

Climate change induced changes in moisture availability in eastern Wyoming ranchlands with management recommendations for adaptation

by
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Abstract

In the future there is an expectation for climate change to have impacts on both natural systems and agricultural enterprises. A number of studies have been conducted for the purpose of determining the effects of a changing climate on agricultural enterprises, but most of these studies are large scale in their scope and give non-specific recommendations for adaptation. In the United States much of agriculture, including ranching, requires large capital shifts to change their products and as such they need to have more specific advice as to how to respond. Having more specific advice today also means that individuals in agriculture can start planning to adapt today, rather than being surprised a few decades from now.

This project utilizes historical climate information and projections of future temperature and precipitation based on IPCC regional expectations and local climate variability. These projected values were used in two versions of the Thornwaite moisture balance model to calculate a range of possible changes for moisture availability from 2009 to the year 2100. The estimated changes in available moisture (potential evapotranspiration, soil moisture, atmospheric moisture deficit, etc.) were compared to the baseline values to determine the decrease from normal values. The literature was searched to determine the amount of decrease in moisture availability that would likely result in ecological drought and hinder production. The evidence indicates that there will be varying degrees of diminishing of available moisture dependent upon the amount of temperature increase. Because of the range of possible impacts, a variety of management practice recommendations are included, as well as mechanisms to monitor the climate more carefully to better spot droughts as they begin. For scenarios with severe shifts in the climate, recommendations are made to make strong changes in their production methods or the uses of the land.

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Introduction

Over the past several years, climate change has become a big issue in the scientific, political and social realms. This is well justified since it is quite likely that the effects of a shift in climate will have impacts on many areas of human life around the world. To understand the risks that we face depends on the level of mitigation that we choose to engage in and the possible adaptations that we will have to utilize to prepare for the future, a wide range of studies need to be conducted. This project is intended to be a part of that literature.

Of the areas of climate change impacts that have been examined thus far in research efforts, studies of regional effects on agriculture and the required management practice changes and adaptation measures has been inadequate. It is an important area of research, since droughts “are still the single most important factor affecting world food security,” and are likely to increase in the future (McWilliam, 1986). This information is necessary for agriculturalists, because they need to have an idea of the level of impact they will experience and how to deal with it as the changes occur. Towards that goal this project worked to understand the likely moisture variations that will occur in the future due to predicted climate changes and make management recommendations for adaptation.

The inspiration for this particular project came from talking with cattle ranchers in eastern Wyoming during the winter of 2005. They spoke of being in a drought for the last few years and having to sell off some of the cattle from their herds to keep their land from deteriorating too much. It occurred to me that their problems with water deficits may already be and may further be affected by the changing climate, and I discussed this issue with them at great length. When I left I told them that I would try to conduct a project for the sake of being able to tell them the changes they should expect in the future and how to respond.

There are a number of changes that are likely to occur which will decrease moisture availability into the future for eastern Wyoming. First, the energy industry growing in Wyoming and the

subsequent growth in population is likely to increase pressures for fresh water from surface sources and groundwater. Second, an increase in evaporation which N.W. Arnell (1999) stated will increase worldwide under climate change. This is because with an increase in temperature the relative humidity decreases, and with a lower relative humidity, evaporation increases. These hazards make preparing today an important task.

Exploration of the relevant literature found that “[studies indicate] 60% of the climate related trends of river flow, winter air temperature, and snow pack between 1950 and 1999 are human induced. They portend, in conjunction with previous work, a coming crisis in water supply for the western United States” (Barnett *et.al.* 2008). Also, Seager *et. al.* (2007) stated that there is wide agreement between climate models that the southwestern United States will experience drying during the 21st century and that it is possible that this effect is already being felt. In that same article they also stated that the subtropical dry zones are expected to shift poleward during the next century due to the shift in atmospheric circulation cells (Hadley cells). With drying trends occurring to the south, and a northward shift in the subtropical dry zones that are currently present in the southwest, it’s likely that climate conditions in Wyoming will shift to being even drier. Since the landscape is already arid, a decrease in moisture could push the climate towards a desert climate such as in the American southwest.

This project is important, not just for the impact of the agricultural loss due to diminishing beef yields in the rangelands of eastern Wyoming, but also from the cultural impact that the change in livelihood would cause for Wyoming ranchers. Their cultural and familial heritage is tied to the ranching lifestyle, and if they are unable to continue ranching, they will not only lose their livelihood but also their way of life. In addition, drought is already an ongoing problem for most of the ranching areas of the country, with the southwest experiencing drought 43% of the time, the southern Great Plains 27%, and the northwest 13% (Howery, 1999). It’s quite possible to make comparisons between the area of study

in Wyoming and other drought prone high plains desert rangelands in the United States. This possible comparison makes the project of some use to people in these other regions.

Settings

In this study, the term eastern Wyoming refers to the flat plains of Wyoming; primarily those that lie east of the Bighorn and Laramie mountain ranges, although a region of flat plains between the two mountain ranges in the area of Casper could be considered to be the same landform. Overall, this region of Wyoming is very dry, which is due to climate variables such as the rain shadow from the Laramie and Big Horn mountain ranges to the west of the state as well as the Rocky Mountains (Figure 1). Most of the precipitation that is received is through regional storms, and because of this the state almost always receives some precipitation (Smith, 2007). The area of particular focus is the region of eastern Wyoming that is fairly uniform in its precipitation and elevation, from Casper to Lusk and northward to Gillette (Figures 1 & 2).



Figure 1. Map of Wyoming showing surface water, landscape relief, and locations of mountain ranges. http://www.lib.utexas.edu/maps/us_2001/wyoming_ref_2001.jpg

small streams or underground water sources being the main sources of water for use for ranching. It is important to note that some of these streams are known to dry up during times of drought.

Data & Methods

General Methodology

For this project, it was necessary to find likely estimates for climate change in eastern Wyoming for the next 100 years. These estimates were acquired from Chapter 11 of the Working Group I of the Intergovernmental Panel on Climate Change's Fourth Assessment Report. This chapter pertained to expected changes in the region for the period of 2080-2099 as compared to 1980 to 1999. The predictions indicate that the area of interest in Wyoming will have a temperature increase between 3.5° and 4.0°C, and the precipitation increases are expected to be 0-10% annually with a 10-15% increase for December, January and February and about a 0-10% decrease in June, July and August.

A baseline of monthly temperature values was created using the 3220 Summary of the Month datasets from the Redbird and Lusk 2 National Climate Data Center (NCDC) sites in Niobrara County in eastern Wyoming. The baseline was created by calculating the temperature averaged for each month over period of 1980-2007, which approximates the methodology of the IPCC's estimates. Starting in the year 2009, the amount of temperature increase being modeled was a linear change from 2009 through 2100. The amounts of temperature increases utilized were 2°, 2.5°, 3°, 3.5°, 4°, 4.5°, and 5°C. These are a reasonable range of values for what will likely happen in the future, due to the possibilities of a range of emissions under varying scenarios and uncertain climate sensitivity. A baseline for precipitation values was created in the same way that a baseline for temperature was, with the difference being that precipitation that fell when the average monthly temperature was below 0 was retained and released in the first month that had above freezing temperatures, to simulate the effect of snowmelt in spring.

Data on soil moisture was acquired using the National Resource Conservation Service's Soil Climate Analysis Network (SCAN) data of volumetric soil moisture percent for Torrington, WY. This data

was used in conjunction with the Thornwaite moisture model to estimate future values for potential evapotranspiration and soil moisture. Current measurements of temperature and pan evaporation for the Sheridan NCDC data site in eastern Wyoming were used to calibrate the model to Wyoming.

Specific Methodology

The first information that was downloaded and manipulated was the soil moisture data from the NRCS's SCAN data. The measurements were on an hourly and a daily basis, and the values from 6:00 AM of every day and for the depths of 2, 4 and 8 inches were averaged over the course of the month. The averaging was conducted for the three separate depths for the same day, and then all days for the month were averaged together. However, the data values from the first years of the record were flawed, with the sensors having too large values in the summer and negative values in the winter, and a break followed this period during which it is likely the instruments were improved or better calibrated. So, the soil data values from these first years are disregarded for further use. Also, due to difficulties with the dataset, data on the precipitation and temperature values for the SCAN site wasn't acquired, and this prevented comparison of calculated soil moisture values to known values.

Before any of the data could be used, it needed to be cleaned up and edited. Extensive manipulation of the data was required, both due to the features of the acquired data and how data needed to be formatted to be useful in Excel. Both the datasets were in text format and were imported into Excel using the "Get External Data" function. The SCAN site data was downloaded in single month segments, and in order to enter the data into a single Excel workbook each month of data from the SCAN site was entered into its own worksheet, creating a workbook with 146 worksheets. The SCAN site data was also in a format that had multiple soil measurements during the course of a single day. This meant that there were multiple measurements for a particular day that were hard to acquire data from, and this posed a challenge since the analysis required a single measurement for each day that was from the same time. To select a single measurement for each day required using Excel's "IF" function to

choose the cells containing soil moisture data that corresponded to the same time every day and label as "FALSE" all the cells that didn't meet the criteria. The cells relabeled "FALSE" by Excel were then located using the "Find" tool to find all cells containing "FALSE", and all of those cells were selected and deleted. I did this for the soil moisture values that corresponded to depths of 2, 4, and 8 inches, and then created a new column that averaged the values of the soil moisture at the three depths for each day. The column of averaged soil moisture data that was produced was transferred to another worksheet where all of the information was compiled. Each column of data in the new compiled worksheet represented a single month of daily soil moisture values. In order to double check the data each month was checked to determine if it had a number of measurements that was equal to or less than the number of days of the month. If there were more data points than there were days in the month, I'd go back to the raw data sheet and use CTRL+Z to go back to before the "FALSE" values were removed from the columns. The cells that slipped past the selection criteria were located by eye and "FALSE" was typed into those cells. After that the "FALSE" cells were removed again and the data was copied over to the compiled worksheet to check if the number of values was equal to or less than the number of days in the month. Then the daily data was averaged to create a column of monthly soil moisture values for the average value of the different soil depths. Finally, after the row of average monthly soil moisture values was created, the row was copied, and pasted into a new worksheet using the "Transpose" function within "Paste Special" to turn the row into a column value. The new worksheet (final worksheet) with the soil moisture value column then had the first column on the left made into a column displaying the date from November 1994 to August 2007, the range of the data from the SCAN site.

The SCAN soil data itself was in units of moisture percentage of the volume fraction of the soil layer. This means that the soil moisture was the percentage of a particular volume of soil that consisted

of water. To utilize this data in further calculations, the soil moisture percent was multiplied by 1000, to determine the volume of moisture out of 1 meter of soil.

The NCDC summary of the month data also required editing to be useable. First, in order to allow for easier data analysis, only one data type was downloaded for each site from the NCDC's summary of the month data at a time. So, data for precipitation values and temperature values were independently downloaded from the website and then added to individual worksheets in a single Excel workbook using "Get External Data". After the data was added to the worksheets, extra columns in the data were deleted so that the monthly data columns were next to each other. Due to the fact that the yearly data values were arranged in rows, in order to transfer more than a single year's worth of data into a column format (which is a much easier format to manipulate the data in), a set of Excel functions had to be linked together to change the format of the cells from being arranged in rows to columns.

This equation was:

$$1) =\text{OFFSET}(\$G\$3,\text{INT}((\text{ROW}()-\text{ROW}(\$G\$3))/12),\text{MOD}(\text{ROW}()-\text{ROW}(\$G\$3),12)).$$

The equation works such that anyplace where \$G\$3 is in the equation, that is the value for the furthest left column of the top row of the area that is to be turned into a column, and that anyplace where 12 appears is the number of columns that the equation recognizes in a single row before starting at the left in the next row. This equation was used to create a new column in the worksheets containing the temperature or precipitation data from that sheet arranged into a column. These columns then had their corresponding dates marked in the column next to them, and were copied over to the worksheet for averaging values for the different sites over the period 1980-2007. The estimation worksheet was used to take the average of the precipitation and temperature for each month for the monitoring sites over the period 1980-2007. The precipitation values were adjusted so that if the average temperature

for the month was below 0°C , then the precipitation was retained as snow, and the sum of all the months with below zero temperatures for a particular winter was added to the precipitation value of the first month with above zero average temperatures. The temperature values were adjusted in a linear fashion, and as the temperature changed, there were impacts on the precipitation values. For the scenario with a 2°C increase by 2100, the year 2009 was the average temperature for the past 20 years, and temperature increases began in 2010. For every year starting at 2010 till 2100, the amount of temperature change expected divided by 91 was cumulatively added to each year.

To calculate the other values for the model, columns were added for calculated soil moisture, soil moisture capacity, E_{sat} , and potential evapotranspiration. Before the new columns had their values calculated, I removed all values in the initial three columns that were errors or zeros that appeared to not belong, and left the cells to which I did this empty. Likewise, any cells whose value would be dependent upon those cells that have had their values removed will remain blank, so that cells without good input information won't be calculated. The soil type at the SCAN site was a loamy fine sand, with an estimated porosity of $0.4\text{cm}^3/\text{cm}^3$. The column that contained soil moisture capacity should have values in mm, since the other values of the equations were in mm, so I converted the porosity value of $0.4\text{cm}^3/\text{cm}^3$ to $400\text{mm}^3/\text{cm}^3$. This value is taken as equivalent to the S_{max} that is used in equation #4 shown below. To calculate E_{sat} , I used equation #2 from below. To calculate potential evapotranspiration I used equation #5. Actual evapotranspiration estimation is normally a part of this model, but I didn't calculate it here because the accuracy of those estimations is dependent upon the accuracy of soil moisture estimations, which is questionable.

The temperature and precipitation data was then used in the Thornwaite moisture balance model. The equations for this model consist of:

The first estimation calculated using the model was the amount of water vapor that could exist in the air when it was saturated.

Calculate the saturated air vapor pressure:

$$2) E_{sat} = 6.112 * \exp((17.67 * T_a) / (243.5 + T_a))$$

Using this information, the potential evapotranspiration (PET) for the month was calculated, and the value was set to 0 for any month in which the average temperature was below 0°C. The coefficient applied to E_{sat} was determined by comparing calculated PET values to actual pan evaporation data and adjusting the coefficient (originally 0.409) to make the calculated PET match the pan evaporation data.

Calculate Potential Evapotranspiration:

$$3) PET = \text{If } T_a < 0, 0$$

$$\text{Else, } 0.8589 * E_{sat}$$

Without the previous month's soil moisture values available during the future projections, the changes in soil moisture are calculated using PET, the previous month's soil moisture, and the maximum effective soil moisture. The first month's soil moisture is the value from before the projections began, and after that the previous month's soil moisture (S_{m-1}) is a calculated value.

Calculate monthly average soil moisture:

$$4) S_m = S_{m-1} * \exp(- (PET - W_m) / S_{max})$$

Using the soil moisture, PET, and W_m information, the actual evapotranspiration is able to be calculated.

Calculate Actual Evapotranspiration:

$$5) \text{ AET} = \text{If } W_m > \text{PET}, W_m$$

$$\text{Else, } W_m + S_{m-1} - S_m$$

I set a minimum value of 40mm (4% volumetric water content) for the soil moisture, since it's unlikely for the moisture to go below that concentration. This is so that when the model attained this amount I set the soil moisture to 40mm until the end of winter (since there isn't sufficient moisture input to increase soil moisture until then).

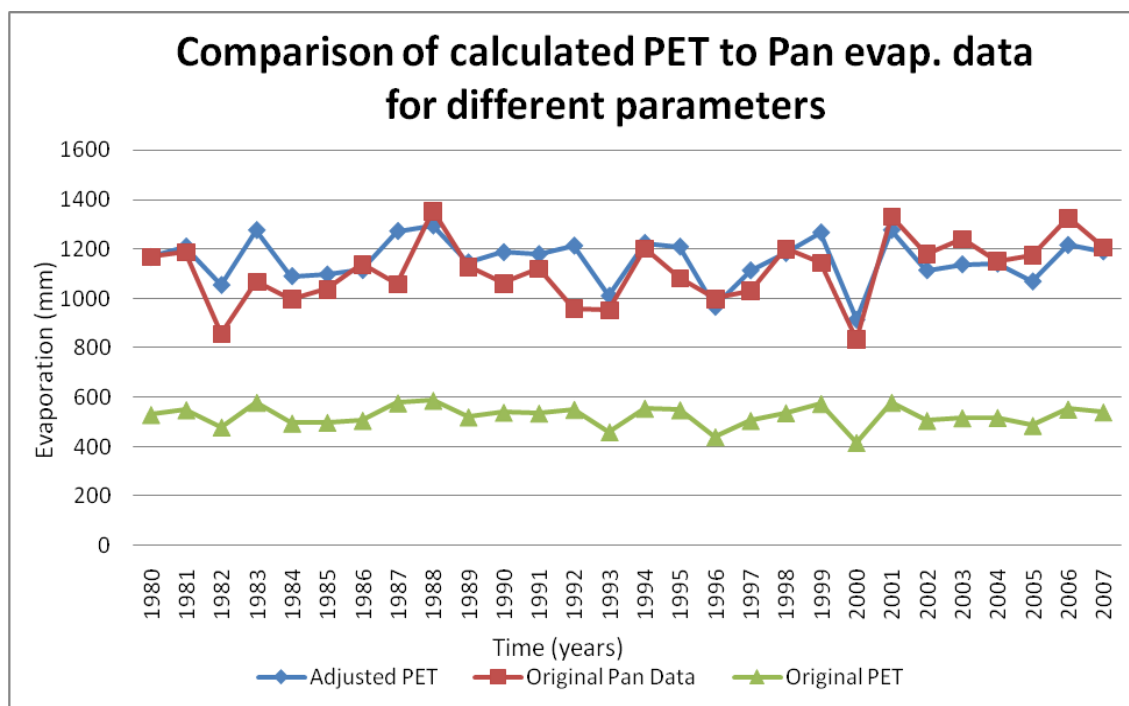


Figure 3. Depiction of the different estimations of PET compared to the pan evaporation data from the Sheridan NCDC station. The original PET data utilized the PET calculation parameter of 0.409, and the Adjusted PET was calculated using an adjusted PET value of 0.8589 to allow the calculated values to more closely match.

The calibration of the simpler Thornthwaite moisture model can be seen in Figure 3. The adjustment of the parameter seen in Equation 3 did result in an improved fit of the calculated PET

values to the original pan data from Wyoming. This improvement in the model's fit for Wyoming improves the ability for the model to accurately predict PET for areas in eastern Wyoming.

Another tool that was utilized was the WebWIMP model from the website created by University of Delaware professor Dr. Cort J. Willmott and his colleagues. This model is web based, and utilizes a database of climate information produced by the Department of Geology at the University of Delaware within a modified Thornwaite moisture model to determine the changes in a number of moisture related variables. The different inputs for this model that can be adjusted are temperature, precipitation, soil moisture holding capacity, location and the declining water availability function. In using the model, I used the soil moisture holding capacity of 75 mm, which was the moderate value of holding capacity from Bowman et. al. For the model runs, the values were calculated with the normal precipitation and temperature inputs, and then calculated with a temperature of a 2-5°C increase.

Results

Using the Thornwaite soil moisture balance model, the values for PET and then the soil moisture values were determined for the time period. The annual sum of PET values for the baseline and the final values for different temperature changes estimated for the year 2100 are shown in Table 1.

Year	Temp change (°C)	PET (mm)	% Change PET from baseline	Winter Length (months)
2009	0	1166	NA	3
2100	2	1325	13.7%	3
2100	2.5	1421	21.8%	2
2100	3	1467	25.8%	2
2100	3.5	1514	29.8%	2
2100	4	1562	34.0%	2
2100	4.5	1718	47.4%	0
2100	5	1774	52.1%	0

Table 1. Results from calculating the PET using the Thornwaite moisture balance model. The values for PET are the sum of the monthly calculated values of PET for the year in question with the corresponding change in temperature, and the % change from baseline values are the change between any particular year and the baseline value. Also shown are the number of months of winter temperatures (below 0°C) for each scenario at the time depicted.

In the estimations that were produced (Table 1), it was found that PET values would increase greatly and that these rates would be much different than those of today. The change of PET relative to today varies from a 13.7% rise in PET with a 2°C temperature increase and an over 50% increase with a 5°C change. It was also found that winter length would decrease substantially, with the number of months with an average temperature below 0°C being the measure of winter length. The length of winter months decreased from 3 months at the baseline level to being completely gone by 2100 with a 4.5 or 5 degree increase. Additionally, the sensitivity of PET is particularly greater as the duration of winter decreases. A change of 4%-5% seems to be the norm for a half degree increase except for when winter decreases by a month, in which case the change is more likely to be between 8% and 13%.

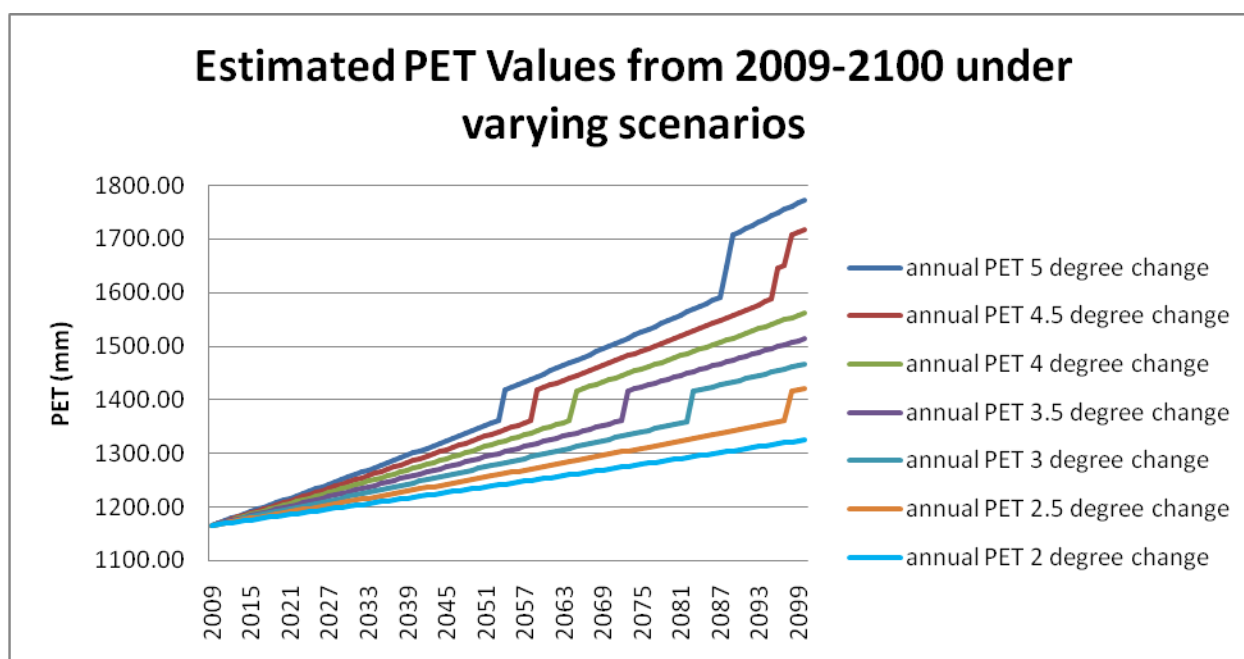


Figure 4. Graphical representation of the path of change in annual sum of PET over the 92 year period. The sensitivity of the PET changes does seem to be greater with increasing temperatures, independent of the jumps in PET that occur when the number of winter months decreases. The point at which winter decreases can be seen for each series.

The changes in yearly PET over time can be seen in Figure 4. For each scenario there is an increase in PET, and the sensitivity of PET increases with higher temperature scenarios. The most

interesting feature of these results is that the values increase sharply at points that correspond to a decrease in the length of winter for that scenario. A decrease in the duration of winter seems to cause the most dramatic increase in annual PET, with the time until this happens decreasing with increasing scenario severity. For the 4.5°C increase scenario, the two increases can be seen as the two points at which winter decreases, while in the 5°C scenario the last two months of winter disappear in one year, causing a single large increase in PET. These results indicate that there may be threshold values at which major climate impacts will occur.

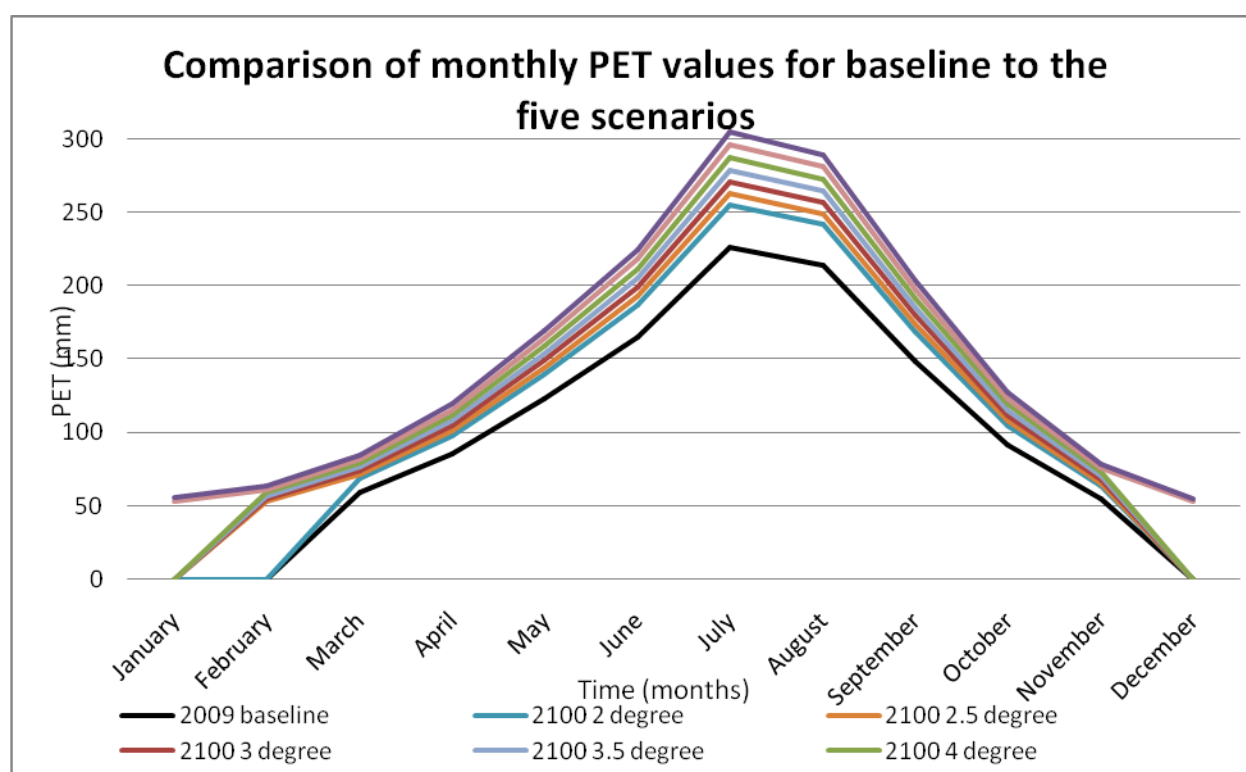


Figure 5. In this figure the PET values over the course of the year are compared, with the 2009 base year shown in comparison to the varying temperature scenarios in the year 2100.

The PET values for different temperature changes over the course of the year indicate which months have too low temperatures to have evapotranspiration occur, and this can be seen in Figure 5. The vulnerability of months to the temperature increase, as ranked by their PET increase is February, December and January. Each of the scenarios has a slight increase for each month over the lower

temperature scenarios, but the increases in PET that occur are primarily due to the increased number of months during which evapotranspiration occurs.

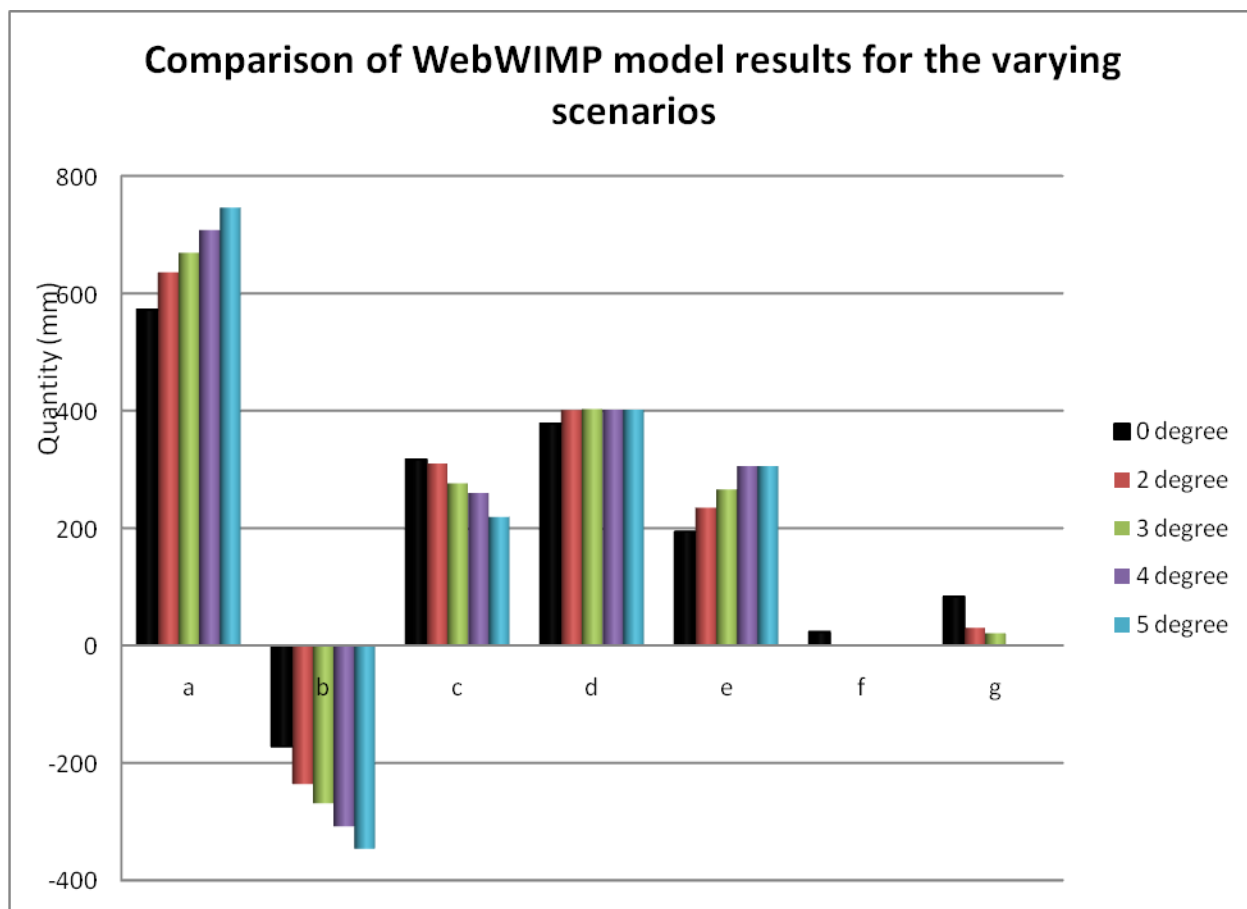


Figure 6. In this figure, the different columns out of each set of bar graphs are for the four different possible future temperature changes (in degrees Celcius) and a baseline. Each set of bar graphs is for a particular parameter regarding moisture: a is the estimated, adjusted (for varying day and month lengths) potential evapotranspiration (mm/month), b is the rainfall and estimated snowmelt minus the adjusted potential evapotranspiration (mm/month), c is the estimated soil moisture (mm) at the end of the month, d is the estimated, actual evapotranspiration (mm/month), e is the estimated deficit or unmet atmospheric demand for moisture (mm/month), f is the estimated surplus (surface runoff plus percolation below the plant root zone) (mm/month), g is the estimated water retained in the snow pack (mm) at the end of each month summed over the year.

In Figure 6, quite a few trends are visible as the temperature rises. First, the adjusted potential evapotranspiration increases with each higher temperature scenario, which is consistent with the results from the simpler Thornwaite model. Second, the value of total precipitation minus the adjusted PET decreased with each increase in temperature, a result that should be expected if PET increases and

precipitation remains the same. From these first two results, the outcome of estimated soil moisture at the end of each month decreasing with increasing temperatures meets with expectations. Meanwhile, the estimated moisture surplus and the estimated water retained in the snow pack decrease to zero, with runoff being much more sensitive to the temperature change. The decrease in the snowpack moisture retained at the end of the month is consistent with previous findings that the duration of winter will decrease, since a decrease in winter length would lead to a decrease in snowpack moisture retention. Also, since snowmelt in the spring is an essential factor for Wyoming moisture during the year, the decreased runoff may be due to the decreased snowpack moisture retention (Smith 2007). Both the estimated actual evapotranspiration and the estimated deficit or unmet atmospheric demand for moisture increase with the increases in temperature, with the actual evapotranspiration reaching its maximum amount of increase at only a 2 degree increase. The reason for the actual evapotranspiration peaking so quickly is likely due to the removal of moisture from increased evaporation, the loss of surface runoff, and the decrease in the amount of moisture retained in the snowpack each month of winter decreasing additional moisture sources that can be evaporated.

Temperature Change	Adj. PET (mm)	Precip. Minus PET (mm)	Est. Soil Moisture (mm)	Est. Actual ET (mm)	Atm. Moisture Deficit (mm)	Surplus Runoff (mm)	Snowpack Moisture Retained (mm)
0 degree	572	-172	317	378	194	23	83
2 degree	636	-236	310	401	235	0	30
3 degree	669	-269	276	403	266	0	21
4 degree	708	-308	260	402	306	0	1
5 degree	746	-346	219	402	306	0	1

Table 2. Actual values for the current temperature and precipitation conditions and a range of increased temperature scenarios for the future.

Temperature Change	Adj. PET (%)	Precip. Minus PET (%)	Est. Soil Moisture (%)	Est. Actual ET (%)	Atm. Moisture Deficit (%)	Surplus Runoff (%)	Snowpack moisture (%)
2	11.2	-37.2	-2.2	6.1	21.1	-100.0	-63.9
3	17.0	-56.4	-12.9	6.6	37.1	-100.0	-74.7
4	23.8	-79.1	-18.0	6.3	57.7	-100.0	-98.8
5	30.4	-101.2	-30.9	6.3	57.7	-100.0	-98.8

Table 3. Percent change in the values for values calculated from the WebWIMP model for a range of temperatures as compared to present values. With the increasing temperatures the projected changes are that adjusted PET increases, estimated soil moisture decreases, estimated actual evapotranspiration increases, the atmospheric moisture deficit increases, surplus runoff decreases 100% from the initial values, and the amount of moisture retained in the snowpack decreases a large amount to an almost complete loss of snowpack.

The information in Tables 2 and 3 provide quantified measurements of the results from the modified Thornwaite moisture balance model. For adjusted PET, the increases range between 11.2 and about 30% for increasing temperature scenarios compared to present values. Both models indicate a decrease in the snow moisture amounts (since the elimination of the winter months indicated for a 4.5 and 5 degree increase in the Thornwaite model would likely have a corresponding large decrease in moisture retained in the snowpack at the end of every month). Both models also indicate an increase in PET, and the implications of the results of the Thornwaite model are in line with the results from the WebWIMP model for the other columns. With increasing PET and precipitation values that aren't increasing at an equivalent rate, an increasing soil moisture deficit, a loss in surplus runoff, a decrease in estimated soil moisture, and an increase in the deficit between precipitation and PET, moisture pressure is expected to increase for all scenarios. Also, the relatively low values for changes in estimated actual ET is likely due to the fact that the landscape has low soil moisture already, and under that situation only so much moisture can be removed from the soil when it's already so dry.

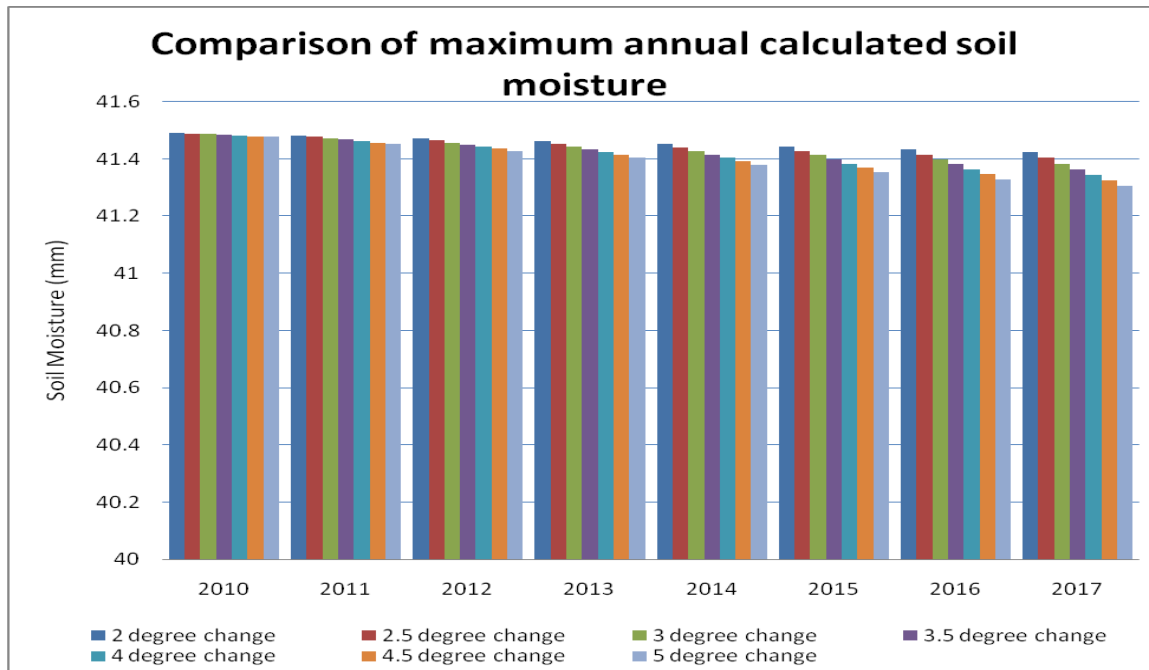


Figure 7. Graphical depiction of the differences in maximum yearly calculated future soil moisture for Torrington, WY during the period 2010 through 2017. Notice the increasing negative slope in comparing the bar graphs as they go from less to more intense temperature change scenarios.

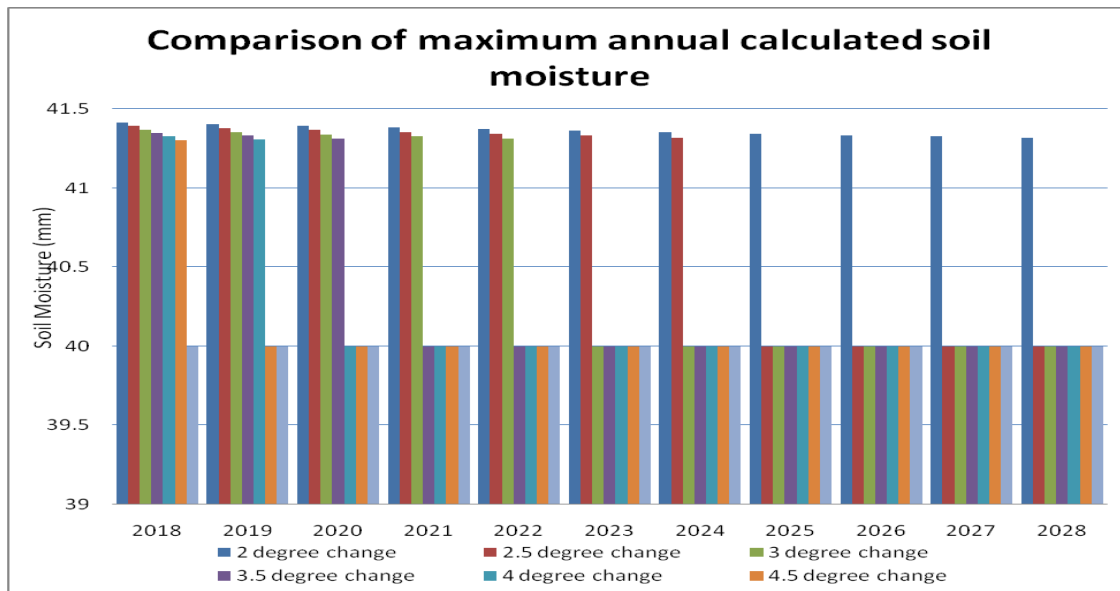


Figure 8. Graphical depiction of the differences in maximum yearly calculated future soil moisture for Torrington, WY during the period 2018 through 2028. Notice the increasing negative slope in comparing the bar graphs as they go from less to more intense temperature change scenarios.

The results from the soil moisture estimates under the varying projections yielded results that shouldn't be viewed as accurate depictions of the real world. However, these model estimates can be viewed relative to each other. Figures 7 and 8 depict the information organized towards this goal,

showing the difference in the rate of decrease in maximum annual soil moisture for the different scenarios. The higher temperature scenarios have greater decreases in soil moisture for the first 8 years, and then the higher temperature scenarios are the first to have their soil moistures drop to 40mm and never rise higher. All scenarios have their soil moisture estimations drop to the minimum value by the year 2029. These results from the model give another indicator of the likelihood of greater moisture pressure at higher temperatures.

Implications of the Results

In the region of eastern Wyoming examined, the snowmelt at the beginning of spring is extremely important for providing water for the rest of the year. The snowmelt allows for the rejuvenation of the landscape from winter dieback and produces surplus water for recharging aquifers and surface waterways, especially since precipitation during fall and winter has little influence on forage production during the growing season (Smith, 2007). This means that the period of winter and the buildup of the snowpack is needed to help ensure enough water is provided in the spring from snowmelt to provide moisture for the growing season, and with a decreasing duration and eventual loss of the winter months, the moisture pressures are going to increase. This increased pressure is due not only to the lack of a large input of moisture from snowmelt in the spring but also an increase in the period during which larger amounts of evapotranspiration is occurring.

In addition to this, there is an increase in the potential evapotranspiration, with percent increase in PET with a 5°C change calculated by the Thornwaite model being 52.1% and the WebWIMP model estimating a 30.4% increase, both of which will cause large moisture pressures. All of the information indicates a strong increase in moisture pressure that would be experienced at such a high temperature increase. According to the WebWIMP model even a small temperature increase of 2°C may cause a loss in surplus moisture (both surface runoff and percolation into the rooting zone). Utilizing the information of expected increases in PET in conjunction with the IPCC AR4 report's

estimated increases in precipitation for the area (5-10%) indicates that even if there is an increase in precipitation that's on the high end of the projections, then it likely won't be enough to compensate for the extra evaporation pressure. Also, due to the indication that there is a threshold of climate change that may cause sharp changes in the moisture system, there may be levels of change that once they are crossed cause extreme secondary effects.

The Society for Rangeland Management defines drought as "prolonged dry weather when precipitation is less than 75% of the average amount." In the WebWIMP model the soil moisture deficit would be at 25% at about a 4.5°C increase in temperature. Since in the WebWIMP model a 25% decrease in soil moisture deficit corresponds to about a 25% increase in PET, the scenario I calculated using the Thornwaite moisture balance model indicated that for an increase of 3°C or more caused a >25% increase in PET and (assuming that the relationship between PET and soil moisture deficit would hold true for the Thornwaite results), this indicates that there would be a >25% decrease in soil moisture as well. Without an increase in precipitation, the landscape would be in nearly perpetual drought with a temperature change between 3° and 4.5°C, and if the IPCC fourth assessment report's predictions of an increase in precipitation between 5 and 10% are correct, a perpetual drought would still be created between 3.5 and 5°C. Since Peterson *et al* says that "drought is a serious obstacle to successful range livestock management", this would cause a significant problem for coping and maintaining adequate moisture for production.

However, the forage difficulties aren't the only issue to be concerned with. Increases in temperature are likely to cause physiological stress, since water requirements for cattle can more than double during hot weather. Without adequate water, cattle will often refuse to eat, begin to drop weight and become sick (Peterson *et al*). These stresses are likely to be worse in the future than under the current situation, and with increased water input stress decreasing supplies the problem of

providing adequate water will be serious indeed. The increased temperatures can also lead to algal blooms in stagnant water, causing illness or death from poisoning (Peterson *et al*).

Table 1. Estimated water consumption by different classes of beef cattle (North Dakota Extension Service).

Class of beef cattle	Estimated water consumption at 88°F (gallons/day)
Cows	
Dry	14
Lactating	17
Bulls	18
Growing cattle	
400 lb	9
600 lb	12
800 lb	14
Finishing cattle	
600 lb	14
800 lb	17
1,000 lb	20
1,200 lb	23

Figure 9. Table depicting water requirements for in gallons per day of different cattle under different conditions at 88°F (31°C). (Peterson *et al*)

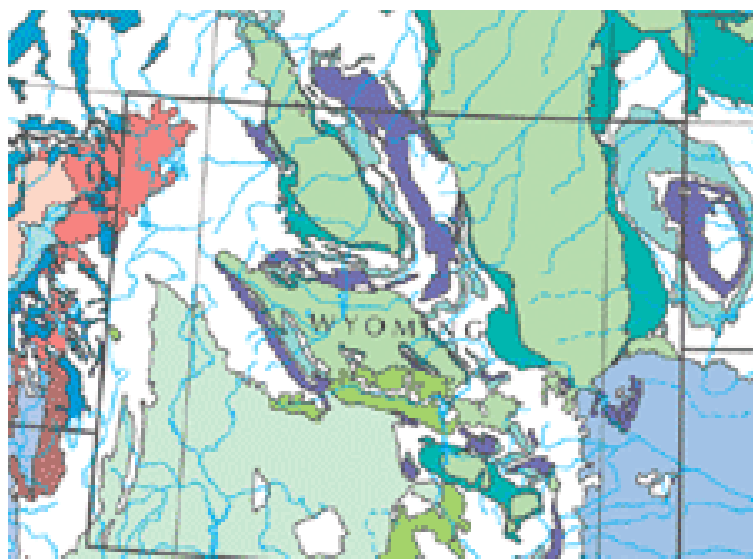


Figure 10. Map of the underground aquifers present in Wyoming, with the aquifer in the southeast being the Ogallala aquifer that covers many of the other Great Plains states, but experiences the smallest moisture input from WY. http://capp.water.usgs.gov/aquiferBasics/images/map_lowtert.gif

From all of the moisture deficiencies that seem likely to occur from the results, it is likely that multiple groups within Wyoming will increase their use of underground aquifers. Since these aquifers

are recharged from surplus water percolating into the ground, it is likely that future recharge of aquifers will decrease. These factors would combine to cause aquifer depletion that may not be compensated for by recharge, and would exacerbate any current depletion problems. This is very important, as under increased moisture stress, having adequate water supplies is essential, and groundwater makes up a significant portion for this area.

On top of all this, it is important to understand that there is an unknown level of variability with regard to the climatic changes that will occur in the future. This means that a major problem for dealing with the shifting climate of the future is the fact that the most damaging climatic effects will occur from the intense events, such as heat waves or extreme droughts. The high intensity, low frequency events are the most likely to cause situations that are taxing on people, agriculture and natural systems. The variations in rainfall could cause a double impact, with intense drought causing a decrease in plant root structure and plant protection of the soil followed by intense rainfall events that cause erosion of the newly unprotected soil. If the regional climate shifts towards having severe rainfall and drought every few years, it will put greater pressure on the landscape, thereby decreasing the ability for the plant life to recover from drought.

Management Recommendations

For the ranching community, ranches vary on the variety of methodologies utilized, their sizes, and their profitability. Some ranches are so large as to require the use of a helicopter to scan the countryside to determine the condition and location of the cattle, while others can be quite small, having only a few dozen head of cattle. Also varying are not only the specific methodologies of management, but also the fate of the cattle. Some ranches utilize their landscape to produce calves that are then sold to feedlots elsewhere in the United States, while other ranches grow beef only on their own land and sell their stock directly to where it will be butchered. Likewise, the treatment of cattle during winter is dependent upon the particular rancher and the size of their herd. Smaller herds or

more temperature sensitive varieties may be kept in a shelter during the winter and overwintered this way, but many ranchers leave the cattle out for winter. For feed during winter they either purchase feed or allow the cattle to graze on the open fields if there is enough forage left over from the growing season and the plants will be able to handle the grazing.

Ranchers depend upon the production of rangeland grass/forage and this makes good caretaking of the land essential for current and future production. The basic physiological reason for drought stress on plants is due to plants having to decrease photosynthesis to prevent excess moisture loss and eventual wilting due to decreased turgor from water loss. Droughts also cause difficulties for plants because they need to recover from the dieback that occurs during dormancy and limited shoot growth from decreased photosynthetic activity during drought decreases root regeneration (Howery, 1999). Ranchlands that have a greater diversity of plant life can also have greater capacities for handling drought, since the plant life in a diverse landscape covers a wide range of growing seasons, rooting habits, and physiological needs (Howery, 1999). Preventing overgrazing of plants is important, particularly during droughts because this is when the plants are most susceptible to being replaced by less productive weedy species and the best forage species are most often the first to disappear (King *et al*, 1997). Of course, ranchers also need to provide adequate drinking water for cattle (which require 15 gallons of water a head a day).

With the implications of a shifting climate in mind, there is a need to recognize the particular adaptations that are the best practices for ranchers, since they have a minimal ability for reducing the impacts via mitigation efforts. Adaptation involves modifying the techniques and methodologies of ranching, both to prepare for and adjust to the changes that are likely to occur in the future, and to have some planning for more intense effects. Since the most likely overall effect is drought, the wide range of information on preparation for and dealing with drought is very useful for making recommendations. However, I'd say it's important to note that the ranchers themselves are the judges of how to utilize

information, since they understand their particular landscape, their uses for it, and the intuition for reacting to situations. The information below is meant to provide new techniques that can be tested and kept in mind while weighing options and planning.

Drought Preparation

There are a wide range of options for preparing for drought, some of which include setting up monitoring stations to keep track of climate conditions, altering the grazing regime, protecting the landscape, and creating an overall management plan for how to deal with drought. Utilizing and recognizing a diversity of options is the best way to recognize opportunities and find the combination of methods that will allow for minimization of damage, since no single aspect of management could single handedly prepare for the situation. The better developed and appropriate the overall management plan and its implementation is, the more likely it is that drought will have a minimum impact on the landscape and production.

Monitoring

The first steps that must be taken are to prepare for long term drought and set up methods for monitoring and keeping track of climatic variables, water and feed inventories, condition of the herd, and financial resources available (Peterson *et al*). This planning is even more important since the options for response to drought decrease as the drought continues (Howery, 1999). To be able to adequately respond to drought, many studies state that it is essential to carefully monitor weather conditions to be able to identify the onset of drought, monitor the duration and severity of the drought, and identify when the drought ends (Howery, 1999) (Peterson *et.al.*,) (Herrick *et.al.*, 2005) (Bellows, 2004). The quicker the onset of drought is recognized through monitoring the more quickly the drought plan can be implemented and the more options are available. However, drought onset and end is very difficult to determine and its impact is affected by both ecological condition and human intervention (King *et al*, 1997). In addition to their own monitoring efforts, ranchers can utilize government data such

as the Bureau of Reclamation and the NRCS's snowpack and expected availability of irrigation water information (Smith 2007). Likewise, if the end of the drought is identified it allows for the change in management techniques from the in drought protection to methodologies to help the landscape recover faster. Of course, detailed knowledge of the severity of the drought is very important, because it allows for specific choices about what actions should be undertaken.

The first act that should be done for monitoring is to define the objectives, followed by assembling information of the area, selecting the indicators to be monitored, keeping track of the management of the monitored sites, and finally establishing permanent monitoring sites and starting monitoring (Herrick *et al*, 2005). Monitoring should include monitoring precipitation, soil moisture at depths of approximately 6", 1' and 3' (or at other varying soil depths that correspond to different root depths of important plants), soil and site stability, hydrologic function, and biotic integrity (Herrick *et al*, 2005), (Howery, 1999). Biotic integrity monitoring includes keeping track of plant growth, and this can be done via a cage surrounding a small plot of land (with growth on it) that is moved every year to avoid buildup of material (Howery, 1999). In the monitoring of drought and determining if a drought is beginning, it's important to take note of the time of year and the likelihood of rain, because this affects the decision of whether a true drought is occurring (Peterson *et al*). The "Monitoring Manual for Grassland, Shrubland, and Savannah Ecosystems" from the USDA-ARS is an excellent resource for designing specific landscape monitoring efforts and provides a wealth of information of what to monitor and how.

Monitoring efforts should include monitoring during the drought as well, not just of climate factors but also of the condition of the herd. Keeping track of the climatic conditions can allow for recognition of when the drought has truly broken. Watching over cattle during drought involves keeping track of weight loss, inadequate performance, body condition score, and any nutritional deficiencies (Peterson *et al*). If the body count score of a cow drops it may lead to reductions in fertility,

especially at the start of the breeding season (Peterson *et al*). During drought many plants become dormant, and due to this their nutritional content decreases, leading to deficiencies in vitamin A, phosphorous and protein (Peterson *et al*).

Drought Management Plan

Decisions regarding the setup and implementation of the plan should be based on logic, and assistance from beef, range, or agricultural specialists should be sought when necessary (Peterson *et al*). The drought management plan should be made so as to have all of the different aspects of response for drought prepared and to be adjustable for the particular drought situation. Features to adjust that should be part of the drought plan include the stocking rate, grazing system, cattle feed/nutrient supplementation, water use, and any other factors that the rancher believes can be changed to adjust to the situation. Careful preparation of this plan can minimize the impacts that drought will have on the landscape, production, and profitability.

Stocking Rate

Many in the management field consider changes to the stocking rate to be the most important change to protect the landscape (Howery, 1999). With regards to the stocking rate, maintaining the stocking rate at the long term carrying capacity and decreasing the carrying capacity during drought isn't an ideal strategy. A better method is to maintain the stocking rate at 90% of the carrying capacity, since this keeps the amount of surface forage grazed to about 40% of the total volume, allowing a 60% retention of annual production (Howery, 1999). This level of grazing of the surface material is important because studies indicate that if grasses have had 70% of their surface matter grazed, then 50% of roots stop growing for 17 days, but grazing that's less than 50% doesn't negatively affect root growth and can allow for plants to improve total growth (Howery, 1999). Even a 60% usage of the current year's growth is considered to be excessive (Peterson *et al*). This lower stocking rate also allows for the landscape to increase the amount of forage growth, and a subsequent increase in stocking rates as the landscape

improves. So, while a short term decrease in stocking rates is implemented, through the increased growth on the landscape, the average long term stocking rates can increase, and with this increase the total cattle that can be maintained sustainably increases. In addition to lowering stocking rates, there is a large amount of literature that agrees that setting aside some pasture for use during droughts is important (Howery, 1999), (Peterson *et.al.*), (Herrick *et.al.*, 2005) (Bellows, 2004). By setting aside these areas, during a drought the rancher can avoid having to choose between buying feed, allowing cattle to graze the sensitive land, or selling off more of the herd.

Grazing System

Utilizing different grazing systems can also have a dramatic impact on the landscape and the resilience of the plant life. Due to the infinite combination of climates, soils, topography and vegetation types, choosing the optimal grazing system is a challenge (Howery *et al* 2000). Overall, and especially during drought, rotational grazing systems are preferred over continuous systems (Peterson *et al*). This is because a rotational system means that more use will be made of less palatable and more grazing tolerant plants and allows for greater plant vigor. It is important to maintain flexibility in the grazing system, due to the arid climate. The forage and cattle management strategy for the summer months should be chosen by April, since it's unlikely for enough moisture to fall in May to compensate for low precipitation early in the year (Smith, 2007). A good list of the definitions of a variety of grazing systems can be found from Howery *et al* from the University of Arizona Cooperative Extension (2000). Monitoring the results of grazing system and management decisions allows for adaptation and responsiveness to maximize effectiveness (Howery *et al*, 2000).

For grazing management it's important to use a flexible annual timetable to make decisions and plan for stocking rates, herd movements, and range improvement practices (Howery, 1999). The schedule can also be used to plan the amount of money available to use on feed and supplements during winter or droughts. Starting with a flexible system such as this allows for putting a template in

place that allows for quick adaptation to the onset of drought. It is a challenge to make cattle move to a new desired location (to shift grazing from a heavily grazed area to a less grazed area) at a minimum of effort and minimum of stress for the cattle. The technique of utilizing pipelines to change where drinking water is located and moving supplemental nutrient placement are known methods for moving cattle with a minimum of effort and stress (Howery, 1999) (Smith, 2007).

Adapting grazing management is just one part of the spectrum of options that should be utilized. Other aspects that deserve attention and exploration are the monitoring of the plant vigor, utilization and range conditions and adjust the location and density of the herd to respond to changes in the range (Howery, 1999). These aspects are further explored in the rest of this document.

Rangeland Condition

Preparing for drought must include an improvement of the rangeland, since rangeland in better condition won't be affected as negatively as poor rangelands due to increased plant vigor and cover (Howery, 1999),(Peterson *et al*). If the rangelands have been grazed moderately rather than heavily, there will be little damage to root growth and plant vigor (Howery, 1999). If the land is heavily grazed, the plants will experience permanent wilting at soil moisture amounts as high as 6-8%, while moderately grazed landscapes can extract soil moisture at values as low as 1-2% (Howery, 1999). Of course, to keep the landscape healthy and vigorous also requires being careful about the frequency and timing of grazing. If photosynthetically active plants are grazed that can make it difficult for the plant to grow new leaf material, so it is important to graze different plant species relative to their growth cycles. The plants are most sensitive to grazing during the period when the meristems (areas from which the plants grow) grow to a height that is susceptible to being eaten by grazing animals (Howery, 1999) (Smith, 2007). If a plant loses this meristem, it has to expend more energy to continue growth, and plants that continually lose their meristems will stop making meristems all together (Howery, 1999). Lower grazing can also help for reducing the impact of drought, since residual vegetation facilitates infiltration and

percolation of moisture into the soil by “reducing evaporation losses, protecting the soil from erosion, and providing a favorable micro climate for seedlings” (Howery, 1999). A depiction of the relationship between low quality and quantity forage and cattle health and production can be seen in Figure 11, and shows the inter-connected responses that can occur.

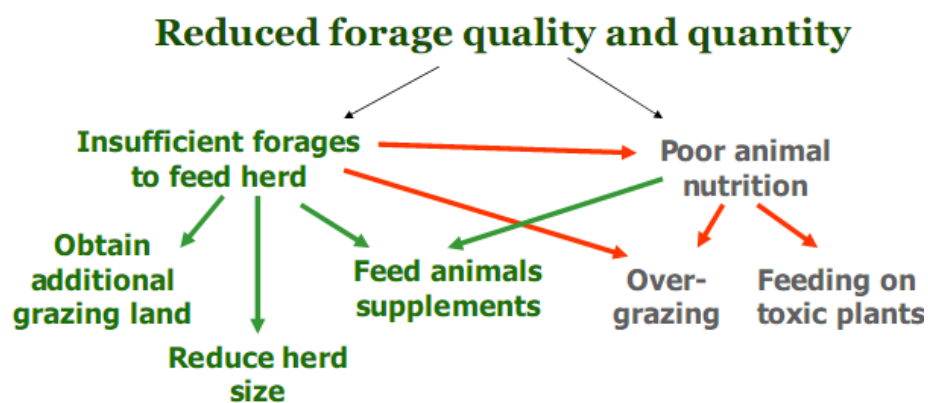


Figure 11. Depiction of the inter-connected effects of lower quality and quantity of forage on cattle, (Bellows, 2004).

At Drought Onset

At first detection of a drought, the drought plan created during the planning should be enacted and firm decisions need to be made (Peterson *et al*). The plan should be individualized to the ranch based upon its unique vegetation, topography and management objectives (Howery, 1999). Using the previously established monitoring techniques to spot when a drought is beginning is essential to minimize the damage and maximize the value of the plan.

Once the onset of drought has been identified, it is important to try to identify the likely impact and duration of the event, since this will allow for an appropriate selling of stock to reduce the stocking rate while prices are still high. This selection of the amount of cattle to reduce is essential to prevent death to drought stressed plants by too much defoliation (King *et al*, 1997). It is important to sell early because prices are likely to drop during the course of a drought as many ranchers have to sell off some of their stock, causing a price decreasing surplus on the market. The animals that should be sold off are those that are the least benefit to the maintained breeding herd. The primary list of animals that are

commonly listed to be sold off are: weaned calves, inferior/nonbreeding cows, low fertility bulls, and inferior heifers (Howery, 1999). Animals that don't use more than one area of the range should be sold as well, since this behavioral feature is passed down from generation to generation (Howery, 1999). The number of heads that have to be sold can be diminished by weaning calves earlier, since dry cows eat less than lactating ones and the newly weaned calves can be sold off (Howery, 1999). The best cows to wean early are those that are having their first or second calf, since they are likely to still have growing left to do (Peterson *et al*). If calves are weaned, they can still grow adequately if they are given a high quality ration (Peterson *et al*). However, if calves can't be weaned, then the best areas and feeds that remain should be preferentially given to nursing and reproductive stock (Bellows, 2004). The level of culling of the herd can be decided upon by the availability and the price of supplemental feeds, weighing the costs of buying the feed to the benefit of retaining the cattle for which the feed is being purchased (Peterson *et al*). In purchasing feed, it's important to avoid buying weed infested hay, since the cost of dealing with the weeds will outweigh the benefit of the feed.

Nutritional Monitoring

Monitoring the plants that are being utilized during the drought is important, since plants change in their nutritional content during drought, leading to either poisoning or nutrition deficiencies (Bellows, 2004). For instance, even if there is adequate forage, drought stressed sorghum, sorghum hybrids, and sudangrasses are more likely to cause prussic acid or cyanide poisoning (Peterson *et al*). The variety of toxins that plants can produce in response to drought conditions includes cyanide, alkaloids, fungal endophytes, tannins/phenols, terpenes, and nitrates (Bellows, 2004). Plants under drought stress are also more likely to be lower in protein, succulence, and overall nutritional quality making possible protein supplements an important inclusion (Peterson *et al*), (Bellows, 2004). The lower succulence makes the plants harder to digest (due to being drier) and also increases the salinity. With the plants having lower protein content and being harder to digest, their energy content decreases,

causing weakness and an increase in toxic plant susceptibility. If the plants haven't been green for more than 90 days, vitamin A, D and E deficiencies in the plants are likely to occur. Using feed and other supplements to increase protein, energy and nutrient ingestion is a good way to respond, both increasing cattle health and increasing toxin resistance (Bellows, 2004).

Financial Considerations

Financially speaking, it is important to be careful with overstretching oneself or borrowing money to get through a drought, because this may diminish the long term profitability of the operation (Peterson *et al*). A drought will often require difficult economic decisions, which depend upon a particular ranch's financial condition, acceptable financial risk, goals, how long until losses are recovered after the drought, and how expendable available assets are. It's also important to compare the cost of replacing cattle to the value of cattle in the current market and weigh the difference in light of the cost of maintaining the herd (Bellows, 2004).

Post Drought Response

The need for careful management doesn't end with the end of the drought. The landscape is still sensitive as it recovers from the drought and plant life tries to regain vigor. This is important to remember, since the plant life will rapidly green up once it receives enough rainfall to begin recovering, and the natural reaction to this is to treat the landscape as normal. Overgrazing the landscape (using it normally) at this point will cause damage and decrease the capacity for forage production. Less intensive grazing may be needed for a period of one to several years to allow for adequate recovery before the land can be utilized to its former capacity (Howery, 1999). After severe droughts pastures may need to be rested for several growing seasons. Overall pressure can be diminished after both less and more serious droughts by grazing least desirable species when green, defer grazing of key forage species until after they've produced seed, and in general, to graze cool growing species during the summer and warm growing species in the spring and fall (Howery, 1999).

Possible Long Term Responses

Depending upon their particular needs and future severity, some ranchers may need to engage in drastic measures to remain economically viable. Some areas in which they may have to change could include changing the composition of their livestock to lessen the strain on the rangeland and maximize their production capacity for the situation. Bison are one example of a creature that can be used for this purpose, since they are less selective in their foraging and can more efficiently digest low quality forage than cattle, which could improve broad use of plant growth. Using bison does require larger ranch size, better facilities, and stronger economic capacity, although their simplicity for management may compensate for these requirements, making the option worth exploring (Plumb & Dodd, 1993). If the climate changes enough to cause the ranges of different plant species to shift (cool grasses and warm season grasses), it may be prudent to lay seed to help the process along (Smith, 2007). Varying plants have different phenotypes, and selecting and seeding those that are deeper rooting phenotypes can help with long term adaptation to dryness (King *et al*, 1997). Ending grazing of certain areas to open them up for wildlife habitat viewing, hunting, and other services is another option, especially since tourism and hunting is already commonly conducted on rancher's land. Ranchers charge money for the opportunity, so this wouldn't be an outlandish idea for more ranchers to decrease their production on the land and increase their services provided.

Concluding Remarks

The results indicate it is likely that there will be increased moisture stress in eastern Wyoming over the next hundred years. This stands to be a hardship for people in this area, but the sooner one begins to plan for bad situations, the better. Hopefully, this document will serve to help ranchers recognize the possible dangers and begin planning for this future.

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