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Annual Rainfall and Dryland Cotton Lint Yield—Southern High Plains of Texas

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Abstract

Agriculture in the Texas High Plains (THP) is in a transition phase of producing crops with a diminishing supply of irrigation-water from the Ogallala aquifer to dryland production systems. This shift is driven by the fact that the depth to the water table of the Ogallala aquifer continues to increase. Dryland cotton production systems are prevalent in the southern counties of the THP and our purpose was to use the long-term dryland cotton lint yields from these counties as precursors of the future cotton production patterns that will emerge in this region. For this purpose, from 1972 to 2018, we calculated the ratio of dryland cotton lint yield per unit of annual rainfall at the county level. This ratio is called crop water productivity (*CWP*) and has units of mass per unit volume (g/m^3). In our analysis, we used cotton lint yield data provided by the National Agricultural Statistics and rainfall data provided by the National Oceanic and Atmospheric Administration. Our results indicated that the three datasets used in our analysis, *i.e.*, cotton lint yield, rainfall and *CWP* were all normally distributed. In this time period, 1972 to 2018, only one year 2011—a year with a record drought of 179 mm of rain failed to produce a dryland cotton crop in all the counties used in our analysis. The mean cotton lint yield ± standard deviation ranged from a high of 400 ± 175 kg/ha in Lubbock County to a low of 252 ± 144 kg/ha in Andrews County. However, the counties with the largest *CWP* > 90 g/m^3 were Glasscock, Midland and Martin County. The importance of this result is that these counties are in the southern region of the THP and are subject to extreme environmental conditions and yet cotton producers manage to produce a cotton crop in most years. We conclude that management production methods used by these dryland producers represent the future schemes that will need to be adopted in other counties to sustain the emerging dryland cropping systems across the THP.

Keywords

Crop Water Productivity, Cotton Cropping Systems, Crop Management, Rainfed, Ogallala Aquifer, Water Use Efficiency

1. Introduction

The effect of water, from either precipitation and/or irrigation, on the cropping systems of the Texas High Plains (THP) has been the subject of early and numerous studies. For example, the impact of irrigation was documented in 1921 by E. P. Arneson [1] and the history of irrigation given by [2] and by [3] providing many examples of research on this subject. Likewise, studies on the relation between precipitation and cotton production are given by [4] [5] [6] and by others. Further, the history of irrigated agriculture in the THP is well documented and summaries are given by [1] [7] and by [8].

The development of current cropping systems in the THP is closely related to the introduction of irrigation-water from the Ogallala aquifer, a large aquifer that covers eight states of the Great Plains of the USA [9]. In the THP, the Ogallala aquifer is classified as a closed system, where the withdrawal of water exceeds recharge and thus with time the depth to the water table has increased [10] [11]. The average increase is about 0.3 m/year and on average the depth to the water table has increased by approximately 15 m since measurements started in 1969 [12]. The overall consequence of the decline of the water table from the Ogallala aquifer has been a gradual transition from crop production using irrigation to dryland production [10] [13] [14] [15]. Given the decline of the water table and the increase of the cost associated to pump the remaining irrigation-water infers that in the future, more of the crop production in the THP will derive from dryland cropping systems [9]. For our purpose, we define dryland farming as crop production without irrigation and in a semiarid environment [9].

In recent studies by [16] [17] [18] [19] [20] and by [21], it was discussed that the longevity of the Ogallala aquifer could be extended by converting fully irrigated center pivots to 50% to 75% dryland production and also by optimizing crop management practices when adopting dryland production schemes. Some of these practices include circular planting [22], use of furrow dikes [23] [24], crop rotations and crop residues [25] [26], and minimum tillage [27]. Further, it was suggested that the key factor to enhance dryland production was to capture precipitation and store this water in the profile [28]. Specifically, in the emerging dryland cropping systems of the THP, the emphasis is to capture and to retain precipitation throughout the year and mainly during the growing season.

In the THP, the average long-term rainfall is about 460 mm and most of the rain falls during the growing season; however, both the monthly and annual pattern are variable. The annual standard deviation for rainfall exceeds 150 mm and the monthly coefficient of variation (CV) exceeds 60% [9] [29]. Further, the capture and storage of rain in the soil is a function of the soil physical properties that affect infiltration and runoff, and of the rainfall rate and amount. Measurements of the rainfall rate and frequency of storms for a location in the THP indicate that about 70% of rain events are <6 mm and 86% of events are <13 mm [30]. The relevancy of this result is that attempting to establish a relation between annual precipitation and crop yield is complicated by the fact that rain events < 6 mm are a large contributor of the overall input of water and thus it is difficult to assess how much of this rainfall is stored in the soil and is either available for crop use or is lost to evaporation of water from the soil. Further, 6% of the total rain events are between 25 and 50 mm and the runoff generated from such storms is estimated to be 50% or higher [31]. Thus, establishing a relation between seasonal rainfall and crop yield is not straightforward, as it is difficult to get an accurate estimate of the weekly and monthly amount of rain that may be stored in the soil and subsequently used by the crop.

Dryland cropping systems are prevalent in the southern counties of the THP (**Figure 1**) as evidence of the decline of irrigation-water from the Ogallala aquifer. As this trend continues it is important to understand the relation between rainfall and cotton lint yield. Therefore, our objective was, on first analysis, to establish a relation between measured annual precipitation and reported values of cotton lint yield for dryland production at the county level. For this purpose we selected sixteen counties of the THP delineated by the red line boundary shown in **Figure 1**. In our analysis we used weather data from the National Oceanic and Atmospheric Administration and dryland cotton lint yield data provided by the National Agricultural Statistics, USDA. The southern counties of the THP were selected as precursors of future cotton production patterns that will emerge as the overall cotton production in the THP will be skewed towards dryland production systems.

2. Materials and Methods

2.1. Area of Study

The study area, about 40,000 km^2, consists of sixteen counties and represents the southern boundary of the Great Plains that extend from Canada to south USA. The counties in the THP's are delineated by the red line that demarks their periphery as shown in **Figure 1**. Also given is the approximate boundary of the Ogallala aquifer (blue shade) as reported by the Texas Water Development Board [32]. Note that towards the eastern and southern counties (Crosby, Garza, Borden, Howard, Glasscock and Midland) and as expected, the extent of the Ogallala aquifer diminishes.

The county name and seat, year founded, area, and elevation of the county seat is given in **Table 1**. In general, most counties are about 2300 km^2 in area. The smallest county is Cochran with 2007 km^2 and the largest county is Gaines with 3893 km^2 closely followed by Andrews with an area of 3888 km^2. The oldest

Table 1. County name and seat, year founded, and area for the sixteen counties of the THP shown in **Figure 1**. Also given is the elevation of the county seat and the last column denotes the extent of the Ogallala aquifer in each county.

County	Seat	Year Founded	Area [km^2]	Elevation$^+$ [m]	Ogallala Aquifer
Andrews	Andrews	1910	3888	969	Marginal
Borden	Gail	1876	2347	779	Marginal
Cochran	Morton	1924	2007	1147	Yes
Crosby	Crosbyton	1886	2336	922	Yes
Dawson	Lamesa	1905	2336	912	Yes
Gaines	Seminole	1905	3893	1005	Yes
Garza	Post	1907	2321	794	Marginal
Glasscock	Garden City	1893	2334	804	Marginal
Hockley	Levelland	1921	2354	1073	Yes
Howard	Big Spring	1882	2341	744	Marginal
Lubbock	Lubbock	1891	2334	978	Yes
Lynn	Tahoka	1903	2313	939	Yes
Martin	Stanton	1884	2372	811	Marginal
Midland	Midland	1885	2336	847	Marginal
Terry	Brownfield	1904	2308	1009	Yes
Yoakum	Plains	1907	2072	1111	Yes

+https://elevation.maplogs.com/poi/gail_tx_usa.36177.html.

county is Borden, founded in 1876, and Andrews is the youngest county, founded in 1910. In terms of elevation, the county seats decrease about 250 m from both north to south and from west to east. The highest elevation is 1147 m in Morton, county seat for Cochran and the lowest elevation is 744 m in Big Spring, county seat for Howard (**Table 1**).

The dominant soil orders in the THP are Alfisols in the northern counties and Aridisols in the southern counties. Soils tend to be sandier in the southern region and finer-textured soils are predominant in the northern region of the THP [29]. There are two soil groups in the north, which include the following soil series: Pullman-Randall-Lofton and Amarillo-Acuff-Olton. In the south there is one main group that includes the soil series: Patricia-Brownfield-Nutivoli [33]. The area is characterized by deep soils with accumulations of clay, and of calcium and magnesium carbonate in sub-soil horizons. These accumulations of calcium and magnesium carbonate are known as caliche [34] [35] and play an important role in the storage of rainfall in the soil profile [9] for dryland production.

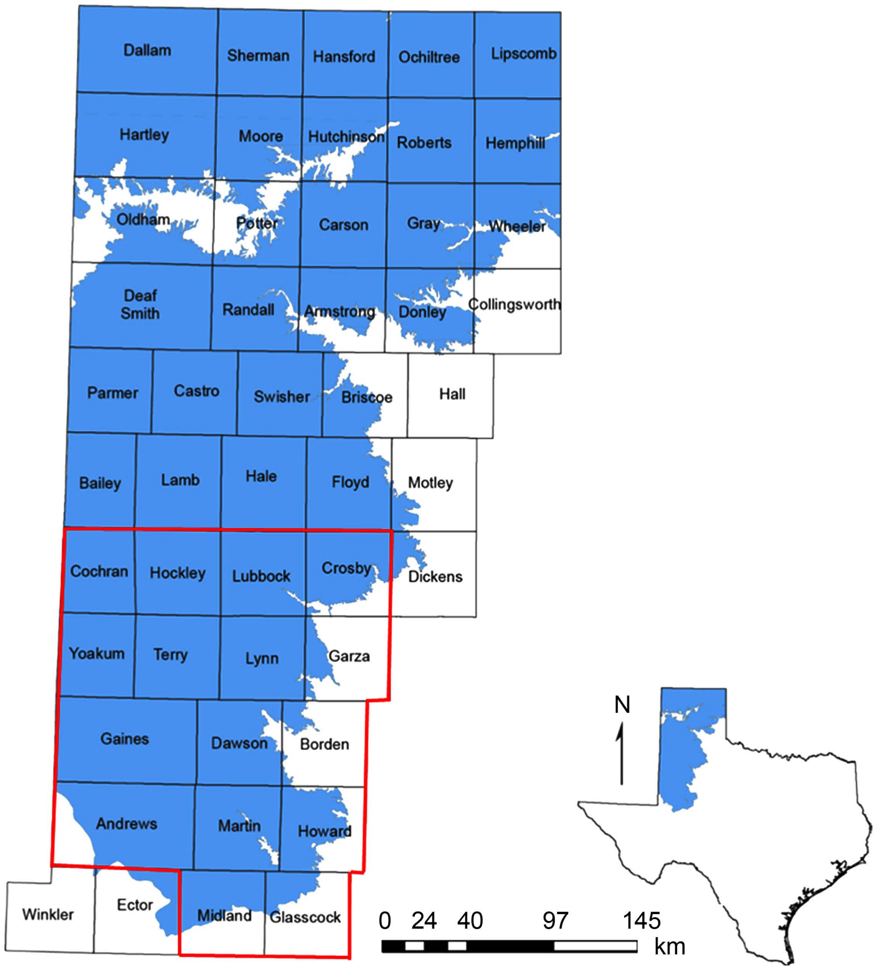

Figure 1. Sixteen counties in north Texas used in the analysis of dryland cotton lint production. The blue area demarks the approximate boundary of the Ogallala aquifer in each county of this region [32].

2.2. Calculation of Crop Water Productivity (*CWP*)

The ratio of cotton lint yield (kg/ha) to evapotranspiration (*ET*, mm) is referred to as water use efficiency (WUE) and as crop water productivity (*CWP*), and both terms have units of mass per unit volume, *i.e.*, kg/ha/mm = 0.1 kg/m^3 = 100 g/m^3. The use of either term, WUE or *CWP*, to reflect crop production has limitations [36] [37] [38]. However, the term *CWP* is preferred over WUE as this metric, *i.e.*, efficiency, implies that both numerator and denominator have the same units, e.g., mass per unit mass (kg/kg) or volume per unit volume (m^3/m^3). An example of a true WUE for cotton of 3.7 g lint per kg of water transpired is given by [39]. Nonetheless, for our analysis we selected and used *CWP* to calculate the ratio of cotton lint yield per unit land area (kg/m^2) and per unit of evapotranspiration (m), *i.e.*, kg/m^3. Thereafter, and for convenience we use g/m^3 as the unit for *CWP*. In the following sections we first describe the numerator (cotton lint yield) and thereafter describe the denominator (*ET*), used to calculate *CWP* as follows:

$$CWP = \text{Cotton Lint Yield}/ET \tag{1}$$

Numerator—Cotton Lint Yield. A record of the values of dryland cotton lint yield for each of the sixteen counties (**Figure 1**) from 1972 to 2018 is given on **Table 2**. This time span represents 36 to 46 values of annual dryland lint yield and this number varies by county. For example, the record for Crosby County from 1972-2018 is for 46 values, and for Midland County, the record is 36 values for the span from 1972 to 2010. Further, missing lint yield values for each county are also listed in **Table 2**. For example, Borden and Midland counties have 11 years were lint yield values are not given likely due to lack of rainfall during those years. The source of this lint yield data is the National Agricultural Statistics Service (NASS) [40]. Values for each county are reported as Cotton Upland Non-Irrigated Yield in Lbs/Acre, which were converted to kg/ha (1.0 Lb/Acre = 1.12 kg/ha). Examples of dryland lint yield values in kg/ha from the NASS website for Crosby, Dawson, Lubbock, Martin and Midland counties are given in **Table 3**. Please note that in all these five counties the cotton lint yield for 2011, is blank, *i.e.*, null value, which was a year with record-low annual rainfall, implying that no dryland cotton was harvested. Also, for Midland County, over a

Table 2. Record of annual dryland cotton lint yield production for each of the sixteen counties in the THP (**Figure 1**) used in our analysis.

County	Record of Dryland Cotton Lint Yield+		
	Span	Number of Years	Number of Missing Years
Andrews	1972-2010	36	8
Borden	1972-2009	36	11
Cochran	1972-2018	40	7
Crosby	1972-2018	46	3
Dawson	1972-2018	45	2
Gaines	1972-2018	44	1
Garza	1972 –2018	44	3
Glasscock	1972-2017	45	2
Hockley	1972-2017	44	3
Howard	1972-2016	42	5
Lubbock	1972-2018	46	1
Lynn	1972-2018	46	1
Martin	1972-2018	45	1
Midland	1972-2010	36	11
Terry	1972-2017	45	3
Yoakum	1972-2017	42	5

+https://quickstats.nass.usda.gov/results/23F8D121-7F98-3A1A-9ABA-E0EF835A5302.

Table 3. Upland non-irrigated dryland lint yield (kg/ha) values as a function of year from 1972 to 2018 for Crosby, Dawson, Lubbock, Martin and Midland counties in the THP (Source: [40]). The number of values (n) for each county is given as the last row.

Year	Upland Non-Irrigated Cotton Yield [kg/ha]				
	Crosby	Dawson	Lubbock	Martin	Midland
1972	661	504	464	334	305
1973	480	555	436	666	392
1974	143	142	171	149	166
1975	285	258	260	451	382
1976	386	475	298	498	371
1977	432	405	517	409	353
1978	188	157	243	198	194
1979	449	473	438	616	565
1980	150	145	156	123	102
1981	343	447	372	489	392
1982	184	322	245	345	351
1983	224	245	312	231	330
1984	295	288	389	210	309
1985	338	349	280	420	356
1986	345	208	203	176	290
1987	423	395	514	554	370
1988	355	544	456	575	461
1989	272	288	318	345	243
1990	318	498	405	545	396
1991	284	303	299	358	268
1992	369	465	582	576	462
1993	351	436	455	544	368
1994	333	223	347	322	268
1995	241	295	280	266	216
1996	382	223	510	306	262
1997	396	377	326	465	373
1998	402	343	225	269	371
1999	294	340	319	313	174
2000	225	256	167	252	187
2001	180	235	206	126	154
2002	268	323	347	272	168

Continued

2003	196	330	250	300	254
2004	651	565	721	398	303
2005	572	599	807	620	469
2006	223	287	211	294	207
2007	718	621	935	798	
2008	344	368	525	445	
2009	383	409	411	467	
2010	526	501	644	494	371
2011					
2012	355	342	306	417	
2013	383		488	272	
2014	428	335	367		
2015	486	465	611	397	
2016	541	493	709	501	
2017	560	534	551	519	
2018	238	540	342	398	
n	46	45	46	45	36

12-year span, between 2007 and 2018, dryland cotton was only harvested and reported in 2010. Midland County is the southmost county of our study area.

Denominator—Evapotranspiration (*ET*). In general, the relationship between crop water use and yield is linear when water is the only limiting factor, and it may be quantified by the water balance of the cropping system with appropriate boundary conditions. A one-dimensional annual water balance is given by the sum of inputs and outputs:

$$Rain + Irrigation + Runon = E_s + E_c + Runoff + Drainage + \Delta Storage \quad (2)$$

where annual inputs are *Rain*, *Irrigation* and *Runon* and annual losses are evaporation of water from the soil (E_s) and crop (E_c), *i.e.*, transpiration (T), and their sum ($E_s + E_c$) is evapotranspiration (*ET*); *Runoff*, *Drainage*, and Δ*Storage* is the annual change of water storage in the profile. In general, the boundary conditions for a crop are set at a screen-height of 2 m above the soil surface and a depth of 2 m below the soil surface. All terms in the water balance equation have units of volume of water per unit ground area, *i.e.*, mm.

As previously noted, we define a dryland system as a crop production without irrigation [9] and thus in Equation (2) the difference between a dryland and an irrigated cropping system is given by the inclusion of the irrigation term. Further, the input *Rain* through the infiltration process can either store water in the soil (Δ*Storage*) or lose water as *Runoff*. Collectively, this is referred to as effective rain, *i.e.*, the net amount of water from a rain event that is stored in the soil. *Drainage* is water that moves below the root zone and *Runon* is surface water that moves from adjacent fields and both these terms for the semiarid conditions of the THP are assumed to be negligible. Thus, the annual water balance for a dryland cropping system and from Equation (2) simplifies to the sum of *ET* and Δ*Storage:*

$$Rain_{effective} = ET + \Delta Storage \tag{3}$$

A further and an important assumption made is that in dry environments (semiarid and arid) and on annual basis is that no rainfall is stored in the soil as it is quickly used by the plants through *ET*, *i.e.*, $\Delta Storage \approx 0$ [41] [42] [43]. This assumption is particularly applicable to the THP where about 85% of the annual rain falls during the growing season from April to September [29]. Thus, Equation (3) further simplifies to:

$$Rain_{effective} = ET \tag{4}$$

In summary, assuming that *Drainage*, *Runoff*, *Runon* and Δ*Storage* are negligible for the annual water balance of a dryland cropping system in a semiarid climate allow us to use measured values of annual *Rain* as a surrogate for annual values of *ET*. Thus, we use *Rain* as the denominator to calculate *CWP* in Equation (1).

2.3. Rainfall Data

As the source of rainfall data for each county in **Figure 1**, we used data given by the National Oceanic and Atmospheric Administration (NOAA) (https://www/ncdc.noaa.gov/cdo-web/). A summary of the number of weather stations, and period of coverage, in both time and percent, number of years, between 1972 and 2018, that rainfall data were not given for each county is given in **Table 4**. This represents the time-period where cotton lint yield data are reported (**Table 2**). All counties include at least two weather stations, Garza includes 5, Midland includes 7, and Lubbock includes 21 weather stations. Most counties have a 100% coverage over the measurement period, start to end, while Cochran has a 74% and Glasscock has a 76% coverage. In nine counties (Andrews, Borden, Dawson, Garza, Glasscock, Lubbock, Lynn, Midland and Terry) rainfall records start in 1911-1915. The longest record is from Crosby County, which is 126 years, and started in 1895. The shortest record is 78 years, starting in 1943 in Howard County. For each county, the average of all the weather stations were used to calculate the annual value of rainfall and this was the value used as *ET* in Equation (1) to calculate *CWP*.

2.4. Statistical Analysis

All cotton lint yield and rainfall data were checked for normality and the four moments of these values were calculated, *i.e.*, mean, variance (standard deviation), skewness and kurtosis. Normality was checked using the χ^2 distribution

Table 4. Weather station details for each county. Shown are the number of weather stations in each county, the period of record where precipitation was reported and the corresponding coverage (source: https://www.ncdc.noaa.gov/cdo-web/).

County	Weather Station Details				
	Period of Record - Precipitation				
	Included No. of Stations	Start	End	Years missing (1972-2018)	Coverage (%)
Andrews	2	01-01-1914	01-01-2018	13	87
Borden	3	01-01-1913	01-01-2021	1	100
Cochran	2	01-05-1936	01-01-2020	9	74
Crosby	3	01-01-1895	01-01-2020	0	100
Dawson	2	01-01-1911	01-01-2017	6	81
Gaines	2	01-01-1923	01-01-2020	4	87
Garza	5	01-01-1911	01-01-2020	7	100
Glasscock	3	01-01-1913	01-01-2020	18	76
Hockley	4	01-01-1936	01-01-2020	2	100
Howard	6	01-01-1943	01-01-2020	3	100
Lubbock	21	01-01-1912	01-01-2020	0	100
Lynn	4	01-01-1914	01-01-2020	0	100
Martin	3	01-01-1941	01-01-2020	14	100
Midland	7	01-01-1912	01-01-2020	0	100
Terry	2	01-01-1915	01-01-2020	1	95
Yoakum	2	01-01-1925	01-01-2020	12	80

function (CHIDIST) that calculates the right-tailed probability of this function, using a *p-Value* of 0.05. The syntax for this function is CHIDIST(x, df), where x is the χ^2 statistic and df are degrees of freedom. We tested the null hypothesis (H_o) that the data is normally distributed using a *p-Value* of 0.05. For all of our statistical calculations we used a spreadsheet and used two tools, *i.e.*, histogram and descriptive statistics (Microsoft® Excel, version 16.17.27). The histogram tool charts the data by grouping the variable of interest into intervals, *i.e.*, bins, of equal width. The descriptive statistics tool calculates the mean, standard error, median, mode, standard deviation, sample variance, kurtosis, skewness, range, maximum, minimum, sum, count, and the confidence level at a 95% for the data set values. We did not attempt to detrend the dryland upland county-level lint yield values as done for example, by [44].

3. Results and Discussion

This section is presented in the same sequence that was used to calculate values of crop water productivity (*CWP*). First, we present results of dryland cotton lint yield; second, we report annual mean rainfall; and third, values of *CWP*, *i.e.*, the ratio of cotton lint yield to rainfall are presented and discussed. Values of cotton lint yield, rainfall and *CWP* are given in both tabular and in graphical format for each of the sixteen counties of the Texas High Plains (**Figure 1**). For each of these datasets we calculated frequency distributions and associated statistical parameters that include the moments of the mean, *i.e.*, standard deviation, skewness and kurtosis, and also the mode and median values.

3.1. Cotton Lint Yield

The descriptive statistics for cotton lint yield are given in **Table 5** and a ranking of these values from high to low, for each of the sixteen counties (**Figure 1**) are given in **Table 6**. The mean value ± standard deviation of dryland lint yield was 353 ± 150 kg/ha, with a range from a low of 38 kg/ha to a high of 1004 kg/ha. The frequency distribution of the annual values of upland lint yield (**Figure 2** and **Figure 3**) indicated that the *p-Value* calculated with the χ^2 distribution function and 38 degrees of freedom was equal to 0.108, which is greater than the *p-Value* of 0.05 and thus we accept the null hypothesis that the data is normally distributed.

The range between the highest mean cotton lint yield (400 kg/ha in Lubbock County) to lowest (252 kg/ha in Andrews County) is 148 kg/ha or a relative

Table 5. Descriptive statistics for upland dryland cotton lint yield, annual rainfall, and calculated values of crop water productivity for all sixteen counties of the THP.

Statistical Parameter	Cotton Lint Yield [kg/ha]	Annual Rainfall [mm]	Crop Water Productivity [g/m^3]
Mean	353	461	77
Standard Error	5.73	4.5	1.49
Median	334	452	73
Mode	262	272	79
Standard Deviation	150	162	36
Sample Variance	22,386.5	26,288.8	1,324.4
Kurtosis	0.596	0.759	3.472
Skewness	0.706	0.622	1.205
Range	966	1052	281
Minimum	38	77	10
Maximum	1,004	1,129	291
Sum	240,141	602,803	46,229
Count	681	1307	597
Confidence Level (95%)	11.3	8.8	2.9

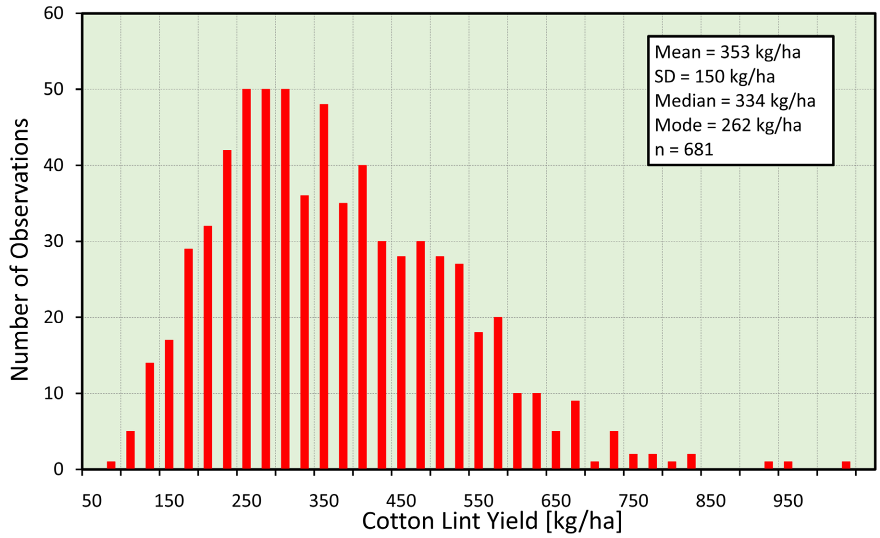

Figure 2. Frequency distribution of upland dryland lint yield values (kg/ha) for all values (n = 681) of the sixteen counties of the THP. The overall mean, standard deviation (SD), mode and median values are given in the insert.

Table 6. Ranking of counties, high to low, for the mean annual upland cotton lint yield and mean calculated values of crop water productivity for the period from 1972 to 2018.

Rank	Cotton Lint Yield [kg/ha]		Crop Water Productivity [g/m³]	
	County	Value	County	Value
1	Lubbock	400	Glasscock	94
2	Martin	394	Midland	93
3	Lynn	385	Martin	91
4	Howard	381	Lubbock	86
5	Dawson	376	Dawson	81
6	Borden	375	Borden	81
7	Glasscock	373	Gaines	79
8	Crosby	361	Cochran	78
9	Garza	356	Lynn	76
10	Hockley	344	Howard	74
11	Gaines	335	Yoakum	74
12	Terry	327	Hockley	73
13	Cochran	321	Terry	70
14	Yoakum	318	Garza	68
15	Midland	311	Crosby	66
16	Andrews	252	Andrews	60

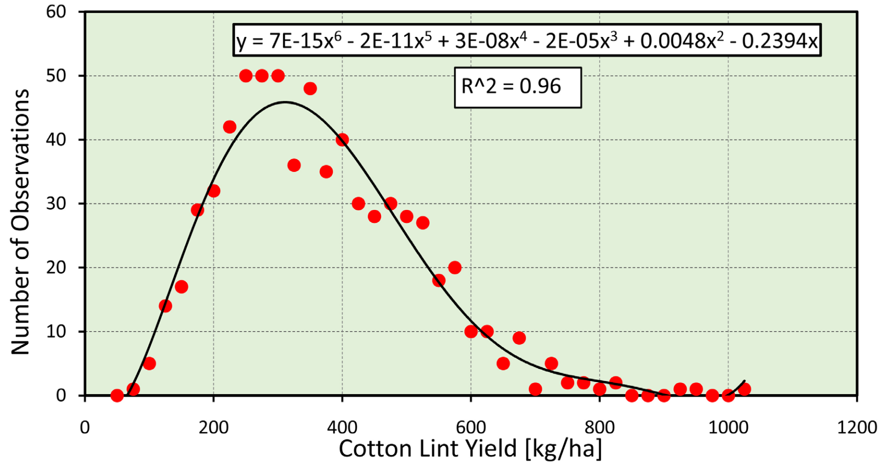

Figure 3. Frequency distribution of upland dryland lint yield (kg/ha) for the sixteen counties of the THP. The equation given is a 6th order polynomial curve with a correlation coefficient (R^2) of 0.96.

difference of 37% (**Table 6**). For the top nine counties, Lubbock, Martin, Lynn, Howard, Dawson, Borden, Glasscock, Crosby and Garza the annual lint yield values are within 11% of each other. For the remaining counties, *i.e.*, Hockley, Gaines, Terry, Cochran, Yoakum, Midland, and Andrews the annual mean lint yield ranged between 14% to 37%, equivalent to about 92 kg/ha from 252 to 344 kg/ha, compared to the highest mean cotton lint yield of 400 kg/ha in Lubbock County. Two counties, Midland and Andrews (**Figure 1**) had the lowest annual mean lint yield values of 311 and 252 kg/ha, respectively. In general, the mean lint yield of five western counties (Cochran, Yoakum, Gaines, Andrews, and Midland) are the lowest; four central counties (Lubbock, Lynn, Dawson, Martin) have the highest annual lint yield values; and four eastern counties (Crosby, Garza, Borden, and Glasscock) are in the middle between the highest and lowest mean cotton lint yield values (**Table 5**, **Figure 1**). Similar values of cotton lint yield under dryland conditions for the THP are given by [5] [6] [45] [46] and by others.

Other statistical parameters given in **Table 5** are two moments of the mean, *i.e.*, kurtosis and skewness. Kurtosis describes the "flatness" of the frequency distribution curve (**Figure 2** and **Figure 3**). Perfectly symmetrical datasets will have a kurtosis of approximately 3 and the values given in **Table 5** suggest a platykurtic distribution. Likewise, skewness is a metric to indicate the symmetry of the dataset and a perfectly normal distribution has a value of zero. The average skewness for the 16 counties is 0.7 (**Table 5**). Other parameters given are the median and mode. The median is a measure of central tendency and ranges from 225 kg/ha (Andrews) to 504 kg/ha (Dawson) with a mean value of 334 kg/ha for the sixteen counties. The mode is also a metric of central tendency and is the most frequent value in the dataset, which was 262 kg/ha. The lowest mode was 183 kg/ha (Borden) and highest mode was 504 kg/ha (Glasscock).

The curve describing the frequency distribution of all the dryland cotton lint yield values (n = 681) is given by a sixth order polynomial equation (**Figure 3**), which has a correlation coefficient (R^2) of 0.96. The mean value (353 kg/ha), SD of 150 kg/ha, median (334 kg/ha) and mode (262 kg/ha) are given in the histogram of the upland lint yield values (**Figure 2**).

3.2. Rainfall

The frequency distribution of all values (n = 1307) of annual rainfall for the sixteen counties of the THP are plotted in **Figure 4** as a histogram and as a curve in **Figure 5**. This histogram includes all rainfall data shown in **Table 4**. The

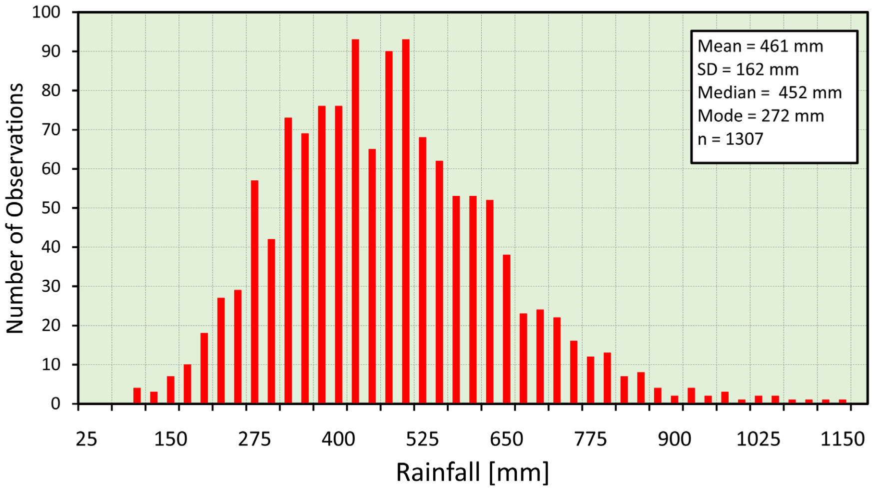

Figure 4. Frequency distribution of annual rainfall (mm) for all values (n = 1307) of the sixteen counties of the THP. Statistical parameters such as the standard deviation (SD) of the mean, mode and median value are given in the insert.

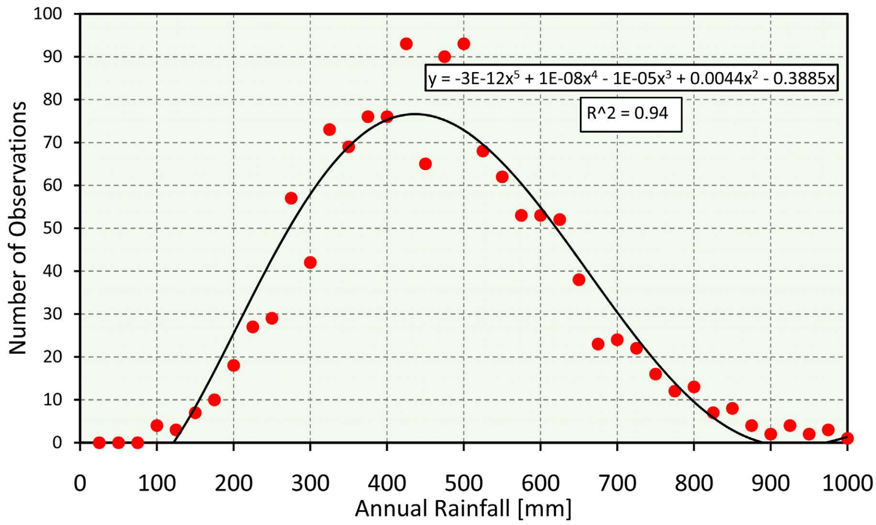

Figure 5. Frequency distribution of the annual values of rainfall for the sixteen counties of the THP. The equation given is a 5th order polynomial curve with a correlation coefficient (R^2) of 0.94.

frequency distribution of the annual values of rainfall (**Figure 4** and **Figure 5**) indicated that the *p-Value* calculated with the χ^2 distribution function and 44 degrees of freedom was equal 0.10, which is greater than the *p-Value* of 0.05 and thus we accept the null hypothesis that the rainfall data is normally distributed. The mean annual rainfall is 461 mm, with a standard deviation of 162 mm, mode of 272 mm and median value of 452 mm (**Figure 4**). This frequency distribution is described by a fifth order polynomial equation with a correlation coefficient (R^2) value of 0.94 (**Figure 5**). Descriptive statistics for the mean annual rainfall of all counties are given in **Table 5**.

The annual mean rainfall for the 49-year period from 1972 to 2020 for all 16 counties is plotted in **Figure 6**. This time-period represents the time-span for the length of cotton lint yield record. The driest county is Midland with an average rainfall of 374 mm (79% of the mean value of 475 mm) and closely followed by Andrews with 380 mm (80% of the mean). The two wettest counties are Garza (547 mm, 115% of the mean) and Crosby (566 mm, 119% of the mean). In general, rainfall increases on average by 30 to 40 mm from west to east. These average values of rainfall are similar to those values reported for the US cotton growing region for a 30-year average rainfall [47]. They indicated an average annual rainfall value between 400 to 500 mm for the sixteen counties of the THP (**Figure 1**) and that this average increased by 100 mm, from 400 to 500 mm from west to east (see their Figure 2 in [47]).

The annual rainfall for each of the sixteen counties of the THP for a 49-year record, from 1972 to 2020 is given in **Figure 7**. The driest year in this time-span was 2011 with 179 mm, followed by 1998 with 278 mm of rain. The 20-year period, 2001 to 2020, has recorded five of the driest years in the THP. The two wettest years were 2004 with 843 mm and 1986 with 736 mm. In the 20-year span, 2001-2020, the THP recorded four of the wettest years. The overall mean ± SD rainfall for the 49-year record was 475 ± 119 mm (**Figure 7**). This value is

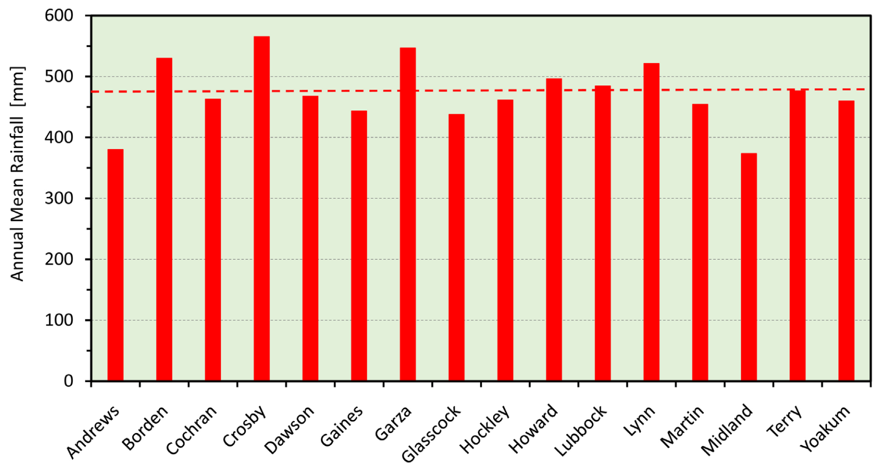

Figure 6. Annual mean rainfall (1972-2020) for each of the sixteen counties of the THP. The red dashed line is the overall mean rainfall of 475 mm for the entire region.

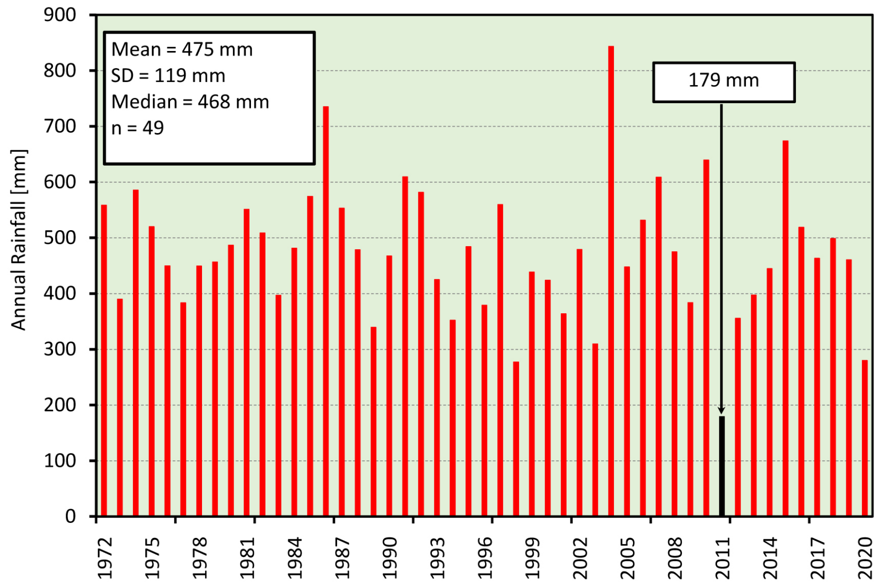

Figure 7. Annual mean rainfall (mm) for all counties of the THP between 1972 and 2020. The black bar is the record low value of 179 mm of rain in 2011. The mean value of rainfall is 475 mm, with standard deviation of 119 mm, and median value of 468 mm.

slightly larger (3%) when compared to the mean rainfall when including all measured values across the THP of 461 ± 162 mm (**Figure 4**). However, the SD of all values was 36% larger, 162 vs. 119 mm.

3.3. Crop Water Productivity (*CWP*)

Descriptive statistics for calculated values of CWP for all counties of the THP are given in **Table 5**, and ranking, from high to low, for each the 16 counties of the THP are given in **Table 6**. The value of *CWP* as defined in Equation (1) is the ratio of lint yield (kg/ha) to annual rainfall (mm) and thus a larger value of *CWP* indicates more production, *i.e.*, more lint (g) per unit of water (m^3), which for this semiarid region is per unit of rainfall. The calculated mean values of *CWP* have a range from a high of 94 g/m^3 (Glasscock) to a low of 60 g/m^3 (Andrews), this difference of 34 g/m^3 is equivalent to 36%. This relative difference is similar as that measured for mean values of cotton lint yield of 400 kg/ha (Lubbock) vs. 252 kg/ha (Andrews) (**Table 6**). The top two counties with the largest *CWP* are Glasscock and Midland with a value of ~93 g/m^3. This is an interesting result given that Midland was penultimate in the ranking of mean annual lint yield (**Table 6**). In general, the *CWP* rankings can be grouped into four categories, *i.e.*, 90's (Glasscock, Midland, Martin, Lubbock); 80's (Dawson, Borden, Gaines, Cochran and Lynn); 70's (Howard, Yoakum, Hockley, Terry, Garza, and Crosby); and 60's (Andrews). These values of *CWP* fall within the range, 70 to 330 g/m^3 for cotton given by [48] and of 50 to 250 g/m^3 given by [47]. As expected, higher values of *CWP* are for irrigated cotton lint yields.

Statistical parameters given in **Table 5** include standard deviation (SD), maximum and minimum values, the moments of the mean (kurtosis and skewness), and mode and median. Values of *CWP* are variable with a high SD of 46 g/m^3 (Midland) to a low SD of 26 g/m^3 (Cochran). The average CV across all values of *CWP* is 47%. The largest value of *CWP* was calculated in 2010 in Cochran County with a value of 291 g/m^3, *i.e.*, lint yield of 553 kg/ha with 190 mm of rain. Values of *CWP* > 200 g/m^3 were recorded twice in Midland in 1998 (371 kg/ha with 143 mm) and in 1977 (353 kg/ha with 174 mm), once in Borden County in 1973 (729 kg/ha with 308 mm), once in Lubbock County in 2005 (807 kg/ha with 393 mm), and once in Glasscock County in 1988 (332 kg/ha with 164 mm). On the opposite end, values of *CWP* < 15 g/m^3 were recorded in 1974 in Borden (86 kg/ha with 578 mm) and in Terry County (67 kg/ha with 664 mm) in 1973 in Andrews County (38 kg/ha and 349 mm), and in 1980 in Cochran County (90 kg/ha with 640 mm). Clearly, the issue here was not lack of rainfall, but rather was likely due to hail damage during the growing season. These are examples, of years with probably excessive rainfall accompanied by low ambient temperatures that negatively affected the cotton crop.

Midland County is an example that illustrates the importance of not only the total amount of rain but also of its distribution during the growing season. Midland recorded two of the largest CWP's in 1977 and in 1988; however, between 2007 and 2018 only one cotton crop, in 2010, was harvested. This high values of *CWP* achieved in Midland are likely to the "timing" of rainfall occurring during critical stages of boll filling and maturation [49]. Clearly, it was not the total amount of rainfall that determined the final cotton lint yield but rather it was due to its timing and distribution throughout the growing season. Also, other environmental factors, such as heat units [50], from planting to harvest [51], and management of the crop (fertilization and tillage operations) contributed to the final lint yield [52].

The statistical parameters for *CWP* given in **Table 5** indicated a kurtosis of 3.47 and a skewness of 1.20, which is an indication of a symmetrical data set. Further the mean value of *CWP* is 77 g/m^3, with a median of 73 g/m^3 and mode of 79 g/m^3 suggesting a normal distribution (**Figure 8** and **Figure 9**). The *p-Value* calculated with the χ^2 distribution function and 27 degrees of freedom was equal to 0.222, which is greater than the *p-Value* of 0.05 and thus we accept the null hypothesis that the *CWP* dataset was normally distributed. The frequency distribution of the calculated values of *CWP* is described by the fifth order polynomial curve plotted in **Figure 9**. The correlation coefficient (R^2) of this curve is 0.94.

The *CWP* is a metric that is often used to compare crop production subject to different conditions [47]. The term *CWP* is preferred over water use efficiency (WUE) [48] as WUE involves an efficiency term that by definition has no units [36] [37] [38]. The scaling of *CWP* from field to a regional scale can be accomplished by using areas that are homogenous with respect to the soil and hydrological properties [53]. In our case we are using mean values of cotton lint yield that are reported at the county level with corresponding mean values of rainfall for the county.

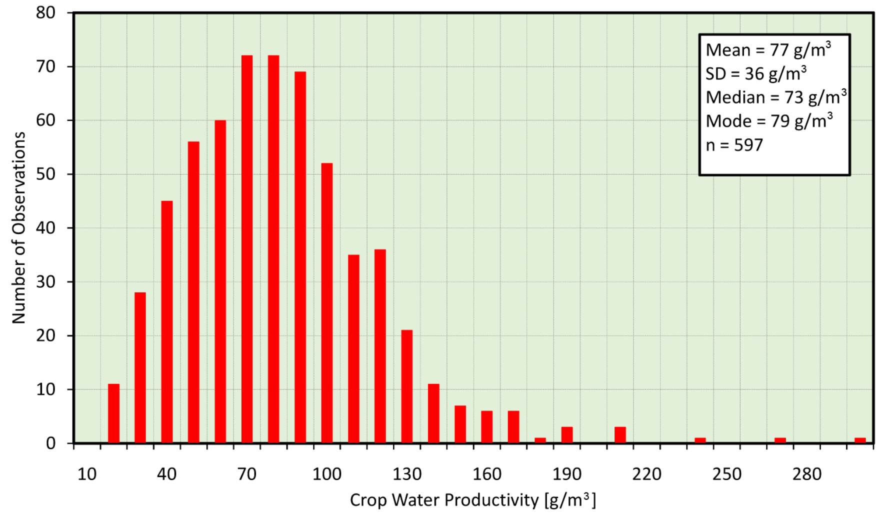

Figure 8. Frequency distribution of Crop Water Productivity (*CWP*, g/m^3) for all values (n = 597) of the sixteen counties of the THP.

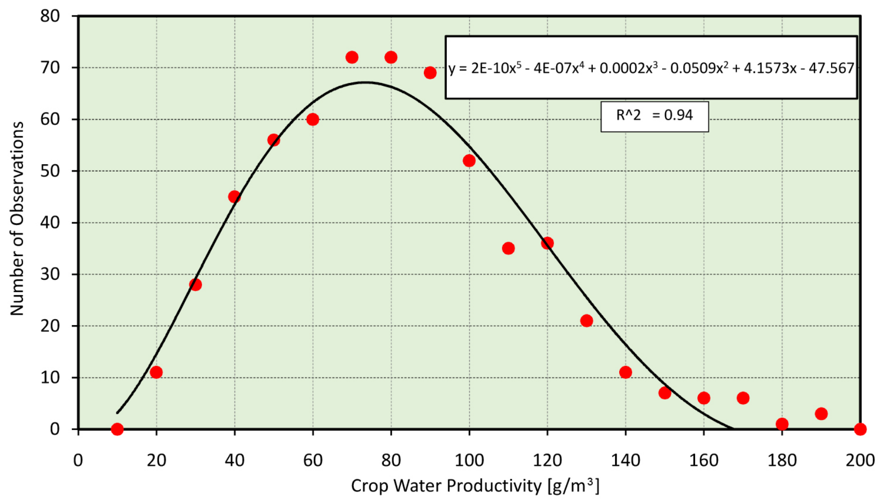

Figure 9. Frequency distribution of calculated values of Crop Water Productivity (*CWP*, g/m^3) for the sixteen counties of the THP. The equation given is a 5th order polynomial curve with a correlation coefficient (R^2) of 0.94.

In a farming operation the final crop yield is a function of many factors. These include crop rotations, the amount of soil water stored in the profile, thermal units throughout the growing season, soil tillage operations, fertilization and pest management, and frequency and amount of rainfall during the growing season. In our analysis we have only considered the annual rainfall amount at the county level. Further, we assume that for the conditions of the THP and its semiarid environment, a proxy of the annual evapotranspiration (*ET*) at the county level is given by the annual amount of rain, *i.e.*, $ET \approx Rain$ [41] [42] [43], and therefore this assumption allow us to calculate *CWP* as the ratio of cotton lint yield to rainfall.

From a water management point of view, the success of a dryland cotton farming operation in the semiarid region of the THP primarily depends on first having adequate soil moisture at planting to germinate and emerge the planted seed. Second, once the crop is established it needs adequate rain throughout the growing season. Third, stored soil water in the profile can provide 25 to 100 mm of additional water [9]. However, the rainfall frequency and amount during the growing season is by far the largest contributor that will determine the cotton lint yield that is harvested. Such is the case based on the length of the record (**Table 2**) of cotton lint yield values (**Table 5**) for the THP. Since 1972, only one year 2011, a record drought (179 mm of rain) failed to provide a harvestable cotton crop across all counties of the THP. Midland, the southmost county of our analysis has failed to produce a cotton crop once every five years in the 1972-2018 time period. However, Midland County also has the distinction of having the largest *CWP* (93 g/m^3) for this time period. Further, three counties located in the South region of the THP, *i.e.*, Glasscock, Midland and Martin County have values of *CWP* > 90 g/m^3 (**Table 6**) and Glasscock and Martin have only twice during this time period failed to harvest a cotton crop. This achievement is due to the excellence of the cotton farmers that manage to produce a cotton crop year-after-year under dryland conditions. This accomplishment means the success of dryland cotton production in the THP and many of the management decisions that are used in these counties can be applied to others to sustain the emerging cotton industry in the THP.

Our analysis of dryland cotton lint yield across sixteen counties of the THP is solely based on annual average values of lint yield and rainfall at the county level, and in our analysis we use average rainfall as a surrogate of annual evapotranspiration to calculate *CWP*. Our results show that dryland cotton production is a sustainable farming enterprise in the THP. Further, the largest values of *CWP* were calculated for counties that normally experience drought and extreme environmental conditions, and yet farmers manage to produce a cotton crop most years. The significance of this result is that management schemes that these producers implement represent the future of emerging dryland cropping systems of the THP. For this purpose we have implemented a long-term project working with dryland cotton producers in Martin County. Our intent is to document and to understand their decision-making process regarding agronomic management practices. In turn, we can then use this information as input to cropping system models to analyze both the short- and long-term sustainability of dryland cropping systems across the THP.

4. Conclusions

Crop production in the Texas High Plains (THP) is a transition phase from using limited irrigation-water from the Ogallala aquifer to dryland practices, where rain is the only source of water. For the continued success of the emerging dryland cropping systems, we need to identify agronomic practices that are viable in this semiarid region. Thus and as first analysis, we calculated for sixteen counties of the THP the ratio of annual dryland cotton lint yield per unit of evapotranspiration for the period from 1972 to 2018. This ratio is called crop water productivity (*CWP*) and has units of mass per unit volume (g/m^3). In the calculation of this ratio, we assumed that for an annual water balance, the evapotranspiration amount can be approximated by the annual measured rainfall. Our results indicated that over this 47-year period only one year, 2011, failed to produce a cotton crop across all counties, which was a year with a record drought of 179 mm of rainfall. Average values of dryland cotton lint yield ranged from a high of 400 kg/ha in Lubbock County to a low of 252 kg/ha in Andrews County. However, counties with the largest values of *CWP* > 90 g/m^3 were Glasscock, Midland and Martin County. This is a significant result as these counties are geographically located in the southern region of the THP, and are subject to extreme environmental conditions, and still farmers manage to produce a cotton crop in most years. Our conclusion is that agronomic practices used by these cotton producers need to be studied and adopted in other counties of the THP. For this purpose, we have established a long-term pilot project with cotton farmers of Martin County with the aim of studying their management practices. Our working hypothesis is that the management production practices currently used by Martin County cotton farmers represent the future schemes that may need to be adopted in other counties of the THP to sustain the emerging dryland cropping systems across the THP.

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Declarations

Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendations or endorsement by the US Department of Agriculture. The USDA is an equal opportunity provider and employer.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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