2011 TERRECO Science Conference
October 2 – 7, 2011; Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany

Simulation of Present and Potential Future Paddy Rice Growth and Yield in the Mountainous Terrain of Haean Basin

Ko, Jonghan (1); Kim, Hanyong (1); Kang, Sinkyu (2); Tenhunen, John (3)

(1) Division of Plant Biotechnology, Chonnam National University, 300 Youngbong-dong, Buk-gu, Gwangju 500-757, Republic of Korea, jonghan.ko@jnu.ac.kr
(2) Department of Environmental Science, Kangwon National University, 192 Hyoja-dong, Chuncheon 200-092, Republic of Korea, kangsk@kangwon.ac.kr
(3) Department of Plant Ecology, University of Bayreuth, 95440 Bayreuth, Germany, john.tenhunen@uni-bayreuth.de

Abstract: Agricultural system simulation models are key tools for assessment of possible impacts of climate change on crop production and environmental quality. In this study, work is proposed to calibrate and validate the CERES-Rice 4.0 model to simulate paddy rice (*Oryza sativa*) production under elevated CO_2 and temperature conditions in a temperature gradient chamber with CO_2 fumigation (TGC-CF system). The experiments have been conducted at Chonnam National University, Gwangju, Republic of Korea (ROK) from 2009 to 2010. The model will then be used to simulate the current and future potential for rice production in the Haean Basin of Yanggu County, Gangwon Province, ROK. Simulations will be performed to explore the possible effects of climate change on the crop over 10 year periods centered on 2050 and 2075 with a projected climate change scenario for the region. The illustrated results from the CERES-wheat 4.0 module applied in the RZWQM2 model demonstrate the promise of the model for simulating climate change impacts on grain production.

Keywords: *climate change, crop modeling, TGC, yield*

1. Introduction

Global CO_2 emissions that represent 77 % of the total anthropogenic greenhouse gases (GHGs) have increased by ca. 80% from 1970 to 2004, and are projected to increase by 40 to 110% between 2000 and 2030 due to energy use alone (IPCC, 2007). Historic records reveal that the increase of anthropogenic GHGs in the atmosphere resulted in an increase in global mean surface temperatures by 0.74 °C ± 0.18 °C over the last 100 years (1906–2005). For the next two decades, a warming of ca. 0.2 °C per decade is predicted according to a range of IPCC Special Report on Emission Scenarios (SRES). The likely doubling of atmospheric CO_2 and associated warming within this century may affect agricultural production through changes in evapotranspiration, plant growth rates, plant litter composition, and the nitrogen-carbon cycle (Long *et al.*, 2006). However, the effect at any location will depend on the magnitude of change and response of the crops, forage or livestock species, and location-specific management. In order to understand the potential effects of climate change on agriculture and recommend timely remedial measures, it is essential to study the impacts of a projected increase in anthropogenic GHG and consequent global climate change on the cropping systems of interest.

In an agricultural system, plant growth and development depend on the integrated response of multiple eco-physiological processes to various interacting environmental variables (temperature, CO_2, nutrients, water, and agronomic management). It is impossible to incorporate all of these variables and their interactions in field experiments in order to study their impacts on agricultural production. Alternatively, well calibrated and validated agricultural system models are essential tools for the integration of the various chemical, physical, and biological processes and their interactions in the system (Ahuja et al., 2000; Kirschbaum, 2000). For example, a validated system model could be employed to explore how the temperature increases associated with enhanced CO_2 level in free atmospheric CO_2 enrichment (FACE) studies will influence the response of crops to CO_2, water and nitrogen.

The objectives of the present planned study are: (1) to gain better understanding of the response of paddy rice to CO_2 and air temperature interactions using the advanced CERES-Rice v4.0 model to simulate the Temperature Gradient Chamber with CO_2 Fumigation (TGC-CF) study carried out at Chonnam University; and (2) to use the model to assess potential effects of changes in temperature and precipitation associated with elevated CO_2 for the future years on the rice crop production at Haean, Kangwon, ROK.

2. Materials and Methods

2.1 Temperature Gradient Chamber with CO_2 Fumigation (TGC-CF) System

The TGC-CF system used in this study (Figure 1, Kim et al., 2011) was designed to simulate the projected shifts in atmospheric CO_2 concentration and air temperature based on the A1B scenario (IPCC, 2007). The fundamental TGC-CF treatments included two CO_2 levels [ambient CO_2 (AC), 371 ppmv and elevated CO_2 (EC), 622 ppmv] and two temperature levels [ambient temperature (AT), 25.8℃ and elevated temperature (ET), 27.8℃]. To increase the CO_2 concentration in EC chambers, artificial CO_2 with δ13C of -37.8‰ was provided, which is more negative in comparison with ambient CO_2. During the experimental periods, the δ13C of the air in AC and EC was -13.3‰ and -22.2‰, respectively.

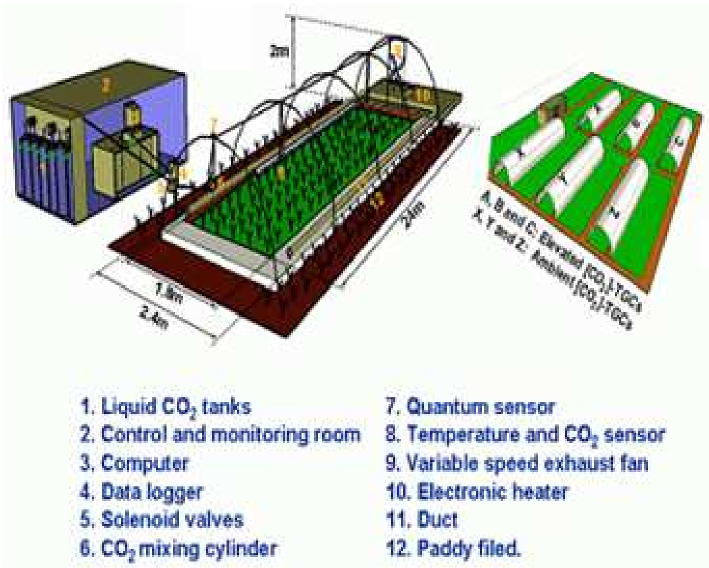

Figure 1. Schematic of the Temperature Gradient Chamber with CO_2 Fumigation (TGC-CF) system

The experimental site of the TGC-CF system (Figure 1) was located at the Chonnam National University's research farm (35°10' N, 126°53' E, 33m above sea level), Gwangju, ROK. The TGC-CFs were arranged with a split-plot design having two CO_2 levels assigned to main plots and two temperature levels assigned to subplots with three replications. The experiment was performed as a series of studies to investigate the effect of the simultaneous elevation of atmospheric CO_2 and air temperature on temperate rice crops (*Oryza sativa* L. subsp. Japonica cv. Dongjinbyeo) grown in a paddy using TGCs. The cultivar Donginbyeo has a medium-late maturing habit with a photosensitivity and maximum culm and panicle length of about 90 cm and 20 cm, respectively, when cultivated under current ambient conditions in the southern regions of Korea (Choung et al. 1998). Considering temperature increase, the use of a similar cultivar in the future in Kangwon is a reasonable assumption.

2.2 DSSAT4.0-CERES-Rice

The DSSAT4.0-CERES plant growth model used in this study (Jones et al., 2003) simulates crop yield components, leaf numbers, and phenological stages. The CERES-Rice model calculates net biomass production using the radiation use efficiency (RUE) approach. The effects of elevated CO_2 on RUE are modeled empirically using curvilinear multipliers (Allen et al., 1987; Peart et al., 1989). A y-intercept term in a modified Michaelis-Menten equation to fit crop responses to CO_2 concentration is used:

$$RUE = \frac{R_m \cdot CO_2}{CO_2 + K_m} + R_i \quad [1]$$

where R_m is the asymptotic response limit of (R – Ri) at high CO_2 concentration, R_i is the intercept on the y-axis, and K_m is the value of the substrate concentration, i.e., CO_2, at which (R – Ri) = 0.5 R_m. Similar approaches are followed for simulations of CO_2 effects on cropping systems in EPIC (Williams et al., 1989), APSIM (along with nitrogen use efficiency and water use efficiency) (Reyenga et al., 1999), and Sirius (Jamieson et al., 2000) models.

2.3 Model Parameterization and Calibration

The 2009-2010 TGC-CF rice data from Gwangju are being used for model parameterization and calibration. The minimum driving variables for the model simulations are daily solar radiation, maximum and minimum temperature, precipitation, soil physical and hydraulic properties, soil texture, and initial soil nitrogen and soil water status. Typical crop management metadata include planting dates, planting depth, row spacing plant population, and amount and method of irrigation and fertilizer applications. To develop cultivar parameters (genetic coefficients) for simulations of the rice cultivar 'Dongjin' using the CERES-rice model, an iterative approach recommended by Godwin et al. (1989) is employed through trial-and-error to match the measured phenology, biomass, LAI, and yield with simulated values. The combination of cultivar parameters that give the minimum RMSD are selected and used in further validation of the model.

2.4 Responses to CO_2, Temperature, and Precipitation

Model sensitivity tests to changes in atmospheric CO_2, temperature, and precipitation inputs are being conducted. The CO_2 concentrations of 100, 200, 300, 380, 475, 570, 700, 791, 995, and 1,200 μmol mol^{-1} are used. Temperature sensitivities are examined by varying the measured daily maximum and minimum temperatures by -3, 0, 1, 3, and 5 ^{o}C, and precipitation sensitivities by modifying the measured values by -50, -20, 0, 20, and 50%.

2.5 Effects of Present and Future Climate Change on Rice in Haean Basin

The CERES-Rice 4.0 model is being used to reproduce the current growth of the crop at Haean-myun in Yanggu, Kangwon, ROK. The model will then be applied to simulate the possible effects of climate change on the crop for a 10 year period centered on 2050 and 2075 with a projected climate change scenario for the region. For this purpose, temperature and precipitation projections in response to radiative forcing due to 550 and 693 ppm atmospheric CO_2 concentrations, e.g. representing future climate conditions (A1B scenario, IPCC, 2007), are obtained from different GCMs for Haean, Kangwon (TERRECO MOU with KMA). In order to include year to year natural variability, each GCM projection is made for 10 year variations centered on 2050 and 2075 and based on a 10 year baseline (2001-2010).

The GCM projections of temperature and precipitation are then superimposed over a 30 year baseline of historical climate data available at Haean, Kangwon. The average temperature increase of each month is added equally to the daily minimum and maximum temperatures in the corresponding month. Likewise, the percent change in precipitation of each month is used to change the daily precipitation in the corresponding month. These projected climate data are used to simulate the climate change effects of CO_2, temperature, and precipitation on spring wheat using the validated model for the FACE data set conditions.

3. Illustration of Expected Results

Simulated wheat grain yields over all the treatments of CO_2, irrigation and N in similar studies carried out previously were in reasonable agreement with the measured values in experimental treatments, with RMSD of 490 kg ha^{-1}, MRD of 1.3 %, and *E* of 0.88 (Figure 2A, Ko et al., 2010). Simulated final biomass also agreed well with the measured values with RMSD of 1154 kg ha^{-1}, MRD of 3.57 %, *E* of 0.78 (Figure 2B). Paired t-tests demonstrate that there were no significant differences between simulated and measured grain yield treated with CO_2, irrigation, and N (p = 0.443) and final biomass (p = 0.111). It was previously reported that models are capable of simulating CO_2 effects of the FACE wheat on crop development and yield (Asseng et al., 2004; Grossman-Clarke et al., 2001; Tubiello et al., 1999). The present study also demonstrates this context using the full data set with the updated CERES-Wheat module in the RZWQM2 model.

Cumulative distribution function (CDF) of simulated yield in WF-CT for the 16 baseline years (BL: 1992-2007) are compared with the projections [CO_2 (A), temp (B), precip (C), and three factors combined (D and E)] for years 2025 to 2100 (Figure 3, Ko et al., under review). With increasing CO_2 concentrations (i.e., 415 ppm for 2025, 550 ppm for 2050, 693 ppm for 2075, and 836 ppm for 2100), yields numerically increased (Figure 3A). With increasing temperatures (e.g., S1.9-W0.8 = 1.9 ^oC in summers and 0.8 ^oC in winters for 2025), yield decreased (Figure 3B) with a significant difference (DMRT at 95 % confidence intervals). With precipitation change scenarios, yield increased numerically but not statistically (Figure 3C). With all three factors-combined for 2025, 2050, 2075, and 2100, yields numerically deceased (Figure 3D). However this decrease was not significantly different according to DMRT at 95 % confidence intervals. CDF of transpiration shows an increase with time, even though the yield decreased (Figure 3E). This suggests that demands on transpiration would increase due to the temperature increase even at some lower yield.

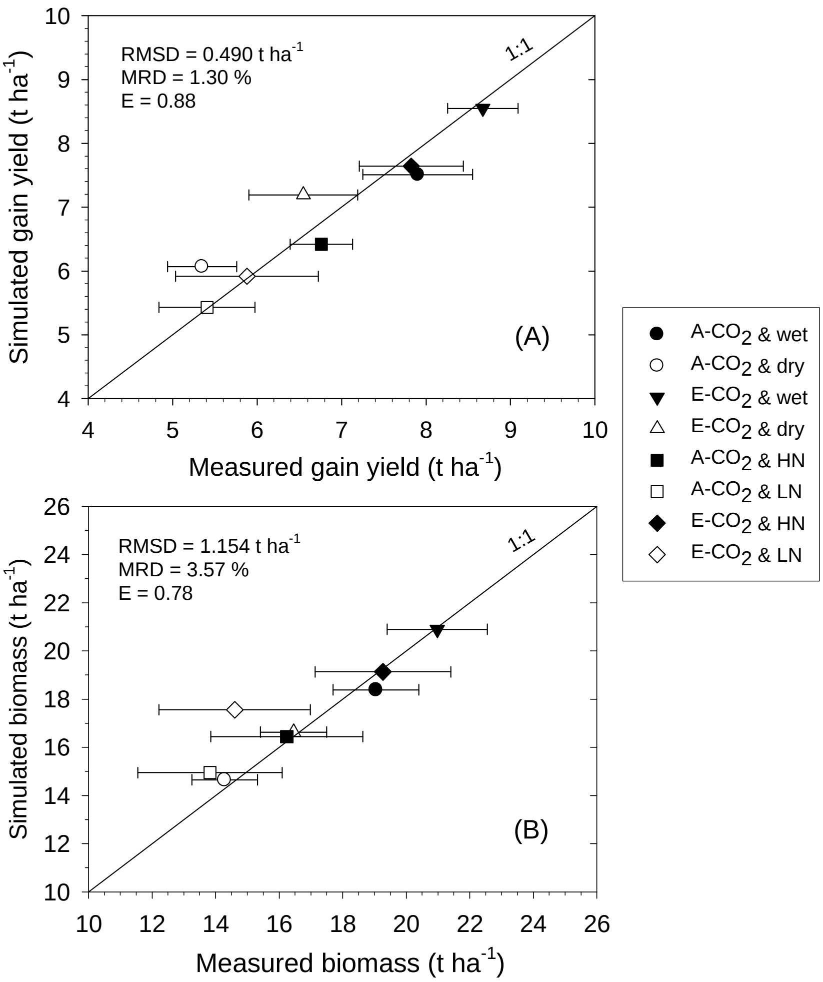

Figure 2. Simulation vs. measurement of grain yield (A) and biomass at maturity (B) for the different treatments applied to wheat (2-yr average for each treatment), using data from 1992-93 to 1996-97. Horizontal bars represent standard deviations (n = 4) (Ko et al., 2010).

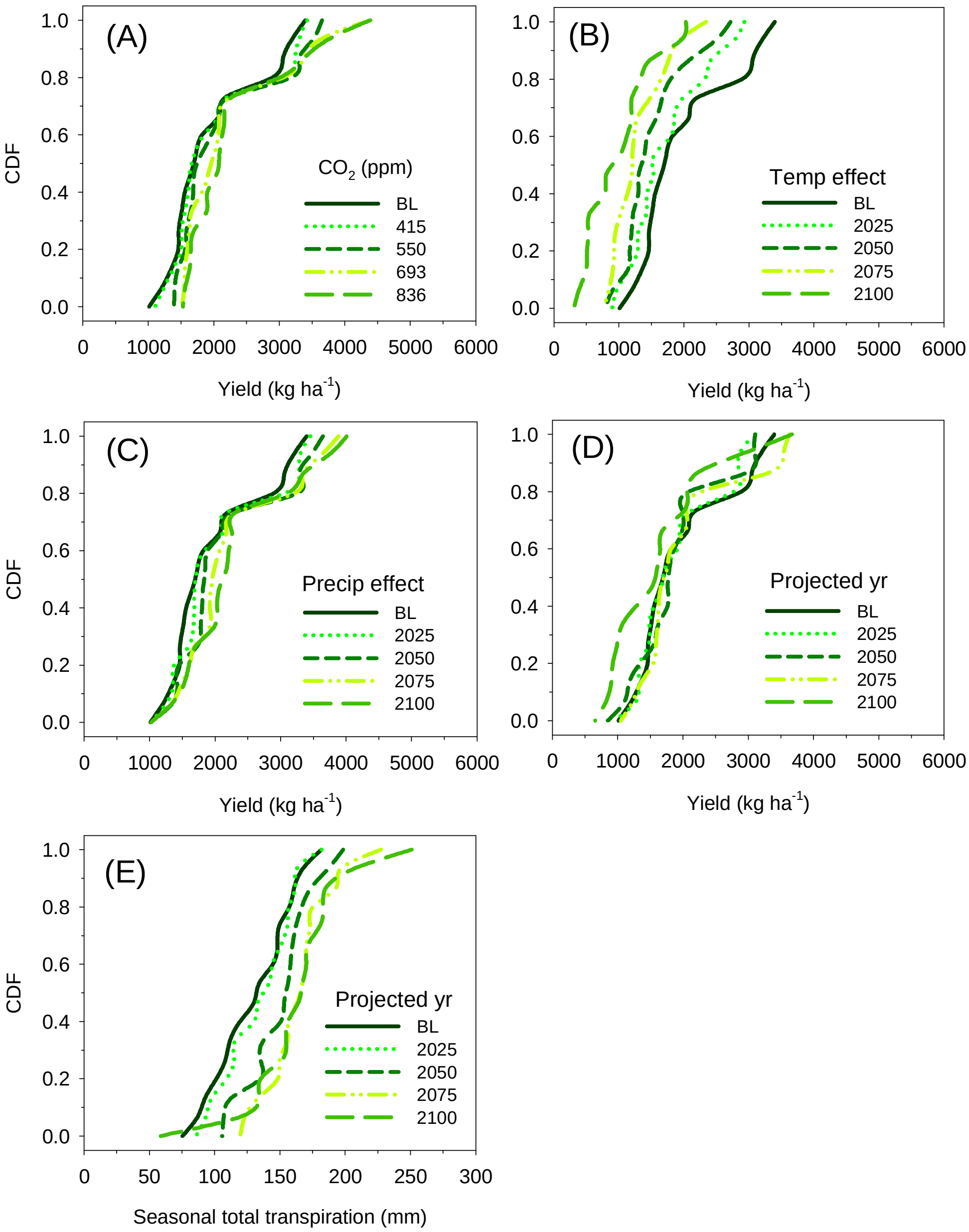

Figure 3. Cumulative distribution function (CDF) of wheat grain yield in conventional tillage (CT) under the wheat-fallow (WF) cropping system comparing simulated yield for the 17 baseline years (1992-2007) with: the projections of only CO_2 (A), temperature (B), and precipitation (C), and all three factors-combined (D) for the years 2025, 2050, 2075, and 2100. CDF of seasonal total transpiration (E) for the projected years corresponding to D (Ko et al., under review).

4. Discussion and Conclusions

CERES-Rice 4.0 will be calibrated and validated for simulations of rice grown in the Temperature Gradient Chamber with CO2 fumigation (TGC-CF) experiments at Chonnam National Univ., Gwangju, ROK. We also will examine the sensitivity of rice to individual climate change variables for future model application as well as simulation with projections from GCMs that include increased temperature and precipitation changes along with CO_2 for 2050 and 2075. The simulations are then comparable with some complex model simulations of photosynthetic carbon uptake in reproducing the dynamics of whole plant level crop growth (Tubiello and Ewert, 2002). A validated model is a good tool for analyzing possible impacts of climate change on wheat production in the region. As shown in the illustrated results, the CERES-wheat 4.0 module in the RZWQM2 model responded satisfactorily to the climate change deriving factors including CO_2, temperature, and precipitation. The results from the model demonstrate the promise of the model for simulating climate change impacts on wheat and rice production with variable climate.

References

Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L. (Eds.), 2000. Root Zone Water Quality Model. Modeling Management Effects on Water Quality and Crop Production. Water resources publications, LLC, CO, USA, p. 372.

Allen, L.H., Boote, K.J., Jones, J.W., Valle, R.R., Acock, B., Rogers, H.H., Dahlman, R.C., 1987. Response of vegetation to rising carbon dioxide: photosynthesis, biomass, and seed yield of soybean. Global Biochem. Cycles 1, 1-14.

Asseng, S., Jamieson, P.D., Kimball, B., Pinter, P., Sayre, K., Bowden, J.W., Howden, S.M., 2004. Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO2. Field Crops Research 85, 85-102.

Choung. JI, Kim, WJ, Lee, JK, 1998. Response of cultural environment in introduced rice varieties. Korean J. Int'l Agr. 14: 260-266.

Godwin, D.C., Ritchie, J.T., Singh, U., Hunt, L.A., 1989. A User's Guide to CERES-wheat – v2.10. International Fertilizer Development Center, Muscle Shoals, p. 89.

Grossman-Clarke, S., Pinter, Jr., P.J., Kartchall, T., Kimball, B.A., Hunsaker, D.J., Wall, G.W., Garcia, R.L., LaMorte, R.L., 2001. Modeling a spring wheat crop under elevated CO_2 and drought. New Phytologist 150, 315-335.

IPCC, 2007. Summary for Policymakers. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jamieson, P.D., Berntsen, J., Ewert, F., Kimball, B.A., Olesen, J.E., Pinter, Jr., P.J., Porter, J.R., Semenov, M.A., 2000. Modeling CO_2 effects on wheat with varying nitrogen supplies. Agr. Ecosys. Environ. 82, 27-37.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boot, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Europ. J. Agron. 18, 235-265.

Kirschbaum, M.U.F., 2000. Forest growth and species distribution in a changing climate. Tree Physiology 20, 09–322.

Kim, H.-Y., Lim, S.-S., Kwak, J.H., Lee, D.-S., Lee, S.-M., Ro, H.-M., Choi, W.-J., 2011. Dry matter and nitrogen accumulation and partitioning in rice (Oryza sativa L.) exposed to experimental warming with elevated CO2. Plant Soil 32: 59-71.

Ko. J., Ahuja, L., Kimball, R., Anapalli, S., Ma, L., Green, T.R., Ruane, A.C., Wall, G., Pinter, P., Bader, D.A., 2010. Simulation of free CO2 enriched wheat growth and interactions with water, nitrogen, and temperature. Agric. Forest Meteo. 150: 1331-1346.

Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nosberger, J., Ort, D.R., 2006. Food for thought: Lower-than-expected crop yield stimulation with rising CO_2 concentrations. Science, 312, pp. 1918-1921.

Lugwig, F., Asseng, S., 2006. Climate change impacts on wheat production in a Mediterranean environment in Western Australia. Agricultural Systems 90, 159-179.

Peart, R.M., Jones, R.B., Curry, K., Boote, K.J., Allen, L.H., 1989. Impacts of climate change on crop yield in the Southern U.S.A. In: Smith, J.B., Tirpak, D.A. (eds), The potential effects of global climate change on the United States, Report to Congress, U.S. Environmental Protection Agency, EPA-230-05-89-050, Washing D.C., Appendix C.

Reyenga, P.J., Howden, S.M., Meinke, H, McKeon, G.M., 1999. Modeling global climate change impacts on wheat cropping in south-east Queensland. Aust. Environ. Model. Software 14(4), 297-306.

Tubiello, F.N., Cynthia, R., Kimball, B.A., Pinter, Jr., P.J., Wall, G.W., Hunsaker, D.J., LaMorte, R.L., Garcia, R.L., 1999. Testing CERES-Wheat with free-air carbon dioxide enrichment (FACE) experiment data: CO2 and water interactions. Agron. J. 91, 247-255.

Tubiello, F.N., Ewert, F., 2002. Simulating the effects of elevated CO2 on crops: approaches and applications for climate change. Europ. J. Agronomy 18, 57-74.

Williams, J.R., Jones, C.A., Kiniry, J.R., Spanel, D.A., 1989. The EPIC crop growth model. Trans. ASAE 32(2), 497–511.