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Climate change and productivity of some wheat cultivars under rainfed and supplementary irrigation conditions

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SUMMARY – Crop model programs are currently needed to study the impact of climate change on agricultural production. This could help the decision makers to implement future agricultural strategies together with different scenarios related to agricultural practices. One of these programs is DSSAT (Decision Support System for Agrotechnology Transfer), which is used to evaluate and predict wheat yield under all environmental conditions such as soil, weather, irrigation and fertilizers and simulate the yield of different wheat cultivars to select the cultivar(s) for different environments. We measured data taken from a field experiment carried out at Maryout (Northwest Coast of Egypt) during 1991-92, 1992-93 and 1993-94 growing seasons to evaluate the productivity of some bread wheat varieties under rainfed and supplementary irrigation conditions at different growth stages. The experiment included twenty-four treatments, which were the combination of four supplementary irrigation schedules: (i) only rainfed 170 mm of rainfall; (ii) one irrigation at heading stage 480 m^3/ha; (iii) one irrigation at milk ripe stage 480 m^3/ha; and (iv) two irrigations at the above stages (960 m^3/ha) and six wheat varieties (i.e. Sakha 8, Sakha 69, Giza 155, Cham 4, Cham 6 and Gomam). Predicted and measured grain were compared and the results indicated that there were significant and favorable differences between the six wheat cultivars where Cham 4 and Giza 155 cultivars had the higher grain yield under rainfed treatment. Whereas, under one supplementary irrigation treatment Sakha 69 cultivar recorded the higher grain yield followed by the Cham 6 cultivar. Moreover, Cham 6 and Sakha 69 cultivars produced the higher grain yield under the two supplementary irrigation treatments. On the other hand, there was a significant increase in the grain yield with increasing supplementary irrigation times. The potential impact of climatic change on wheat production was evaluated by simulation of wheat production under climatic change conditions by the year 2040 compared to the predicted production under current conditions. In this respect results indicated that the grain yield increased differently according to the wheat cultivar. This may be due to the positive effect of duplication in CO_2 on wheat as C_3 plants.

Key words: Climate change, wheat, rainfed, irrigation.

***RÉSUMÉ –** "Changement climatique et productivité de quelques cultivars de blé en conditions non irriguées et avec irrigation supplémentaire". Des logiciels de modélisation des cultures sont actuellement nécessaires pour étudier l'impact du changement climatique sur la production agricole. Ceci pourrait aider les décideurs à mettre en place de futures stratégies agricoles en même temps que différents scénarios liés aux pratiques agricoles. L'un de ces logiciels est le DSSAT (*Decision Support System for Agrotechnology Transfer – *Système d'Aide à la Décision pour le Transfert d'Agrotechnologie), qui est utilisé pour évaluer et prédire le rendement en blé sous toutes caractéristiques environnementales telles que sol, météorologie, irrigation et fertilisation, et pour simuler le rendement de différents cultivars de blé afin de sélectionner le(s) cultivar(s) pour différents milieux. On a mesuré les données enregistrées lors d'une expérience au champ menée à Maryout (Côte Nord-Ouest de l'Egypte) pendant les campagnes 1991-92, 1992-93 et 1993-94 pour évaluer la productivité de certaines variétés de blé panifiable en conditions non irriguées et avec irrigation supplémentaire à différentes stades de croissance. L'expérience a comporté vingt-quatre traitements, qui étaient la combinaison de quatre calendriers d'irrigation supplémentaire à savoir : (i) en sec avec 170 mm de précipitations ; (ii) une irrigation au stade d'épiaison de 480 m^3/ha ; (iii) une irrigation au stade laiteux de 480 m^3/h ; et (iv) deux irrigations aux stades cités auparavant (960 m^3/ha) et six variétés de blé (à savoir Sakha 8, Sakha 69, Giza 155, Cham 4, Cham 6 et Gomam). Le rendement en grain prévu et mesuré a été comparé et les résultats ont indiqué qu'il y avait des différences significatives et favorables entre les six cultivars de blé, où les cultivars Cham 4 et Giza 155 présentaient les meilleurs rendements en grain sous le traitement non irrigué. Tandis qu'avec le traitement à une irrigation supplémentaire, le cultivar Sakha 69 a montré le meilleur rendement en grain suivi par le cultivar Cham 6. En outre, les cultivars Cham 6 et Sakha 69 ont donné le meilleur rendement en grain sous les traitements à deux irrigations supplémentaires. D'autre part, il y avait une augmentation significative du rendement en grain avec des temps croissants d'irrigation supplémentaire. L'impact potentiel du changement climatique sur la* *production de blé a été évalué par simulation de la production de blé en conditions de changement climatique à l'horizon 2040 en comparaison avec la production prévue sous les conditions actuelles. A cet égard les résultats ont indiqué que le rendement en grain augmentait différemment selon le cultivar de blé. Ceci pourrait être dû à l'effet positif de la duplication du CO_2 du blé chez les plantes C_3 telles que le blé.*

Mots-clés : *Changement climatique, blé, pluvial, irrigation.*

Introduction

Wheat is considered to be one of the main crops in Egypt as well as in the world. Enormous efforts were carried out to reduce the vast gap between production and consumption of wheat. The level of self-sufficiency will not be achieved unless researchers manage to make better use of resources and new technology transfer. Researchers can change wheat cultivars, fertilizer levels, irrigation regime and agricultural practices to maximize wheat crop yield under the current conditions. The breeder usually records data and makes his selection on the basis of a large number of agronomic characters among which significant positive and negative correlations may exist (Johnson and Schmidt, 1968; Lee and Kaltsikes, 1973). Under climatic change conditions researchers need to use a crop model to predict the wheat production. DSSAT (Decision Support System for Agrotechnology Transfer) is a crop model that has the ability to take that source of variability into account. Cultivars are characterized by a specific set of genetic coefficients that express the genetic potential of each genotype independently of all environmental constraints such as soil, weather, fertilizer, etc. The best available genotypes can be explored by simulating the yield of different wheat cultivars. The CERES (Crop Estimation through Resource and Environment Synthesis) model was CERES-Wheat (Godwin *et al.*, 1989), a yield simulation model that was originally developed under the auspices of the USDA-ARS Wheat Yield. The model is also one of the main models that have been incorporated in DSSAT (Hoogenboom *et al.*, 1994). The CERES-Wheat model simulates the impacts of the main environmental factors, such as weather, soil type, and major soil characteristics, and crop management on wheat growth, development, and yield (Ritchie *et al.*, 1998). Input requirements for CERES-Wheat include weather and soil conditions, plant characteristics, and crop management (Hunt *et al.*, 2001). The minimum weather input requirements of the model are daily solar radiation, maximum and minimum air temperature, and precipitation. Soil inputs include drainage and runoff coefficients, first-stage evaporation and soil albedo, and water-holding characteristics for each individual soil layer. The model also requires saturated soil water content and initial soil water content for the first day of simulation. Required crop genetic inputs are coefficients related to photoperiod sensitivity, duration of grain filling, conversion of mass to grain number, grain-filling rates, vernalization requirements, stem size, and cold hardiness (Hunt *et al.*, 1993). If the crop is irrigated, the date of application and amount is required. Latitude is required for calculating day length. The model can use different weather, soils, genetic, and management information within a growing season or for different seasons in a single model execution. The model simulates: (i) phenological development; (ii) biomass accumulation and partitioning; (iii) leaf area index (LAI); (iv) grain growth; and (v) the soil and plant water and N balance from planting until harvest maturity based on daily time steps (Godwin and Singh, 1998; Ritchie, 1998; Ritchie *et al.*, 1998). When using a crop model for any application, one first has to estimate the cultivar characteristics if they have not been previously determined. Weather data, soil analysis, genetic coefficients and crop data are sufficient for crop modeling study. The characterization and selection of morpho-physiological traits play an important role in identifying stress-tolerant genotypes for dry areas. Understanding the impacts of weather on crop production by applying simulation models provides a credible basis for a quantitative estimate of the range of yields farmers can expect for a given set of management conditions (Arkin and Dugas, 1981; Hammer *et al.*, 1996; Tsuji *et al.*, 1998). Chauhan *et al.* (1970) demonstrate that wheat yield increased with increasing number of irrigations. They demonstrated that the treatment which received one irrigation after 25 days from sowing (crown root initiation) increased the yield by 327% over the non-irrigated one. At the northwest coast of Egypt, Sabry *et al.* (1994) studied the effect of one irrigation at planting time on wheat yield. They reported that significant differences in grain yield shown between wheat cultivars varied in mean grain yield under rainfed conditions with or without an irrigation after the sowing date. In the West Asia North Africa (WANA) region, rainfall is low and generally poorly distributed, so periods of water deficit occur during the grain-filling stage of wheat almost every year (Oweis *et al.*, 1992). As a result, crop yield and water use efficiency (WUE) are generally low and variable. The production of 1 kg of wheat (*T. aestivum* L.) grain under fully irrigated conditions requires about 1 to 2 m^3 of irrigation (Perrier and

Salkini, 1991); in rainfed areas it requires from 1 to 3 m^3 of rainwater (Cooper *et al.*, 1987a; Perrier and Salkini, 1991). Since water is the major limiting factor for agriculture in the WANA region, improving WUE is vital for meeting the increasing food demand (Cooper *et al.*, 1987b). Supplemental irrigation (SI) is defined as the application of a limited amount of water to rainfed crops when precipitation fails to provide the essential moisture for normal plant growth. This practice has shown potential in alleviating the adverse effects of unfavorable rain patterns and thus improving and stabilizing crop yields (Perrier and Salkini, 1991; Oweis *et al.*, 1998; Zhang and Oweis, 1999). Early studies at ICARDA showed that applying two or three irrigations (80-200 mm) to wheat increased crop grain yield by 36 to 450%, and produced similar or even higher grain yields than in fully irrigated conditions (Perrier and Salkini, 1991; Oweis, 1994). Supplemental irrigation is widely practised in Syria and in southern and eastern Mediterranean countries. However, excessive use of water in SI because of low irrigation costs and attractive gains from increased yields has resulted in a decline of aquifers and deterioration of water quality in many areas (Ward and Smith, 1994). The objective of this study was to determine if the DSSAT program could be used to forecast final grain yield for environmental conditions and management under rainfed and supplementary irrigation conditions at the North Coast of Egypt.

Materials and methods

Field experimental data of morpho-physiological, yield and yield attributes were obtained from previous studies that have been fully described by Abd El-Gawad *et al*. (1998a,b,c). These studies were carried out at the Maryot Agricultural Experiment Station (Northwestern Coast of Egypt) during 1991-92, 1992-93 and 1993-94 growing seasons to evaluate the performance of six bread wheat cultivars (Sakha 8, Sakha 69, Giza 155, Cham 4, Cham 6 and Gomom) under rainfed and supplementary irrigation conditions (rainfed only, one irrigation at heading stage, one irrigation at milk ripe stage, and two irrigation one at heading stage and the other at milk ripe stage). Standard meteorological data, total rainfall, maximum and minimum temperature, relative humidity, sunshine period and wind speed during the season are shown in Table 1.

Table 1. Meteorological data of the Maryot location (Northwestern Coast of Egypt)

Month Days	Growth stage	Temperature above 2 m (°C)			Rainfall (mm)			Relative humidity	Sun shine	Wind speed
		Max	Min	Mean	1991-92	1992-93	1993-94	(%)	period (h)	(km/h)
November	Germination									
1-10		25.2	19.0	22.0	33.1	0.0	6.5	66	10.8	2.3
11-20		23.8	14.7	19.6	0.6	0.0	6.2	66	10.6	2.1
21-30		20.2	12.5	16.9	53.0	1.1	1.0	62	10.2	3.3
December	Jointing									
1-10		20.4	11.4	15.6	34.5	9.3	0.0	68	10.2	2.4
11-20		17.8	10.5	13.9	44.6	3.6	2.1	74	10.2	3.6
21-31		15.7	9.0	12.1	62.2	8.3	10.0	69	10.2	2.8
January	Tillering									
1-10		16.2	8.3	12.3	24.6	45.0	31.0	72	10.2	3.5
11-20		16.8	8.7	12.7	21.6	15.0	4.4	69	10.3	2.1
21-31		17.6	9.6	13.7	45.9	19.0	7.8	66	10.5	1.8
February	Max vegetative									
1-10		14.9	8.4	11.7	12.9	35.2	0.5	65	10.8	3.1
11-20		15.8	8.7	12.8	11.6	14.0	0.0	66	10.5	2.4
21-29		17.2	8.3	12.2	31.3	12.6	3.3	68	11.6	3.5
March	Reproductive									
1-10		18.5	10.5	14.3	0.0	3.3	8.0	67	11.7	4.4
11-20		16.7	9.1	13.1	0.2	0.0	10.6	63	12.0	2.7
21-30		19.4	12.1	15.7	0.0	0.0	5.0	70	12.3	3.2
April	Grain maturity									
1-10		20.6	11.6	16.3	0.0	0.0	0.0	68	12.6	2.7
11-20		30.0	15.6	22.4	0.9	0.0	0.0	50	12.9	2.5
21-30		21.8	15.2	18.4	0.0	3.8	0.0	70	13.2	3.1
Total					337.0	170.2	96.4			

Theoretical study was conducted at the Central Laboratory for Agricultural Climate (CLAC) to estimate the efficiency of DSSAT in predicting the wheat yield and climate change effect on the yield prediction. The crop simulation models used in this study are included in DSSAT 3.1 (Tsuji *et al*., 1994). To calculate the six cultivar coefficients required by the CERES-Wheat model, DSSAT includes a program called the Genotype Coefficient Calculator (GENCALC). This program estimates the coefficients for a genotype by iteratively running the crop model with an approximate value of the coefficients concerned, comparing the simulated and measured data, then automatically altering the cultivar coefficient until the simulated and measured values match or are within predefined error limits. The required crop measurements are the key phenological dates, such as anthesis and harvest maturity, and yield and yield components (Hunt *et al*., 1993). Daily meteorological data simulated by the PROMES model for the 1xCO_2 and 2xCO_2 scenarios were processed and adapted to the needs of the weather files managed by DSSAT. The available data included emergence date, anthesis date, maturity date, grain yield, aboveground crop biomass, grain number per unit of ground area, individual grain weight, maximum LAI, and final grain yield. To achieve this research objective, the first step was to assess the accuracy of the model simulation compared with the observations. Therefore, observed weather data for the growing seasons used for calibrating the cultivar coefficients were applied to run the model. The program WeatherMan (Pickering *et al*., 1994) was used in this study to generate 30 years of daily weather data for the site. The daily weather variables that were generated included minimum and maximum temperature, total solar radiation and precipitation. WeatherMan is also part of the DSSAT system (Tsuji *et al*., 1994; Hoogenboom *et al*., 1999) and contains two different weather generator methods, i.e., WGEN and SIMMETEO. WGEN is based on daily historical weather data to determine its input coefficients while SIMMETEO is based on monthly data. Historical weather data is used to provide the monthly mean data required by WeatherMan. The model simulates crop response to climate change, management variables, soils and different levels of CO_2 in the atmosphere and was developed by DSSAT and includes database management, crop models and application programs (Tsuji *et al*., 1994). Potential changes in wheat morpho-physiological responses and yield estimated by using the CERES-Wheat model under different climate scenarios. The model simulates (water balance, phenology and growth throughout the season) on a daily basis of the major climate factors (daily solar radiation, maximum and minimum temperature and precipitation), soil and management (cultivars, plant data, plant population, row spacing and sowing depth).

Results and discussions

Effect of the interaction between supplementary irrigation and wheat cultivars on the measured and the simulated grain yield of some wheat varieties

Results presented in Table 2 showed that there were significant differences among the six wheat cultivars in grain yield. Choosing the results of season 1992-93 to exhibit in this study was due to the moderate rainfall (170.2 mm) as a common pattern of the rainfall in this area. Under rainfed only treatment Cham 4 and Giza 155 cultivars had the higher grain yield. Under one supplementary irrigation at heading stage conditions, the Sakha 69 cultivar recorded the highest grain yield followed by the Cham 6 cultivar. Whereas, at milk-ripe stage Cham 6 cultivar showed the highest value in grain yield as compared with the other wheat cultivars. Under the two supplementary irrigations (one at heading stage and one at milk-ripe stage treatment) the six wheat cultivars could be divided into two categories with regard to grain yield. The average values of Cham 6, Sakha 8, and Cham 4 category were higher in grain yield than those of Gomam, Sakha 69, and Giza 155 category. In this respect, Entz and Fowler (1990) found that there was a differential response of winter wheat cultivars to the moisture stress. Moreover, Ghanem *et al*. (1994) reported that there were significant differences ($P < 0.05$) between fourteen bread and durum wheat cultivars in grain yield under rainfed conditions at the Northwest Coast of Egypt. Comparing the measured and simulated grain yield by DSSAT program, Table 2 showed that simulated grain yield by DSSAT in the 1xCO_2 scenario were closer to the measured data. There was relative increase in the simulated grain yield ranging from 0.51 to 4.86%. The lower differences between the measured and simulated data were recorded for the Cham 6 variety under all supplementary irrigation treatments. Whereas the higher differences between the measured and simulated data were recorded for the Sakha 8 variety under rainfed only and adding two irrigation treatments. In the treatment adding one supplementary irrigation, the Gomam variety recorded the higher differences between the measured and simulated data.

Table 2. Simulation of the effect of the interaction between supplementary irrigation and wheat cultivars on the measured and the simulated grain yield of wheat plants

Irrigation treatment	Wheat cultivar	Grain yield		
		Measured (kg/ha)	Simulated (kg/ha)	Overall increasing (%)
Rainfed only (170.2 mm)	Sakha 8	1704de	1782	4.58
	Sakha 69	1800cde	1879	4.39
	Giza 155	1850cde	1898	2.53
	Cham 4	1850cde	1880	1.62
	Cham 6	1656e	1665	0.54
	Gomam	1740de	1779	2.24
One irrigation at heading stage	Sakha 8	2520ae	2608	3.49
	Sakha 69	3072ab	3164	3.00
	Giza 155	2616ae	2676	2.29
	Cham 4	2760ad	2806	1.67
	Cham 6	2880abc	2897	0.59
	Gomam	2544ae	2660	4.56
One irrigation at milk ripe stage	Sakha 8	2040be	2066	1.27
	Sakha 69	2616ae	2708	3.52
	Giza 155	2046be	2084	1.86
	Cham 4	2736ae	2773	1.35
	Cham 6	2952ab	2967	0.51
	Gomam	2540ae	2658	4.65
Two irrigation, at heading and at milk ripe stages	Sakha 8	3456a	3624	4.86
	Sakha 69	3096ab	3188	2.97
	Giza 155	3108ab	3221	3.64
	Cham 4	3432a	3586	4.49
	Cham 6	3552a	3652	2.82
	Gomam	3072ab	3145	2.38

[a,b,c,d,e]Means with the same letters are not significantly different at $P < 0.05$.

Climate change scenarios

Data presented in Table 3 showed the current and the predicted values by the year 2040 of some climate parameters, i.e. temperature (C°), precipitation (mm/day) and solar radiation (W/m^2). Selecting of the year 2040 was due to the doubled CO_2 concentration of this year. In this respect, Guereña *et al.* (2001) reported that the impact of climate change is reflected in the phenology, grain yield, aboveground biomass, and water use of winter wheat, winter barley, and maize, which are regarded as being representative of the common field crops grown in Spain. They pointed out that until 1990, the increase of greenhouse gases followed observations (Shine *et al.*, 1990), and from 1990 to 2100, the increment was 1% per year. This increase corresponds to the "business as usual" scenario (Mitchell and Gregory, 1992). They demonstrated that the reason for choosing years from 2040 to 2049 is that the CO_2 concentration in this period will be twice that of the preindustrial concentration. Results in Table 4 revealed that temperature would be increased. The increase in temperature will be in the range of about 2-5 °C during different months of the year. While the opposite trend will be noticeable regarding precipitation, except for a few months, i.e. September, October and December. Regarding solar radiation, there is a slight difference between the present status and the predicted values at year 2040.

Effect of the climate change by the year 2040 on the grain yield of some wheat cultivars under rainfed and supplementary irrigation conditions

Validation of DSSAT program is shown in Table 4. The potential impact of climate change in wheat production was evaluated by simulating wheat cultivar production under climate change by the year 2040 compared to that predicted under current conditions under rainfed and supplementary irrigation conditions.

Table 3. Temperature, precipitation and solar radiation for the current (CO_2 = 300 ppm) and the expected change situation (CO_2 = 600 ppm) by the year 2040

Month	Temperature (°C)			Precipitation (mm/day)			Solar radiation (W/m^2)		
	$1xCO_2$ 0.03%	$2xCO_2$ 0.06%	Ratio	$1xCO_2$ 0.03%	$2xCO_2$ 0.06%	Ratio	$1xCO_2$ 0.03%	$2xCO_2$ 0.06%	Ratio
January	11.9	14.8	2.85	0.7	0.5	0.66	155	159	1.02
February	13.1	17.9	4.84	0.5	0.4	0.78	198	199	1.01
March	17.2	21.0	3.86	0.9	0.7	0.84	259	262	1.01
April	21.5	26.9	5.35	0.3	0.2	0.55	318	315	0.99
May	26.3	32.3	5.97	0.2	0.4	2.59	341	338	0.99
June	32.0	35.9	3.98	0.2	0.5	3.10	350	341	0.97
July	33.8	37.5	3.63	0.3	1.2	3.80	346	327	0.94
August	33.7	35.8	2.07	0.3	1.9	5.00	317	302	0.95
September	29.2	33.5	4.31	0.8	1.2	1.56	275	268	0.97
October	23.2	26.9	3.69	0.9	1.1	1.16	222	222	1.00
November	16.2	21.3	5.15	0.5	0.5	0.93	175	174	1.00
December	12.7	16.9	4.21	0.5	0.9	1.83	151	146	0.97

Table 4. Effect of the climate change by the year 2040 on the grain yield of some wheat cultivars under rainfed and supplementary irrigation conditions

Irrigation treatment	Wheat cultivar	Grain yield		
		Predicted $1xCO_2$ (kg/ha)	Prediction by the year 2040 $2xCO_2$ (kg/ha)	Overall increase (%)
Rainfed only (170.2 mm)	Sakha 8	1782	2397	34.5
	Sakha 69	1879	2666	41.9
	Giza 155	1898	2408	26.9
	Cham 4	1880	2668	41.9
	Cham 6	1665	2302	38.3
	Gomam	1779	2531	42.3
One irrigation at heading stage	Sakha 8	2608	3508	34.5
	Sakha 69	3164	4380	38.4
	Giza 155	2676	3553	32.8
	Cham 4	2806	3824	26.7
	Cham 6	2897	4036	39.3
	Gomam	2660	3591	35.0
One irrigation at milk ripe stage	Sakha 8	2066	2640	27.8
	Sakha 69	2708	3703	36.7
	Giza 155	2084	2616	25.5
	Cham 4	2773	3721	34.2
	Cham 6	2967	4087	37.7
	Gomam	2658	3529	32.7
Two irrigation, at heading and at milk ripe stages	Sakha 8	3624	4675	29.0
	Sakha 69	3188	4218	32.3
	Giza 155	3221	3852	19.6
	Cham 4	3586	4793	33.7
	Cham 6	3652	4887	33.8
	Gomam	3145	4280	36.1

Genotype variation in response to climate has changed. The grain yield differed according to type of variety and supplementary irrigation schedule. Results obtained showed that under rainfed only treatment Gomam cultivar had the highest overall grain yield increase (42.3%) followed by Cham 4 and Sakha 69 cultivars (41.9%). On the other hand the Giza 155 cultivar had the lowest value (26.9%). By adding one supplementary irrigation at heading stage, the Cham 6 cultivar showed the highest increase in the grain yield (39.3%) compared with the other cultivars, whereas the Cham 4 cultivar recorded the lowest value (26.7%). Under the treatment of one supplementary irrigation at milk-ripe stage, the grain yield of Gomam cultivar increased more than the other wheat cultivars followed by the Sakha 69 cultivar, whereas the Giza 155 cultivar recorded the lowest increase in the grain yield. Moreover, under two supplementary irrigation treatments, the introduced cultivars (Gomam, Cham 6 and Cham 4) had the higher overall increase in grain yield (36.1, 33.8 and 33.7% respectively), whereas the local cultivars recorded the lower values. These results indicated that the Gomam cultivar has the major opportunity in the grain yield increase with the climate change by the year 2040, as shown previously in Table 3, when CO_2 will be duplicated and the precipitation will increase sharply in some winter months. The general trend is that the predicted grain yield in year 2040 ($2xCO_2$) will be increased more than the current ($1xCO_2$) yield predicted. In this respect, Guereña *et al*. (2001) reported that DSSAT predicted more pronounced WUE_b increases for wheat and barley as expected from the modeling of the beneficial effects of higher CO_2 concentrations on C_3 metabolism. This led to higher air temperature predictions, which were responsible for the shortening of crop duration and greater developmental rates. In the $2xCO_2$ scenario temperatures during the winter and early spring accelerated crop establishment and reduced the low-temperature limitation of photosynthesis for the C_3 species, thereby allowing for a higher shoot biomass to accumulate in a shorter time. The positive effect of the warmer spring air temperatures in the C_3 species is compensated by the shorter crop duration. They concluded that milder air temperatures during winter and early spring accelerated crop establishment and reduced the low-temperature limitation, thereby allowing for biomass to accumulate in a shorter time and compensate for the shorter crop duration.

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