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Growth and water use of wheat under present and future levels of CO_2

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Abstract

A mechanistic simulation model was used to examine the expected responses of wheat to a doubling in atmospheric CO_2 concentration in combination with a 2 °C rise in temperature. The model produced satisfactory simulations of total biomass, leaf area and canopy transpiration under present climatic conditions. However, soil evaporation was underestimated by up to 35% by the simulations. Model predictions suggested that increased CO_2 levels should lead to increased biomass and potential yields of wheat up to about 550 ppm, after which photosynthesis under full sunlight increases only gradually with CO_2. Higher temperatures are expected to decrease biomass production by shortening the growing season and by increasing plant respiration. A doubling of CO_2 concentration and a temperature increase of 2 °C is expected to cause only marginal changes in biomass production. Transpiration use efficiency may be enhanced by ~20% with a doubling of CO_2 above current levels.

Key words: wheat simulation modelling, climate change

1. Introduction

Plant leaves respond to increasing CO_2 by increasing photosynthesis and decreasing stomatal conductance (Fig. 1). The magnitude of the response depends on such factors as irradiance, atmospheric humidity, the level of mineral nutrients in leaves and plant water stress. Fully sunlit leaves of C_3 plants increase photosynthesis rates *approximately* linearly with increasing CO_2 concentration until levels reach about 550 ppm, after which photosynthesis becomes limited by leaf photochemistry, and assimilation rates increase only slowly with further increases in CO_2 levels. (Fig. 1). Saturation by CO_2 occurs at lower levels for shaded leaves. In contrast, transpiration rates decrease with increasing CO_2 (Fig. 1), and thus transpiration use efficiency (TUE: mass of CO_2 assimilated per unit water transpired) at the leaf level will increase with rising atmospheric CO_2.

Crop growth depends on many processes other than photosynthesis, and it is not immediately clear whether increasing CO_2 levels will lead to greater yields. The total amount of water available to a crop is a major determinant of grain yield in a water-limited environment (Wang et al., 1993) and full yield potential can only be achieved if there is sufficient water supply following anthesis. Crop water use efficiency will improve with higher CO_2 levels, but total water demand by the crop may not decrease because of rapid canopy development before anthesis (Gifford, 1988). The dynamics of canopy and root development, seasonal rainfall and soil water extraction by the crop will determine whether grain yields will be affected by changes in CO_2 and temperature as a result of climate change. This paper explores expected responses of wheat to a doubling in CO_2 concentration and an increase in air temperature of 2 °C on leaf area development, biomass production and water use of a wheat crop using a mechanistically-based simulation model.

2. Description of the model

Processes described in the model are (1) carbon assimilation, (2) biomass allocation, (3) root extension, (4) soil evaporation, (5) crop transpiration and (6) soil water balance. A full description of the model is given by Wang et al. (1993) and Handoko (1992). Crop growth is calculated as

$$dW/dt = a\, A_c f_w - r\, W \qquad (1)$$

where W is crop biomass at time t, A_c is photosynthetic carbon assimilation in the absence of plant water stress, a is growth efficiency (amount of dry matter produced per mass of CO_2 assimilated) and r is respiration rate. The factor $f_w = T/T_p$, where T is crop transpiration and T_p is potential transpiration, calculated using the Penman-Monteith combination equation. Transpiration is calculated as $T = min\{T_x, T_p\}$, in which T_x is soil-limited transpiration. A similar approach to calculation of crop production was used by van Keulen and Seligman (1987). To solve these equations, calculations are made of radiation absorption by the canopy, carbon allocation and phasic development. Growth of roots is also simulated and is used to estimate water extraction in a soil water balance. Input information includes daily weather data, parameters describing phasic development (degree-days), initial soil water content and soil water holding capacity.

Four simulations were performed for the wheat cultivar Matong: (1) c = 350, $\Delta T = 0$, (2) c = 350, $\Delta T = +2$, (3) c = 700, $\Delta T = 0$ and (4) c = 700, $\Delta T = +2$, where c refers to CO_2 concentration (ppm) and ΔT is the assumed uniform change in temperature (°C) relative to current conditions. Daily weather data for 1989 at Wagga Wagga (NSW, Australia) were used for the simulations. Results of simulation (1) were compared to measurements of biomass production, leaf area development and crop water use components of a wheat crop grown in a 5 ha field at Wagga Wagga in 1989.

3. Results

Good agreement was obtained between simulated and measured biomass components under currrent climatic conditions (Fig. 2a), and leaf area development was also simulated satisfactorily (Fig. 2b). Two distinct functions were used to describe LAI development before and after anthesis, producing an unrealistically sharp transition in LAI. However, this did not have a major impact on the predicted biomass development (Fig 2a).

Seasonal transpiration, soil evaporation and total crop water use are shown in Fig. 2c. Excellent agreement was obtained between measured and simulated transpiration, but the model significantly underestimated soil evaporation, with a consequent underestimate in total crop water use (ET). Soil evaporation was estimated using the method of Ritchie (1972), and it appears that further refinement of the model is needed before we can have complete confidence in simulated soil evaporation. Reasons for discrepancies between model and measurements are under investigation (Leuning et al., 1993).

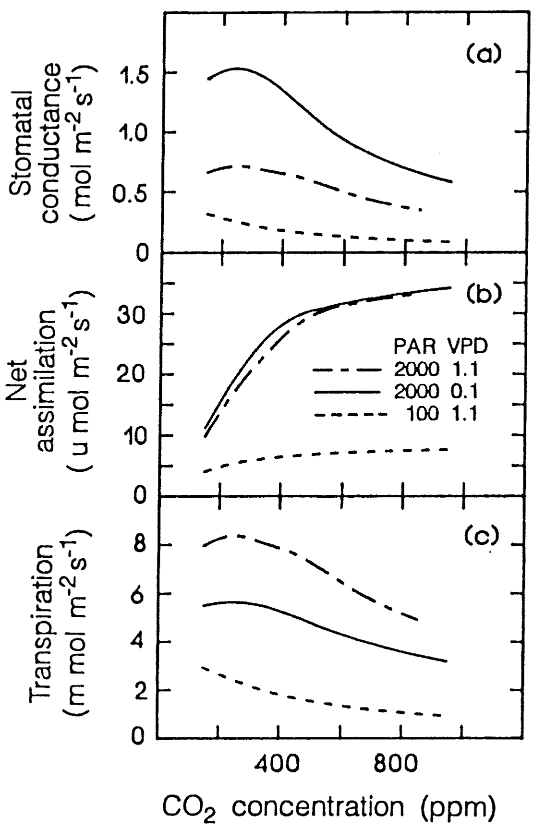

Fig.1 Responses of wheat leaves to ambient CO_2 concentration at two levels of irradiance (PAR: $\mu mol\ m^{-2}\ s^{-1}$) and water vapour deficit (VPD: kPA); (a) stomatal conductance, (b) net assimilation and (c) transpiration. Note small effect of VPD on assimilation but strong effect on conductance and transpiration. (Based on unpublished data of D. de Pury 1992).

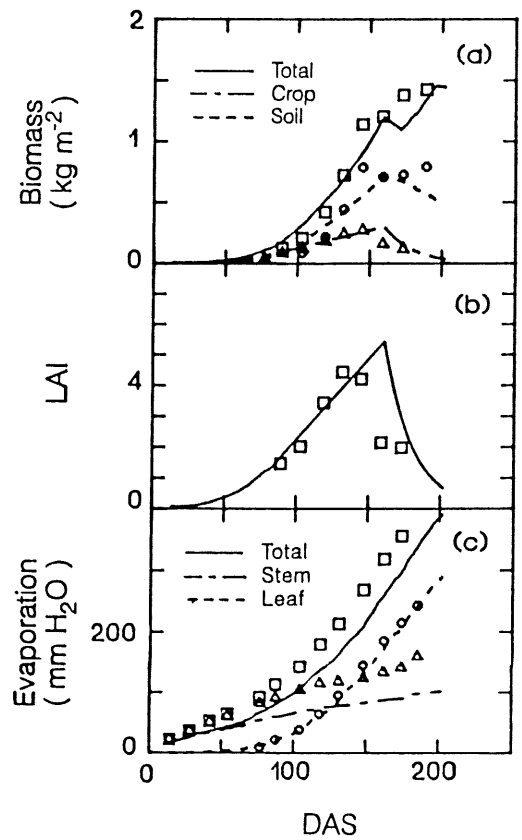

Fig. 2 Comparison of simulations (lines) and measurements (symbols) for (a) biomass, (b) leaf area index (c) evaporation for wheat under current climatic conditions.

Simulations of total biomass production for cases (1) to (4) are presented in Fig. 3. The model predicts that a 2 °C increase in temperature (case 2) will reduce the growing season by 14 days and reduce total biomass by ~30% relative to present-day conditions (case 1). Gifford (1988) also predicted a reduction of 30% in grain-yield for well-watered wheat crops subject to a temperature rise of 2°C. Raised temperatures accelerate crop development, increase plant respiration and increases potential transpiration, all of which lead to reduced biomass at harvest. Increasing CO_2 from 350 to 700 ppm, without a change in temperature (case 3), is expected to increase biomass production by ~30%, whereas a combined temperature increase of 2 °C and a doubling of CO_2 (case 4) is expected to yield only a marginal increase in total biomass.

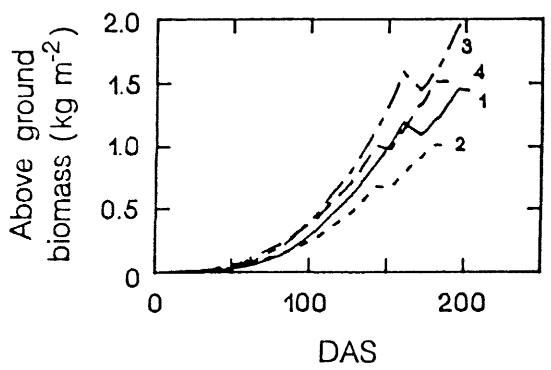

Fig. 3 Simulated seasonal development of total above ground biomass for wheat (cultivar, Matong) for four climates: (1) c = 350, $\Delta T = 0$, (2) c = 350, $\Delta T = +2$, (3) c = 700, $\Delta T = 0$, (4) c = 700, $\Delta T = +2$.

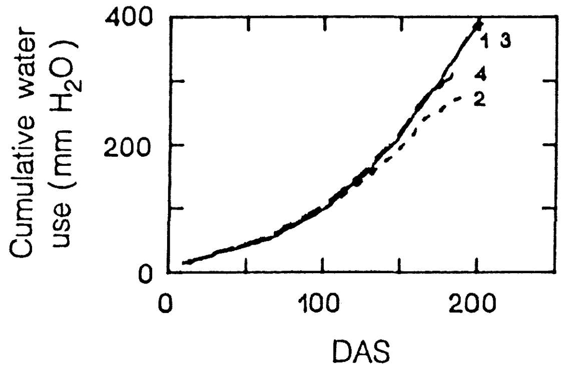

Fig. 4 Simulated seasonal cumulative water use by cv Matong for the four climate cases given in Fig. 3. Note similar water use by cases 1, 3 and 4.

The seasonal progression of cumulative crop water use was quite similar for all cases simulated, except when c = 350 ppm and $\Delta T = +2$ °C (case 2), when predicted ET is reduced by ~26% (Fig. 4). Doubling CO_2 without a change in temperature (case 3) resulted in no change in total crop water use. These predictions have been confirmed in recent experiments on a cotton crop exposed to enriched CO_2 in the field (B.A. Kimball, 1992, pers. comm.). Total crop water use in case (4) was predicted to be ~15% lower than for current conditions, with differences appearing only late in the season and caused by a reduced growing season and accelerated leaf senescence at higher temperatures. These simulations confirm predictions by Gifford (1988) that total water use by crops will be unaffected by increasing CO_2 because of enhanced development of LAI during the vegetative stages (Fig. 5). This figure also shows that increased temperatures are expected to reduce LAI at both current and double CO_2 levels.

Expected transpiration use efficiencies (TUE) are shown in Fig. 6 for simulation cases 1 and 3. (TUE is used here because of good agreement between simulated and measured transpiration (Fig. 2c), and because TUE, normalised by VPD, is expected to be constant for a given crop (Tanner and Sinclair, 1983)). Increased temperatures caused little change in TUE at c = 350 ppm, but reduced TUE by ~15% late in the season when c = 700 ppm (results not shown). A doubling of CO_2 concentration is expected to increase TUE by ~20% over much of the season (Fig. 6). Transpiration use efficiency is predicted to be relatively constant after about 40 DAS, the decrease being attributable to increased VPD late in the season.

4. Discussion

A fundamental assumption in the above results is that plant characteristics are unaltered by the changes in CO_2 and temperature used in the simulations, i.e. it is assumed that plants do not acclimate to a changing environment. A further assumption is that productivity is limited by carbon availability and that plants will distribute any increase in carbon assimilation resulting from higher CO_2 levels in the same manner as observed under present climatic conditions. A corollary is that there is an abundant supply of other resources required for growth (e.g. mineral nutrients), whereas limits to growth by water availability and light interception are included in the model. Possible changes in rainfall distribution patterns and amounts have also not been considered. Furthermore, no attention has been given to changes in management practices, such as altering sowing date with increased temperature or selection of cultivars more suited to a new climate. Such strategies have been

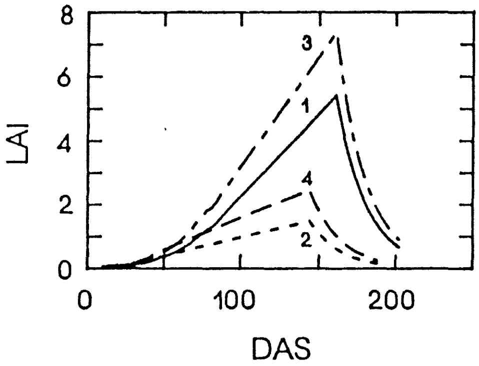

Fig. 5 Simulated seasonal development of LAI for the four climate cases given in Fig. 3. LAI is predicted to be sensitive to both mean temperatures and CO_2 concentrations.

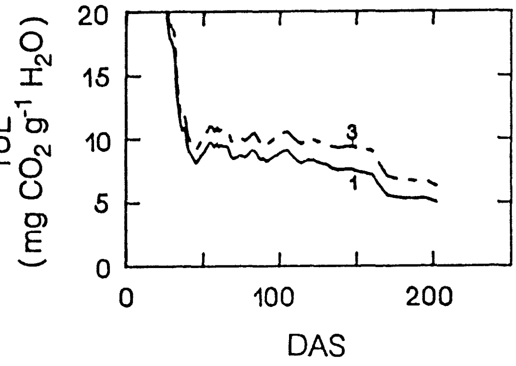

Fig. 6 Simulated seasonal variation in crop transpiration use efficiency for cases 1 and 3. TUE is high initially then remains relatively stable during most of the season. Doubling CO_2 concentration increases TUE by ~ 20%.

explored by Wang et al. (1993) when they compared the expected performance of two wheat cultivars currently grown in Victoria and another in Queensland (Australia). They predicted that earlier planting, combined with longer-season varieties would counteract detrimental effects of increased temperatures on yields of current varieties. A similar conclusion was made by Easterling et al. (1992). Doubling CO_2 concentration and increasing temperature by 2 °C is expected to have a marginal impact on crop productivity (Fig. 4), while an increase in CO_2 unaccompanied by a change in temperature is expected to produce significant increases in biomass and potential yields. However, the magnitude of the response to these factors will depend on rainfall and soil water availability (Nonhebel, 1993; Wang et al., 1993). Based on the very limited number of simulations considered here, it would appear that climate change will have only a limited impact on wheat production in south-eastern Australia provided rainfall patterns do not change substantially and that temperature increases are relatively moderate.

5. Conclusions

Increased CO_2 levels should lead to increased biomass and potential yields of wheat up to ~ 550 ppm, after which photosynthesis under full sunlight increases gradually with further increases in CO_2 concentration. Higher temperatures are expected to decrease biomass production by shortening the growing season and by increasing plant respiration. A doubling of CO_2 concentration and a temperature increase of 2 °C is expected to cause only marginal changes in biomass production because of compensating effects between increased growth rates and reduced length of growing season. Transpiration use efficiency may be enhanced by ~20% with a doubling of CO_2 above current levels.

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