The Impact of Doubled CO2 on Alfalfa Production in California

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ABSTRACT

California produces 8.4% of the United States alfalfa hay production on 4% of the nation's alfalfa acreage. It is expected that global climate change should have a significant influence on alfalfa production and suitable variety in California. This study used the simulation approach to evaluate the potential influence. Three simulation models were used in the study: OSU-GCM, a General Circulation Model; SIMMETEO, a dynamic weather generator; and ALFALFA, a dynamic physiological growth model. The summary of weather data from SIMMETEO indicated that mean annual maximum temperature increased 4.6°C, and mean annual minimum temperature increased 4.8°C at four locations in California under doubled CO_2 conditions. The average temperature increase was 0.4°C higher at the northernmost location (Tule Lake) than at the southernmost location (El Centro). The standard deviations of the temperatures increased slightly under doubled CO_2 conditions. Yield decreased 14% at the El Centro location, and increased 29% at the Tule Lake location under doubled CO_2 conditions and the current production practices. Yield response to adjusted production practices under double CO_2 conditions and the relationship between weather variables and yield were also investigated. These results provide useful information for forecasting alfalfa hay production and on suitable cultivar characteristics for breeding under conditions of global climate change.

INTRODUCTION

The global atmospheric CO_2 concentration is increasing. Most predictive models indicate that it is likely to double by the second half of the next century, and that there will be a concomitant increase in temperature and redistribution of rainfall (Barry and Geng, 1991). Idso et al. (1987) reported an average temperature increase of 3°C and Rosenberg (1988) reported an world-wide average warming of 1.5 to 5.5°C. These global climate changes would have tremendous impact on crop yields and food production (Barry and Geng, 1991; Barry and Geng, 1992; Ryle et al., 1992).

Alfalfa is one of the most important crops in California, that was first introduced to California during the 1850's (Barnes et al., 1988). Today, California produces 8.4% of the United States alfalfa hay production on 4% of the nation's alfalfa acreage (Peterson et al., 1992). If the predicted climate change is realized, then California alfalfa production will be affected and alternative agricultural practices have to be developed in order to sustain the productivity.

Because the increase of temperature under the doubled CO_2 condition is accompanied by a change of weather variables, it is difficult to investigate the impact of the change experimentally. Advancements in computing technology have provided powerful tools with which the influence of alternative management strategies and different scenarios of environmental changes on crop production can be evaluated.

The objectives of this study were to describe alfalfa cropping systems in four climate regions in California; to characterize future trends of climatic change; to assess the impact of doubled CO_2 on alfalfa hay production; and to evaluate alternative crop management strategies.

CALIFORNIA ALFALFA

Alfalfa, a perennial crop, has a relatively complex growth system, since the yields of the forage are accumulated over several cutting and regrowth cycles. The yield is composed of both leaf and stem tissues and the proportion of each determines the forage quality. The size of the crown and taproot and their reserves of carbon and nitrogen substrates influence the number and vigor of the regenerated stems after each cutting. Other factors such as irrigation scheduling, and cultivar characteristics also influence the yield of alfalfa.

The analysis of climatic and geographic data (Teuber et al., 1984) showed eight distinct climatic and geographic regions in California which are grouped into four alfalfa growing zones (intermountain, Sacramento Valley, San Joaquin Valley and Low desert zones).

The intermountain zone including Tule Lake, Butte Valley and Scott Valley produces about 11% of the alfalfa in California. Varieties, with fall dormancy ratings of 2-4, are grown in this area. Stands usually last for about 5 years before being taken out. The first cutting usually takes place in mid to late May and is followed by 2 or 3 more cuttings a year producing an annual yield of 5-7 tons per acre. Five to six flood irrigations are applied totaling approximately 30 inches per growing season. Soils are highly variable, mostly volcanic parent material, with texture ranging from sandy soils to heavy clay loams. Soil organic matter is highly variable, ranging from about 0-16% (Kirby, pers. commun.).

The Sacramento Valley zone includes the Sacramento and Davis areas that produce 8% of the state's alfalfa. Alfalfa varieties used in this area are usually non-dormant, with a fall dormant rating of 7-8. The first cutting is done in April with a 30 days cutting interval and 28 days in summer. The annual yield is about 7 tons per acre with 6-7 cuttings. Stands remain about 4 years. Most farmers use flood irrigation.

The San Joaquin Valley zone includes the locations of Five Points and the Kearney Agricultural Center and provides 60-68% of California alfalfa. Alfalfa varieties used are non-dormant, with a dormancy rating of 8, and fall planting is recommended. Stands are kept for 3 or sometimes 4 years. Established stands are cut for the first time in early April and harvested through October. Growers typically get 8 cuttings per year with an average yield of 9 tons per acre. However, yields dropped to an average of 7.5 tons per acre due to the drought in 1991. Growers irrigate twice between cuttings in July and August and once between cuttings in the spring (April-June) and fall (Sept.). Flood irrigation was applied. Neither of these soils have very high organic matter contents (< 2%) and the soil depth is unlimited.

The low desert zone is represented by the University of California desert Research and Extension Center, that produces 20% of alfalfa in the area. The climate in this area is warm with little rainfall (about 3 in.) a year. Alfalfa varieties are very nondormant with ratings of 8-9. The annual yield is about 10 tons per acre with about 9-10 cuttings. The first cutting starts in January or February, with cutting cycle of 28 days in summer and 6-8 weeks in winter. Flood irrigation is used in the area, with two irrigations between each cutting. Most soils are clays with depth 50 to 70 cm.

MATERIALS AND METHODS

Three models were used in this study: OSU-GCM, a General Circulation Model; SIMMETEO, a dynamic weather generator; and ALFALFA, a dynamic physiological growth model. OSU-GCM model is the Oregon State University Mixed-Layer General Circulation Model that predicts the changes of temperature and rainfall. SIMMETEO, a dynamic weather generator (Geng et al., 1988), requires only monthly long-term averages of meteorological variables and it simulates daily observations of maximum and minimum temperature, rainfall, and solar radiation. Thirty years (1951-1980) of National Oceanic and Atmospheric Administration weather station means (NOAA, 1985) were used for each of the selected locations under the current climate conditions. ALFALFA (Denison and Loomis, 1991) is a dynamic integrative model of the physiological growth of alfalfa. This model requires weather variables and crop physiological functions as inputs, and it simulates hourly values for a large number of state variables. The central feature of the model is its simulation of carbon accumulation and partitioning in the form of dry matter.

In this study, four locations were selected from on different alfalfa growing zones: Tule Lake, Davis, Five Point and El Centro. Current and doubled CO_2 scenarios, and two management practices were studied. Thirty years of weather data were generated and thirty years of alfalfa yield were simulated under each defined condition.

Several physiological functions in the ALFALFA model were modified to account for the direct effect of CO_2 on alfalfa yield. The photosynthetic response to light function (Figure 1) was modified based on a clover study under doubled CO_2 conditions (Ryle et al. 1992). The effect of relative water content on stomata opening was reduced for doubled CO_2 conditions (Denison, pers. commu.). The current cultural practices for each location were used as inputs to ALFALFA, that were obtained from University Cooperative Extension specialists and farmer advisers. However, simulation were not performed for water stress conditions. Experiment files were created for alternative management for doubled CO_2 conditions. The alternate management were based on the weather conditions generated by SIMMETEO. The harvest scheduling under doubled CO_2 conditions was adjusted according to the temperature requirements for initiation of spring growth, and the interval required between cuttings and the final cutting date. The date for initial spring growth and for the last harvest would be at the same mean monthly minimum temperatures as for current weather conditions. As a result, the harvest interval was adjusted to produce approximately the same number of day between cuttings as is being used under current weather conditions.

RESULTS AND DISCUSSION

California Weather

Table 1 shows that mean annual maximum temperature increased 4.6^{0}C, and mean annual minimum temperature increased 4.8^{0}C at the four locations studied under the doubled CO_2 conditions. The average temperature increased 0.4^{0}C more at the northernmost location (Tule Lake) than at the southernmost location (El Centro). The standard deviations of the temperatures increased slightly under doubled CO_2 conditions (Table 2).

Mean monthly maximum temperatures were presented in Figure 2 for both the $1XCO_2$ and $2XCO_2$ conditions at the four locations studied. The increases in mean annual maximum temperatures ranged from 1.4^0C to 7^0C (Table 6) at the four locations with an average increase of 4.6^0C. Within seasons, the largest increases occurred in the fall months followed by the summer months. Smaller increase occurred in the winter and spring months. The increase in maximum temperature within seasons was similar at all locations (Table 5).

The increases in mean annual minimum temperature for doubled CO_2 conditions were also similar at all locations (Figure 3), from 3^0C to 6.3^0C (Table 6) with an average increase of 4.8^0C. Within seasons, the patterns of the increase were similar to the increase for mean annual maximum temperature at all locations.

Figure 4 shows the amount and distribution of annual rainfall for both the $1XCO_2$ and $2XCO_2$ conditions at the four locations. Under doubled CO_2 conditions, all locations experienced a slight increase in annual rainfall (Table 1). The largest increase occurred during the fall and winter months. These increases may enhance the alfalfa growth in early months. This information is useful in designing an alfalfa production system using less irrigation in fall and winter seasons.

Alfalfa Production

Simulated average alfalfa yields at the four locations showed that the yield increased dramatically in the colder areas, and decreased significantly in the warmer areas under doubled CO_2 conditions (Table 3). Under doubled CO_2 conditions at Tule Lake, yield increased 29% and the yield increased 90% with alternative management. In El Centro, yield decreased 14% under $2XCO_2$. In Davis and Five Points, the yield did not change significantly with alternative management under $2XCO_2$. This change of alfalfa yield in four locations corresponded with the change of leaf area index, plant populations, total structural biomass and the increasing reserve nonstructural carbohydrate and total losses from frost, pests and harvest (Table 4 and 5). Higher yield resulted from higher leaf area index, plant population, and total structural biomass that were directly influenced by temperature.

Figure 5 shows that the yield increased in the spring and summer at each location, then decreased in the late summer and in the fall. Alfalfa in El Centro has the longest growth period, Five Points is the second longest, followed by Davis and then Tule Lake which has the shortest growth period. The response shapes of the yield curves (Figure 5) are latitudinally related. In El Centro, yields of the first two harvests were slightly increased and the rest of the yields decreased under doubled CO_2. This results indicates that the present cultivar does not adapt to the increased temperature environment.

Alfalfa yield of each harvest was not consistently related to average temperature (Figure 6). The direct effect of temperature on yield was most apparent at Tule Lake under current condition while at Five Points and El Centro the yield per cut was better related to the accumulative solar radiation. One of the reasons for these results may be that temperature is more critical in spring and fall to alfalfa growth in the colder areas, while solar radiation is a more important factor in alfalfa growth in the warmer area, since temperature is not as limiting a factor for alfalfa growth.

Under doubled CO_2 conditions, temperature increased by an average of 4.6^0C, with an increase of 7^0C during the summer months, and the growth of alfalfa started earlier in the year and demanded more water in the summer. The yield of the last few harvests in Figure 6 were lower than expected from the effects of temperature. The pattern was observed at all four locations. In Five Points and Davis, under doubled CO_2 condition, the yield decrease in later harvests are probably attributable to the shortened daylength and the resulting reduction of solar radiation and the redistribution of photosyntheses to the roots. In Tule Lake, the length of the optimal temperature for alfalfa growth was increased under doubled CO_2, thus increasing the total yearly yield in this location. The most noticeable yield reduction due to high temperature occurred at El Centro. At this location, yields are reduced during the summer months as well as in the fall. This may be why the yield in the warmer areas decreased under $2XCO_2$ with the current management. With increased temperature in the spring months as well as rainfall under $2XCO_2$ conditions, early alfalfa growth was likely to occur and the harvest of the first alfalfa cut should be earlier than that in the current condition in order to make full use of the available natural resources. Therefore, the yield increased significantly in the colder areas (Tule Lake) when alternative cultural practices are used in the model. Figure 6 also showed that the yield of the last three harvests went backward. This may be partly because of the limiting factors for growth and partly because of the underestimation from alfalfa model.

CONCLUSIONS

The predicted climate change revealed a great impact on alfalfa production in California. We found that under $2XCO_2$, the greatest temperature increase was in the colder areas by an average of 4.8 to 5.0^{0}C, with a small increase in rainfall at all locations. Growing season and water requirement increased in all locations. Yield increased in the colder areas by 29% with current practices and 90% with the alternative management. Yield decreased by 14% in the hottest areas and remained the same in the more moderate climate regions.

The need for alternative management practices is strongly indicated by longer growing seasons, higher temperatures and a growing seasons which includes more days of lower total solar radiation and shorter day lengths. Water requirements, while not directly studied in these simulations, will almost certainly increase. Since significant rainfall increases are not predicted, the appropriate use of scarce water resources will become that much more critical.

The changed climate implies that the alfalfa crop in California would shift northward. Additional research is needed to further characterize the impact of climate change on California agriculture as a whole, particularly, its implications on water management and cultivar selection.

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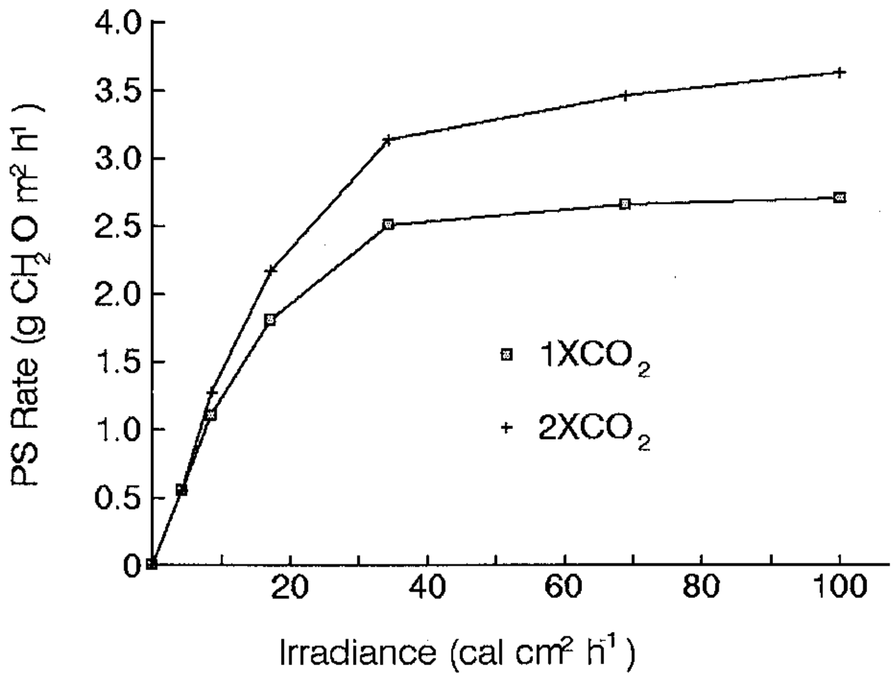

Fig.1 The light response function used for alfalfa leaves (LITPHS). Adapted from Sheehy et al. (1979) for 1×CO2 and from Ryle et al. (1992) for 2×CO2.

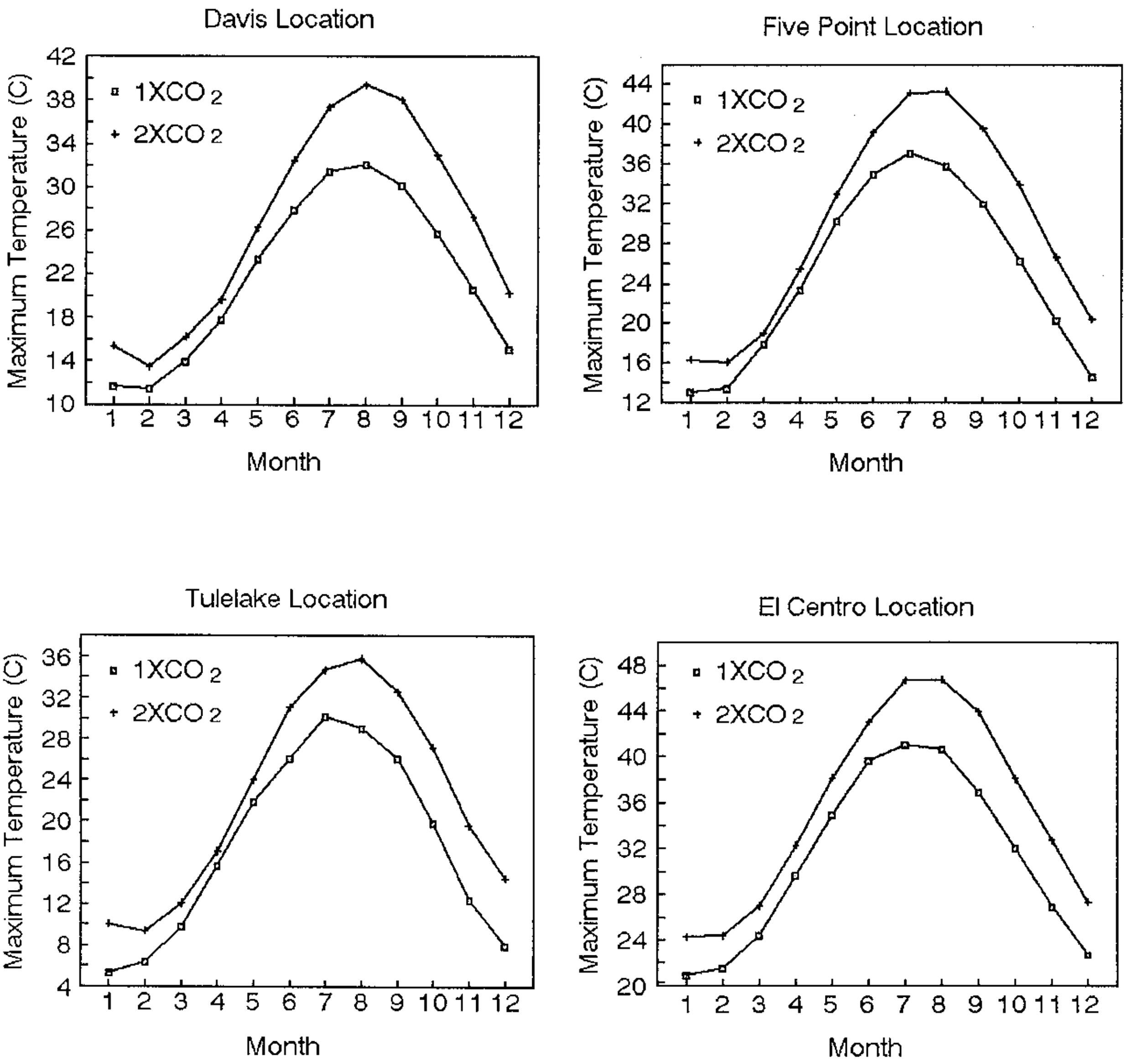

Fig.2 Mean monthly maximum temperature under 1×CO2 and 2×CO2 at four locations.

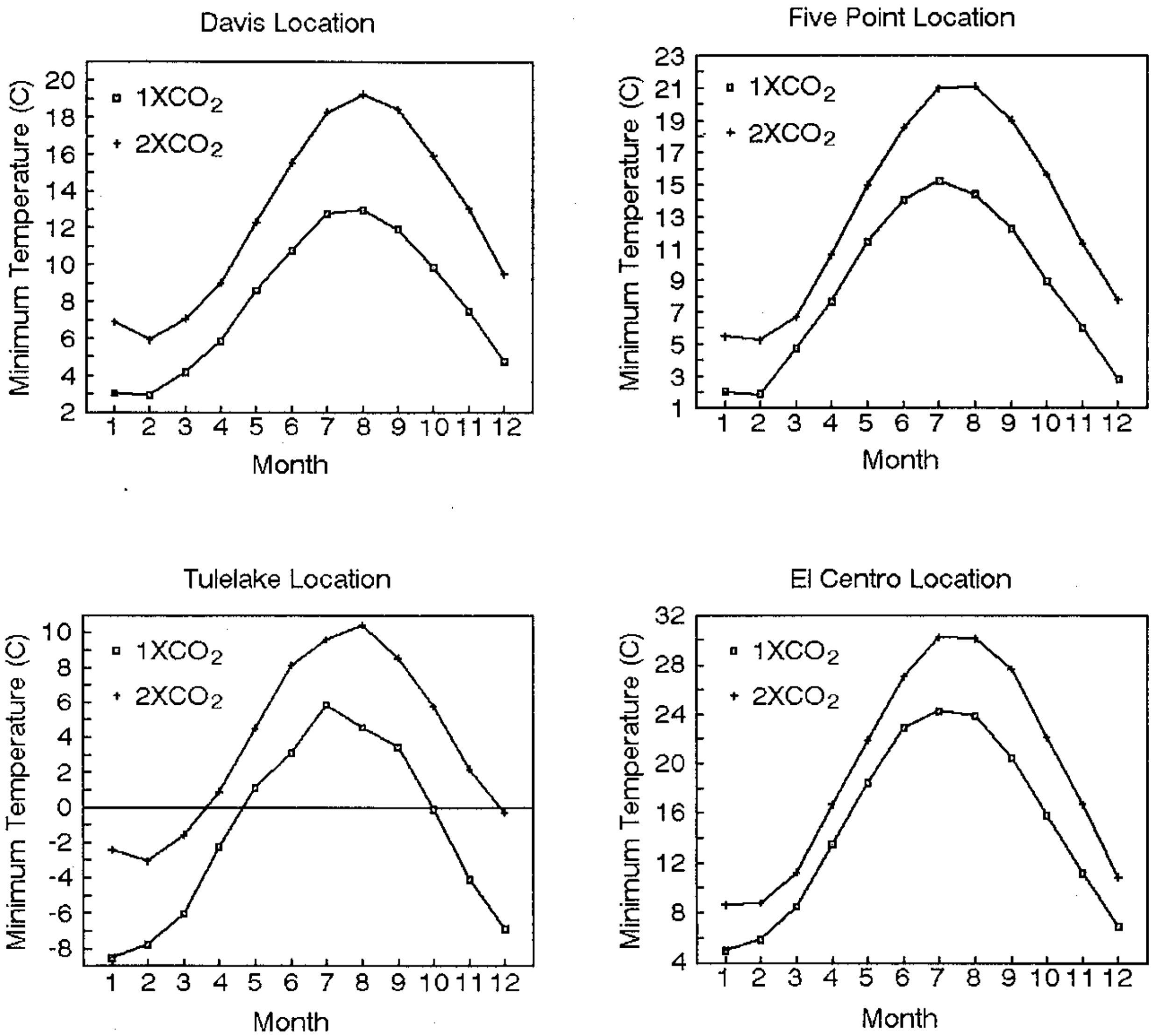

Fig.3 Mean monthly minimum temperature under 1×CO2 and 2×CO2 at four locations.

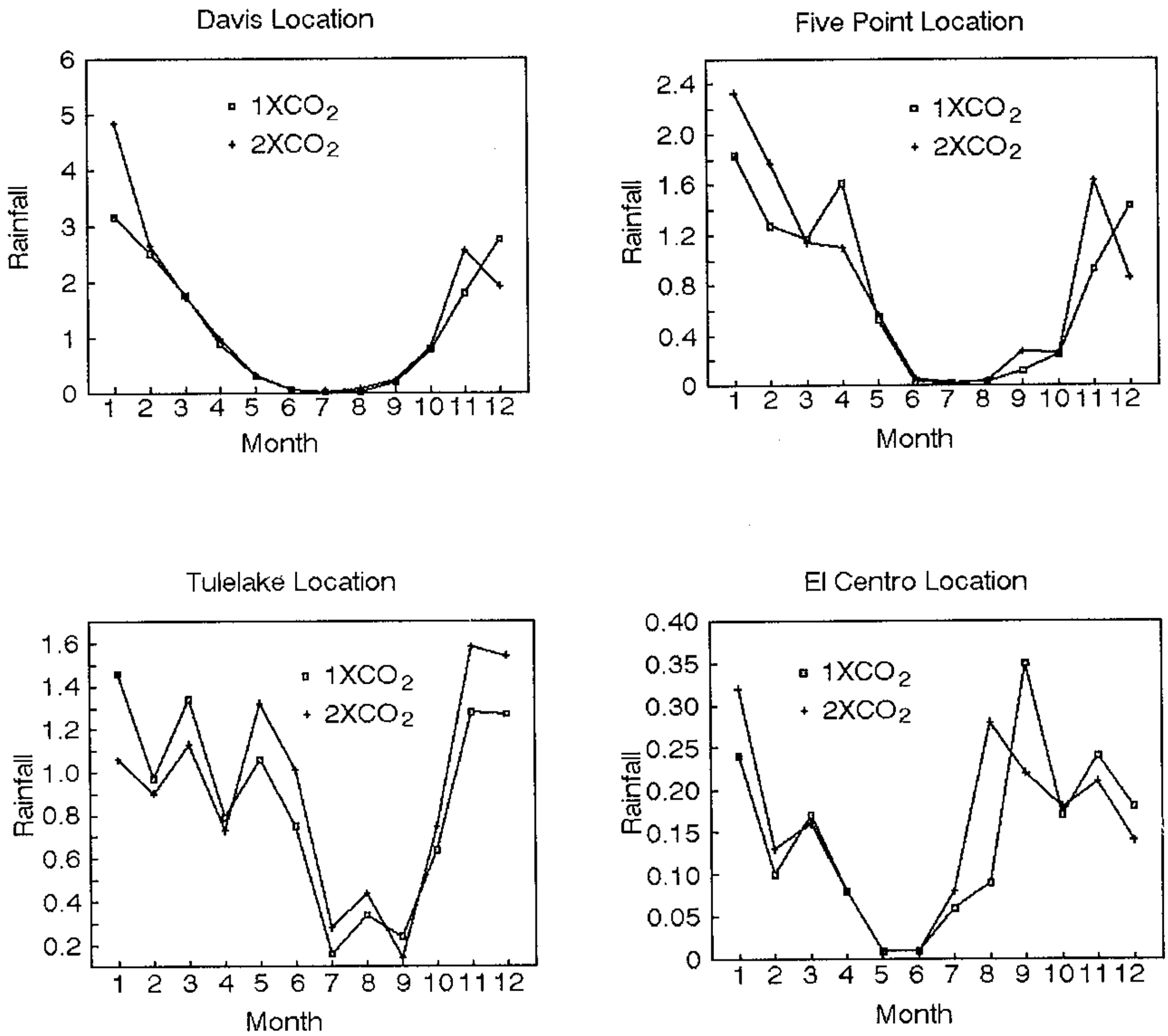

Fig.4 Mean monthly rainfall under 1×CO2 and 2×CO2 at four locations.

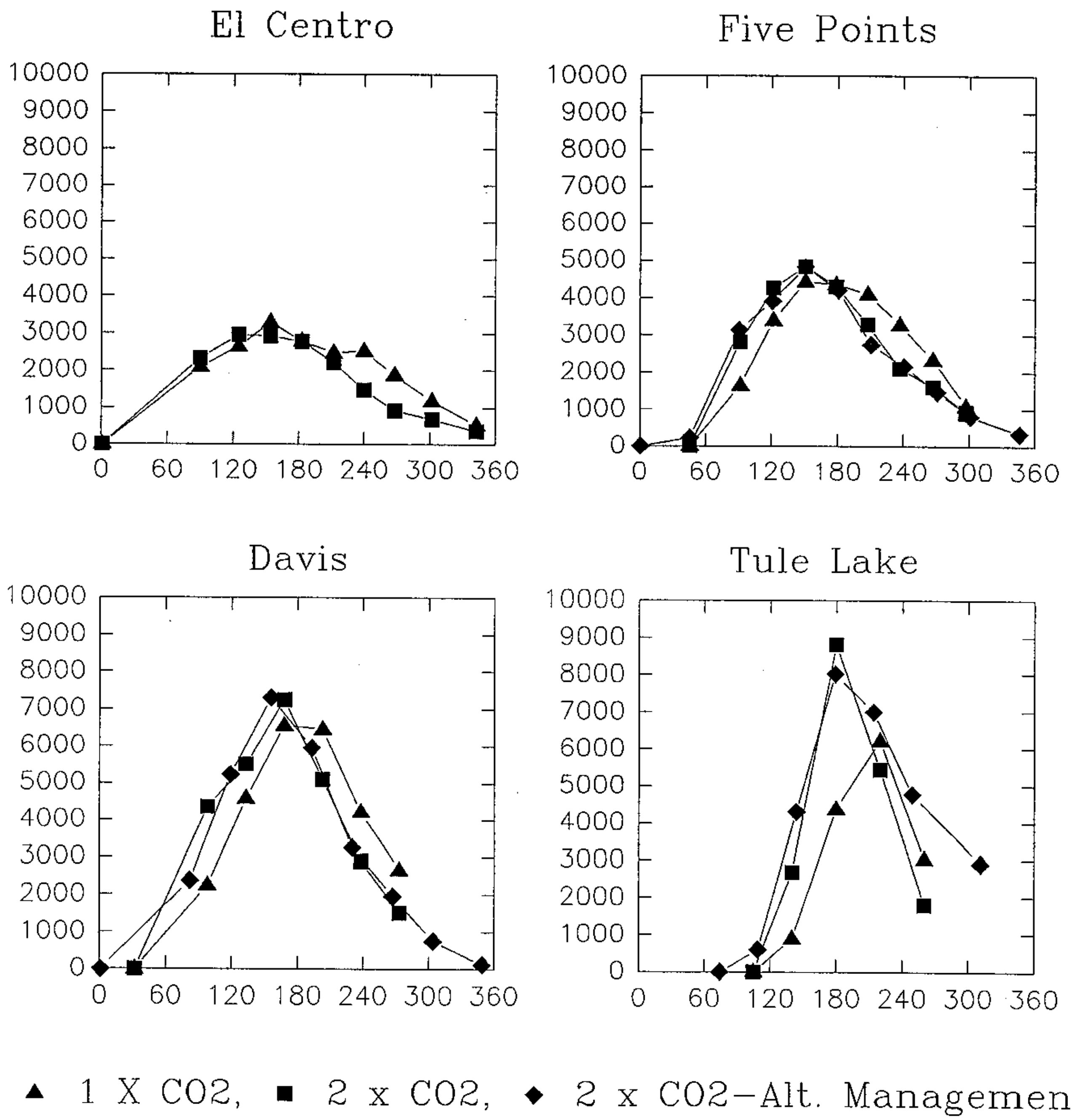

Fig.5 Mean yield (kg/ha) vs. cutting date (Julian).

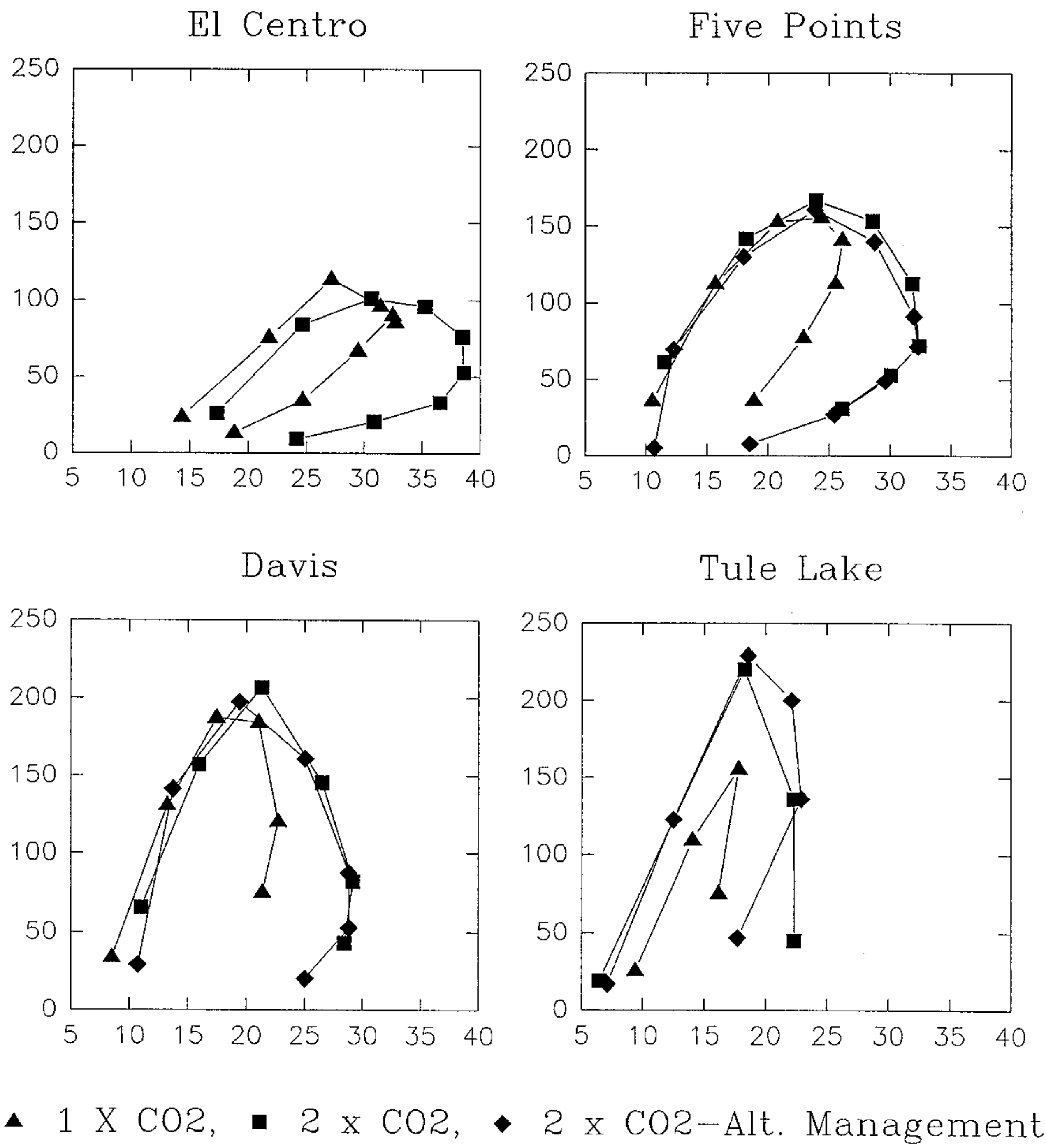

Fig.6 Mean yield (kg/ha/day) vs. mean temperature(℃) by cutting.

Table 1. Average yearly change of mean maximum and minimum temperatures and rainfall under $2XCO_2$ conditions. Positive value means an increase and negative value means an decrease under $2XCO_2$ conditions.

Location	Maxi. Temp.(C)	Mini. Temp.(C)	Rainfall
Tule Lake	4.79	5.02	0.05
Davis	4.78	4.67	0.16
Five Point	4.71	4.66	0.07
El Centro	4.42	4.59	0.01

Table 2. Average yearly change of standard deviations of maximum and minimum temperature and rainfall under $2XCO_2$ conditions. Positive value means an increase and negative value means an decrease under $2XCO_2$ conditions.

Location	Maxi. Temp.(C)	Mini. Temp.(C)	Rainfall
Tule Lake	-0.26	-0.88	0.25
Davis	0.99	0.65	1.01
Five Point	1.09	0.84	0.46
El Centro	0.69	1.02	0.17

Table 3. Simulated alfalfa yield (kg/ha) and percent of change under $2XCO_2$ and the modified management.

Location	Management	$1XCO_2$	$2XCO_2$	% Change
Tule Lake	Current	14527.1	18745.7	29
	Modified		27589.8	90
Davis	Current	26704.5	26597.9	-0.4
	Modified		26950.1	0.9
Five Point	Current	24619.9	24112.9	-2
	Modified		23815.0	-3.3
El Centro	Current	19417.5	16649.4	-14

Table 4. Description of the variables in Table 5.

Variables	Explanation
LAREA	Leaf area index
PLPOP	Plant population #/m_2
TOTSB	Total structural biomass per m_2 (g/m_2)
TTOPS	Top dry weight per m_2 (g/m_2)
TTNCQ	Reserve nonstructural carbonhydrate (g/m_2)
TLOST	Total losses from frost, pests and harvest (g/m_2 d)

Table 5. Simulated alfalfa yield of 30 years average in $1XCO_2$ and $2XCO_2$ conditions.

LOCATION	CO_2's	Yield(kg/ha)	LAREA	PLPOP	TOTSB	TTOPS
Tule Lake	$1XCO_2$	14527.1	18.66	1600	6635.1	2394.2
	$2XCO_2$	18745.7	18.43	1600	7043.3	2743.1
Davis	$1XCO_2$	26704.5	29.38	2378.6	10403.7	3791.0
	$2XCO_2$	26597.9	25.35	2328.2	10218.4	3756.5
Five Point	$1XCO_2$	24619.9	36.81	3084.5	12858.3	4026.0
	$2XCO_2$	24112.9	32.49	2912.8	12050.0	3847.9
El Centro	$1XCO_2$	19417.5	26.47	3420.6	12947.0	3480.1
	$2XCO_2$	16649.4	20.31	2757.1	10427.1	2930.8

Table 6. Average monthly increase (^{0}C) of maximum temperature under $2XCO_2$ conditions at four locations.

Month	Tule Lake	Davis	Five Point	El Centro
January	4.77	3.74	3.21	3.34
Feburary	3.00	1.98	2.55	2.82
March	2.28	2.27	1.03	2.52
April	1.43	1.81	2.05	2.60
May	2.12	2.84	2.67	3.18
June	4.93	4.60	4.20	3.38
July	4.53	5.89	6.01	5.62
August	6.70	7.31	7.42	6.07
September	6.48	7.83	7.56	7.02
October	7.37	7.18	7.68	6.01
November	7.17	6.69	6.39	5.78
December	6.57	5.07	5.69	4.60