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RESEARCH REPORT

A hybrid decision tool for optimizing broccoli production in a changing climate

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Abstract

Climatic changes are already influencing the frequency, magnitude, and duration of extreme weathers (e.g. drought) in California. California is a leading state for vegetable production in United States (U.S.). Since vegetables are very sensitive to extreme weathers, it is critical to evaluate the effects of climate change on yield and to find the potential adaptive management strategies for the sustainable vegetable production. The objectives of this study were to develop a plant-oriented cropping model to evaluate the impacts of different cropping managements on yields under various climate condition and atmospheric CO_2 levels. To improve modeling performance, numerous previous studies that reported broccoli yields in different managements were used. After model calibration and validation, 560 scenarios under the conditions of combinations of climate changes, four broccoli cultivars, five nitrogen fertilizer application rates, and four plant densities were simulated in two study locations in Monterey County, CA where produces almost 40% of total California broccoli production. Based on results from 33,600 simulations, broccoli yields were highly related to nitrogen fertilizer application. However, at high nitrogen rates (above 75 kg N ha^{-1}), yields were barely changed. In general, under stressful conditions, all cultivars produced their maximum yields at low plant density, and their yields did not respond to addition of nutrient in soil. However, CO_2 enrichment and warmer temperature under RCP8.5 pathways, yield responded positively with fertilizer application rate and plant density. It seems likely that the effects of cropping managements will depend upon CO_2 level and temperature.

Keywords ALMANAC · Broccoli · California · Climate change · Process based crop model

1 Introduction

Dealing with the increased frequency and intensity of extreme weather has become more challenging to the United States (U.S.) farmers and ranchers. In California, agricultural production is highly sensitive to climate changes. Since almost 90% of the harvested crops in California were produced under irrigation systems, drought stress can negatively affect water supply for irrigation and can decrease crop yield and reduce crop quality (Tanaka et al. 2006). This state is the leading state for vegetable production, accounting for 57% of total vegetable production in the U.S. (USDA-NASS 2018). Many researchers project yield declines of 20–40% in various types of vegetables due to changes in patterns of temperature and precipitation (Thorne et al. 2017; Pathak et al. 2018). Since different vegetables react to weather changes differently, more research efforts focusing on documenting crop-specific potential threats due to climate changes are needed (Pathak et al. 2018). Such research should relate to local environmental conditions, so that effective strategies

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for cropping management adaptive to local environmental conditions can be designed.

In this study, a decision-making tool that can be used to improve the reliability of yield forecasting of vegetable crop production and to suggest adaptation cropping management strategies for sustainable vegetable production will be used to help policy makers and research scientists to minimize impacts of climate change. The results from this modeling work will provide useful information to support building effective adaptation strategies for continuing sustainable agricultural productions under environmental stress conditions. Broccoli is one of California's leading crops as they produce about 90% of U.S. broccoli, with $ 37.5 billion in revenue (USDA-NASS 2020). However, there are lack of information on impacts of climate change associated with changes in atmospheric CO_2 levels, temperature, and precipitation on broccoli yields in U.S. In this study, we will use a cropping modeling system to optimize broccoli cropping management adapted to different climate conditions.

Process-oriented crop models are valuable tools for quantifying the effects of different environments and aiding management decisions on crop growth and water use, which enhances the quality of planning and making management decisions at different spatial scales (field to small watershed), time periods (short and long term) and for different climatic conditions (average and extreme) (Vahrmeijer et al. 2018). Such models are increasingly used to evaluate the consequences of climate changes on crop yields for given regions, as well as evaluating changes in species, cultivars, and cropping management (e.g. date of planting and harvesting, fertility management practice, irrigation amount, and schedules, etc.) for adapting to the effects of climate change. In this study, the ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) will be used. This model is well known as an effective tool for strategic tests that can be accurately parameterized and tested to simulate effects of changes in climate and cropping management on crop yields in field scale areas (Behrman et al. 2014; Kim et al. 2020). ALMANAC model simulations can be conducted with sufficient detail in topological characteristics (e.g. soil characteristics, slope, etc.) and weather parameters including temperature, precipitation, wind speed, and humidity to quantify short- and long-term changes in soil carbon, nutrient (N&P) cycling, water resources, and plant production across diverse environmental settings (Williams et al. 2008).

To improve model performance, we will review several previous studies that studied broccoli productivity data from multiple locations and determine important management factors (e.g. nitrogen fertilizer, planting density, dates of planting and harvest, etc.) that affect broccoli yields. Reported yields from different locations and time periods will be used for model calibration and validation. After successful calibrating and validating the ALMANAC model, future broccoli yields will be simulated with long-term changes in environmental factors (e.g. CO_2 level, precipitation, and temperature) under various cropping management strategies. The simulation results from 560 scenario combinations of different study locations, atmospheric CO_2 levels, climate, and management conditions will be used to identify adaptation strategies for improved yields under stressful climate conditions (e.g. drought or excess moisture) and different atmospheric CO_2 levels.

2 Materials and methods

2.1 Data collection

The experimental datasets used in this study were compiled from numerous peer-reviewed studies that reported yields of broccoli marketable heads in experiments conducted in research farms (Supplementary Material Table S1). In total, 17 different locations from 16 peer-reviewed publications were analyzed and included 30 broccoli cultivars. Fertilizer rates ranged from 0 to 625 kg N ha^{-1} yr^{-1}. Plant density ranged from 2.8 to 14.8 plants m^{-2}. In most studies, seedlings at 2 to 5 leaf stages were transplanted at their research plots. In the study of Pasakdee et al. (2006), broccoli was planted in the research plots by direct seeding each growing season. In most studies, irrigation was applied daily or weekly to maintain soil water tensions. However, in study of Paskdee et al. (2006), three different water application rates (e.g. 80, 100, and 150% of evapotranspiration rates) were applied to the research plots. The study locations, broccoli cultivars, maximum and minimum fresh weights of marketable heads within each study location, treatment types, and reference were listed in Table S1. Based on the database, marketable head yield responses to nitrogen and density were analyzed. Broccoli head yields for different nitrogen applications, plant densities, and transplanting ages were compared using the Eq. 1 to calculate relative head yield for each harvest in terms of the specific treatment leading to the highest yield as reference in each study site (Pias et al. 2019).

$$\textit{Relative broccoi head yield}\,(\%\textit{ within each study site}) = \frac{\textit{Treatment yield}\,\left(Mg\ ha^{-1}\right)}{\textit{Treatment with maximum head yield}\,\left(Mg\ ha^{-1}\right)} \times 100 \qquad (1)$$

Potential relationships between the relative broccoli head yields and each treatment of total annual nitrogen fertilizer application rate, plant density, and transplanting age were examined for 11 broccoli cultivars in 12 studies, 4 cultivars in 2 studies, and 2 cultivars in 2 studies (Table S1).

2.2 ALMANAC model simulation of development

The ALMANAC model is a process-oriented simulator that is capable of simulating the dynamic of plant development, growth, fruit and seed formations, and total biomass. This model simulates yields based on various environmental conditions and management which are specified as input data. Thus, to improve the accuracy of yield prediction, high-quality input data for weather, soil, and management are required (Grassini et al. 2015). Basic soil parameter data are available for many soil types within the U.S. for ALMANAC. Using the Soil Survey Geographic (SSURGO) database (NRCS-USDA 2018), we can determine soil water holding capacity for potential plant rooting depth. The ALMANAC model is a daily time step crop simulation model that uses daily weather data, including precipitation (mm), maximum temperature (°C), minimum temperature (°C), solar radiation (MJ m^{-2}), wind speed (m s^{-1}), humidity (%), as input data. These weather data were collected from National Oceanic and Atmospheric Administration (NOAA) (NOAA 2012). Since extensive soil and weather data are readily available for each of U.S. county, for model calibration and validation, five studies which were conducted in U.S. were used. For the calibration, two studies (Study 1–2) (Kahn et al. 1991; Pasakdee et al. 2006) were used. Managements for each study are given below.

2.2.1 Calibration_Study1

The field study was conducted between 2002 and 2004 at UCSC Farm in Santa Cruz, CA. Broccoli cultivar 'Legacy' was grown between May and July in 2002, between July and September in 2003, and between June and August in 2004. Plots were irrigated in three different rates: 80, 100, and 150% of total annual evapotranspiration rate in each year. For the simulation, two total organic N fertilizer rates (140 kg h^{-1} and 252 kg ha^{-1}) were applied to plots. Plant density was 33 plants m^{-2}. Dates for planting, harvesting, irrigation, and fertilizers were followed as the study described. For high nitrogen application, yields from applying three different types of nitrogen fertilizers (fish powder, phytamin, and phytamin and $NaNO_3$) were averaged and compared with simulated yields. More detailed information is available in Pasakdee et al. (2006).

2.2.2 Calibration_Study2

The field study was conducted between 1986 and 1988 at the Vegetable Research Station, Bixby, OK. The soil type was Severn very fine sandy loam. Broccoli cultivar 'Premium Crop' were transplanted in 14.8 or 7.4 plants m^{-2}. Four different nitrogen fertilizer rates were applied to plots. The amount of nitrogen fertilizer varied by year. The fertilizer rates were 37, 74, 112, and 149 kg ha^{-1} applied in August to September in 1986; 112, 168, 224, and 280 kg ha^{-1}in February to April in 1987; 97, 144, 181, and 219 kg ha^{-1} in August to September in 1987; and 112, 168, 224, and 280 kg ha^{-1} in February to April in 1988. Plots received 8 to 13 mm of water per application. Measured yields were averaged over four harvests within each of treatments (nitrogen fertilizer and density) to compare to simulated yields. More detailed information is available in Kahn et al. (1991).

Weather data, including precipitation, maximum temperature, and minimum temperature, were from weather stations nearest the yield trial for each study location (NOAA 2012). Soil data for each study location was obtained from the USDA NRCS SSURGO database (NRCS-USDA 2018).

In the ALMANAC plant database, a set of plant parameters named BROC was created for broccoli (Tables 1 and 2). During calibration, most of plant parameters were determined based on the reported values in previous studies. The values of TB, optimal temperature, and TG, minimum temperatures, were obtained from Strange, Cahn et al. (2010) and Tan et al. (2000), respectively. The values of TB and TG are 16 °C and 0 °C. The value of DMLA, maximum potential leaf area index, was 4.83 (VÅgen et al. 2004; Francescangeli et al. 2006). Values of DLAI, fraction of growing season when leaf are begins to decline, was 0.75 (Vahrmeijer

Table 1 Plant parameters in ALMANAC adjusted for broccoli. The values of WA, HI, and PHU were varied by cultivar and study location (see Table 2)

Parameters	Description	BROC
WA	Biomass-energy ratio, g MJ^{-1} m^{-2}	Vary
HI	Harvest Index	Vary
TB	Optimal temperature for plant growth	16
TG	Minimum temperature for plant growth	0
DMLA	Max. leaf area index	4.83
DLAI	Fraction of season when LAI starts to decline	0.75
DLAP1	First point on optimal LAI curve	17.18
DLAP2	Second point on optimal LAI curve	67.62
PPL1	Plant population parameter	2.23
PPL2	Second plant population parameter	6.71
EXTINC	Extinction coefficient for calculating light interception	1.15
IDC	Crop category number	5
PHU	Potential heat use	Vary

Table 2 Study sites, treatment type, cultivar, the values of plant parameters (WA and HI) for each cultivar, and PHU of six studies used for ALMANAC model calibration and validation

	Calibration		Validation			
	Study 1[z]	Study 2[y]	Study 3[x]	Study 3[x]	Study 4[w]	Study 5[v]
Study site	Santa Cruz, CA	Bixby, OK	Charleston, SC	Charleston, SC	Santa Ana, CA	Maricopa, AZ
Study type	N	N and Density	Density	Density	N	N
Cultivar	Legacy	Premium crop	Emerald Crown	Durapak19	Green Comet	Claudia
WA	40	35	38	40	31	40
HI	0.25	0.2	0.22	0.24	0.2	0.24
PHU	1600	1600	1800	1800	1600	1600

WA is biomass-energy ratio (g MJ^{-1} m^{-2}). HI is harvest index. PHU is potential heat use.

[z] Pasakdee et al. (2006)

[y] Kahn et al. (1991)

[x] Ward et al. (2014)

[w] Letey et al. (1983)

[v] Thompson et al. (2002)

et al. 2018). The value of EXT, extinction coefficient, was 1.15 (Francescangeli et al. 2006; Vahrmeijer et al. 2018). The values of PPL1 and PPL2, plant population parameters, were derived from Francescangeli, Sangiacomo et al. (2006). The values of LAP1 and LAP2, first and second points on leaf area development curve, were derived from Vahrmeijer et al. (2018). The value of root depth was 0.6 m (Vahrmeijer et al. 2018). The values of WA, Energy to biomass conversion factor, and HI, harvest index, were varied by cultivar. The values of WA and HI for Legacy and Premium Crop were 40 and 0.25 and 35 and 0.2, respectively. The values of PHU for both Santa Cruz, CA and Bixby, OK were 1600. Other broccoli parameters were derived from ALMANAC plant database or scientific knowledge.

For model validation, three studies (Study 3–5) (Letey et al. 1983; Thompson et al. 2002; Ward et al. 2014) were used. Each study used a different broccoli cultivar. Values of WA and HI differed among cultivars (Table 2). Values of PHU varied among locations. The values of PHU for Charleston, SC, Santa Ana, CA, and Maricopa, AZ were 1800, 1600, and 1600, respectively. Management for each study are given below.

2.2.3 Validation_Study3

The field study was conducted in Summerton, SC and Charleston, SC. Since there were missing values in soil database of Web Soil Survey for Summerton (NRCS-USDA 2018), only trials in Charleston were used for the study. Two broccoli cultivars, 'Emerald Crown' and 'Durapak 19′, were transplanted on 29 August 2013 with three plant densities: 5.4, 7.2, and 10.8 plants m^{-2}. 138 kg N ha^{-1} fertilizer applied to plots before planting, and 1.5 kg N ha^{-1} was applied to plots three times a week after planting. More detailed information is available in Ward et al. (2014).

2.2.4 Validation_Study4

The field experiment was conducted in Santa Ana, CA in 1980. The soil type is San Emigdio sandy loam. Broccoli cultivar 'Green Comet' was transplanted on the plots treated by three different nitrogen fertilizer rates: 90, 180, and 270 kg N ha^{-1}. The plots were irrigated. More detailed information is available in Letey et al. (1983).

2.2.5 Validation_Study5

The field experiment was conducted at University of Arizona Maricopa Agricultural Center in southern Arizona during the 1993 through 1996 winter growing seasons. Broccoli cultivar 'Claudia' was transplanted in September in each year. The plots were treated with four different fertilizer rates: 60, 240, 350, and 500 kg N ha^{-1} in 1993–1994; 100, 200, 300, and 500 kg N ha^{-1} in 1994–1995; and 100, 200, 300, and 500 kg N ha^{-1} in 1995–1996. The plant density was 10 plants m^{-2}. Plots were irrigated with three different amounts of 728, 489, and 440 mm for 1993–1994, 1994–1995, and 1995–1996, respectively. More detailed information is available in Thompson et al. (2002).

For calibration and validation, simulated wet yields of broccoli marketable heads were compared with wet measured values that came from measurements of the previous studies (Letey et al. 1983; Kahn et al. 1991; Thompson et al. 2002; Pasakdee et al. 2006; Ward et al. 2014). According to Yilmaz et al. (2019), the moisture content of broccoli was 82.9%. Thus, the simulated dry yields were divided by 0.17 to convert to wet yields and compared with measured wet yields. The root-mean square error (RMSE), RMSE-observations standard deviation ratio (RSR), Nash–Sutcliffe efficiency (NSE), and percent bias (PBIAS) were calculated to quantify the model adequacy.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(O_i - S_i\right)^2}{n}} \tag{2}$$

$$RSR = \frac{\sqrt{\sum_{i=1}^{n}\left(O_i - S_i\right)^2}}{\sqrt{\left(O_i - O_{mean}\right)^2}} \tag{3}$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(O_i - S_i\right)^2}{\sum_{i=1}^{n}\left(O_i - O_{mean}\right)^2}\right] \tag{4}$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(O_i - S_i\right) * 100}{\sum_{i=1}^{n} O_i}\right] \tag{5}$$

where i is the ith observation, n is the total number of observations, S_i is the ith simulated value, O_i is ith observed value, O_{mean} is the mean of observed data. Additionally, Pearson's correlation coefficient of determination (R^2) was estimated using Proc REG in Statistical Analysis Software version 9.3 (SAS 9.3).

2.3 Analytical approach

We developed and modeled 560 scenarios that represent projected broccoli production management conditions under different combinations of five climates, four plant densities, five nitrogen application rates, and four cultivars using the calibrated ALMANAC model (Table 3). In the simulations, plants were planted on September 13th and harvested on December 15th. To satisfy plant requirements, during growing season, the plants were irrigated with 8 mm per application, three times per week. Fertilizer was applied on the planting date. For this analysis, two study sites in Monterey County, CA were selected because this county produces most (~ 40%) of total broccoli production from California where about 90% of total U.S. broccoli production occurs (Geisseler and Horwath 2016, USDA-NASS 2020). Two sites near Leonardi and Blanco ranches were selected because they produce mainly broccoli. The information can be found in County of Monterey Map Gallery (available at https://www.co.monterey.ca.us/government/departments-a-h/agricultural-commissioner/forms-publications/map-gallery#ag). The soil types of Leonardi and Blanco ranches are Elder sandy loam and Santa Ynez fine sandy loam, respectively (NRCS-USDA 2018). The values of PHU for these two locations were 1800.

To test the calibrated model performance in the county, the simulated broccoli head yields of four cultivars (Legacy, Premium Crop, Emerald Crown, and Green Comet) were compared with the measured yields between 2006 and 2015. Since the detailed information on crop management for broccoli production in Monterey County, CA was not available, in the simulations, to make optimal conditions for plant growth, 200 kg N ha^{-1} was annually applied to plots. Plots were irrigated three times per week with 10 mm per application from September 20 to November 30 in each year. Broccoli plants were grown in winter season as plants were planted on September 13 and heads harvested on December 15. Data for broccoli marketable measured yields in Monterey County, CA were obtained from Monterey County Crop Reports (available at https://www.co.monterey.ca.us/government/departments-a-h/agricultural-commissioner/forms-publications/crop-reports-economic-contributions#ag). Yield data from 2006 to 2015 were compared with the simulated yields for each cultivar. The model was evaluated using PBIAS and RMSE shown in Eqs. (2) and (5), respectively.

Table 3 Key characteristics of 560 scenarios under the conditions of combinations of climate changes, four broccoli cultivars, five nitrogen fertilizer application rates, and four plant densities projected in this study

Scenario	Variable	Time period			Broccoli cultivar	N fertilizer	Plant density (plant m^{-2})
		1976–2005	2031–2060	2061–2090			
Baseline	CO_2	380 ppm			Legacy	0	3
RCP4.5	CO_2		550 ppm	550 ppm	Premium Crop	25	6
	Tmax		(+)1.5	(+)2.22	Emerald Crown	50	9
	Tmin		(+)1.45	(+)2.17	Green Comet	75	12
	Prep		(*)1.08	(*)1.04		100	
RCP8.5	CO_2		936 ppm	936 ppm		150	
	Tmax		(+)1.83	(+)3.27		200	
	Tmin		(+)1.84	(+)3.28			
	Prep		(*)1.08	(*)1.12			

CO_2 is atmospheric CO_2 levels. Tmax is maximum temperature. Tmin is minimum temperature. Prep. is daily total precipitation

For future climate projection, Cal-Adapt (available at https://cal-adapt.org/tools/annual-averages/) was used to downscale climate change scenario information using four Global Circulation models (GCMs), including HadGEM2-ES, CNRM-CM5, CanESM2, and MIROC5, from CMIP5 (Coupled Model Intercomparison Project Phases). Two core Representative Concentration Pathways (RCP) scenarios including RCP4.5 and RCP8.5 were analyzed. Cal-Adapt provided average total precipitation and maximum and minimum temperatures for the historical period (1976–2005) and two future periods (2031–2060 and 2061–2090) on the two study sites in Monterey County, CA. The differences of averages of precipitation and maximum and minimum temperatures between historical period and future period are listed in Table 3. Atmospheric CO_2 levels will reach 550 ppm and 936 ppm under RCP 4.5 and RCP8.5 scenarios, respectively (Thomson et al. 2011; van Vuuren et al. 2011). During the historical period, CO_2 concentration was 380 ppm (corresponding to the concentration in 2005). In simulations, five climate scenarios (historical climate scenario and two future climate scenarios) were created and run for a 30-year time period. Other climate variables in the future, such as wind speed, relative humidity, and sunshine hours, were also assumed to be the same as the baseline period. In each climate scenario, five different rates of N fertilizer (0, 25, 50, 75, and 100 kg ha^{-1}) were applied on four cultivars (Legacy, Premium Crop, Emerald Crown, and Green Comet) planted in four different plant densities (3, 6, 9, and 12 plants m^{-2}). 560 scenarios were run in each of the two sites, so a total of 1200 simulations were performed.

For statistical analysis, Minitab 18 statistical software was used to understand the impact of six elements on wet yields of four cultivars such as EmerdCrown ($i=1$), GreenComent ($i=2$), Legacy ($i=3$), and Premium ($i=4$). Six elements include CO_2, maximum temperature (Tmax), minimum temperature (Tmin), precipitation (prep), N fertilizer (N), and density. The data were normalized using Eq. (6), and Figs. 1, 2 reveals result of correlation analysis.

$$z_{ij} = \frac{\left(x_{ij} - \overline{x}_i\right)}{s_i} \tag{6}$$

where z_{ij} is normalized data point j of cultivar i; x_{ij} is original data point j of cultivar i; $\overline{x}_i$ is a sample mean of cultivar i; and s_i is a sample standard deviation of cultivar i.

2.4 Adaptation strategies

We have selected the most drought and wet years within each time period of five time periods, including baseline (1975–2005) and future periods (2031–2060 and 2061–2090 of both RCP 4.5 and 8.5 pathways). From baseline, year of 2002 was selected as drought year, while year 1995 was selected as wet year. According to Mann and Gleick (2015) who analyzed

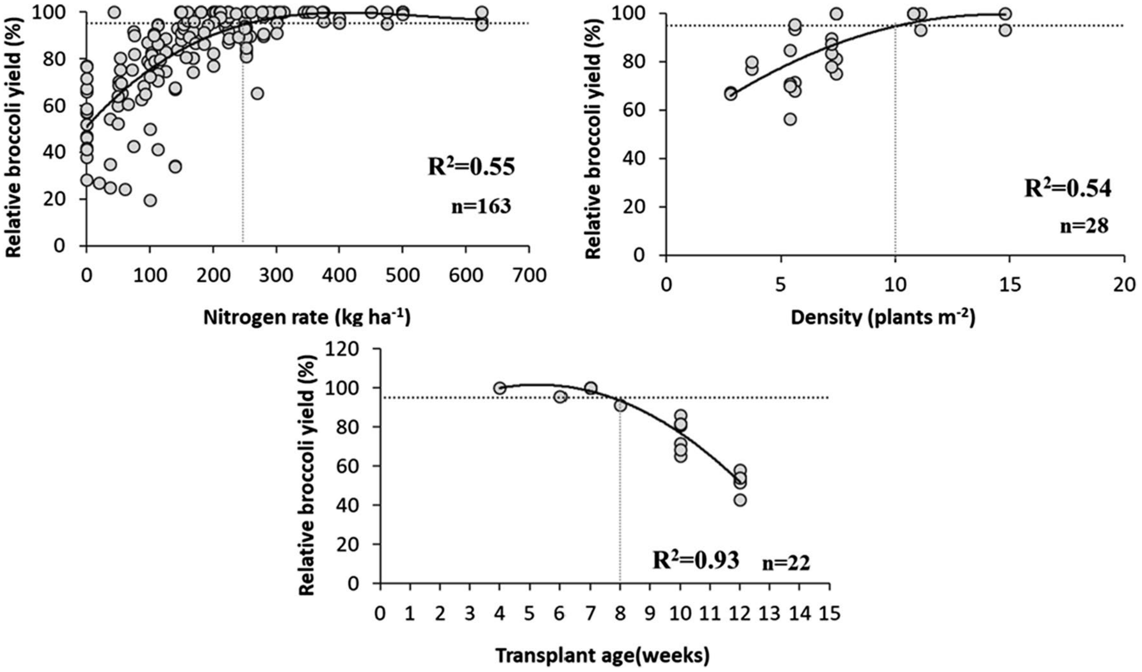

Fig. 1 Relationships between relative wet yields of broccoli marketable heads and amount of nitrogen fertilizer applied, plant density, and transplanting age. Black line represents the best-fitting line through the points. The grey dot lines indicate the obtaining yields of 95% of the relative broccoli head yields. The number of observations in each treatment is shown in parentheses

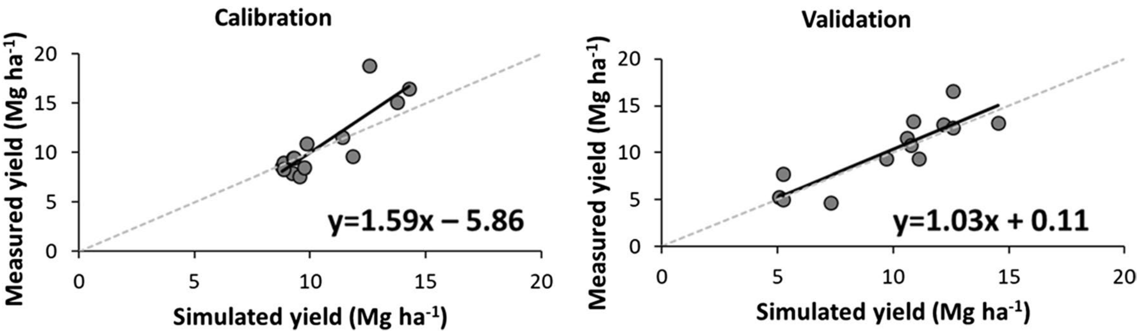

Fig. 2 Comparison of measured wet yields and ALMANAC simulated wet yields of broccoli marketable heads at calibration and validation study sites. The solid line is the fitted regression line and dash line is the 1:1 line

the California historical weather pattern between 1895 and 2014 and divided historical years into four different groups: dry/hot, wet/hot, dry/cold, and wet/cold, 2002 and 1995 were categorized as dry/hot and wet/hot, respectively. For future periods, 2057 and 2087 were selected as drought year. And 2051 and 2081 were selected as wet year. Total precipitation, maximum temperature, and atmospheric CO_2 level for each location and each year were listed in Supplementary Table S2. We will compare the simulation yield results in the selected years and will select which cropping management provide the highest yields with five different climate conditions, including baseline (1975–2005) and future periods (2031–2060 and 2061–2090 of both RCP 4.5 and 8.5 pathways) (Table 3).

3 Results and discussion

3.1 A review of broccoli yield responses to various cropping managements

A total of 18 studies were used to evaluate the effects of nitrogen fertilization rate, plant density, and transplanting age on the broccoli marketable yields (Mg ha^{-1}) (Table S1). The maximum nitrogen fertilizer application rates that obtained the maximum broccoli yields varied among locations and cultivars. For example, the 'Emperor' broccoli produced its maximum yield of 20.3 Mg ha^{-1} when nitrogen fertilizer application rate was above 375 kg N ha^{-1} at the research farm in British Columbia, Canada (Toivonen et al. 1994). However, 'Captain' broccoli reached to its maximum yield of 17.25 Mg ha^{-1} at 200 kg N ha^{-1} at the research farm in Simcoe, Ontario, Canada, and the yields did not change at higher nitrogen applications at 300 and 400 kg N ha^{-1}(Bakker et al. 2009). Broccoli yield responses to nitrogen application rates vary by soil, weather, cultivars and crop management (Yildirim, Guvenc et al. 2007; Giri et al. 2013). Under non-optimal conditions, broccoli may require less nitrogen for maximum yields (Mourão and Brito 2001). In addition, excessive nitrogen may cause physiological disorders like hollow stem or some pathological problem like head rot, resulting yield reduction (Belec et al. 2001). Overall, however, broccoli marketable head yields increased with increasing rates of N fertilization (Fig. 1). Based on the fitting curve in Fig. 1, the critical levels for obtaining yields exceeding 95% of the maximum possible value was 250 kg N ha^{-1} (Fig. 1). This result was supported by Zhang et al. (2017) who reported that higher nitrogen application increased root activity, root dry weight, and chlorophyll content in leaves, resulting in higher seedling production in *Brassica oleracea*.

While yield responses to plant density can vary among cultivars and locations, two studies at much different locations showed similar densities for maximum yields. 'Green Valiant' produced its maximum yield at 11.1 plants m^{-2} at research farm located near Fairbanks, Alaska (Griffith and Carling 1991) and 'Emerald Crown' reached its maximum yield at a density of 10.8 plants m^{-2} in trials located in South Carolina (Ward et al. 2014). On the basis of the overall results from multiple studies, broccoli yields increased in the denser spacing (Fig. 1). Based on the fitting line in Fig. 1, the critical levels for obtaining yield exceeding 95% of the maximum possible value was 10 plants m^{-2}. The yields remained at their maximum levels at densities between 10 to 15 plants m^{-2}. However, while the highest yields are at the more dense spacings, the qualities of heads can be poor at dense spacings due to maturity delays (Ward et al. 2014).

Unlike nitrogen fertilizer application and plant density treatments, broccoli yields negatively responded to transplant ages (Fig. 1). Based on the fitting curve, the critical levels for obtaining yield exceeding 95% of the maximum possible value was 8 weeks transplant age. The broccoli yields dramatically decreased from 8 to 12 weeks transplant ages. Increasing seedling age decreased lateral shoot number, weight, diameter and length, resulting in yield decreases (Kaymak et al. 2009). Also, transplanting age influenced harvest time which plays a critical role in yields (Kaymak et al. 2009).

3.2 ALMANAC model calibration and validation

The ALMANAC model was calibrated against measured data for yields of broccoli marketable heads from Study 1–2 (Table 2). The Study 1 was carried out on ‘Legacy’ broccoli cultivar, applying different amounts of nitrogen fertilizer and irrigation. In the study, as fertilizer and irrigation amounts increased, the broccoli yields increased. In the simulation, broccoli yield positively responded to the fertilizer N amount, while broccoli yields decreased slightly when broccoli plots were irrigated at 150% of evapotranspiration (ET) rate due to increases in runoff. In simulation, the significant increase in runoff lead a decline of soil fertility as a result of loss of topsoil and nutrients and increased number of days when plants experienced nitrogen stress. For example, at the low nitrogen level and 100% of ET irrigation level, the measured and simulated yields averaged over 2003–2004 were 11.6 and 11.4 Mg ha^{-1}, respectively. However, when plots were irrigated with 150% of ET rate, the measured and simulated yields in 2003–2004 were 10.9 and 9.85 Mg ha^{-1}, respectively. In Study 2, the ‘Premium Crop’ broccoli crops were treated by three different nitrogen rates (low, medium, and high) and three different densities. For the measured data, broccoli approached 100% of its maximum yield at medium nitrogen fertilizer application during the experimental periods. The yields at medium nitrogen rates were 9.0 Mg ha^{-1} at 7.4 plants m^{-2} and 9.5 Mg ha^{-1} at 14.8 plants m^{-2}. However, with high nitrogen fertilizer applications, measured yields were slightly decreased to 8.35 Mg ha^{-1} at a density of 7.4 plants m^{-2} and to 9.45 Mg ha^{-1} at a density of 14.8 plants m^{-2}. The simulated yields showed the similar responses to fertilizer and density treatments, except for the high nitrogen rate. For simulation, yields slightly increased from 8.85 to 8.87 Mg ha^{-1} at 7.4 plants m^{-2} from 9.28 to 9.31 at 14.8 plants m^{-2} at medium and high nitrogen rates, respectively. Because the model underestimated and overestimated at high irrigation rate in Study 1 and high nitrogen application rate in Study 2, respectively, the values of RSR and NSE were 0.61 and 0.63, respectively. This means that the model performance was “satisfactory”, based on the general performance rating of Moriasi, Arnold et al. (2007) (Table 4). However, the PB value was under 5%, which means that model overall predictions were “very good” (Table 4). The RMSE and R^2 for calibration were 2.06 Mg ha^{-1} and 0.73, respectively.

For model validation, Studies 3–5 were carried out on 4 different cultivars, applying different treatments of nitrogen fertilizer application rates and plant densities (Table 2). The model underestimated at high plant density in the Study 3. At a density of 10.8 plants m^{-2}, the measured yields of ‘Emerald Crown’ and ‘Durapak19′ broccoli crops were 13.3 and 16.6 Mg ha^{-1}, respectively, while the simulated yields of were 10.9 and 12.6 Mg ha^{-1} for ‘Emerald Crown’ and ‘Durapak19′, respectively. However, overall, the simulated yields responded reasonably to nitrogen and plant density treatments. Both measured and simulated yields increased with increased nitrogen application and plant densities. Based on the values of NSE (0.74) and RSR (0.51), the model performance can be evaluated as “good”. Based on the value of PB (3.58%), the simulation was “very good” (Table 4). The RMSE and R^2 for validation were 1.8 Mg ha^{-1} and 0.76, respectively.

3.3 ALMANAC model evaluation in Monterey County, CA

After calibration and validation of the model using reported values from 5 studies, the developed broccoli model was used to evaluate the impacts of climate change on the yields in Monterey County, CA. Before simulating the 564 combination scenarios of different climate and management conditions, the model was tested using the measured yield data reported in Monterey County crop reports. The measured yields from 2006 to 2015 were compared with the simulated yields using RMSE and PB for four cultivars (Fig. 3 and Table 5). As shown in Fig. 3, Monterey County consistently produced around 7.4 Mg ha^{-1} across years. Among cultivars, the simulated yields for ‘Emerald Crown’ were closest to measured values across years (Fig. 3).

The average yield of ‘Emerald Crown’ was 7.6 Mg ha^{-1}. RMSE and PB were 0.23 and − 2.22%, respectively (Table 5). Based on the simulation results, the yields for ‘Legacy’ were higher than actual yields in Monterey County,

Table 4 Measured and simulated yields and ALMANAC model calibration and validation performances based on RMSE, NSE, PB, RSR, and R^2. RMSE is Root Mean Square Error; NSE is Nash–Sutcliffe efficiency; PB is Percent Bias; RSR is RMSE-observations standard deviation ratio; and R^2 is Pearson’s correlation coefficient of determination

	Measured Mg ha^{-1}	Simulated Mg ha^{-1}	RMSE Mg ha^{-1}	NSE	PB %	RSR	R^2
Calibration	10.82	10.52	2.06	0.63	2.82	0.61	0.73
Validation	10.19	9.83	1.80	0.74	3.58	0.51	0.76

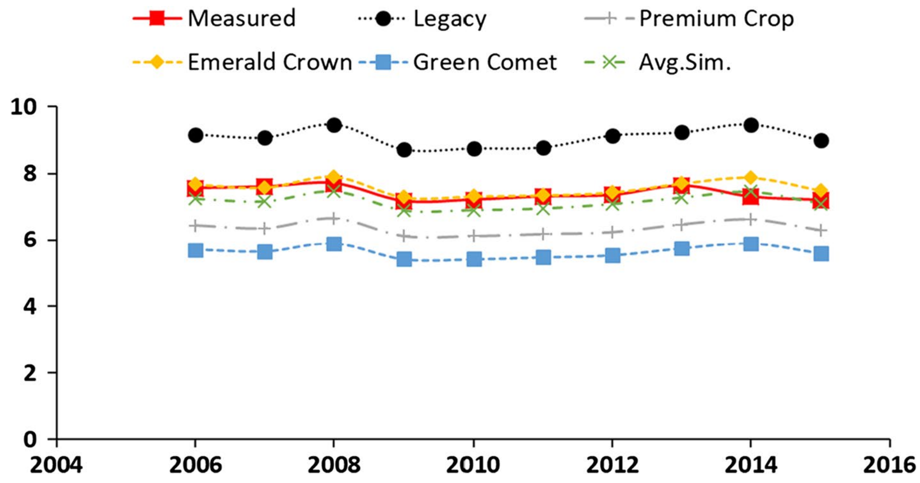

Fig. 3 Comparisons between measured wet yields of broccoli marketable heads produced in Monterey County, CA between 2006 and 2015 and simulated yields of 4 different broccoli cultivars and average simulated yield over all 4 cultivars

Table 5 Comparison between measured and simulated yields of 4 broccoli cultivars and average simulated yield over 4 cultivars between 2006 and 2015 at two study locations in Monterey County, CA

	Measured yield	Simulated yield				Avg
		Broccoli cultivars				
		'Legacy'	'Premium Crop'	'Emerald Crown'	'Green Comet'	
Mean yield (Mg ha^{-1})	7.4	9.09	6.35	7.57	5.63	7.16
RMSE		1.70	1.07	0.23	1.78	0.29
PB		− 22.76	14.26	− 2.22	24.00	3.32

RMSE, root mean square error. PB, percent bias

CA. 'Green Comet' produced the lowest yields (Fig. 3). Since simulated yields were in "good" to "very good" ranges, the developed broccoli model can predict the average yield patterns in Monterey County, CA.

3.4 Simulated broccoli yields for different scenarios

Simulations for 564 scenarios were run to test the effects of climate (precipitation, maximum temperature, and minimum temperature, atmospheric CO_2 level, and cropping management (cultivars, nitrogen fertilizer application, and plant density) on yields in Monterey County, CA. All broccoli cultivars showed similar responses to climate and management conditions (Fig. 4). Among 6 factors (density, nitrogen fertilizer, CO_2 level, maximum temperature, minimum temperature, precipitation), the nitrogen application rate was had the greatest impact on yields. The CO_2 level had the second greatest impact on yields. When we compare among CO_2 levels, when CO_2 level was 936 ppm, the yields were only affected by density and nitrogen rate, while when CO_2 level was either 380 or 550 ppm, yields were slightly influenced by climate conditions. At 550 ppm level, the yield was also affected by plant density. At a plant density of 6 plants m^{-2}, all three factors, including CO_2 level, nitrogen rate, and precipitation, were equally important factor for broccoli yields, while yields at other plant densities were mostly affected by nitrogen rate. At all nitrogen fertilizer application rates, CO_2 level was the most significant factor among 6 factors. When no nitrogen fertilizer applied to plots, there was no effect of plant density on yield.

Simulated wet yields of broccoli marketable heads averaged over four cultivars and four plant densities differed among nitrogen fertilizer application rates under RCP 4.5 and 8.5 pathways (Fig. 5a). For all climate change scenarios, broccoli yields responded positively with nitrogen application rates. However, at high nitrogen rates (above 75 kg N ha^{-1}), yields were only slightly increased or did not change. Under RCP 4.5 pathway, in comparison with reference yields, broccoli yields decreased across all 7 different nitrogen application rates for both periods, 2031–2060 and 2061–2090. The simulated yields under RCP 8.5 pathways for both periods were greater than reference yields (1976–2005) across all nitrogen treatments.

The simulated wet yields of broccoli marketable heads averaged over four different cultivars and 7 different nitrogen fertilizer application rates differed among plant densities under RCP 4.5 and 8.5 pathways (Fig. 5b). At a density of 3 plants m^{-2}, there were no yield differences among the scenarios, but yields responded differently under different climate conditions. In the reference period, yields increased as density increased. Under RCP 4.5 pathway, yields decreased from 3 to 6 plants m^{-2} and remained constant after 6 plants

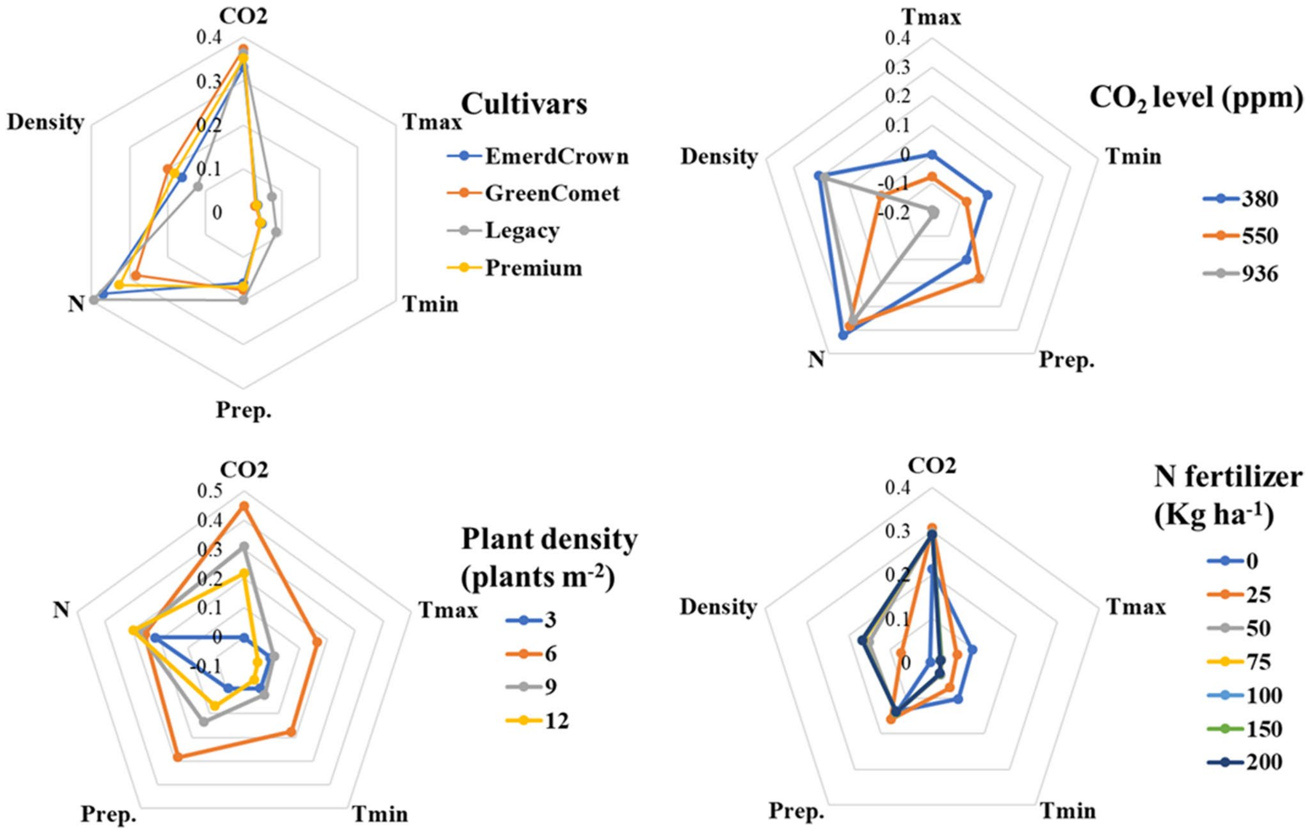

Fig. 4 Spider web graphs showing comparison of quantitative variables impacting broccoli simulated yields, including atmospheric CO_2 levels (380, 550, and 936 ppm), maximum temperature (°C), minimum temperature (°C), daily total precipitation (mm), nitrogen fertilizer application rates (0, 25, 50, 75, 100, 150, and 200 kg N ha^{-1}), and plant density (3, 6, 9, and 12 plants m^{-2}). All of variables being normalized on a scale of 0–1

m^{-2} for both periods (2031–2060 and 2061–2090). Under RCP8.5 pathway, yields increased at a density of 6 plants m^{-2} for both periods, and yield decreased slightly above 6 plants m^{-2}.

3.5 Adaptation strategies

In previous section, totally 33,600 simulations were carried out to compare the nitrogen fertilizer application and plant density management strategies in different weather and atmospheric CO_2 level conditions. In this section, the potential management strategies that provided the highest yields under environmental stressful conditions (e.g. drought and wet) were found (Table 6). Many scientists have expected that the warmer temperature increase risk of drought in the western U.S. even though there is no clear trend in precipitation (Diffenbaugh et al. 2015; Mann and Gleick 2015). Vegetables are highly sensitive to environmental extremes, and water plays an important key influencing yield and quality of vegetables (Abewoy 2017). In this section, thus, we have selected two stressful environmental conditions: drought and wet. And the potential cropping management strategies that provided the highest yields in study locations when water was either limited or excessed were defined.

All yield responses of each broccoli cultivar to climate and cropping management were summarized in Table 6. In drought year of all five time periods, the precipitation was only between 121 and 135 mm, while precipitation in wet year was in range of 546–618 mm (Table S2). Among the four broccoli cultivars, ‘Legacy’, ‘Emerald Crown’, ‘Green Comet’, and ‘Premium Crop’, ‘Legacy’ appeared to have the highest yields in both drought and wet years. For example, in 2002 (drought year), legacy produced the highest yield of 0.62 Mg ha^{-1} in plant density of 3 plants m^{-2} with low nitrogen application (25–50 kg N ha^{-1}). In 1995 (wet year), ‘Legacy’ produced 1.66 Mg ha^{-1} in plant density of 3 plants m^{-2} with 50–100 kg N ha^{-1}. After ‘Legacy’, ‘Emerald Crown’ produced the second highest yields for in both drought and wet conditions.

In overall, in drought years, yields did not respond to nitrogen fertilizer application when atmospheric CO_2 concentrations were between 385 and 550 ppm. However, increases in CO_2 level and temperature in 2087 under RCP 4.5 pathway yields at doubling rate. At the highest CO_2 level

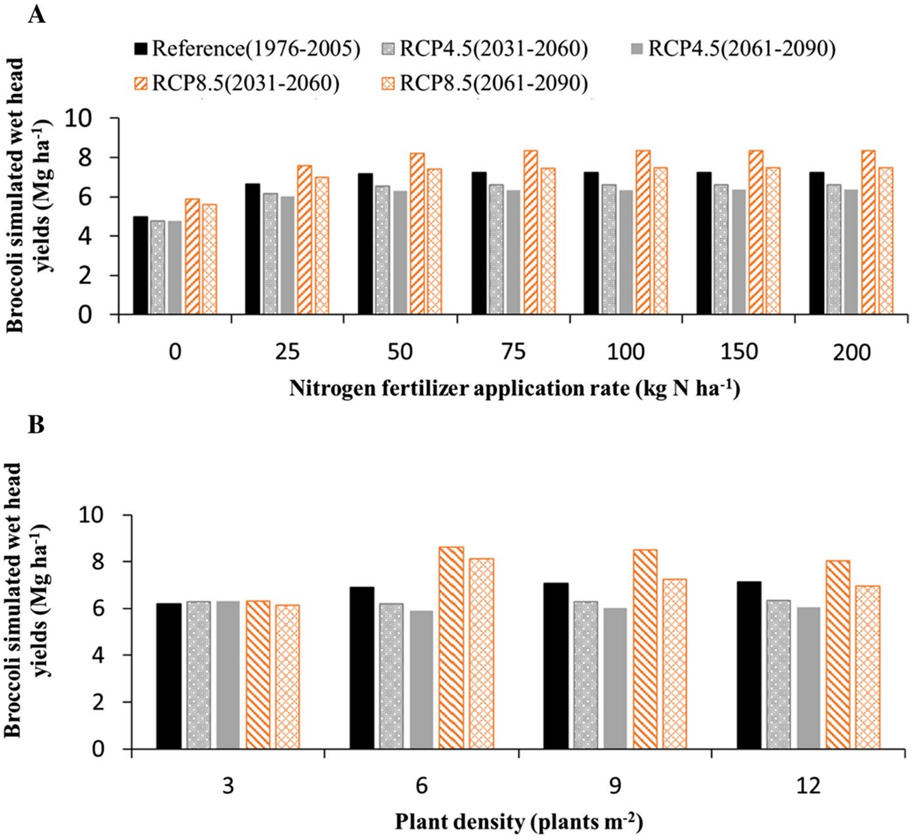

Fig. 5 ALMANAC simulated yields for four broccoli cultivars in (**a**) treatments of 7 nitrogen fertilizer application rates, 0 to 200 kg N ha^{-1}, and (**b**) 4 plant densities, 3, 6, 9, and 12 plants m^{-2}. The simulated yields were averaged over four broccoli cultivars ('Emerald Crown,' 'Green Comet,' 'Legacy,' and 'Premium Crop') and either 4 plant densities or fertilizer application rates in Monterey County, CA. The five periods include reference period (1976–2005) and future periods (2031–2060 and 2061–2090) within each of the RCP4.5 and RCP 8.5 pathways

(RCP 8.5 pathway), all cultivars responded positively to addition of nitrogen fertilizer application under drought condition. The yields at high CO_2 level were much higher than yields at low CO_2 level. The similar results were observed by Erda et al. (2005) who simulated yields of rice, maize, and wheat at various CO_2 level and found that CO_2 enrichment under irrigated field condition consistently increased biomass and yields. Under wet conditions, broccoli plants produced higher yields than yields in drought years, which means that broccoli can tolerate temporary wet soils. According to Shipman (1972), broccoli is mostly grown in raining season because the soil should be wet at root depth. With CO_2 enrichment and temperature increase, 'Legacy' could produce up to 14.6 Mg ha^{-1}.

In both drought and wet condition, plant density was also an important factor that influence yields. As space between plants decreases, neighboring plants begin to interfere one another (Forbes et al. 1992). Thus, high plant density can reduce the growth of individual plant by increasing competition for water, soil nutrient, and light intensity between plants. In drought year, 'Legacy' produced the highest yield at density of 3 plants m^{-2}, while other cultivars produced their highest yields at density of 6 plants m^{-2}. Wide spacing should be beneficial to plants by reducing water competition between plants (Forbes et al.1992). With increasing CO_2 level and temperature under RCP 8.5 pathway in both drought and wet years, an increase in plant density could be expected to give yield improvement.

The results of simulation show that broccoli yield responses to nitrogen rates and plant density differed between drought and wet years. This means that an appropriate combinations of plant density and fertilizer application rate can reduce the negative impacts of climate change on broccoli yield to certain extent, especially in western U.S. According to Strange et al. (2010), broccoli is mainly produced in four areas in California, including the southern desert valley, the southern coast, the central coast, and the Central valley, where either wet or dry conditions can exist during the broccoli growing seasons. Thus, the findings will be useful to find a sustainable and effective agricultural management system to maintain food security and relieve environmental risk. Influence of different combinations of fertilizer rates and plant density on quality and yields of broccoli should be studied further to conquer increasing environmental stress.

4 Conclusion

Based on the literature reviews, broccoli yields were highly influenced by nitrogen fertilizer application, plant density, and transplanting ages. Due to limited to researches on the

Table 6 For each of four broccoli cultivars, the potential cropping management conditions (nitrogen (N) fertilizer application amount, plant density) that produced the highest yields over two study locations (Soil types: 1, Elder sandy loam and 2, Santa Ynez fine sandy loam) during doughtiest and wettest years among five time periods, including baseline (1975–2005) and future periods (2031–2060 and 2061–2090 of both RCP 4.5 and 8.5 pathways)

	Year	Study location	N kg ha^{-1}	Density no./m^2	Yield Mg ha^{-1}	N kg ha^{-1}	Density no. m^{-2}	Yield Mg ha^{-1}	N kg ha^{-1}	Density no./m^2	Yield Mg ha^{-1}	N kg ha^{-1}	Density no. m^{-2}	Yield Mg ha^{-1}
			'Legacy'			'Emerald crown'			'Green comet'			'Premium crop'		
Drought year														
Baseline	2002	1	50	3	3.6	50	6	3.2	50	6	2.4	50	6	2.6
	2002	2	25	3	3.6	50	6	3.2	25	6	2.4	25	6	2.7
RCP4.5	2057	1	50	3	3.8	50	3	3.2	50	3	2.4	50	3	2.6
	2057	2	50	3	3.8	50	3	3.2	50	3	2.4	50	3	2.6
	2087	1	50	3	7.5	50	3	6.3	50	3	4.6	50	3	5.3
	2087	2	50	3	7.5	50	3	6.3	50	3	4.6	50	3	5.2
RCP8.5	2057	1	100	6	8.1	100	6	6.8	50	6	5.0	100	6	5.6
	2057	2	75	6	8.1	75	6	6.8	0	6	4.8	25	6	5.6
	2087	1	100	6	12.8	100	6	9.6	50	6	7.1	50	6	8.0
	2087	2	50	6	12.9	50	9	8.8	50	6	7.9	50	6	9.0
Wet year														
Baseline	1995	1	100	3	9.8	100	3	8.2	50	3	6.1	100	3	6.8
	1995	2	50	3	9.8	50	3	8.2	50	3	6.1	50	3	6.8
RCP4.5	2051	1	100	3	9.5	75	3	7.9	50	3	5.9	50	3	6.6
	2051	2	50	3	9.5	50	3	7.9	50	3	5.9	50	3	6.6
	2081	1	100	3	9.2	50	3	7.6	50	3	5.7	50	3	6.4
	2081	2	50	3	9.2	50	3	7.6	50	3	5.7	50	3	6.4
RCP8.5	2051	1	150	6	13.4	100	6	11.2	100	6	8.3	100	6	9.4
	2051	2	75	9	14.5	75	9	12.2	75	9	9.0	75	9	10.2
	2081	1	100	6	12.1	100	6	10.1	50	6	7.5	100	6	8.5
	2081	2	100	9	14.6	50	6	11.2	50	9	9.0	50	9	10.2

effects of transplanting age on yields, only studies on the effects of nitrogen fertilizer application and plant density on yields were used for model calibration and validation. ALMANAC model can simulate key physiological processes linking weather, soil to plant yield production. Many of the key broccoli parameters in the model for various broccoli cultivars have established through experiments or literature reviews. As a result, the ALMANAC model can relatively well predict broccoli marketable wet yields for all six broccoli cultivars. The successfully calibrated ALMANAC model was used to evaluate the broccoli yields in Monterey County, CA where produced almost 40% of California total broccoli production. The simulation results in two study location in Monterey County were validated with the actual produced yields in the county. 'Emerald Crown' produced yields mostly close to the reported yields. Total 560 scenarios under the conditions of combinations of climate changes, four broccoli cultivars ('Emerald Crown' 'Premium Crop', 'Green Comet', and 'Legacy'), five nitrogen fertilizer application rates, and four plant densities were created. Totally 33,600 simulations were carried out to evaluate the effects of cultivar, nitrogen fertilizer application, and plant density on yields under different climate and atmospheric CO_2 levels.

Among 6 factors (density, nitrogen fertilizer, CO_2 level, maximum temperature, minimum temperature, precipitation), the nitrogen fertilizer application rate was had the greatest impact on yields. The CO_2 level had the second greatest impact on yields. For all climate change scenarios, broccoli yields responded positively with nitrogen application rates. However, at high nitrogen rates (above 75 kg N ha^{-1}), yields were barely changed. ALMANAC model has also enabled to suggest the potential cropping management strategies under drought and wet conditions. According to simulation results, 'Legacy' could produce the highest yields among four cultivars at low density with low nitrogen application rates under stressful conditions. Other cultivars approached to their maximum yields with similar cropping management strategies (low density and low fertilizer application) in drought and wet condition. However, as the atmospheric CO_2 level and temperature increased, yields of all four cultivars were increased at higher plant density with higher fertilizer application. This finding will be useful to overcome impacts of climate change on broccoli yield and make broccoli more adapted and performed well under extreme weather conditions in western U.S. It would be necessary to do further investigations that include integration of outputs of this study with assessment of impacts of climate change on land use and water resources availability for irrigation at national and regional levels.

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Compliance with ethical standards

Conflict of interest All authors confirm that they have no conflict of interest.

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