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Climate change impacts on crop yield and quality with CO_2 fertilization in China

Lin Erda*, **Xiong Wei, Ju Hui, Xu Yinlong, Li Yue, Bai Liping and Xie Liyong**

Agro-environment and Sustainable Development Institute, Chinese Academy of Agricultural Sciences, Beijing 100081, China

A regional climate change model (PRECIS) for China, developed by the UK's Hadley Centre, was used to simulate China's climate and to develop climate change scenarios for the country. Results from this project suggest that, depending on the level of future emissions, the average annual temperature increase in China by the end of the twenty-first century may be between 3 and 4 °C. Regional crop models were driven by PRECIS output to predict changes in yields of key Chinese food crops: rice, maize and wheat. Modelling suggests that climate change without carbon dioxide (CO_2) fertilization could reduce the rice, maize and wheat yields by up to 37% in the next 20–80 years. Interactions of CO_2 with limiting factors, especially water and nitrogen, are increasingly well understood and capable of strongly modulating observed growth responses in crops. More complete reporting of free-air carbon enrichment experiments than was possible in the Intergovernmental Panel on Climate Change's Third Assessment Report confirms that CO_2 enrichment under field conditions consistently increases biomass and yields in the range of 5–15%, with CO_2 concentration elevated to 550 ppm Levels of CO_2 that are elevated to more than 450 ppm will probably cause some deleterious effects in grain quality. It seems likely that the extent of the CO_2 fertilization effect will depend upon other factors such as optimum breeding, irrigation and nutrient applications.

Keywords: climate change impact; food crops; CO_2 concentration; adaptation

1. INTRODUCTION

In his speech to Earth Summit+5 in June 1997, the UK Prime Minister, Tony Blair, drew attention to the problem of global warming and stated that industrialized countries must work with developing countries to help combat climate change. As a result of this commitment, the UK's Department for Environment, Food and Rural Affairs (DEFRA) and the Chinese Ministry of Science and Technology (MOST) signed the Statement on Joint Work on Climate Change Research on 6th July 2001. This provided for funding and collaboration for a UK/Chinese project to assess the impact of climate change on agriculture in China using advanced computer models developed in the UK.

This paper summarizes the key findings from a successful collaborative project during 2001–2004 between the United Kingdom and the People's Republic of China to develop climate change scenarios for China and to examine their impact on rice, maize and wheat production during the twenty-first century.

This modelling work took into account climatic variables, irrigation, soil variables and the influence of higher atmospheric concentrations of carbon dioxide (CO_2) on plant metabolism. In general, climate change itself tends to reduce crop yield but the fertilization effect of CO_2 tends to increase yield. The balance between these two effects is likely to depend, in reality, on factors such as the availability of water and nutrients and the prevalence of pests and diseases, all of which are also likely to be affected by climate change. This paper also introduces a preliminary supplementary study of CO_2 fertilization and its impacts on crop quality.

2. REGIONAL CLIMATE MODELLING AND CLIMATE CHANGE SCENARIOS

A regional climate change model (PRECIS), developed by the UK's Hadley Centre for Climate Prediction and Research, was used to simulate China's climate and to develop climate change scenarios for the country (Xu & Jones 2004). The PRECIS regional climate model was designed by the Hadley Centre to run on a desktop personal computer (PC) and to be applied to any part of the world to generate detailed climate change predictions at a 50×50 km or 25×25 km scale. Regional climate models are downscaling tools, adding detail to chosen general circulation model simulations. They have a much higher resolution than general circulation models and thus allow a more detailed assessment of a country's vulnerability to climate change.

PRECIS was used to predict changes in average rainfall, daily temperatures (minimum and maximum) and CO_2 concentration for the whole of China for the period 2070–2079; results of the three parameters for the intermediate decades, 2040–2049 and 2010–2019, were obtained by a nonlinear interpolation pattern scaling method according to CO_2 concentration levels. Table 1 summarizes the average predictions for three decades for the emissions scenarios A2 and B2[1] over the whole of China for 2010–1019, 2040–2049 and

* Author for correspondence (lined@ami.ac.cn).

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Table 1. Average climate change scenarios in China under IPCC Special Report on Emission Scenarios (SRES) A2 and B2 scenarios from PRECIS relative to baseline simulation (1961–1990), plus corresponding CO_2 concentrations.

	A2 (medium–high emissions)			B2 (medium–low emissions)		
time-period	temperature increase (°C)	rainfall increase (%)	CO_2 (ppmv[a])	temperature increase (°C)	rainfall increase (%)	CO_2 (ppmv[a])
2010–2019	1.00	3.3	440	1.16	3.7	429
2040–2049	2.11	7.0	559	2.20	7.0	492
2070–2079	3.89	12.9	721	3.20	10.2	561

[a] parts per million by volume.

2071–2079. Outputs suggest that there are likely to be more extremely high temperature events during the summer and fewer extremely cold events during the winter. The number of days with heavy rainfall is also projected to increase. Seasonal changes were also incorporated into the climate scenarios used for modelling the impact on the four crops.

The applicability of the PRECIS model to the Chinese climate was validated by comparing historical temperature and rainfall data over China for 1961–1990 with modelled data for this baseline period (figure 1). The generally good agreement between observed and simulated data for 1961–1990 provided confidence in the results obtained when PRECIS was used to project climate change over China into the twenty-first century using Special Report on Emission Scenarios (SRES) for future greenhouse gas emissions.

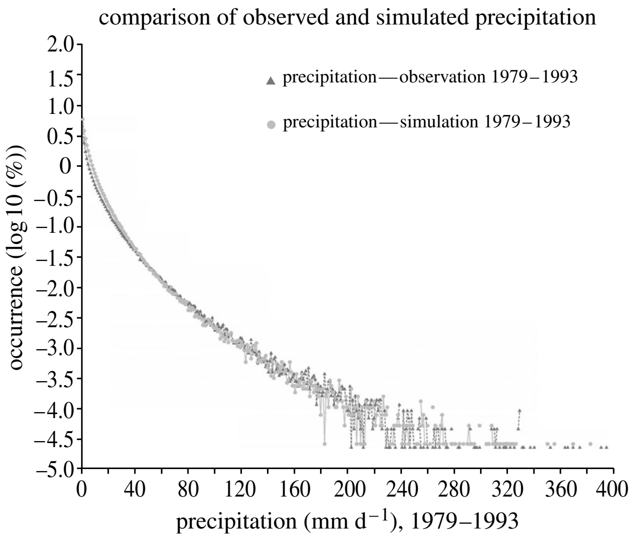

Figure 1. Statistical analysis of the simulated and observed daily precipitation (mm d^{-1}) in all 740 stations over China.

3. CROP MODELLING WITH CO_2 FERTILIZATION

Regional crop models were driven by PRECIS output to predict changes in yields of four key Chinese agricultural crops (rice, maize, wheat and cotton) on a desktop PC; these changes were then applied to all sowing areas of China to generate detailed crop predictions on a 50×50 km grid scale. National-level yields were calculated by

$$yc_{m,n,i,r} = \frac{\sum_{j=1}^{2622}\left(\frac{M_{m,n,i,r,j}-M_{0,i,r,j}}{M_{0,i,r,j}}100\%\right)}{2622},$$

where $yc_{m,n,i,r}$ is the mean yield change for m climate change scenario, n is the time-period, i is the crop and r is the management scenario (rainfed or irrigated with or without CO_2 fertilization effect). $M_{m,n,i,r,j}$ means mean yield of m climate change scenario, n is the time-period, i is the crop and r is the management scenario for j grid. $M_{0,i,r,j}$ stands for the mean yield of i crop at baseline for no. j grid under r management scenario; 2622 is sowing areas by grids.

The Crop Environment Resource Synthesis (CERES) crop simulation models (Ritchie *et al.* 1998) were used and information on the areas allocated to irrigated and rainfed crops was obtained from a national survey carried out in 2000. Previous studies have validated the CERES models for China. Matthews *et al.* (2000) used the CERES-rice as a core model to simulate the methane (CH_4) emission from East Asia, Rosenzweig *et al.* (1999) specified and validated eight sites in the major wheat-growing regions of China, Wu *et al.* (1989) used the CERES-maize to simulate maize yields for 1979–1984 in the North China Plain after calibrating the model based on local data. For this study, a validation on a regional scale for CERES-maize (Xiong *et al.* 2005) found that the simulated yield in the Jilin province, northeast China slightly overestimated historical yields (China National Agricultural Statistics), but more closely approximated the yields from agronomic experiments. Other crop models were validated against observed yields during 1995–2001 (Ju *et al.* 2005) and used to evaluate the impact on yields and production areas of climate scenarios provided by PRECIS for the A2 and B2 emissions scenarios. The variables captured in the model included:

- (i) climatic (temperature and rainfall);
- (ii) whether the crop is irrigated (with higher baseline yield, assuming no limits on water supply in future) or rainfed (with smaller baseline yield, no irrigation supply in future);
- (iii) CO_2 fertilization effect;
- (iv) soil variables.

The following variables were not captured.

- (i) Pests and diseases.
- (ii) The availability of water for irrigation.
- (iii) The availability of nutrients.
- (iv) Other crop/farming management practices
- (v) Socio-economic factors (considered separately).
- (vi) Possible improvements in crop varieties in the future.

Table 2. Projected changes in China's rice yield compared with yield under baseline (1961–1990). (The ranges of the changes in yield show regional changes which include some very low baseline yields.)

	change in average yield (%)					
	2020s		2050s		2080s	
	with CO_2 fertilization	without CO_2 fertilization	with CO_2 fertilization	without CO_2 fertilization	with CO_2 fertilization	without CO_2 fertilization
A2: rainfed	2.1 (−86–356)	−12.9 (−98–356)	3.4 (−84–491)	−13.6 (−84–376)	4.3 (−79–291)	−28.6 (−93–276)
A2: irrigated	3.8 (−89–465)	−8.9 (−94–321)	6.2 (−79–458)	−12.4 (−79–516)	7.8 (−77–343)	−16.8 (−91–116)
B2: rainfed	0.2 (−89–295)	−5.3 (−100–273)	−0.9 (−87–278)	−8.5 (−100–423)	−2.5 (−82–195)	−15.7 (−92–173)
B2: irrigated	−0.4 (−97–573)	−1.1 (−98–320)	−1.2 (−87–356)	−4.3 (−95–325)	−4.9 (−92–273)	−12.4 (−84–210)

Table 3. Projected changes in average maize yield compared with yield under baseline (1961–1990). (The ranges of the changes in yield show regional changes which include some very low baseline yields.)

	2020s		2050s		2080s	
	with CO_2 fertilization	without CO_2 fertilization	with CO_2 fertilization	without CO_2 fertilization	with CO_2 fertilization	without CO_2 fertilization
A2: rainfed	9.8 (−85–465)	−10.3 (−98–352)	18.4 (−87–452)	−22.8 (−93–281)	20.3 (−74–392)	−36.4 (−83–224)
A2: irrigated	−0.6 (−100–655)	−5.3 (−96–254)	−2.2 (−81–541)	−11.9 (−96–210)	−2.8 (−94–492)	−14.4 (−96–111)
B2: rainfed	1.1 (−87–287)	−11.3 (−95–214)	8.5 (−94–567)	−14.5 (−97–227)	10.4 (−84–267)	−26.9 (−79–127)
B2: irrigated	−0.1 (−98–531)	0.2 (−89–211)	−1.3 (−94–431)	−0.4 (−90–147)	−2.2 (−90–131)	−3.8 (−92–187)

Table 4. Projected changes in average wheat yield compared with yield under baseline (1961–1990). (The ranges of the changes in yield show regional changes which include some very low baseline yields.)

	change in average yield (%)					
	2020s		2050s		2080s	
	with CO_2 fertilization	without CO_2 fertilization	with CO_2 fertilization	without CO_2 fertilization	with CO_2 fertilization	without CO_2 fertilization
A2: rainfed	15.4 (−85–654)	−18.5 (−96–485)	20.0 (−92–431)	−20.4 (−78–234)	23.6 (−72–331)	−21.7 (−63–144)
A2: irrigated	13.3 (−65–655)	−5.6 (−88–356)	25.1 (−63–558)	−6.7 (−74–145)	40.3 (−53–458)	−8.9 (−64–98)
B2: rainfed	4.5 (−88–389)	−10.2 (−87–213)	6.6 (−88–305)	−11.4 (−76–118)	12.7 (−83–205)	−12.9 (−76–95)
B2: irrigated	11.0 (−89–485)	−0.5 (−86–356)	14.2 (−80–278)	−2.2 (−84–201)	25.5 (−70–378)	−8.4 (−73–109)

In general, higher CO_2 levels in the atmosphere, resulting from global human activities, increase growth and yield, mainly through their effect on the crop's photosynthetic processes (higher levels of CO_2 mean that plants absorb more CO_2—a process known as CO_2 fertilization (Hendrey & Kimball 1994)). However, higher temperatures generally decrease yield by speeding up a plant's development so that it matures sooner (thus reducing the period available for yield production); they often also exacerbate stress on water resources that are essential for crop growth. Warmer and wetter conditions also tend to affect the prevalence of pests, diseases and weeds (not included in this yield model). Interactions of CO_2 with limiting factors, especially water and nitrogen, are capable of strongly modulating simulated growth responses in crop plants between 0 and 50% (tables 2–4). Even the photosynthetic ratios adopted in CERES are only 1.17 for wheat/rice and 1.06 for maize with CO_2 at a level of 550 ppm, compared with 330 ppm (Ritchie *et al.* 1998). Free-air carbon enrichment experiments confirm that CO_2 enrichment responses under field conditions consistently increase biomass and yields in the range of 5–15% with CO_2 concentration elevated to 550 ppm (Ainsworth & Long 2005). So the CO_2 fertilization simulation has considerable scope for improvement in the future.

(a) *Key findings: rice*

Averaged across the country, yields are generally shown to increase under the A2 emissions scenario and decrease under the B2 emission scenario when the CO_2 direct effect is included in the simulation (see table 2). This is because CO_2 fertilization effectively offsets yield decreases caused by shorter growth duration due to higher temperatures. The CO_2 effect is more evident under A2 than B2. Without the CO_2 direct effect and keeping the same sowing date and rice varieties as today, average yields are likely to fall under both the A2 and B2 emission scenarios (see table 2). Note, however, the large regional variability in the yield changes.

Table 5. Flour protein (%) attributes: averages comparing CO_2 levels and genotypes.

treatment	CO_2 levels (μmol mol^{-1})	Beijing 9701	ZhongYu five
CO_2 gradient	451	15.48 (15.42–15.54)	13.46 (13.39–13.53)
	508	15.09 (15.02–15.17)	13.37 (13.36–13.38)
	565	15.01 (15.01–15.02)	12.86 (12.76–12.95)
mean values	508	15.20	13.23
Control	413	15.57 (15.47–15.66)	13.67 (13.40–13.76)

(b) *Key findings: maize*

If the direct effect of CO_2 is included, average yields are projected to increase for rainfed maize and decrease for irrigated maize under both the A2 and B2 emissions scenarios (see table 3) in the 2080s. The increase is likely to be highest for rainfed maize under the A2 emissions scenario, possibly because the higher CO_2 concentration would boost the yield of rainfed maize under the current water-limited conditions prevalent in North China (the biggest maize cultivation area). Without the CO_2 fertilization effect, the average yield of both rainfed and irrigated maize is likely to fall for both A2 and B2 emission scenarios (see table 3) because the higher temperature may shorten the growth period by between 4 and 8 days. While irrigation might counteract the trend towards a decrease in yield (assuming sufficient water is available), it is not expected to stop it completely (for the B2 scenario, yields could remain similar to current levels if good irrigation is available). Yield decreases would be greatest if higher temperatures occur during the period when the maize ears are swelling (Southworth *et al.* 2000; Jones & Thornton 2003). These results show a large relative benefit to maize yields from elevated CO_2. This is in contrast to most C_4 crop experiments which show minor absolute changes in yield due to CO_2 enrichment. As with rice, there is large regional variability in the yield change (table 3). This could be due to the use of calibrated irrigation and nutrition parameters in the model which were validated under present CO_2 concentration rather than in a higher CO_2 environment.

(c) *Key findings: wheat*

If the effect of CO_2 fertilization is included, average wheat yields are shown to increase in China in the 2020s, 2050s and 2080s under the A2 emissions scenario for both rainfed and irrigated wheat (see table 4). Spatial variability is again large. The response of wheat to future atmospheric CO_2 increases is likely to significantly constrain potential increases in yield. But for irrigated wheat to benefit from the effects of CO_2 fertilization, nutrients need to be non-limiting. Without CO_2 fertilization, wheat yields are expected to be some 20% and 10% lower by 2080 compared with current yields for the A2 and B2 emissions scenarios, respectively.

4. EFFECTS OF ELEVATED CO_2 ON GRAIN QUALITY

Wheat of two genotypes (ZhongYu five and Beijing 9701) was grown in the field under CO_2 gradient enrichment (CGE—half of open) with a controlled chamber in the Chinese Academy of Agricultural Science experiment station in Beijing in 2001–2002 (Bai *et al.* 2004). The gradient CO_2 enrichment was from 451 to 565 mg kg^{-1}. Measurement for effects of elevated CO_2 on grain quality showed that: (i) protein content for flour was found to significantly decrease with CO_2 concentration gradient enrichment (at range 57 μmol mol^{-1}; table 5); (ii)the sedimentation value of ZhongYu five was found to decrease a little (table 6). Even though there were some errors and uncertainties due to limited samples, significant differences between different varieties still exist after strict measurements. These results indicate that elevated CO_2 levels may cause a decrease in the quality of bread wheat due to generally lowered protein content.

Table 6. Sedimentation value (ml) attributes: averages comparing CO_2 levels.

treatment	CO_2 levels (μmol mol^{-1})	ZhongYu five
CO_2 gradient	451	34.3 (33.8–35.0)
	508	34.0 (33.8–34.2)
	565	33.9 (33.8–34.0)
mean values	508	34.1
control	413	35.0 (34.0–36.0)

The above results from CGE experiments have confirmed the results from previous studies (Blumenthal 1996; Rogers *et al.* 1996; Hakala 1998; Monje & Bugbee 1998; Kimball 2001): elevated CO_2 can cause more or less deleterious effects on grain quality. In addition, there would be distinct differences between varieties. Most of the experiments showed reductions in grain nitrogen content or grain protein at elevated levels of CO_2, although some found no significant effect of elevated CO_2 on grain quality.

Rises in the concentration of CO_2 in the atmosphere are likely to be accompanied by temperature increases. Small increases in temperature (2–4 °C) had a larger effect than elevated CO_2 on grain quality (Tester *et al.* 1995; Williams *et al.* 1995). Moreover, the effects of elevated CO_2 on grain quality may be partially balanced because temperature increases can enhance grain protein content (Campbell 1981; Blanche & Benzian 1986; Randall & Moss 1990; Wrigley *et al.* 1994). However, it is unlikely that any high temperature effects will totally compensate for CO_2 enrichment. Data from Kimball's experiments (2001) suggest that adequate fertilizer is necessary to attain good quality grain and that with ample fertilizer the deleterious effects of elevated CO_2 will be minor. Furthermore, crops grown with limiting levels of nitrogen probably have poorer quality grain than they could have. CO_2 enrichment in the atmosphere during coming decades is likely to make the quality poorer still.

5. POTENTIAL ADAPTATION TECHNOLOGIES OF ACCLIMATION TO CO_2 FERTILIZATION

Measurements have shown that with prolonged exposure to elevated atmospheric CO_2, the photosynthetic rate gradually declined, approaching or even less than that in ambient (Tang *et al*. 1998). These results indicate an acclimation or downregulation to the higher CO_2 levels. But CO_2 fertilization still can be favoured for adaptation in a future climate. A detailed understanding of CO_2 fertilization should be taken into account in developing adaptation technology.

New varieties by seed selection are one of the key methods of increasing crop yield and improving crop quality as well as adapting to environment change. With increasing ambient CO_2 concentration and a warmer climate, especially in winter, new crop varieties with high yield, warm-winter resistance under higher CO_2 should be favoured for adaptation in a future climate. For rice, cross breeding of Indica and Japanica varieties is considered ideal for enhancing morphological characteristics. In recent years, maintaining the breeding theory, which was suggested by Shaobing & Khush (2003), from the International Rice Research Institute has attracted much attention. This aims to overcome the impact of soil and climate on yield, as well as environment change, to keep yield at a high level. It is also significant for acclimation to CO_2 fertilization effect. So some suitable crop breeding methods can be selected to adapt to changed climate.

Improving crop cultivation would be another helpful technique for acclimation of crops to the CO_2 fertilization effect. For example, adjusting crop planting time could avoid light energy loss while adjusting the planting area and region of C_3 and C_4 crops and increasing plant density could increase the accumulation and efficient use of CO_2.

It is very difficult to understand the interactive impact of elevated atmosphere CO_2 and raising temperature on crop growth and yield formation. More CO_2 fertilization can be practiced through adjusting planted crop distributions and sowing times.

6. CLOSING COMMENTS AND DISCUSSION

The modelling work reported here has provided much useful information about the impact of climate change for the whole of China, but it would be useful to further explore the effects of CO_2 fertilization that are likely to be realized in practice. Modelling suggests that climate change without CO_2 fertilization could reduce the rice, maize and wheat yields by up to 18–37% in the next 20–80 years. However, the results were highly variable across space. Interactions of CO_2 with limiting factors, especially water and nitrogen, are increasingly well understood and capable of strongly modulating observed growth responses in crops. Results from CGE experiments have confirmed the results from previous studies: CO_2 concentrations of more than 460 ppm can cause more or less deleterious effects on wheat quality. At present, uncertainties still exist, such as the fact that the CERES model does not differentiate between the changes under long periods of high CO_2 concentration and the changes with shorter periods of elevated CO_2; also, the model has not shown impacts on crop quality. The project study has also enabled the results from the socio-economic study to be integrated with those from climate change modelling, but this kind of socio-economic scenario needs further improvement. Suggested areas for further investigation include integration of the outputs of this study with assessment of the impact of climate change on land use and water resources availability at the national and regional level.

ENDNOTES

[1]A2: globally inhomogeneous economic development, with a continuous increase in the world's population and a medium–high rise in greenhouse gas emissions.

B2: regional sustainable development, with a slower (but continuous) increase in the world's population and a medium–low rise in greenhouse gas emissions.

REFERENCES

Ainsworth, E. A. & Long, S. P. 2005 What have we learned from fifteen years of Free Air Carbon Dioxide Enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytol.* **165**, 351–372. (doi:10.1111/j.1469-8137.2004.01224.x.)

Bai, L.-P., Tong, C.-F., Lin, E. -D, Yang, L., Rao, M.-J. & Lu, Z.-G. 2004 Effects of elevated CO_2 on processing quality characteristics of two winter wheat genotypes under CGC experiment system. *Proc. World Engineers' Convention. vol. E, agricultural engineering and food security*, pp. 252–256. Beijing: China Science and Technology Press.

Blanche, Benzian *et al*. 1986 Protein concentration of grain in relation to some weather and soil factors during 17 years of English winter wheat experiments. *J. Sci. Food Agric.* **37**, 435–444.

Blumenthal, C. *et al*. 1996 Changes in wheat grain quality due to doubling the level of atmospheric CO_2. *Cereal Chem.* **73**, 762–766.

Campbell, C. A. *et al*. 1981 Effect of nitrogen, temperature, growth stage all duration of moisture stress on yield components and protein content of Manifou spring wheat. *Can. J. Plant Sci.* **61**, 435–444.

Hakala, K. 1998 Growth and yield potential of spring wheat in a simulated changed climate with increased CO_2 and higher temperature. *Eur. J. Agron.* **9**, 41–52. (doi:10.1016/S1161-0301(98)00025-2.)

Hendrey, G. R. & Kimball, B. A. 1994 The FACE program. *Agric. Forest Meteorol.* **70**, 3–14. (doi:10.1016/0168-1923(94)90044-2.)

Jones, P. G. & Thornton, P. K. 2003 The potential impacts of climate change on maize production in Africa and Latin American in 2055. *Global Environ. Change* **13**, 51–59. (doi:10.1016/S0959-3780(02)00090-0.)

Ju, H., Xiong, W., Xu, Y. & Lin, Erda 2005 The impacts of climate change on wheat yield in China. *Acta Agronomic Sinica* **31**, 24–29.

Kimball, B. A. *et al.* 2001 Wheat grain quality as affected by elevated CO_2, drought, and soil nitrogen. *Plant Pathol.* **150**, 295–303.

Matthews, R. B., Wassmann, R., Buendia, L. A. & Knox, J. W. 2000 Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia. II. Model validation and sensitivity analysis. *Nutr. Cycl. Agroecosys.* **58**, 161–177. (doi:10.1023/A:1009846703516.)

Monje, O. & Bugbee, B. 1998 Adaptation to high CO_2 concentration in an optimal environment: radiation capture, canopy quantum yield and carbon use efficiency. *Plant Cell Environ.* **21**, 315–324. (doi:10.1046/j.1365-3040.1998.00284.x.)

Randall, P. J. & Moss, H. J. 1990 Some effects of temperature regimes during grain filling on wheat quality. *Aust. J. Agric. Res.* **41**, 603–617.

Ritchie, J. T., Singh, U., Godwin, D. C. & Bowen, W. T. 1998 Cereal growth, development and yield. In *Understanding options for agricultural production* (ed. G. Y. Tsuji, G. Hoogenboom & P. K. Thornton), pp. 79–99. Dordrecht: Kluwer Academic Publishers. ISBN: 0-7923-4833-8.

Rogers, G. S., Milham, P. J., Gillings, M. & Conroy, J. P. 1996 Sink strength may be the key to growth and nitrogen responses in N-deficient wheat at elevated CO_2. *Aust. J. Plant Physiol.* **23**, 253–264.

Rosenzweig, C., Lglesias, A., Fischer, G., Liu, Y. H., Baethgen, W. & Jones, W. 1999 Wheat yield functions for analysis of land-use change in China. *Environ. Model. Assess.* **4**, 115–132. (doi:10.1023/A:1019008116251.)

Shaobing, Peng & Khush, Gurdew 2003 Four decades of breeding for varietal improvement of irrigated lowland rice in the International Rice Research Institute. *Plant Prod. Sci.* **6**, 157–164. (doi:10.1626/pps.6.157.)

Southworth, J., Randolph, J. C., Habeck, M., Doering, O. C., Pfeifer, R. A., Rao, D. G. & Johnston, J. J. 2000 Consequences of future climate change and changing climate variability on maize yields in the Midwestern United States. *Agric. Ecosyst. Environ.* **82**, 139–158. (doi:10.1016/S0167-8809(00)00223-1.)

Tang, R. & Liren, Li 1998 The research development of Rubisco active enzyme. *Life Sci.* **10**, 159–166.

Tester, R. F., Morrison, W. R., Ellis, R. H., Pigott, J. R., Batts, G. R., Wheeler, T. R., Morison, J. I. L., Hadley, P. & Ledward, D. A. 1995 Effects of elevated growth temperature and CO_2 levels on some physicochemical properties of wheat starch. *J. Cereal Sci.* **22**, 63–71. (doi:10.1016/S0733-5210(05)80008-6.)

Williams, M., Shewry, P. R., Lawlor, D. W. & Harwood, J. L. 1995 The effects of elevated temperature and atmospheric CO_2 concentration on the quality of grain lipids in wheat (*Triticum aestivum* L.) grown at two levels of nitrogen application. *Plant Cell Environ.* **18**, 999–1009.

Wrigley *et al.* 1994 Temperature variation during grain filling and changes in wheat-grain quality. *Aust. J. Plant Physiol.* **21**, 875–885.

Wu, Y., Sakamoto, C. M. & Botner, B. M. 1989 On the application of the CERES-maize model to the North China Plain. *Agric. Forest Meteorol.* **49**, 9–22. (doi:10.1016/0168-1923(89)90058-0.)

Xiong, W., Xu, Y. L., Lin, E. D. & Lu, Z. G. 2005 Regional simulation of maize yield under IPCC SRES A2 and B2 scenarios. *Chin. J. Agrometeorol.* **26**, 11–16.

Yinlong, Xu & Richard, Jones 2004 Validating PRECIS with ECMWF reanalysis data over China. *Chin. J. Agrometeorol.* **25**, 5–9.