Irrigated Sugarbeet Sucrose Content in Relation to Growing Season Climatic Conditions in the Northwest U.S.

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ABSTRACT

The potential effects of changing climate on world food production have become a political and scientific focus. This study was conducted to investigate linkages between seasonal climatic conditions and sugarbeet sucrose content in southern Idaho and eastern Oregon. Sucrose content of irrigated sugarbeets delivered to 74 receiving stations in southern Idaho and eastern Oregon from 1997 through 2014, and daily climate data (growing degree days [GDD] and accumulated alfalfa reference crop evapotranspiration, maximum air temperature, minimum air temperature and mean air temperature, global solar radiation, accumulated growing degree days, and mean relative humidity) from regional weather stations were collected and analyzed using various regression techniques to investigate linkages between climate variables and sugarbeet sucrose content. Ninety-nine climatic parameters were analyzed with 34 having correlations with sugarbeet sucrose content > |0.3|. The most important climatic parameter related to mean sucrose content was early stage sugarbeet growth (late April to mid-May). In general, as temperature and GDD increased sucrose content decreased. Results indicate increases in both early season and mid-season temperatures will lead to decreases in sugarbeet sucrose concentrations. However, if sugarbeet root yields increase due to increasing temperatures and GDD accumulation, the sucrose yield changes would be buffered.

Additional Key words: air temperature, growing degree days, evapotranspiration, climate change

INTRODUCTION

The potential effects of changing climate and population growth on global food production have become a political and scientific focus as concerns over feeding the world's population rise. The scientific community that influences crop production has made progress in development of technologies and management practices that have increased production. Advancements in genetics and other management practices across a broad spectrum of disciplines (e.g. nutrients, irrigation, rotations, etc.) have played an important role. Many crop yields per unit area have been increasing over time. For example, Idaho sugarbeet yields have increased by an average of 0.53 Mg ha^{-1} $year^{-1}$ from 1924 to 2012 (Tarkalson et al., 2016). The same yield increase trends can be seen with many other crops such as corn, wheat and rice (Hammer et al., 2009; Hafner, 2013). However, with the potential for changing climatic conditions, the influence of these conditions on crop production becomes a concern and needs to be evaluated.

Global warming is predicted to change climatic conditions and the irrigation water supply by the end of the century in the Pacific Northwest (Mote et al., 2014). Specific predictions depend upon location, climatic model used and assumptions about increased levels of carbon dioxide in the atmosphere. Agricultural crop production in the Pacific Northwest is in a better position to adapt to climate change than some industries as it currently responds to annual climate variations and is found in a wide range of existing climates across the region. Average annual temperatures are predicted to increase 2 to 5°C by the end of the century with the greatest increase in summer (Mote et al., 2014). This will result in longer growing seasons, which may allow for higher yields in some crops and new cropping opportunities, but may also reduce yields/quality or displace production of crops less tolerant to heat stress. Increased carbon dioxide concentration in the atmosphere is predicted to minimize temperature related yield losses for some crops supplied with sufficient nutrients and water. The irrigation water supply from snowmelt is expected to decrease due to reduced snowpack and earlier snowmelt resulting in lower summer stream flows (Mote et al., 2014) and associated increased demand for environmental, municipal and power generation uses.

Irrigated sugarbeet production in the arid western U.S. (CA, ID, OR) comprises about 18% of the total U.S. production or 90,500 ha. Production in eastern Oregon and southern Idaho is about 79,500 ha or 16% of total U.S. production (NASS, 2014). In 2011, the value of receipts from sugarbeet production exceeded $370 million and ranked 5th in Idaho for agricultural crop sales (IDA 2012; ODA 2013). Climate has been shown to influence sugarbeet growth, yield, and quality (Ulrich, 1952; Ohki and Ulruch, 1973; Jones et al., 2003; Kenter et al., 2006; Cleland et al., 2007; Hoffmann et al., 2009).

No data has been collected assessing the effects of growing season climatic conditions on western U.S. irrigated sugarbeet production. Thus, it is difficult to assess potential impact climate change will have on sugarbeet production in arid regions such as southern Idaho and eastern Oregon. Most research on the effects of climatic variables such as air temperature has been assessed for sugarbeet, primarily in rain-fed environments. Ulrich (1952) and Ohki and Ulruch (1973) found that season to season variability in sugarbeet sucrose concentration is in part associated with air temperature. Ohki and Ulruch (1973) found that sucrose concentrations increased with decreasing night time temperatures, with maximum concentrations occurring at 2°C for 17 weeks. Early growing season (early spring) air temperature effects on plant phenology has been shown to be more significant than late spring and summer air temperatures (Chmielewski et al., 2004). In Great Britain, Milford et al. (1985) found that increased air temperature during the early part of the growing season when leaves are unfolding had a greater effect on increasing leaf area than air temperatures during leaf expansion. Scott et al. (1973) found that sugarbeet yields were correlated with the amount of light intercepted, which is related to leaf area. Combined, the effects of air temperature on leaf development and light interception are important climatic factors influencing yield and yield components (e.g. sucrose concentration) (Scott et al., 1973; Milford et al., 1985). Fredkleton et al. (1999) showed that within a given growing season, periods exist that changes in environment can have a significant effect on sugarbeet yield. They found that mean temperature during April, and mean temperature and rainfall during late July and August were related with sugarbeet yields. In China, changes in temperatures have significantly influenced the yields of rice, wheat and corn over time (Tao et al., 2006). Chemielewski et al. (2004) shows that phenological models need to be developed to estimate the impact of climate change on crop production.

While irrigated sugarbeet yield may increase due to a longer growing season as evident from yields in regions with longer growing seasons, the effect of increased summer temperatures on sucrose content in the arid Northwest U.S. is unknown. This paper focuses on the effects of climatic conditions in the arid Pacific Northwest on irrigated sugarbeet sucrose content because the concentration of sucrose has a large effect on final sucrose yield and climatic conditions can have a significant effect on sucrose concentration. Improving sucrose content is a major goal of the sucrose industry. Amalgamated Sugar Company has a goal to increase average growing area sucrose content to 18% by 2020 (Laubacher, 2016). Sucrose content is determined in the sugarbeet quality lab operated by the sugar processing cooperative from a minimum sample rate of one out of three delivered loads at receiving stations along with net root weight of each load delivered. Root yield is determined based on total delivered net weight and total area harvested. Sugar yield is determined from sucrose content and net weight of sugarbeets delivered and used to determine payment. Yield over the period from 1997 through 2014 has steadily increased with few seasonal variations (Figure 1). The steady increase in yield since 2006 may be related to the introduction of Genuity® RoundUp Ready® (Monsanto Company, St. Louis, MO) sugar-

Figure 1. Mean sugarbeet yield for the study region from 1997 through 2014. Bars represent the 95% confidence interval of the mean.

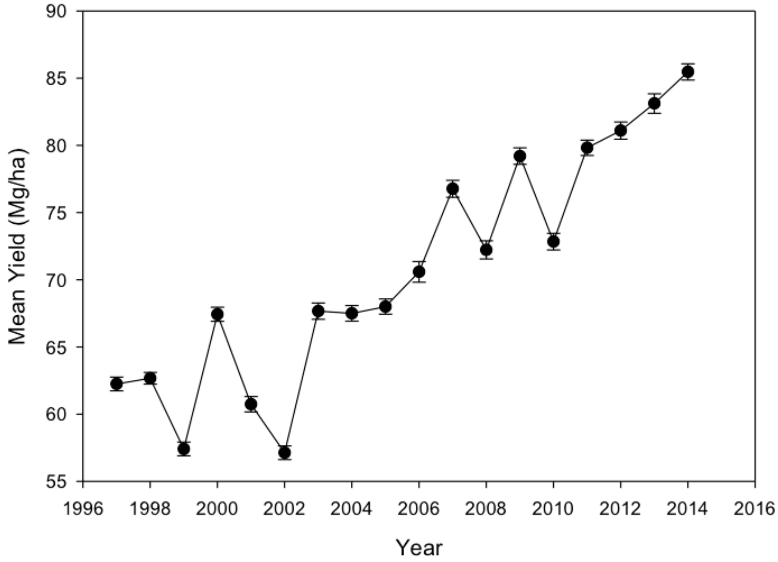
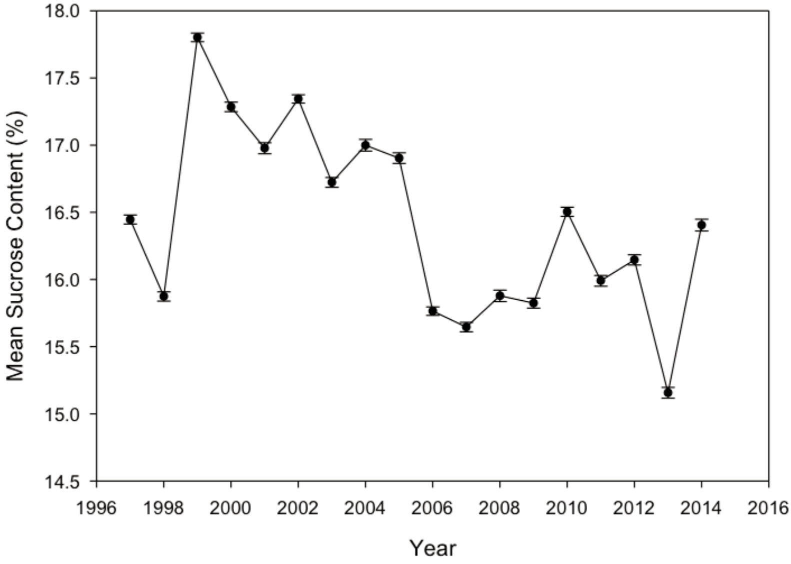


Figure 2. Mean sugarbeet sucrose content for the study area from 1997 through 2014. Bars represent the 95% confidence interval of the mean.



beets. In contrast, sucrose content has shown a steady decline over the period of 1997 through 2014 with differences as great as 2% sucrose content between consecutive years (Figure 2) and well below the target value of 18% for the region. The relatively large change in sucrose content between consecutive years may be related to differences in seasonal climatic conditions rather than cultural practices as the latter is rather static in consecutive years with exception of the introduction in Roundup Ready sugarbeets in 2006. If sucrose yield is substantially affected by seasonal climatic conditions, increased climatic variability and summer temperatures due to climate change may adversely affect sustainability of irrigated sugarbeet production in southern Idaho and eastern Oregon. The objective of this study is to investigate linkages between seasonal climatic conditions and sucrose content of sugarbeets from producer fields from 1997 through 2014 in southern Idaho and eastern Oregon.

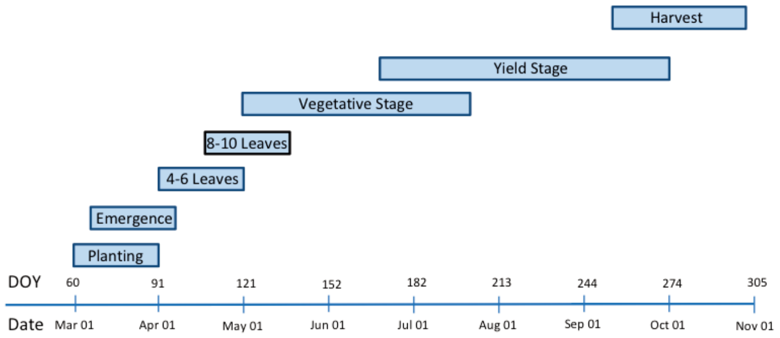
METHODS AND MATERIALS

Sucrose content of sugarbeet samples delivered to 74 receiving stations in southern Idaho and eastern Oregon from 1997 through 2014 were obtained from the sugarbeet processing cooperative Amalgamated Sugar Company (John Schorr, personal communication). Amalgamated Sugar samples a minimum of 33% of all loads that are delivered to receiving stations annually. Sucrose content was measured by the processing cooperative quality lab and the data summarized as a mean by producer field resulting in a total of 48192 data values.

Daily climatic data, growing degree days (GDD) and accumulated alfalfa reference crop evapotranspiration (ETr) was obtained from the regional weather station network (AgriMet) operated by the U.S. Bureau of Reclamation (http://www.usbr.gov/pn/agrimet/). Daily climatic data included maximum, minimum and mean air temperatures (°C), daily global solar radiation (MJm^{-2}), accumulated growing degree days (10°C base), and mean relative humidity (%). The climatic data was obtained for 13 weather stations in eastern Oregon and southern Idaho sugarbeet growing area. The database for each weather station was summarized into 15 day periods from day of the year (DOY) 60 through DOY 285 to make the data set manageable. The resulting parameters for each 15 day period were accumulated ET_r and GDD from DOY 1, average minimum and maximum daily air temperature, average global solar radiation, and average ET_r. Each of the 74 sugarbeet receiving stations was associated with climatic data from the nearest weather station. Mean sugarbeet sucrose content for the receiving stations associated with each weather station was computed and linked with the weather station's climatic data resulting in 215 records spanning 1997 through 2014 with 99 climatic variables.

For reference purposes, general sugarbeet growth stages in relation to dates and DOY are shown in Figure 3. There is at least a 30 day range in planting dates due to the wide range in climatic conditions across the region partially due to elevation. Planting starts at lowest elevations

Figure 3. General sugarbeet growth stages across the study region in relation to date and DOY.

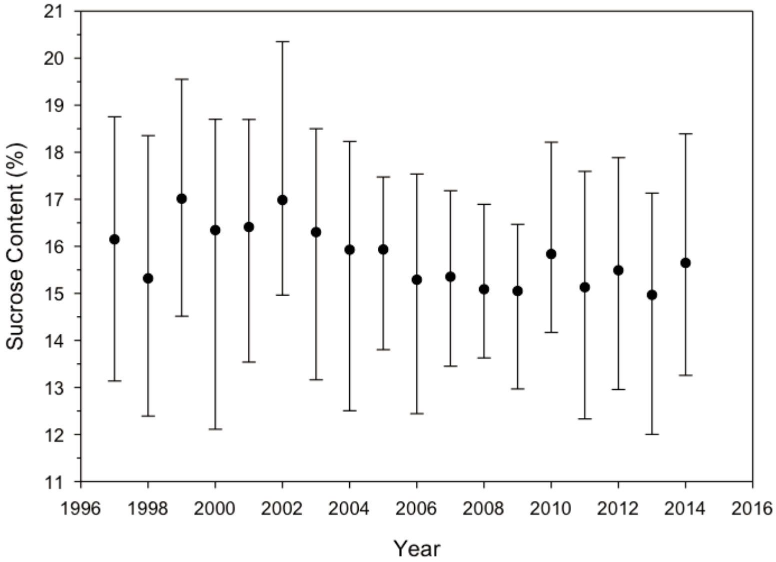


such as Ontario, OR (elev. 655 m) and progresses to higher elevations such as Blackfoot, ID (elev. 1371) as daily minimum temperatures increase and soil moisture from winter precipitation decrease sufficiently for tillage and planting. Consequently, there is a range in sugarbeet growth stages across the region for any given date.

Various exploratory analysis techniques were used to investigate relationships between climatic data and sugarbeet sucrose content. Mean, maximum, minimum, standard deviation, and 95% mean confidence intervals for sucrose content were determined grouped by weather station and overall. Mean values for all 15-day period climatic parameters were determined for each weather station. Correlations between sucrose content and all climatic parameters across all locations were determined. These correlations were used to screen climatic parameters having the greatest association with sucrose content for further consideration. Climatic parameters with correlations $< |0.3|$ were eliminated from further consideration. Regression analysis using SAS Proc Reg (SAS ver. 9.4) was used to compute multiple linear regression equations for estimating sucrose content for all combinations of the climatic parameters retained in the data set. Goodness of fit measures computed for each equation included sum of square errors (SSE), mean square error (MSE), adjusted R^2, and Akaike's Information Criteria (AIC) (Bozdogan 1987). The latter is a measure of fit or uncertainty for the range of values in the data set and was used to select climatic parameters having the greatest predictive value for mean sucrose content. A minimum set of climatic factors related to sucrose content was selected based on change in MSE and R^2 for each additional parameter included in a multiple linear regression equation.

Exploratory common factor analysis was used to investigate for presence of latent factors related to mean sucrose content underlying the selected minimum set of climatic variables using SAS Proc Factor (SAS

Figure 4. Mean sugarbeet sucrose content for area associated with the Ontario, OR weather station. Bars represent data range.

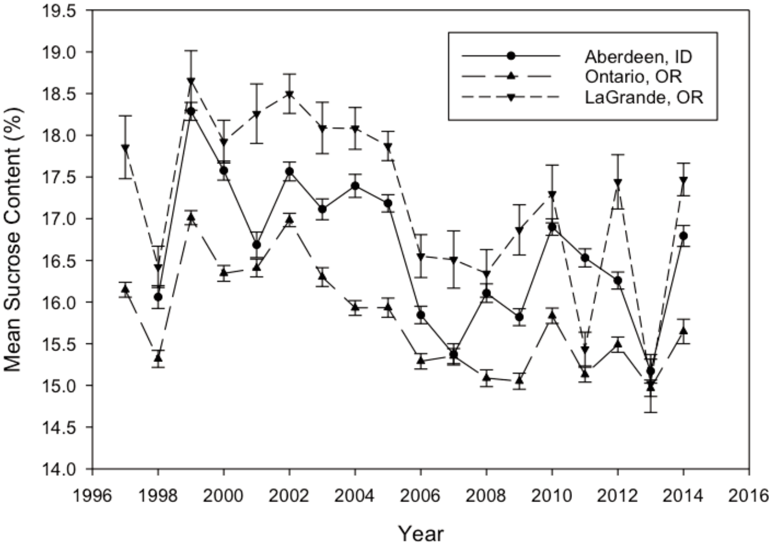


ver. 9.4). The principle component method was used for extracting factors and the varimax method used for orthogonal rotation. The Kaiser-Meyer-Olkin measure of sampling adequacy (KSA) was used to verify factor analysis was appropriate.

RESULTS AND DISCUSSION

A wide range in sugarbeet sucrose content was present for a given location and year, (Figure 4). This variation was attributed to differences in grower production practices (tillage, crop rotation, and pest, fertility and irrigation management) and seed genetics. Mean sucrose contents were often significantly different between locations in a given year (Figure 5). Mean sucrose content at LaGrande, OR was often significantly greater than at either Ontario, OR or Aberdeen, ID. This location difference in mean sucrose content may be largely attributed to climatic differences between locations, but could partially be due to irrigation method. Variability in other factors such as soil type and management practices could also contribute to variation in sucrose content. Locations in southwestern Idaho often had the lowest sucrose content (data not shown), which historically has a greater portion of furrow irrigated fields than other locations. Water management under furrow irrigation is not as easily controlled compared to sprinkler irrigation. Yearly trends in sucrose content were often consistent across locations (Figure 5), for exam-

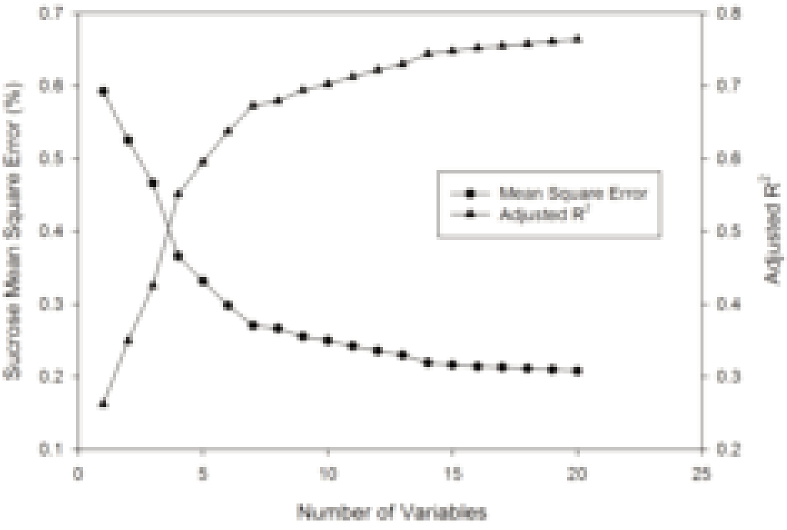
Figure 5. Mean sugarbeet sucrose content associated three weather station locations in the study area from 1997 through 2014. Bars represent 95% confidence interval of the mean.



ple sucrose contents were relatively low in 1998 and relatively high in 1999, indicating presence of some yearly variable factor.

Thirty four of the 99 climatic variables had correlations < -0.30 with mean sugarbeet sucrose content across years and locations (data not show). All 34 correlations were negative indicating that a greater climatic parameter value decreased mean sucrose content. Multiple linear regression analysis reduced the number of important climatic variables to 20 based on optimization of AIC resulting in an adjusted R^2 of 0.76 and mean square error (MSE) of 0.21. A smaller MSE value indicates a smaller error in estimated values of sucrose content when compared to the measured values. Sucrose MSE gradually increased and adjusted R^2 gradually decreased when the number of climatic variables used in the multiple linear regression equation was further reduced (Figure 6). Sucrose MSE and adjusted R^2 began to rapidly change when less than seven climatic parameters were included in the multiple linear regression equation indicating the seven remaining climatic parameters had the greatest relationship with mean sucrose content across all locations and years. The seven climatic parameters were DOY 121 to 135 mean daily maximum air temperature (135AvgMX), DOY 196 to 210 mean maximum daily air temperature (210AvgMX), DOY 195 GDD (195GDD), DOY 270 GDD (270GDD), DOY 181 to 195 mean daily minimum air temperature (195AvgMN), DOY 150 accumulated reference ET (150CumET),

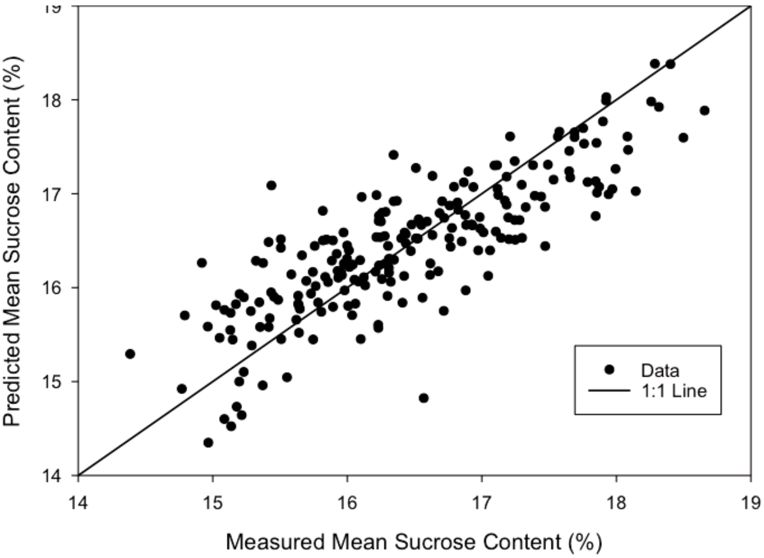
Figure 6. Sugarbeet sucrose mean square error and adjusted R^2 value as a function of the number of climatic parameters include in the multiple linear regression prediction equation.



and DOY 225 accumulated reference ET (225CumET) resulting in a R^2 of 0.67 and MSE of 0.27 (Figure 7). Multiple linear regression equations for predicting mean sugar content using one to seven climatic variables are listed in Table 1. Different combinations of climatic parameters are included when the number of parameters ranges from one to seven. The single most important climatic parameter related to mean sucrose content was 135AvgMX as it was included in every regression equation (Table 1). As the average maximum temperature during this early growth increases the sucrose concentration at harvest decreases. Other studies have found that early spring air temperature influences sugarbeet phenology (Chmielewski et al., 2004; Milford et al., 1985). The second most important climatic parameter was 210AvgMX as it was included in the two parameter regression equation for estimating sucrose content. It also had the lowest correlation with 135AvgMX (Table 2) and contributed maximum new information into the regression equation among the five other climatic parameters.

Several of the seven climatic variables were highly positively correlated, Table 2, indicating that they may be related to a common underlying measure. The KSA values for the seven climatic parameters ranged from 0.70 to 0.94 (data not shown) with an overall KSA of 0.77 indicating the presence of a good degree of common variance. Two primary common factors were found for the seven climatic parameters, Table 3. Factor

Figure 7. Comparison of measured mean sucrose content with predicted mean sucrose content using multiple linear regression equation with seven seasonal climatic parameters.



one accounted for 88% of the common variance between the climatic parameters and the second factor accounted for approximately 12% of the common variance. Factor one accounted for 65% of the total variance in the seven climatic parameters and over 80 percent of the total variance in 195GDD, 195AvgMN, 225CumET and 270GDD. The two factors accounted for nearly 74% of the total variance in the seven climatic parameters but less than 50% of the total variance of climatic parameters 135AvgMX and 210AvgMX. This may be due to the presence of occasional short term temperature extremes in the region that are less directly related (less collinearity) with the other climatic parameters. Factor 1 is largely dependent upon daily temperature throughout the growing season and temperature extremes as indicated by orthogonally rotated factor loadings >0.5 (Table 3). Factor 2 is largely dependent upon early (late May) and mid-season (early August) seasonal evaporative demand as indicated by the orthogonally rotated factor loadings >0.5. Factor 1 may be considered a vegetative growth stage temperature measure since it is highly dependent upon early (May – June), mid-season (mid-July) temperature extremes and seasonal temperature trends (GDD's). Factor 2 may be considered an evaporative demand measure since it is largely dependent upon accumulated ET_r. Factor 2 is not mathematically independent of factor 1 as temperature is one of the primary inputs in calculation of ET_r. Overall, factor 1 is the most important indicating

Table 1. Multiple linear regression equation coefficients for models to estimate mean sugar beet sucrose content having up to seven climatic parameters. Climatic parameters are: DOY 121 to 135 mean daily maximum air temperature (°C) (135AvgMX), DOY 196 to 210 mean maximum daily air temperature (°C) (210AvgMX), DOY 195 growing degree day (°C) (195GDD), DOY 270 growing degree day (°C) (270GDD), DOY 181 to 195 mean daily minimum air temperature (°C) (195AvgMN), DOY 150 accumulated reference ET (mm) (150CumET), and DOY 225 accumulated reference ET (mm) (225CumET).

Number Climatic Parameters	Intercept	135AvgMX °C	150CumET mm x10^{-3}	195GDD °C x10^{-3}	195AvgMN °C	210AvgMX °C	225CumET mm x10^{-3}	270GDD °C x10^{-3}	Mean Square Error	R^2
1	19.207	-0.141	--	--	--	--	--	--	0.59	0.26
2	22.389	-0.114	--	--	--	-0.113	--	--	0.52	0.35
3	22.705	-0.159	--	11.36	--	--	--	-7.69	0.47	0.43
4	23.374	-0.167	--	5.73	-0.196	-0.160	--	--	0.37	0.55
5	24.701	-0.164	-5.08	7.12	-0.197	-0.173	--	--	0.33	0.59
6	24.328	-0.147	-12.56	6.88	-0.229	-0.206	-4.60	--	0.30	0.64
7	26.017	-0.146	-13.93	12.21	-0.166	-0.185	4.85	-4.47	0.27	0.67

Table 2. Correlation coefficients between the seven climatic parameters included in linear multiple regression equations. Climatic parameters are: DOY 121 to 135 mean daily maximum air temperature (°C) (135AvgMX), DOY 196 to 210 mean maximum daily air temperature (°C) (210AvgMX), DOY 195 growing degree day (°C) (195GDD), DOY 270 growing degree day (°C) (270GDD), DOY 181 to 195 mean daily minimum air temperature (°C) (195AvgMN), DOY 150 accumulated reference ET (mm) (150CumET), and DOY 225 accumulated reference ET (mm) (225CumET).

	135AvgMX	150CumET	195GDD	195AvgMN	210AvgMX	225CumET	270GDD
135AvgMX	1						
150CumET	0.498	1					
195GDD	0.710	0.660	1				
195AvgMN	0.560	0.504	0.771	1			
210AvgMX	0.322	0.268	0.543	0.405	1		
225CumET	0.471	0.887	0.720	0.623	0.444	1	
270GDD	0.684	0.600	0.968	0.832	0.574	0.687	1

Table 3. Unrotated and orthogonally rotated factor loadings for the seven variables used in multiple regression equations. Climatic parameters are: DOY 121 to 135 mean daily maximum air temperature (°C) (135AvgMX), DOY 196 to 210 mean maximum daily air temperature (°C) (210AvgMX), DOY 195 growing degree day (°C) (195GDD), DOY 270 growing degree day (°C) (270GDD), DOY 181 to 195 mean daily minimum air temperature (°C) (195AvgMN), DOY 150 accumulated reference ET (mm) (150CumET), and DOY 225 accumulated reference ET (mm) (225CumET).

	Unrotated Factors			Orthogonally Rotated Factors	
Parameters	**Factor 1**	**Factor 2**	**Communality**	**Factor 1**	**Factor 2**
135AvgMX	0.68	-0.12	0.48	0.62	0.31
150CumET	0.77	0.52	0.86	0.30	0.88
195GDD	0.96	-0.17	0.95	0.87	0.44
195AvgMN	0.80	-0.18	0.68	0.75	0.34
210AvgMX	0.53	-0.19	0.32	0.54	0.17
225CumET	0.84	0.41	0.88	0.42	0.83
270GDD	0.96	-0.26	0.98	0.92	0.36
Percent Total Variance	65.0	8.6	73.6	44.6	29.0
Percent Common Variance	88.0	12.0		60.6	39.4
Eigenvalues	4.54	0.62			

that vegetative growth stage temperature extremes and overall seasonal temperature are the primary climatic parameters related to mean sucrose content across the region.

The identified linkages between seasonal climatic parameters and sugarbeet sucrose content indicate that anticipated increased seasonal temperature associated with climate change will likely negatively impact sugarbeet sucrose content. The effect of climate change on sugarbeet sugar yield maybe buffered due to possible increases in yield resulting from a longer growing season when adequate nutrients and water are supplied. However, as the root yield:sucrose content ratio increases sucrose extraction costs will increase (Amalgamated Sugar Company, personal communication). Also a longer growing season and higher temperatures will increase irrigation water requirements when water resources are predicted to decrease due to diminished snowpack. Increased concentrations of atmospheric carbon dioxide may increase water use efficiency (Hatfield, J. et al., 2014) and buffer increases in crop water use due to increased seasonal temperature and longer growing season. Increased yields will increase producer costs for harvest and transportation to receiving stations. Research to develop sugarbeet varieties with higher sucrose concentration provides one of the best opportunities for sustaining sucrose yield of irrigated sugarbeets in the region and worldwide with anticipated climate change.

CONCLUSIONS

Changes in seasonal climatic temperatures were linked to sugarbeet sucrose content and thus potentially sucrose yields. Seven climatic variables were most related to sugarbeet sucrose concentrations providing good multiple linear regression estimates of sucrose content. Early sugarbeet growth period maximum temperature was the most important climatic parameter related to mean sucrose content. Temperature in growth periods later in the growing season after full plant cover also influenced sucrose concentrations. In general, as temperature and GDD increased sucrose content decreased. Increases in both early season and mid-season temperatures will likely lead to decreases in sugarbeet sucrose concentrations. If sugarbeet yields increase due to increasing temperatures and GDD accumulation, the sucrose yield changes would be buffered. However, as the root yield:sucrose content ratio increases sucrose extraction costs will increase. Increasing sucrose content in sugar beet using genetic and agronomic management tools will be important if climate change leads to increased temperatures over time to optimize sugar production and economics for the industry.

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