forage crops and precipitation, temperature, crude oil production, crude oil prices, beef cattle population, and range condition.

2. Methodology

2.1. Study Area

The study focused on the production and prices of hay, grain sorghum, and corn in New Mexico. NM, which is located in the southwestern US, is known for its normally dry conditions [53], with an average precipitation of about 350 mm. Most precipitation falls during the summer months (July and August) while small amounts fall in January and February. NM's long-term mean temperature is about 11.5 °C, with the mean maximum temperature reaching up to 40.6 °C during summer months. The annual evaporation rate exceeds 250 mm. In terms of crude oil production, NM produces approximately 5% of the US's total production.

2.2. Variables Selection and Data

Historical datasets since the 1950's on NM's climatic, energy, socioeconomics, and food production were obtained and used to evaluate the observed behavior of forage crops production. The variables considered in the study were selected to reflect climate variability based on precipitation and temperature; energy as represented by crude oil production; socioeconomics as represented by the prices of crude oil and forage crops (i.e., hay, grain sorghum, and corn) [10,32,34]; and food production as represented by forage crop production, beef cattle production [11,27], and rangelands forage availability as represented by range conditions. Except for range conditions, the data for all the selected variables were available for the period between 1958 and 2017. The mean annual precipitation (mm) and mean annual temperature (°C) data were retrieved from the Western Regional Climate Center [54]. Crude oil production data (barrel) were retrieved from the Go-TECH [55], while the mean annual crude oil prices data (\$/barrel) were obtained from the Federal Reserve Economic Data (FRED) [50]. Beef cattle population (head); the production of corn (ton), grain sorghum (ton), and hay (ton); and mean annual prices of corn (\$/25.4 kg), grain sorghum (\$/45.3 kg), and hay (\$/ton) datasets were obtained from the US Department of Agriculture National Agricultural Statistics Service (USDA NASS) [26]. Similarly, the data for mean annual range conditions (%), which can be used as a surrogate for rangelands forage production, were also obtained from USDA NASS but for a relatively shorter period, between 1973 and 2017 [26].

2.3. Statistical Analysis

For a consistent evaluation of relative market values for all commodities, all prices were adjusted for inflation to reflect 2017 dollars using the consumer price index (CPI), which was retrieved from the Federal Reserve Economic Data [50]. Simple regression models were used to determine statistically significant predictors for forage crops production and prices. Before conducting the statistical analysis, data were evaluated to account for homoscedasticity, normality, and autocorrelation using the portmanteau test statistics and the Engle–Lagrange multiplier tests at time lags (years) 1–12; Shapiro–Wilk tests; and Durbin–Watson tests, respectively. Because the data showed autocorrelation and heteroscedasticity, exponential generalized autoregressive conditional heteroscedasticity (EGARCH) models were used. When Quane optimization could not be completed, generalized autoregressive conditional heteroscedasticity (GARCH) models were used to identify the patterns of the relationships between the dependent variables and each independent variable [56]. The analysis was conducted using Proc AUTOREG in SAS 9.4 (SAS Institute, Cary, NC, US). R^2 statistics was used to report the behavior of the obtained relationships. Additional statistical performance indicators were used to evaluate some of the obtained relationships that include mean error (ME), mean absolute error (MAE), and root mean square error (RMSE), which can be calculated by comparing observed with predicted values.

3. Results and Discussion

The results shown below provide a description of the obtained individual relationships between each forage crop and precipitation, temperature, crude oil production, crude oil prices, beef cattle population, and range conditions.

3.1. Hay Production

The data showed an increased hay production between 1958 and 2000 that was followed by a decreasing trend since 2001 (Figure 1). In 2017, hay production showed a 33% decline compared to the peak production of 2000. The results showed that crude oil production and beef cattle population were the only variables that were significantly correlated with, and able to explain some of the variation in hay production (Table 1). Crude oil production was negatively correlated with and was able to explain about 83% of the variation in hay production. A decline in crude oil production to 68.82 million barrels coincided with an increase in hay production to 1.69 million tons in 2000, whereas an increase in crude oil production in 2017 to 170.18 million barrels coincided with a decrease in hay production to 1.13 million tons (Figure 1). A possible explanation for this correlation can partially be attributed to the conversion of lands used for hay production to crude oil extraction pads [42,51]. The findings of the study by [51], which were validated using remote sensing, indicated that loss of vegetation (as well as cropland and rangeland areas) was directly linked to crude oil and natural gas activities in North America. The study was conducted for the 2000–2012 period. A recent study by [57] suggested that there is a significant land use/land cover change in some areas in NM that resulted in a decline in agricultural lands.

Beef cattle population was negatively correlated with, and able to explain about 85% of the variation in hay production (Table 1). A comparison between beef cattle population and hay production showed that in 1959, the beef cattle population of 7.38 million heads coincided with the lowest hay production (611,000 tons). Similarly, a decrease in beef cattle population to 572,000 heads in 1999 coincided with the peak in hay production of 1.71 million tons (Figure 1). A look at NM's rangelands and some other factors can partially provide a reasonable explanation for this correlation between hay production and beef cattle population. In NM, rangelands on average have not shown signs of significant improvement even when precipitation was above the long-term average [40]. In other words, NM's rangelands potentially indicated some signs of long-term degradation [11,12,58]. To adapt to these low rangeland productivity conditions, some ranchers may widely depend on hay to feed their cattle. The reliance on hay (and other forage crops) can also increase during late winter to early spring periods [38]. Ranchers' dependency (i.e., demand) on hay may also increase during drought periods [36] to retain their cattle and avoid the liquidation operations [37,38]. However, this increased demand for hay may not be adequately addressed also due to drought [11,27]. Another possible explanation for the decline in hay production can partially be attributed to a potential time lag in beef cattle numbers to adjust to drought conditions [11,27]. In other words, an increased beef cattle number during a drought year can be followed by a decline in the beef cattle number in the following year. Drought can also provide a reasonable explanation to the observed decline in hay production. For example, the worst drought on record in NM's history occurred during early to mid-1950s and can be used to explain the lowest hay production that was experienced in 1959.

Additional analysis is needed to evaluate the combined effects of drought, crude oil production, and beef cattle numbers on hay production. To evaluate these combined effects, as a future next step, the authors have considered and obtained preliminary results [19] that suggested that using an integrated system dynamics approach can be appropriate to account for the weighted contribution (i.e., effects) of these variables on hay production and generally on NM's food production systems.

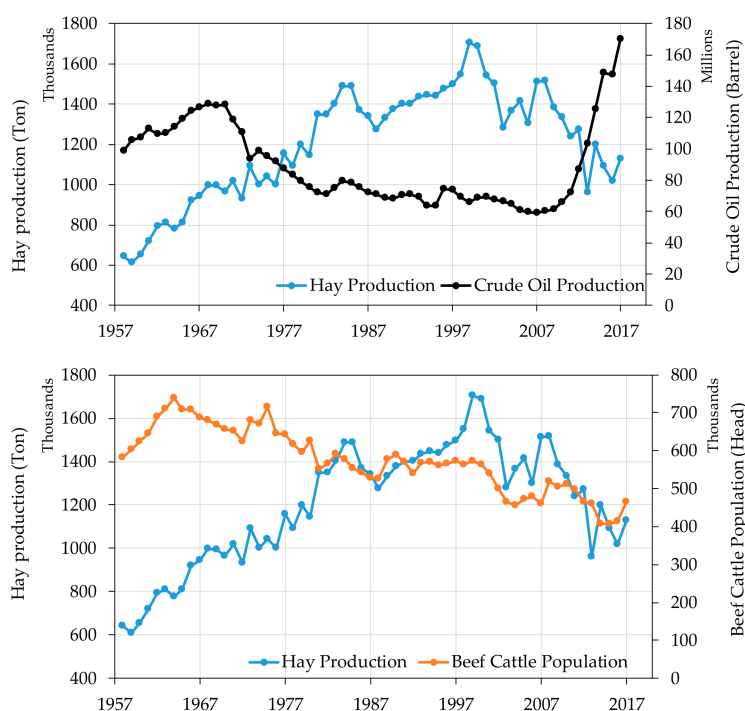


Figure 1. Time series plots of hay production (ton) [26], crude oil production (barrel) [55], and beef cattle population (head) [26] in New Mexico between 1958 and 2017.

Table 1. A summary of the statistical analysis results of the obtained individual relationships between hay production (ton) and the selected variables using a generalized autoregressive conditional heteroscedasticity (GARCH) or an exponential GARCH (EGARCH) model based on the data described in Section 2.2.

Independent Variables	Intercept	Estimate (β)	P-Value	R ²
Mean annual precipitation (mm) ¹	1,159,728	−25.44	0.90	
Mean annual temperature (°C) ¹	1,019,242	11,341	0.20	
Crude oil production (barrels) ²	1,558,947	-74.12×10^{-4}	<0.001	0.83
Mean annual crude oil prices (\$/barrels) ¹	1,091,087	959.29	0.48	
Beef cattle population (head) ¹	1,252,113	-96.16×10^{-2}	0.001	0.85
Mean annual range conditions (%) ¹	1,057,590	355.86	0.73	

¹ EGARCH model; ² GARCH model.

3.2. Hay Prices

Mean annual hay prices fluctuated during the entire period (i.e., 1958–2017) but generally showed a slight declining trend since 1974. The mean annual hay prices in 2017 were about 43% of the peak prices in 1974 (Figure 2). Initial results showed that mean annual precipitation, crude oil production, mean annual crude oil prices, and mean annual range conditions were able to explain some of the variation in hay prices (Table 2).

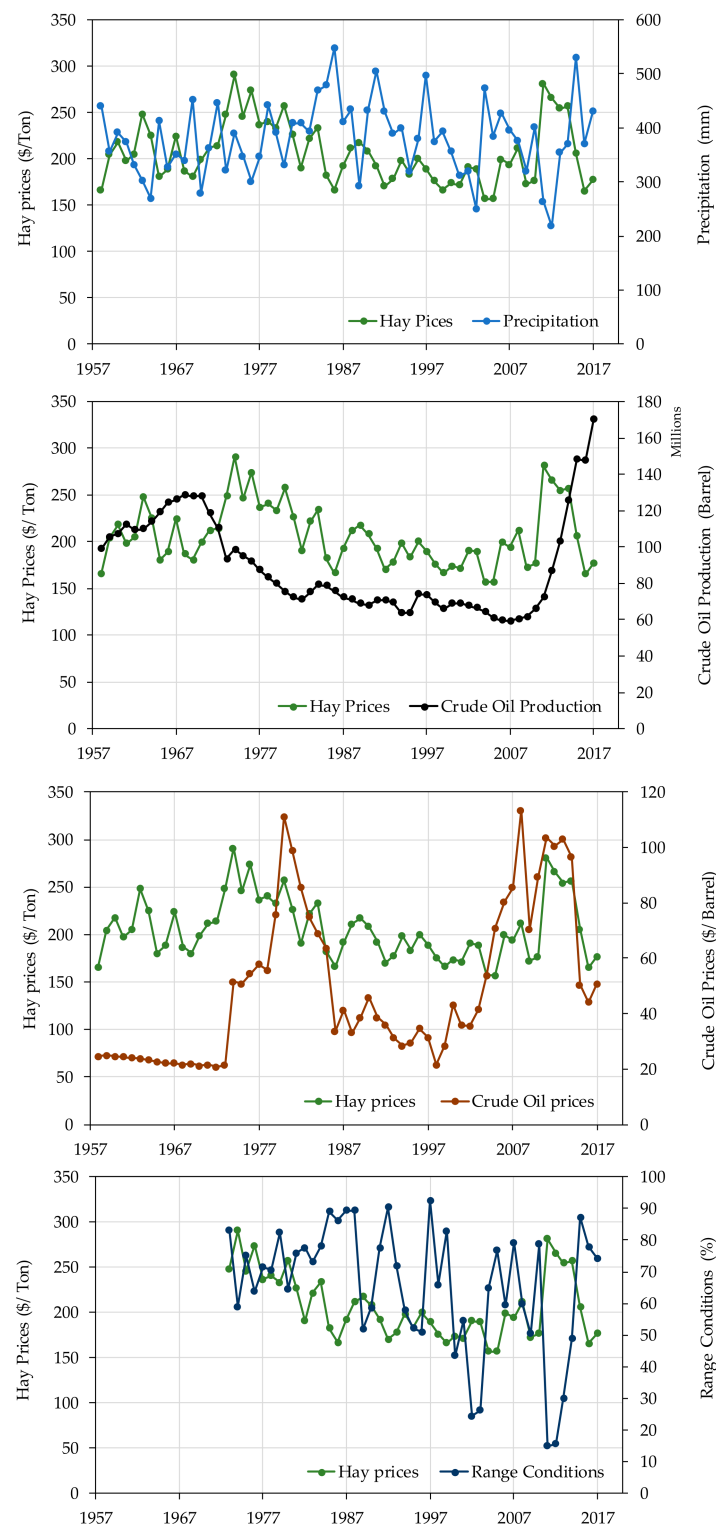


Figure 2. Time series plots of mean annual hay prices (\$/ton) [26], mean annual precipitation (mm) [54], crude oil production (barrel) [55], mean annual crude oil prices (\$/barrel) [50], and range conditions (%) [26] in New Mexico between 1958 and 2017.

Table 2. A summary of the statistical analysis results showing the obtained individual relationships between hay prices (\$/ton) and the selected variables using a generalized autoregressive conditional heteroscedasticity (GARCH) or an exponential GARCH (EGARCH) model based on the data described in Section 2.2.

Independent Variables	Intercept	Estimate (β)	<i>p</i> -Value	R ²
Mean annual precipitation (mm) ¹	265.76	-15.57×10^{-2}	0.003	0.45
Mean annual temperature (°C) ¹	182.01	23.93×10^{-2}	0.97	
Crude oil production (barrels) ¹	184.81	9.45×10^{-10}	<0.001	0.33
Mean annual crude oil prices (\$/barrels) ¹	165.90	77.13×10^{-2}	0.01	0.48
Beef cattle population (head) ¹	150.32	6.33×10^{-5}	0.23	
Mean annual range conditions (%) ¹	267.26	-81.28×10^{-2}	<0.001	0.60

¹ EGARCH model.

Mean annual precipitation and mean annual range conditions were negatively correlated with the mean annual hay prices and were able to explain about 41% and 60% of the variation in hay prices, respectively (Table 2). In 1986, an increase in mean annual precipitation to 547.6 mm and mean annual range condition to 86% coincided with a decrease in hay prices to \$ 166 per ton (Figure 2). On the other hand, a decrease in mean precipitation to 264 mm and range condition to 15% coincided with a significant increase in hay prices to \$ 281 per ton in 2011. During favorable conditions (i.e., increased precipitation), rangelands forage productivity and the corresponding carrying capacity can increase. Such conditions can allow to feed an increased number of animals for longer periods [37,38]. Consequently, this can result in a decreased demand for hay, and thus potentially lowering its prices. On the contrary, lack of (or reduced) precipitation can affect rangeland forage productivity and increase ranchers' dependency (demand) on hay which can result in increased hay prices [36,58]. Also, during drought periods, farmers and ranchers may increase their reliance on groundwater resources to complement a potential reduction in surface water supply to meet irrigation requirements for hay production. Such increased reliance on groundwater resources can increase the cost (expenses) of crop production due to pumping and can consequently result in increased hay prices.

These initial results, however, also suggested that there can be a relationship (i.e., correlation) between mean annual precipitation and mean annual range conditions that can directly or indirectly affect their corresponding individual relationships with hay prices [11,59,60]. A regression analysis was conducted to evaluate the significance of this relationship between these two predictors (i.e., mean annual precipitation and mean annual range conditions) and it was found to be significant at $P \leq 0.05$ with $R^2 = 0.52$. One of these relationships can be considered to provide a better representation of the behavior of mean annual hay prices. A comparison between these two relationships was conducted using additional performance statistics that include RMSE, ME, and MAE which were estimated by comparing observed with predicted values. The relationship between mean annual precipitation and mean annual hay prices resulted in predicted values with higher RMSE, ME, and MAE of \$ 193, \$ −3, and \$ 20 compared to those obtained from the relationship between mean annual precipitation and mean annual range conditions of \$ 150, \$ 1.6, and \$ 18.3, respectively. This comparison suggested that mean range conditions can provide a better representation of the mean annual hay prices behavior compared to mean annual precipitation.

As shown in Table 2, the obtained initial results also indicated that both crude oil production and mean annual crude oil prices were both positively correlated with and were able to explain about 33% and 48% of the variation in mean annual hay prices, respectively. From 2009–2011, crude oil production increased 15%, and crude oil prices also climbed 32%. This was associated with a ~38% rise in hay prices (Figure 2). Like all agricultural crops, hay production requires the use of considerable energy inputs (e.g., for cultivation, harvesting, and transportation) which mostly comes from crude oil (or generally fossil fuels) throughout the forage crops production process [48]. Thus, the increased use

of energy in the production process can result in increased expenses [49], which, in turn, can result in increased hay prices.

However, the potential relationship (i.e., correlation) between crude oil production and its prices [61] can directly or indirectly affect their corresponding individual relationships with mean annual hay prices [62]. An evaluation of the potential relationship between crude oil production and prices indicated that this relationship between these two predictors is significant at $P \leq 0.05$ with R^2 of 0.69. The individual relationships were further evaluated to determine which one of these two correlated predictors can best describe the behavior of mean annual hay prices. The relationship between crude oil production and mean annual hay prices resulted in predicted values with higher RMSE, ME, and MAE of \$ 202, \$ -6.3, and \$ 20 compared to those obtained from the relationship between mean annual crude oil prices and mean annual hay prices of \$ 182, \$ -2.4, and \$ 19, respectively. This comparison suggested that mean annual crude oil prices can provide a better representation of the of mean annual hay prices behavior compared to mean annual precipitation.

3.3. Grain Sorghum Production

A visual inspection of the grain sorghum time series indicated that the period between 1971 and 2017 featured a declining trend in its production. In 2017, grain sorghum production decreased by about 91% from the peak that occurred in 1971 (Figure 3). The statistical analysis showed that mean annual temperature, beef cattle population, and range condition were the only statistically significant variable that were able to explain some of the variation in grain sorghum production (Table 3). Mean annual temperature was negatively correlated with and was able to explain about 58% of the variation in grain sorghum production (Table 3). In 1971, the mean annual temperature was 11 °C, while the grain sorghum production was at its peak at ~520,039.6 tons. However, almost parallel with the increase in mean annual temperature to 13.4 °C in 2017, grain sorghum production declined significantly to 42,672 tons. As shown in Figure 3, the mean annual temperature experienced an increasing trend since 1973, whereas grain sorghum production experienced a declining trend since then. It should be noted that grain sorghum can be produced following dryland (i.e., rainfed or non-irrigated) and irrigated practices. On average during the 1958–2016 period, about 60% of the total area planted by grain sorghum was non-irrigated (Figure 4) [26]. An evaluation of the total irrigated and non-irrigated areas of grain sorghum during this period revealed a declining (increasing) trend in irrigated (non-irrigated) areas. This suggested that there is an increased reliance on rainfed grain sorghum production. Apparently, NM's precipitation has been near the long-term average without significant change. However, NM's temperature has been on the rise since 1973. The declining trend in grain sorghum production can partially be attributed to water deficiency caused by a combination of increased temperatures and evaporation rates and low to average precipitation amounts [29,31,33,34].

Table 3. A summary of the statistical analysis results of the obtained individual relationships between grain sorghum production (ton) and the selected variables using a generalized autoregressive conditional heteroscedasticity (GARCH) or an exponential GARCH (EGARCH) model based on the data described in Section 2.2.

Independent Variables	Intercept	Estimate (β)	p -Value	R^2
Mean annual precipitation (mm) ²	109,751	220.29	0.28	
Mean annual temperature (°C) ¹	1,323,432	−92,444	<0.001	0.58
Crude oil production (barrels) ¹	147,053	5.45×10^{-10}	0.35	
Mean annual crude oil prices (\$/barrels) ¹	249,907	−654.60	0.33	
Beef cattle population (head) ¹	−377,843	0.97	<0.001	0.61
Mean annual range conditions (%) ¹	7193	2509	<0.001	0.51

¹ EGARCH model; ² GARCH model.

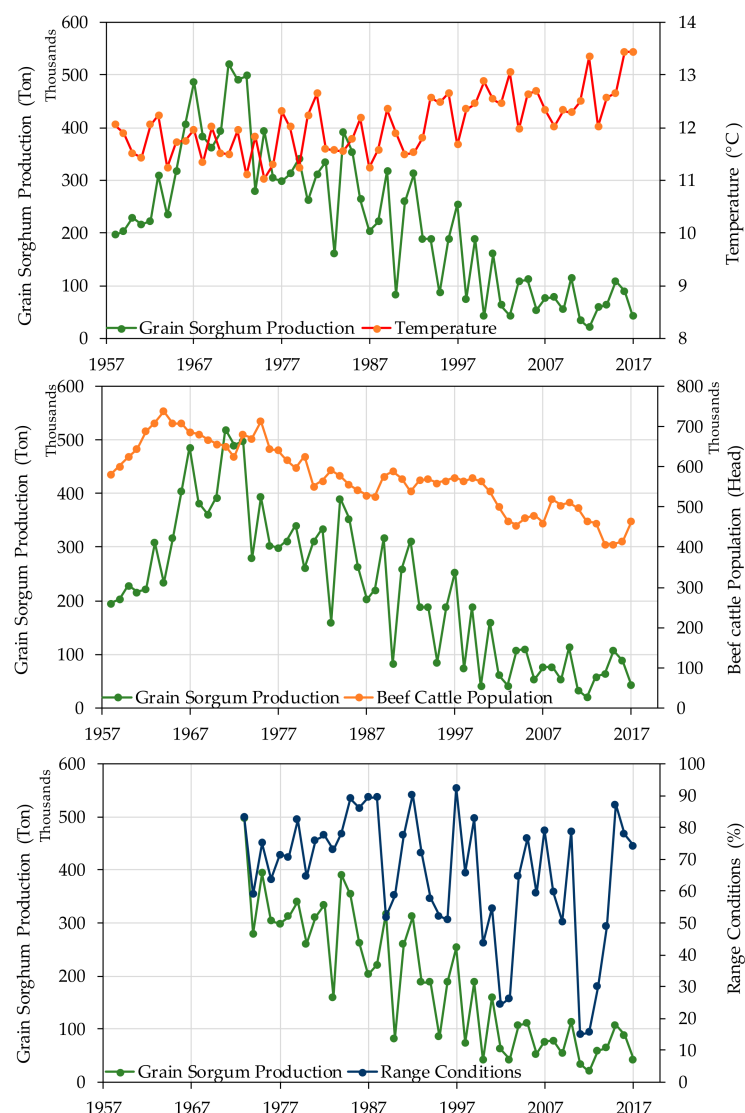


Figure 3. Time series plots of grain sorghum production (ton) [26], mean annual temperature (°C) [54], beef cattle population (head) [26], and mean annual range conditions (%) [26] in New Mexico between 1973 and 2017.

The results also suggested that beef cattle population and mean annual range condition were positively correlated with and were able to explain about 60% and 51% of the variation in grain sorghum production, respectively (Table 3). In 1973, grain sorghum production was about 497,891 tons, while beef cattle population and range condition were 680,000 heads and 83%, respectively (Figure 3). However, a decline in beef cattle population to 465,000 and range condition to 16% in 2012 coincided with a sharp drop in grain sorghum production to 20,269 tons. As part of their traditional management practices, when rangelands are in good condition, ranchers tend to increase the herd size [37], which can result in increased calf production. In addition, ranchers can also retain their calves longer to sell them as long yearlings when the range is in good condition and there is an increased rangeland forage production that can allow for an increased grazing capacity [38]. Therefore, an increase in beef cattle population can partially result from improved range condition [38]. Another possible explanation for this relationship between grain sorghum and beef cattle numbers is that grain sorghum is mostly used in the finishing phase of beef cattle (i.e., feedlots). So, when there are fewer calves being weaned (i.e., based on lower cattle numbers) there are less calves going to the feedlots to be finished and there is a less need for grain sorghum.

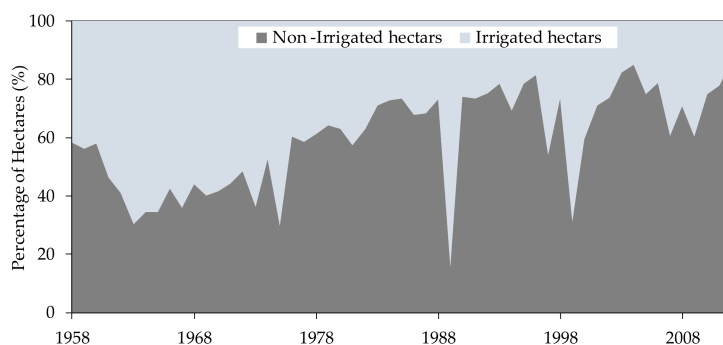


Figure 4. Time series plot of percentage of irrigated and non-irrigated of areas [27] planted with grain sorghum in New Mexico between 1958 and 2012.

3.4. Grain Sorghum Prices

Mean annual grain sorghum prices showed a declining trend since 1974. In 2017, the mean annual prices of grain sorghum were about 77% lower than the peak prices of 1974 (Figure 5). The obtained results indicated that crude oil production, mean annual crude oil prices, and beef cattle population were the only statistically significant variables that were able to explain some of the variation in mean annual grain sorghum prices (Table 4). The three variables (i.e., crude oil production, crude oil prices, and beef cattle population) were positively correlated with and were able to explain about 71%, 72%, and 73% of the variation in mean annual grain sorghum prices, respectively (Table 4). Energy, as represented here by crude oil production and prices, is a major input in grain sorghum production. A decrease in crude oil prices can result in reduced production expenses and consequently, decreased grain sorghum (as well as other forage crops) prices [21]. In 1974, the price of crude oil was \$ 51.5 per barrel, while the price of grain sorghum was \$ 27.4 per 45.3 kg. A decline in crude oil price to \$ 44 per barrel in 2016 coincided with a decline in grain sorghum price to \$ 5.6 per 45.3 kg (Figure 5).

However, as indicated in Section 3.2 above, the correlation between crude oil production and prices can affect their individual relationships with mean annual grain sorghum prices. An evaluation of these two individual relationships indicated that the relationship between crude oil production and mean annual grain sorghum prices resulted in predicted values with slightly higher RMSE, ME, and MAE of \$ 19.7, \$ 0.6, and \$ 1.9 compared to those obtained from the relationship between mean annual crude oil prices and mean annual hay prices of \$ 19.6, \$ 0.4, and \$ 1.8, respectively. This comparison suggested that mean annual crude oil prices can provide a better representation of the mean annual grain sorghum prices behavior compared to mean annual crude oil prices.

Moreover, among other factors that can affect grain sorghum prices, is the decline in beef cattle population which comes secondary only to crude oil prices. A decrease in beef population can represent a drop in the demand for this good, which can potentially result in decreased grain sorghum prices (Figure 5). The presence of a possible relationship between crude oil production and prices can directly or indirectly affect their relationships with grain sorghum prices. As indicated in Sections 3.2 and 5, the evaluation of a potential relationship between crude oil production and prices is beyond the scope of this analysis.

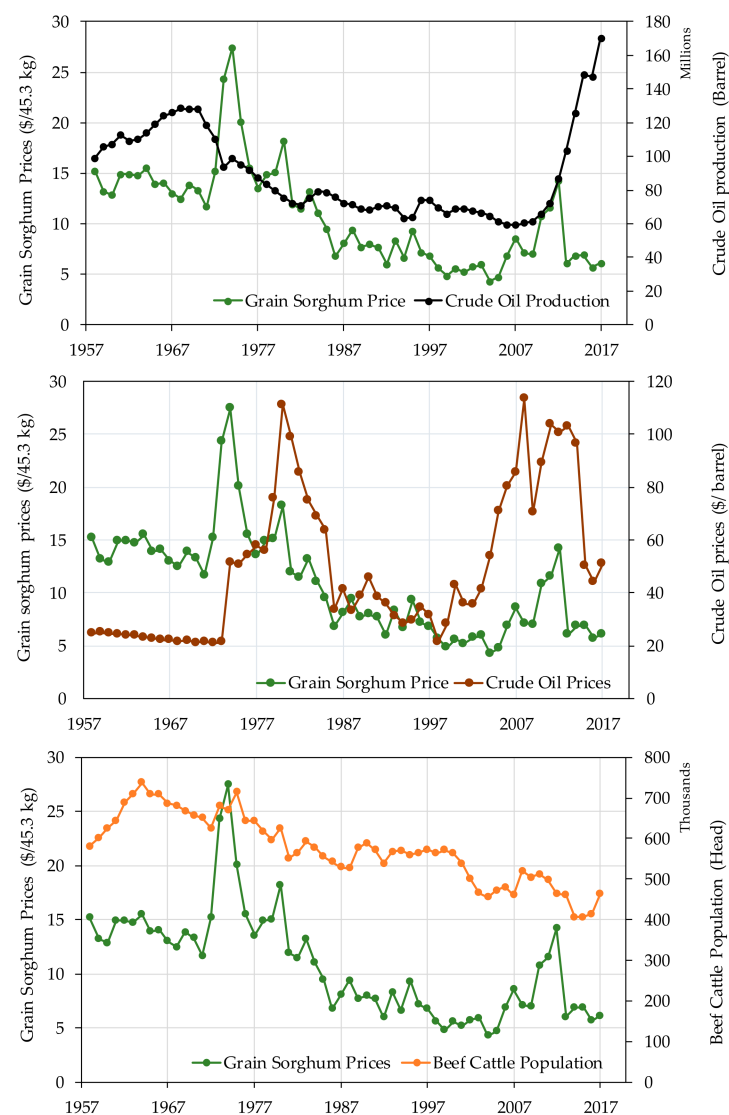


Figure 5. Time series plots of mean annual grain sorghum prices (\$/45.3 kg) [26], crude oil production (barrel) [55], mean annual crude oil prices (\$/barrel) [50], and beef cattle population (head) [26] in New Mexico between 1958 and 2017.

Table 4. A summary of the statistical analysis results showing the obtained individual relationships between grain sorghum prices (\$/45.3 kg) and the selected variables using a generalized autoregressive conditional heteroscedasticity (GARCH) or an exponential GARCH (EGARCH) model based on the data described in Section 2.2.

Independent Variables	Intercept	Estimate (β)	<i>p</i> -Value	R^2
Mean annual precipitation (mm) ¹	14.46	-1.23×10^{-3}	0.69	
Mean annual temperature(°C) ¹	12.09	0.15	0.73	
Crude oil production (barrels) ¹	12.49	1.39×10^{-8}	<0.001	0.71
Mean annual crude oil prices (\$/barrels) ¹	13.11	3.62×10^{-2}	0.01	0.72
Beef cattle population (head) ¹	2.66	1.98×10^{-5}	0.04	0.73
Mean annual range conditions (%) ²	22.95	-4.87×10^{-3}	0.79	

¹ EGARCH model; ² GARCH model.

3.5. Corn Production

Corn production showed an increasing trend during the 1958–1999 period with a peak production of 379,476 tons in 1999. However, since 2000, corn production continued to decline until 2017 with a total production of 146,355 tons. In 2017, corn production was about 61% compared to the peak that occurred in 1999 (Figure 6). Crude oil production and beef cattle population were the only statistically significant variables that were able to explain some of the variation in corn production (Table 5).

Table 5. A summary of the statistical analysis results showing the obtained individual relationships between corn production (ton) and the selected variables using a generalized autoregressive conditional heteroscedasticity (GARCH) or an exponential GARCH (EGARCH) model based on the data described in Section 2.2.

Independent Variables	Intercept	Estimate (β)	p -Value	R^2
Mean annual precipitation (mm) ²	128,383	−12.59	0.73	
Mean annual temperature (°C) ¹	219,963	−4.34	0.08	
Crude oil production (barrel) ¹	286,359	-1.68×10^{-3}	<0.001	0.85
Mean annual crude oil prices (\$/barrel) ²	146,538	−140.20	0.74	
Beef cattle population (head) ²	277,661	−0.39	<0.001	0.86
Mean annual range conditions (%) ¹	178,085	371.04	0.14	

¹ EGARCH model; ² GARCH model.

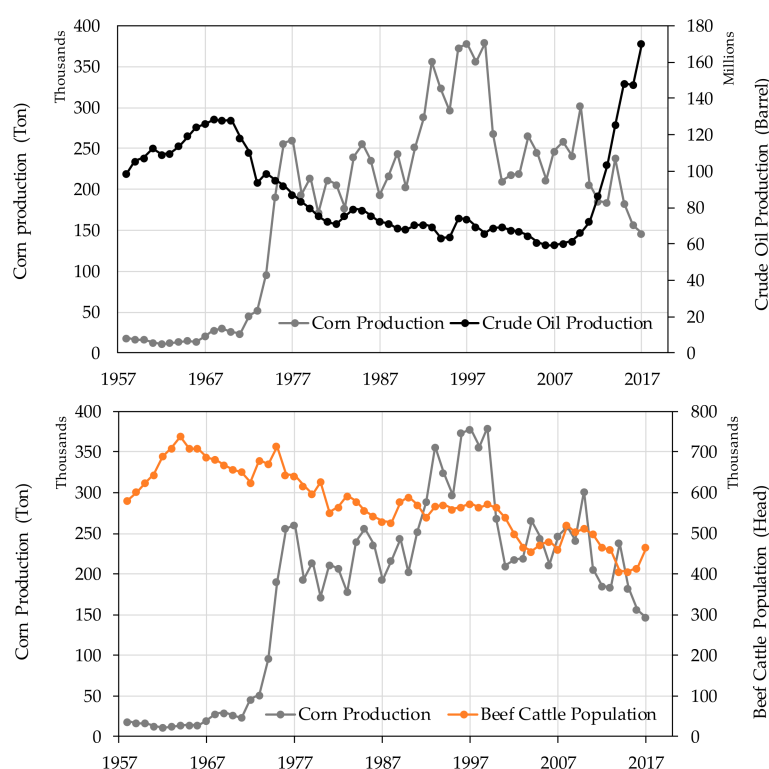


Figure 6. Time series plots of corn production (ton) [26], crude oil production (barrel) [55], and beef cattle population (head) [26] in New Mexico between 1958 and 2017.

Crude oil production and beef cattle population were negatively correlated with, and able to explain about 85% and 86% of the variation in, corn production, respectively (Table 5). A decline in crude oil production in 1999 to 66 million barrels coincided with an increase in corn production to 379,476 tons. Similarly, an increase in crude oil production to 170 million barrels in 2017 coincided with a decrease in corn production to 146,354 tons (Figure 6). A possible explanation for such correlation can partially be attributed to the conversion of crop lands to be used for crude oil extraction. This conversion can partially

result in a decline in corn production as also previously suggested by [42,51]. Another possible reason is that an increase in crude oil production can result in an increase in supply (surplus) which can result in a decrease in prices [61]. The decrease in crude oil prices can consequently result in a decline in profitability from corn biofuels [63] and discouraging the need to increase corn production [64].

Similarly, corn production was negatively correlated with beef cattle population. In 1964, the beef cattle population was 738,000 heads, while corn production was 13,868.4 tons. In 1999, the decrease in beef cattle population to 572,000 heads coincided with an increase in corn production to 379,476 tons (Figure 6). There is a number of factors that can affect the demand for corn in different ways that need to be considered in order to properly explain this negative correlation between corn production and beef cattle production. For example, one possible explanation for this relationship is that a decrease in beef cattle population can result in a reduced demand for forage crop supplements including corn, which can result in a decrease in cultivated areas of corn [57]. On the contrary, while corn is used as a feed supplement, it can also be widely used for other purposes such as biofuel production [63] and human consumption, which can then result in an increased demand for corn. Additionally, it should also be noted that corn (as well as other forage crop supplements) is mostly used during the feedlot phase of beef production as well as in the dairy sector (i.e., corn silage). Depending on their availability, other forage crops (i.e., hay and grain sorghum) can be replaced with corn in response to a decline in their production. This combination can result in an increased demand for corn, and thus an increased corn production. Figure 7 shows that since 1958, both beef cattle population and lands used to cultivate grain sorghum have shown a declining trend, whereas cornfields have shown an increasing trend [26]. Additional analysis is needed to further explain these interrelated variables to better understand how they affect NM's food production systems.

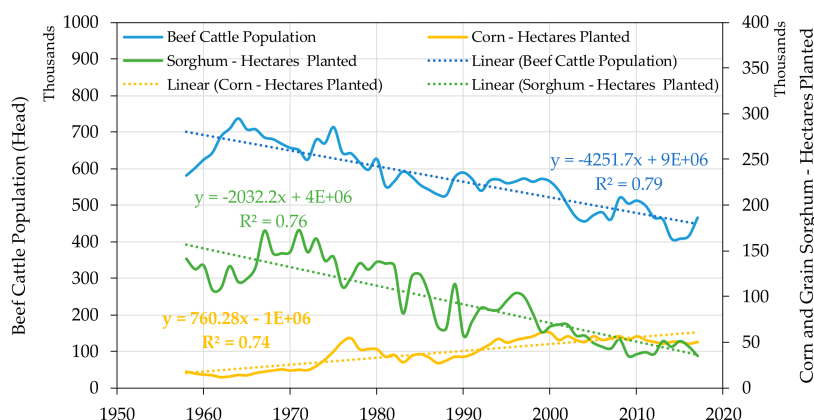


Figure 7. Time series plot of total planted area of corn (hectare), grain sorghum (hectare), and beef cattle population (head) in New Mexico between 1958 and 2017 based on the data obtained from [26].

3.6. Corn Prices

Mean annual corn prices showed a declining trend since 1974. Mean annual corn prices in 2017 were about 75% lower than the peak prices of 1974 (Figure 8). As shown in Table 6, mean annual precipitation and crude oil production were the only variables that were significantly correlated with, and able to explain some of the variation in mean annual corn prices.

Mean annual precipitation showed a positive linear relationship with mean annual corn prices and explained 83% of its variation (Table 6). As shown in Figure 8, the mean annual corn price peaked at \$ 15.2 per 25.4 kg in 1974 when the mean precipitation was 390 mm. In 2001, a decline in mean annual precipitation to 311 mm coincided with a decrease in mean annual corn price to \$ 3.3. A previous study suggested that increased precipitation can result in increased corn production which, in turn, can result in reduced corn prices [65]. However, the obtained results in this study which indicated a positive correlation between precipitation and corn prices does not agree with previous findings

by [65]. This analysis suggested that mean annual precipitation can indirectly affect the demand for corn in feedlots, and thus its prices. In other words, during dry (drought) years, there can be a decline in calf production from cattle that feed on rangelands and potentially less calves being finished which can result in a reduced demand for corn, and thus lower corn prices. The opposite would be true during wet years. However, other factors can also play a role in partially explaining some of these relationships such as the fact that corn can also be used in the energy sector (i.e., biofuels production) and in the dairy sector.

Table 6. A summary of the statistical analysis results showing the obtained individual relationships between corn prices (\$/25.4 kg) and the selected variables using a generalized autoregressive conditional heteroscedasticity (GARCH) or an exponential GARCH (EGARCH) model based on the data described in Section 2.2.

Independent Variables	Intercept	Estimate (β)	<i>p</i> -Value	R^2
Mean annual precipitation (mm) ¹	10.42	2.38×10^{-3}	0.01	0.83
Mean annual temperature (°C) ¹	12.27	-6.69×10^{-2}	0.76	
Crude oil production (barrel) ¹	11.67	-2.011×10^{-9}	<0.001	0.84
Mean annual crude oil prices (\$/barrel) ¹	11.25	8.63×10^{-3}	0.31	
Beef cattle population (head) ¹	7.15	7.42×10^{-6}	0.13	
Mean annual range conditions (%) ²	13.81	-5.37×10^{-3}	0.49	

¹ EGARCH model; ² GARCH model.

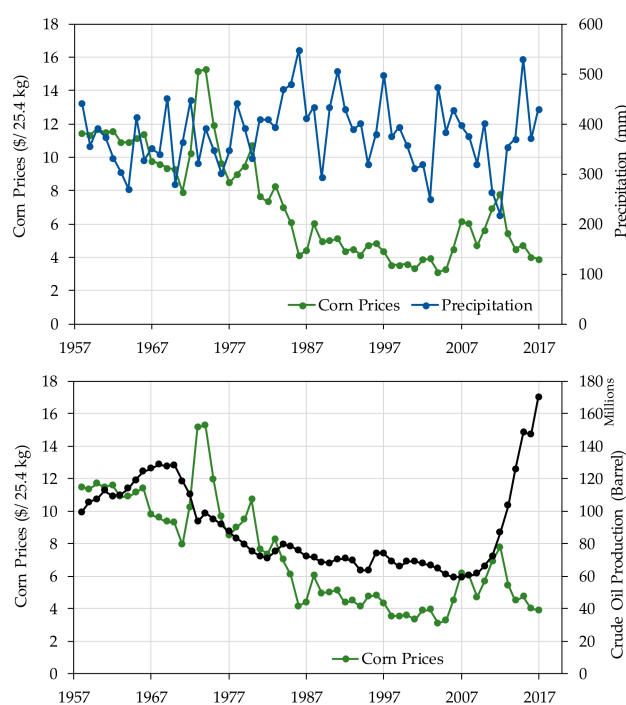


Figure 8. Time series plots of corn prices (\$/45.3 kg) [27] with mean annual precipitation (mm) [54] and crude oil production (barrel) [58] in New Mexico between 1958 and 2017.

Crude oil production was significantly correlated with and was able to explain 84% of the variation in corn prices (Table 6). The mean annual corn prices showed an overall declining trend during the 1958–2017 period, while crude oil production showed a declining trend between 1958–2008, which was followed by an increasing trend between 2009–2017. The data showed that the decline in crude oil production in some cases coincided with a rise in mean annual corn prices. For instance, the decline in crude oil production in 1973, 1987, and 1995 coincided with an increase in mean annual corn prices. In contrast, an increase in crude oil production in 1970, 1985, and 2017 coincided with a decrease in mean annual corn prices

(Figure 8). This negative correlation can partially be attributed to competitive market conditions between crude oil and ethanol produced from corn [66]. It should be noted that crude oil production and crude oil prices can show, in some cases, a strong correlation, such that crude oil prices are usually high when there is insufficient production to meet the market demand [61]. This can lead to increased demand for corn to produce ethanol, which can lead to a rise in corn prices [63]. Additional analysis is needed and will be conducted in the future to characterize the weighted contribution of these variable (i.e., crude oil production and prices as well as the use of corn in biofuel production) on NM's food production systems using a system dynamics approach (see Section 5).

4. Implications and a Sustainability Perspective

This analysis highlighted some of the potential impacts of climatic changes on one of NM's food production systems—rangeland livestock (as represented by beef cattle). These systems are heavily dependent on rangeland and pasture lands that constitute more than 90% of NM's land. The observed behavior of range conditions, which can be considered as an indicator for its productivity, showed a consistent declining trend since 1973. This declining trend has put pressure on NM's rangeland livestock production in multiple ways. Rangeland is considered as a low-cost input. The decline in range conditions can result in reducing grazing capacity which can force farmers and ranchers to either increase the use of (reliance on) supplemental feeds from irrigated forage crops, reduce the number of herds, or both to sustain livestock production. However, the observed behavior suggested there is a consistent decline in grain sorghum production since 1958, an increase in hay and corn production until 1997, which was followed by a consistent declining trend since then. Apparently, rangeland livestock production itself has seen a declining trend since 1973 [11]. A summary of the obtained relationships is shown in Table 7. Some of the variables used in this analysis may be correlated with each other and have direct or indirect effects on forage crops production and prices. These results highlighted the need to conduct additional analysis to untangle these relationships to provide a more robust characterization of the effects of the selected variables on NM's food production systems which will be conducted in the future as an integrated system dynamics approach [20].

Table 7. Summary of the relationships between the selected variables and forage crops production (i.e., hay, grain sorghum, and corn) in NM ¹ represented by R² when a predictor is significant at $p \leq 0.05$.

Predictor	Hay		Grain Sorghum		Corn	
	Production (ton)	Prices (\$/ton)	Production (ton)	Prices (\$/45.3 kg)	Production (ton)	Prices (\$/25.4 kg)
Mean annual precipitation (mm)						(+) 0.83
Mean annual temperature (°C)			(−) 0.58			
Crude oil production (barrel)	(−) 0.83				(−) 0.85	(−) 0.84
Crude oil prices (\$/barrel)		(+) 0.48		(+) 0.72		
Beef cattle population (head)	(−) 0.85		(+) 0.61	(+) 0.73	(−) 0.86	
Mean annual range conditions (%)		(−) 0.60	(+) 0.51			

¹ Relationship either positive relationship (+) or negative relationship (−).

Global warming effects on NM was evident as shown in the observed increased temperatures since 1973, which coincided with a declining trend in range condition [11,28]. Climate projections suggested that temperature would continue to rise [67–69]. Consequently, rangeland productivity would continue to decrease and as a result, farmers and ranchers would see an increased reliance on irrigated forage crops. Moreover, one of the other expected impacts of climate change on NM is the reduction in available water supply. The recently developed water stress index provided by the World Research Institute [1,70] indicated that NM can experience extremely high water stress conditions. Such conditions can significantly impact the state's ability to meet irrigation requirements for a sustainable forage crop production at a reasonable cost in case of increased reliance on groundwater resource. Further analysis is needed to provide more management options (e.g., [71,72]) for sustainable forage

crop, rangeland livestock production, and the overall food production systems in NM, which can also be applicable to other parts of the worlds with similar conditions.

5. Limitations and Future Directions

One of the limitations of the analysis is related to the lack of rigorous economic assessment of NM's farm and ranch budgets which account for all relevant production expenses that include cost of feed supplement, energy use, labor among others. Such analysis would allow evaluating the feasibility of using these forage crop supplements compared to following other livestock production management options such as reducing the number of herd size, the introduction of genetically adapted cattle, or some other options as suggested by [4,71–74]. Additionally, this study did not include a drought indicator that can highlight and allow to evaluate some of the variability in the use of these forage crops supplements during drought and normal conditions. Drought conditions can affect the demand (i.e., increase) for these supplements and consequently, their production and prices. Drought can also affect the availability of the water supply that is needed for irrigation for a sustainable forage crop production. Moreover, the weighted contribution of some of the selected variables needs to be evaluated in a more holistic way. One of the future directions that the authors are considering is related to using an integrated system dynamics approach to account for the weighted contribution of these variables with the provision of additional data. In this regard, the authors obtained some promising preliminary results to support this future direction, as shown in [19].

6. Conclusions

The study focused on evaluating production of hay, grain sorghum, and corn—forage crops that are mainly used as feed supplemental in beef cattle production systems in New Mexico. The study aimed at understanding the relationship between these forage crops and some environmental and socioeconomic variables that include mean annual precipitation, mean annual temperature, crude oil production, crude oil prices, beef cattle population, and mean annual range conditions over New Mexico between 1958 and 2017. Our findings can be summarized as follows.

1. Since 2000, hay production showed a declining trend. In 2017, hay production dropped by about 33% compared to the peak that occurred in 2000. Crude oil production and beef cattle population can partially explain some of the observed declining trend. A declining trend in mean annual hay prices was also observed, but was relatively moderate. In 2017, mean annual hay prices dropped by about 43% compared to the peak that occurred in 1974. Mean annual range conditions were negatively correlated with mean annual hay prices, whereas mean annual crude oil prices showed a positive relationship.
2. Following the peak of 1971, grain sorghum production showed a consistent declining trend since then. In 2017, grain sorghum production dropped by about 91% compared to that of the 1971. Mean annual temperature showed a negative linear relationship with grain sorghum production, while beef cattle population and range conditions showed positive linear relationships. Mean annual grain sorghum prices decreased since the peak of 1974. In 2017, mean annual grain sorghum prices dropped by about 77% compared to those of 1974. Crude oil prices and beef cattle population showed positive linear relationships with mean annual grain sorghum prices.
3. In 2017, corn production dropped by about 61%, compared to the peak that occurred in 1999. Crude oil production and beef cattle population were negatively correlated with corn production. Additionally, mean annual corn prices showed a declining trend since 1974. In 2017, mean annual corn prices dropped by about 75% compared to those of 1974. These findings suggested that a combination of an increased mean annual precipitation and a decrease in crude oil production can result in an increase in mean annual corn prices.

In summary, the findings of this study were aimed at providing an improved understanding of the behavior of forage crop production to support the sustainability of FEW systems in New Mexico

and other similar regions. Particularly, these finding can help in developing a more holistic model (e.g., using system dynamics) that integrates FEW system components to explain their response to internal (i.e., management practices) and external (i.e., environmental) stressors. Such a holistic model can further inform the development and adoption of more sustainable production and resource use practices.

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