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ORIGINAL ARTICLE

Climate change effects on the processing tomato growing season in California using growing degree day model

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Abstract
California has a unique Mediterranean climate, well suited for irrigated agriculture. The climate is an important factor in making California a global leader in production of many high value crops, including procesing tomatoes (*Lycopersicon esculentum* Mill*)*, with production of approximately 95% nation's and 30% of world's processing tomatoes. However, climate change poses many immediate and long-term challenges for state's highly productive agricultural industry. In order to help growers manage risks, it is important to study locally relevant agronomic indicators that are viable and aligned with growers' interests. Growing degree day models translate raw climate data into meaningful agricultural indicators which growers can utilize for immediate and long-term strategic decisions. Objective of this study was to analyze growing season trend in top five processing tomato-producing counties in California through the use of growing degree-days model and historical and future climate scenarios generated from the general circulation model (GCM). Based on the findings, the models indicated a significant decrease in the number of days between transplanting and maturity, with an expected harvest 2–3 weeks earlier than normal under current conditions and cultivars. Results from this study could be utilized to make strategic decisions such as variety selection, planting and harvest dates, agricultural water management, and studying trends in pests and diseases due to shifts and lengthening of tomato growing season in the tomato production areas of California.

Keywords Climate change · Growing season · Processing tomato · Growing degree-days · California · Impacts of climate change

Introduction

Tomato (*Lycopersicon esculentum* Mill.) industry is one of the most globalized and advanced horticultural industries. The global annual production of tomatoes (fresh and processed) has increased by about 300% during the last four decades (Costa and Heuvelink 2007). In 2017, global tomato production is approximately 160 million tons. The United States, China, the European Union, Turkey, and India are the leading producers of tomatoes. Out of 160 million tons total tomato production, about 40 million tons are processed tomato production. Mostly grown in temperate climate zone, roughly 91% of the production is concentrated in northern hemisphere and remaining 9% of the production is located in southern hemisphere. In 2017, North America and the European Union led processed tomato production with approximately 28% of the global share each, followed by AsiaPacific region that contributed about 16.6% of the processing tomato production worldwide (tomatonews 2018).

California is one of the most productive and diverse agricultural states in the United States that has about 77,500 farms producing more than 400 commodities and generates an estimated value of agricultural production of $50.5 billion (CDFA 2016). Processing tomatoes are among the top 10 most valued commodities in California. More than 90% of the nation's processed are produced in California (Hartz et al. 2008). The area planted to processing tomatoes in California has increased considerably in recent years. The 2007–2017 area planted to processing tomatoes in California averaged 271,000 acres (NASS 2017). The top five processing tomato producing counties are Fresno, Kings, Merced, San Joaquin, and Yolo counties, accounting for more than 75% of total processing tomato production in California.

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While tomato industry is growing significantly worldwide, climate change may pose many challenges. Observed and projected increases in temperature in California have been well documented in the literature (Cayan et al. 2009; Hansen et al. 2010; Abatzoglou et al. 2009; Pathak et al. 2018). Apart from increased temperature, other recognized possible impacts include low chill hour accumulations, decreased winter snowpack, earlier timing of snowmelt, and vulnerability to pest and pollinator changes (Lobell et al. 2007; Tanaka et al. 2006).

Temperature has a direct impact on growth and development of crops and could significantly alter plant phenology. These are often overlooked aspects of plant ecology (Cleland et al. 2007; Anandhi 2016; Darand and Mansouri Daneshvar 2015) and have important implications for agricultural production. Study done by Saadi et al. (2015) show that air temperature is foreseen to have a dominant role on the shortening and anticipation of the tomato growing cycle over the Mediterranean region. Ventrella et al. (2012) studied agronomic adaptation strategies in Italy under climate change for several crops in including tomatoes and found that tomato phenology may alter by 2050 due to warmer temperature and may reduce tomato yields. Whereas in the United States, specifically in California, modeling studies showed that tomato yields may not decline and might even increase slightly (Lee et al. 2011) under future climate. Climate change has often been studied as a global issue, while research efforts on translating it into useful indicators and identifying commodity specific adaptation strategies at local and regional scales that provide meaningful resource and decision-making capabilities to stakeholders are lacking. The current format used for raw climate data makes it unclear how or even if they can be used at the farm scale.

Use of past and future climate information offers the potential to enhance agricultural resilience to climate change through improved agricultural decision making, such as preparing for expected adverse or favorable conditions. Skills in climate model outputs have improved over time, and more recently, a set of climate change scenarios known as representative concentration pathways (RCPs) has been adopted by climate researchers to provide a range of possible futures for the evolution of atmospheric composition and implications on various sectors (Collins et al. 2013; Gharbia et al. 2016; Zahid and Iqbal 2015; Deb et al. 2018; Manish et al. 2016; Clarke et al. 2007; Smith and Wigley 2006; Thomson et al. 2011; Wise et al. 2009). However, it needs to be presented in a format which can provide useful information to growers.

Growing degree-days (GDD) can be a useful agro-climatic indicator, because the models can translate complex climate trends and projections into meaningful agricultural indicators for producers. A growing degree-day model is mathematical model to accumulate daily heat units with variations and combinations of base temperature and upper temperature cutoff limits to predict growth stages for crops (Roltsch et al. 1999). These base and cutoff temperature limits, as well as methods to calculate daily GDD, vary considerably with respect to different crops (Snyder et al. 1999). The GDD models have been used worldwide for predicting phonological stages of crops worldwide (Miller et al. 2001; Thuiller et al. 2005). In California, Zalom and Wilson (1999) evaluated GDD model with different base temperature and upper cutoff limits and found that the combination of 10 °C base temperature and 30 °C upper cutoff provided optimum match with observed growth stages in processing tomatoes. Apart from predicting various growth stages, GDD model can provide helpful prediction of time to maturity and length of the total growing season (Anandhi 2016; Castillo and Gaitán Ospina 2016; Machado et al. 2004; Saadi et al. 2015). The ability to predict maturity and identifying trends over the future could assist in many important strategic and management decisions such as labor management, linking with tomato processors, and long-term water management based on the length of the growing season trend and GDD accumulations.

Evaluation of the GDD model in predicting growth stages in California have been investigated (Zalom and Wilson 1999), however, to the best of our knowledge, research on detecting growing season trends over historical records and future climate projections for processing tomatoes in California has not yet been investigated. Objective of this study was to analyze growing season trend in top five processing tomato-producing counties in California through the use of growing degree-days model and historical and future climate scenarios generated from the general circulation model (GCM).

Materials and methods

Study region

This study was focused on the top five tomato producing counties in California. According to the NASS (2017), top five tomato producing counties were Fresno, Kings, Merced, San Joaquin, and Yolo counties. These counties are located in central California from the southern end of the Sacramento Valley (38°55′N) to the southern extent of the San Joaquin Valley (35°56′N) (Fig. 1). Tomato production was about 3,982,000 tons for Fresno, 1,478,000 tons for Kings, 1,098,000 tons for Merced, 1,054,000 tons for San Joaquin, and 1,679,000 for Yolo counties in 2016, respectively. These counties make up 76% of the 2017 total contracted planted acreage for California (NASS 2017), and were selected for this study not only because they make up significant portion of processing tomato production in California but also represent a broad but typical production area for processing tomatoes.

Fig. 1 California counties represented in this study include (1) Yolo (2) San Joaquin (3) Merced (4) Fresno, and (5) Kings. (Map curtsey of United States Census Bureau)

Tomato transplanting dates

Nearly all commercial processing tomato fields in California are transplanted. Transplants are mechanically planted into fields starting from early March and continuing until early June (Hartz et al. 2008). To cover the processing tomato planting window, five planting dates were selected for input in the growing degree days (GDD) model: March 15, April 1, April 15, May 1, and May 15. Based on the expert opinions of tomato researchers and Extension professionals at the University of California, these dates would encompass early, average, and late planting periods where processing tomatoes are produced in California.

Modeled data

For this study, local scale projections were obtained from the Australian Community Climate and Earth-System Simulator (ACCESS 1.0) Global Circulation Model (GCM). ACCESS 1.0 model has an atmospheric resolution of 1.875° by 1.25° in the horizontal with 38 vertical levels and an atmospheric top at approximately 40 km. The ocean model has 50 vertical levels and 1° horizontal resolution, increasing to 1/3° near the equator (Bi et al. 2013). This modeling group is part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) and successfully completed historical simulations of global average surface air temperatures. Selection of ACCESS 1.0 for this study was based on it performed better compared to other GCMs in California. The California department of water resources (DWR 2015) utilized 3-step model selection procedure to identify a subset of the better GCMs for developing assessments and plans for California water resource issues. Based on their analysis 10 CMIP5 GCMs passed the collective screening process and overall the ACCESS 1.0 provided the best performance. Based on that finding, we utilized ACCESS 1.0 GCM for this study.

For future projection trajectory, Representative Concentration Pathways 4.5 (RCP 4.5) and Representative Concentration Pathways 8.5 (RCP 8.5) were selected. The RCP 4.5 was developed by the modeling team at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI), in the United States. It is a stabilization scenario in which total radiative forcing is designed to increase by 4.5 watts/m^2. and stabilized shortly after 2100, without overshooting the long-run radiative forcing target level (Clarke et al. 2007; Smith and Wigley 2006; Thomson et al. 2011; Wise et al. 2009). RCP 8.5 was developed by the International Institute for applied systems analysis (IIASA), Austria which was designed to increasing greenhouse gas emissions over time, representative of scenarios in the literature that lead to high greenhouse gas concentration levels (Riahi et al. 2007). In other words, RCP 4.5 would mimic low emission scenario whereas RCP 8.5 would mimic "business as usual" or high emission scenario. Model outputs utilized in this study were statistically downscaled daily maximum and minimum temperatures over historical period of 1950–2005 and projected values over the period of 2006 to 2080; as Representative Concentration Pathways (RCP) scenarios typically start at 2006 (Collin et al. 2013).

Data are being made available by collaborators that include Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Santa Clara University, Scripps Institution of Oceanography, US Army Corps of Engineers, US Geological Survey, and National Center for Atmospheric Research. We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison and the World Climate Research Program's (WCRP) Working Group on Coupled Modeling for their roles in making available the WCRP Coupled Model Intercomparison Project (CMIP) phase 3 multi-model dataset. The Office of Science, US Department of Energy, provides support of this dataset.

Growing degree days (GDD) phenology model

Crops require certain amount of accumulated heat in order to move from one growth stage to the other. This is oftern referred to as physiological time. Growing degree-day models, which are mathematical combinations of various temperature thresholds, calculate cumulative heat units to relate to physiological times of various crops. Zalom and Wilson (1999) conducted a study on predicting phenological events for processing tomatoes in California. Based on their experiment with 536 datasets collected from commercial fields in California over 4 years, they reported that a growing degree day model with base temperature of 10 °C and upper cutoff of 30 °C significant improved prediction of various growth stages of processing tomatoes. According to their model validation, there was a significant accuracy and robustness in predicting physiological maturity when 1214 degree-days accumulated after planting.

Daily GDDs for the length of tomato growing season, i.e. duration from transplanting of tomatoes in the field to maturity was calculated using the following GDD model.

$$\begin{aligned} GDD &= \frac{Tmax + Tmin}{2} - Tbase; \\ &\quad if\ \frac{Tmax + Tmin}{2} > Tbase\ \ and \\ &\quad \frac{Tmax + Tmin}{2} < Tcutoff \qquad (1) \\ GDD &= Tcutoff - Tbase; \quad if\ \frac{Tmax + Tmin}{2} \geqslant Tcutoff \\ GDD &= 0; \quad if\ \frac{Tmax + Tmin}{2} \leqslant Tbase \end{aligned}$$

where *Tmax* and *Tmin* are maximum and minimum daily temperatures, respectively. *Tbase* and *Tcutoff* are defined as base temperature and cutoff temperatures, respectively. It is a horizontal cut-off model, which assumes that the degree days accumulations above the cutoff limit do not count.

Modeling application to analyze trends in growing season length

Procedure to estimate length of the growing season through the use of growing degree-days model and historical and future climate scenarios generated from the ACCESS 1.0 GCM model, over historical and projected timeframe is described in following steps.

Step 1: Determine transplant dates. Typical tomato transplanting dates for California is described in "Tomato Transplanting Dates" section.

Step 2: Gather daily minimum and maximum temperature data for study time period. For this research, minimum and maximum temperature for historical period (1950–2005) and future period (2006–2080) was obtained from ACCESS1.0 GCM downscaled data. Please refer to "Modeled Data" section.

Step 3: Calculate daily GDD for each of five planting dates for each of five locations using conditions defined in Eq. 1

Step 4: Calculate cumulative GDDs for each of five planting dates for each year for each county

Step 5: Determine day of the year for each year when accumulated GDDs reach minimum required cumulative GDDs for maturity as defined in "Growing Degree Days Phenology Model" section.

Step 6: Estimate trends in days to maturity and length of the growing season (duration between planting and maturity) for each of five planting dates for each of five counties through linear trend. Statistical significance was tested using the t-test ($p < 0.05$).

Results and discussion

Modeled duration between tomato transplanting to maturity for historical climate

For early planting date (March 15), average length of the period from transplanting to maturity (1214 GDDs) ranged between 117 days to about 135 days across five counties; year-to-year variations ranged from 102 days to about 150 days. In comparison to early planting date, growing season length for a May 15 transplant date, ranged from 79 to 97 days, with year-to-year variations from 70 to 111 days (Table 1). To accumulate the same amount of GDDs (1214), latest planting date (May 15) took an average of approximately 40 days less compared to the earliest planting date (March 15) across all five counties. Average daily maximum and minimum temperature ranges are relatively higher for later planting dates and thus GDDs accumulate faster and plants reach maturity earlier. Additionally, Yolo and San Joaquin counties accumulated more days to reach maturity compared to Merced, Kings, and Fresno counties. This is mainly because Yolo and San Joaquin counties are in northern side of the valley and these changes were mainly because temperature differences.

Trends in tomato growing season for historical climate

Using historical data, all top five tomato-producing counties in California exhibit a decrease in the time needed to achieve maturity between 1950 and 2005. This decrease was statistically significant for Merced, San Joaquin, and Yolo counties, whereas, Fresno and Kings counties exhibit statistically significant reductions in time for certain planting dates. Strongest reductions were observed for late planting dates (May 1) for San Joaquin County. Between 1950 and 2005, the number of days needed to reach 1214 GDDs was reduced at the rate of 0.17 days per year. Thus, maturity occurred 9 days sooner in 2005 than 1950, on average, for this location. Yolo and San Joaquin counties showed relatively steeper declines in days to reach maturity, followed by Merced, Fresno, and Kings counties, respectively, during the historical records evaluated with this model (Table 2).

Modeled duration between tomato transplanting to maturity for future climate

As discussed in the methodology, trends in growing season length and days to maturity for various plantings dates were analyzed under both low (RCP 4.5) and high (RCP 8.5) emission trajectories. The length of time needed to achieve physiological maturity (1214 GDDs) was reduced substantially under future climate projections compared to historical records (Table 1). For instance, average growing season length in early planting date (March 15) varied between 104 and 118 days for low emission scenario and 102–116 days under high emission scenario, compared to 117–135 days for historical records. Thus, on average, the number of days between transplanting and harvest for processing tomatoes is expected to be reduced about 15–19 days under future climate scenarios as compared to historical records. The late planting date (May 15) average time to reach 1214 GDDs ranged between 69–83 and 67–80 days under low and high emission scenarios respectively. Compared with historical records, average time needed is expected to be reduced 12–17 days under future climate scenarios. Although impacts on yield are

Table 1 Average length of the growing season (duration between transplanting and maturity) for historical records and future climate projections for Fresno, Kings, Merced, San Joaquin, and Yolo counties in California

County	Planting dates	Average expected length of the tomato growing season (days) for historical records (1950–2005)	Average expected length of the tomato growing season (days) under low emission scenario, RCP4.5 (2006–2080)	Average expected length of the tomato growing season (days) under high emission scenario, RCP8.5 (2006–2080)
Fresno, CA	March 15	119	106	104
	April 1	106	94	92
	April 15	96	84	83
	May 1	86	75	74
	May 15	79	69	68
Kings, CA	March 15	117	104	102
	April 1	104	92	91
	April 15	95	83	82
	May 1	85	75	73
	May 15	78	69	67
Merced, CA	March 15	126	111	110
	April 1	112	99	98
	April 15	103	90	89
	May 1	93	81	79
	May 15	86	75	73
San Joaquin, CA	March 15	135	118	116
	April 1	122	106	104
	April 15	113	97	95
	May 1	103	89	86
	May 15	97	83	80
Yolo, CA	March 15	128	114	112
	April 1	115	102	100
	April 15	106	93	91
	May 1	96	84	81
	May 15	90	77	75

beyond the scope of this paper, it would be interesting to investigate if this would have negative impacts on yield. High temperatures > 35 °C can cause poor pollination and flower abortion (Hartz et al. 2008), and thus increased heat during the important blooming period would reduce yield.

Trends in tomato growing season for future climate

All five counties exhibited strong statistically significant declining trends in day of the year to reach maturity over 2006–2080 time period. Slopes of the linear trend line across all five counties and planting dates are shown in Table 2. The strongest declining slope of − 0.29 was obtained for San Joaquin County under high emission scenario. Trends in days to maturity for all five counties for early (March 15) and late (May 15) planting dates are shown in Figs. 2 and 3, respectively.

Discussion

Based on the analyses of five top tomato producing counties in California over the total period of 131 years of historical and future projections, the models clearly showed a significant linear reduction in the number of days required to achieve physiological maturity for processing tomatoes across all planting dates and locations. Furthermore, the rate of decrease is expected to accelerate in the future. Under future climate change models, temperature is expected to increase; as a result, crops should reach various stages of their growth and development cycle faster. This implies that processing tomatoes in California will mature quicker and will be harvested earlier than what occurred in the late twentieth century. Potential implications of this scenario are yield influences due to shortened vegetative and/or blooming periods, as well as the direct impact of daytime high temperatures on

Table 2 Linear trend slopes of average Julian day of the year at which tomato maturity is expected based on historical records and future climate change projections for Fresno, Kings, Merced, San Joaquin, and Yolo counties in California

County	Planting Dates	Slope of the linear trend in average expected length of the tomato growing season over the historical records (1950–2005)	Slope of the linear trend in average expected length of the tomato growing season over the low emission scenario, RCP4.5 (2006–2080)	Slope of the linear trend in average expected length of the tomato growing season over the high emission scenario, RCP8.5 (2006–2080)
Fresno, CA	March 15	−0.06	**−0.16**	**−0.25**
	April 1	−0.08	**−0.14**	**−0.22**
	April 15	**−0.09**	**−0.14**	**−0.19**
	May 1	**−0.09**	**−0.13**	**−0.19**
	May 15	**−0.09**	**−0.12**	**−0.16**
Kings, CA	March 15	−0.07	**−0.13**	**−0.25**
	April 1	−0.08	**−0.11**	**−0.23**
	April 15	−0.08	**−0.12**	**−0.21**
	May 1	**−0.08**	**−0.12**	**−0.19**
	May 15	**−0.07**	**−0.10**	**−0.16**
Merced, CA	March 15	−0.10	**−0.18**	**−0.25**
	April 1	**−0.10**	**−0.16**	**−0.23**
	April 15	**−0.10**	**−0.16**	**−0.22**
	May 1	**−0.09**	**−0.16**	**−0.22**
	May 15	**−0.08**	**−0.15**	**−0.21**
San Joaquin, CA	March 15	**−0.13**	**−0.25**	**−0.29**
	April 1	**−0.15**	**−0.22**	**−0.27**
	April 15	**−0.16**	**−0.21**	**−0.26**
	May 1	**−0.17**	**−0.21**	**−0.25**
	May 15	**−0.16**	**−0.20**	**−0.23**
Yolo, CA	March 15	**−0.12**	**−0.21**	**−0.25**
	April 1	**−0.14**	**−0.18**	**−0.23**
	April 15	**−0.14**	**−0.18**	**−0.22**
	May 1	**−0.15**	**−0.18**	**−0.23**
	May 15	**−0.14**	**−0.18**	**−0.23**

Statistically significant (P, 0.05) trends are in bold

pollen germination and growth. Results from this study could be utilized to make adaptive management decisions such as shifting transplant periods, changing/developing new cultivars with increased GDD maturity requirements, increase the use of extended field storage varieties, change irrigation management to slow late-season physiological development, and multiple harvests during the growing season. Growers need to plant their tomatoes such that fields are ready for harvest in a time frame negotiated with processors. Results from this study would help growers make strategic decisions to meet these demands.

According to the Intergovernmental Panel on Climate Change (IPCC) report, the southwestern US would expect drier than normal conditions, including more frequent and prolonged droughts. During drought periods, tomato growers may need to implement management strategies under limited water supply. Better understanding of the GDDs and growing season length under future climate presented in this paper could potentially help tomato growers in California to make careful considerations for future water management such as implementing deficit irrigation strategies, or determining expected water demand and reducing irrigated acreage to match that water supply.

In California, pests and diseases pose many challenges in agriculture. Under future climate models, many insect pests are expected to extend their ranges into new areas, and new insect pests might appear. Climate-driven changes present new and complex challenges and opportunities for sustainable agricultural programs based on integrated pest management (IPM) (Trumble and Butler 2009). Growing degree-day models do exist for many of these pests and diseases to monitor their growth cycle. The declines in the time needed to reach maturity for processing tomatoes presented in this study may provide increased motivation to investigate changes in the growth cycle of many climate

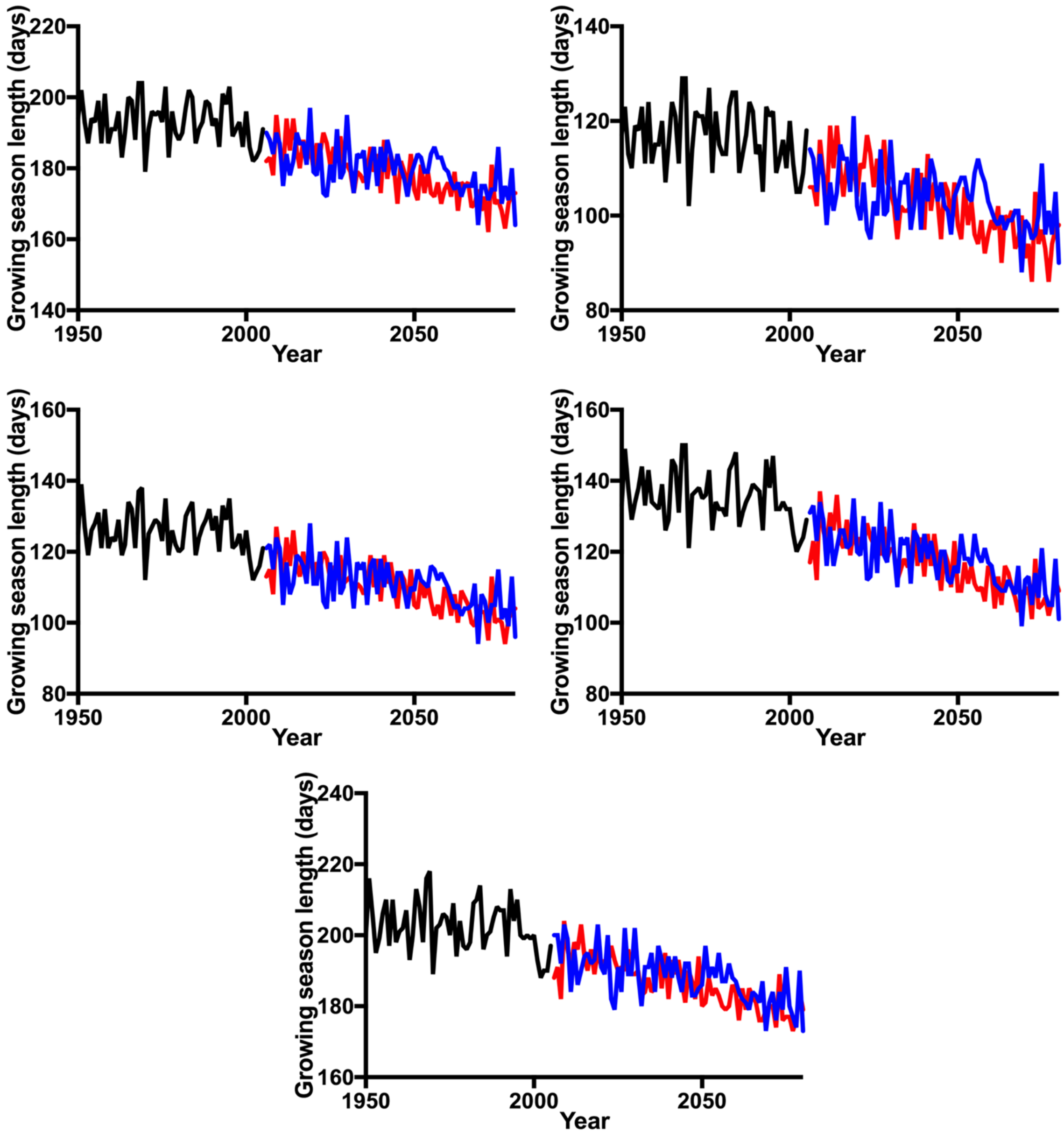

Fig. 2 Trends in tomato transplanting to maturity duration estimated for early planting date (March 15) based on the GDD model for historical and future projections for Fresno (top left), Kings (top right), Merced (middle left), San Joaquin (middle right), and Yolo (bottom) counties. Black, blue, and red line represents historical records, low emission scenario (RCP 4.5) projections, and high emission scenario (RCP 8.5) projections, respectively

driven pests and diseases and develop systems approaches that address these changes.

Conclusions

In this study we analyzed the projected change in the amount of time required for processing tomatoes in California to achieve physiological maturity using growing degree days (GDDs) into the twenty-first century. The analysis was focused on top five most productive counties for processing tomatoes in California. Historical (1950–2005) data showed a trend of declining GDDs in all five counties: significant ($p < 0.05$) linear declines were observed for most counties depending on transplant date. Representative Concentration Pathways 4.5 (RCP 4.5) and RCP 8.5 were used to model possible future impacts through 2080 on GDDs for these same counties. In comparison with historical records, the model output showed a strong and significant linear decline in the number of

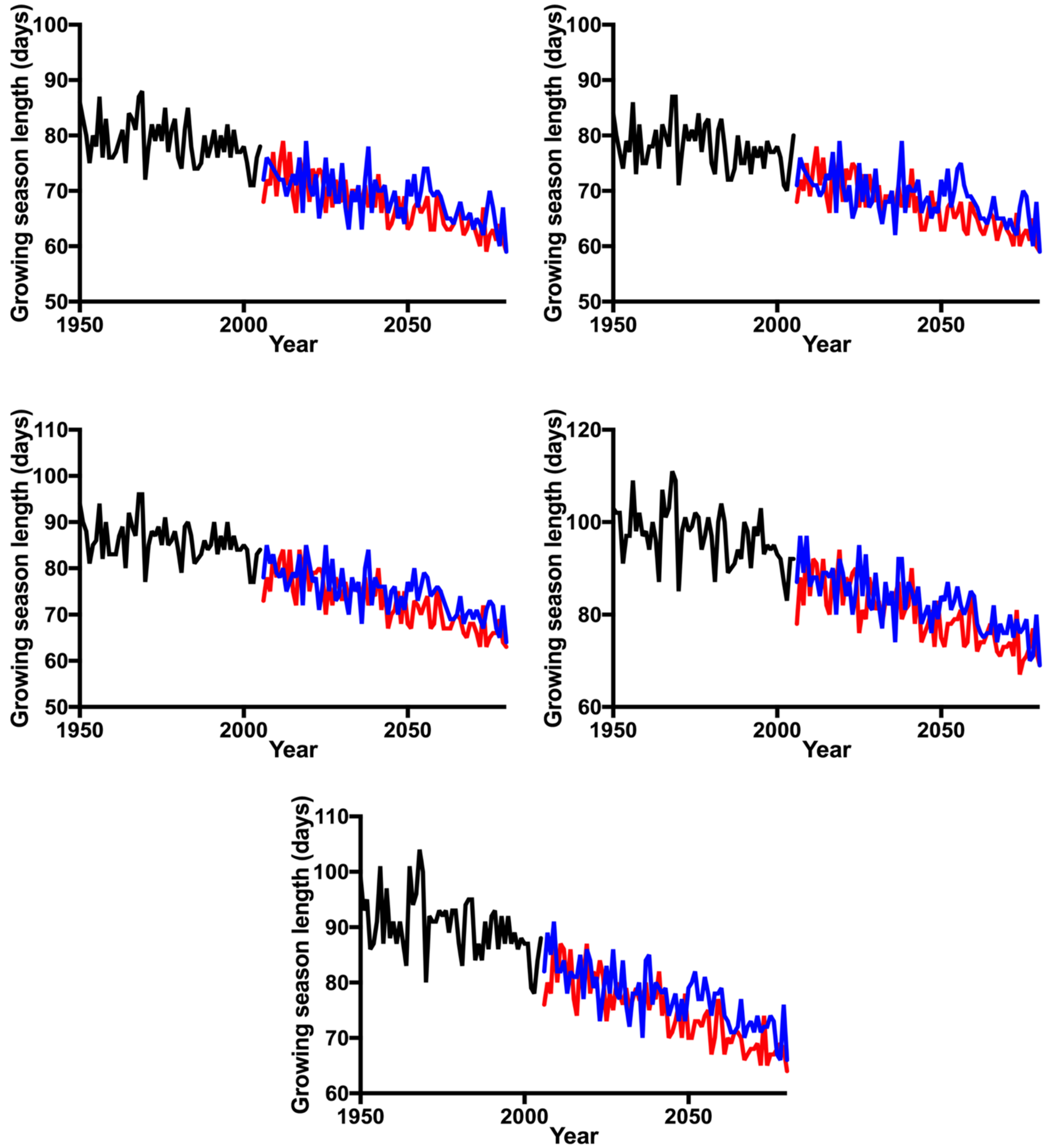

Fig. 3 Trends in tomato transplanting to maturity duration estimated for late planting date (May 15) based on the GDD model for historical and future projections for Fresno (top left), Kings (top right), Merced (middle left), San Joaquin (middle right), and Yolo (bottom) counties. Black, blue, and red line represents historical records, low emission scenario (RCP 4.5) projections, and high emission scenario (RCP 8.5) projections, respectively

days needed to achieve 1214 GDDs for all top five tomato producing counties in California. Due to increased temperature projections, length of the growing season under future climate scenarios in the tomato production areas of California is expected to be reduced by approximately 2–3 weeks on average. Rate of maturity is relatively faster in high emission scenario (RCP 8.5) as opposed to low emission scenario (RCP 4.5). Results from this study could be utilized to make important management decisions such as transplant and harvest dates, efficient agricultural water management, choosing appropriate cultivars, and investigating growth cycle trends for pests and diseases and their impacts on tomato production. Similar efforts should be conducted for other high value crops in California to better understand shifts in growing seasons. Additionally, changes in the climate that creates a warmer growing season and corresponding reduction in the time to accumulate the necessary degree days for physiological maturity could have negative effects on yield, and future efforts should be focused on investigating these potential impacts.

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