IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 113, No. 1–2, January–June 2009, pp. 79–88

Testing different CO_2 response algorithms against a face crop rotation experiment and application for climate change impact assessment at different sites in Germany

K.C. Kersebaum[1,*], **C. Nendel**[1], **W. Mirschel**[1], **R. Manderscheid**[2],
H.-J. Weigel[2], and **K. -O. Wenkel**[1]

[1]*Leibniz-Centre of Agricultural Landscape Research, Institute of Landscape Systems Analysis,*
Eberswalder Str. 84, D-15374 Müncheberg, Germany

[2]*Johann Heinrich von Thünen-Institute (Federal Research Institute for Rural Areas,*
Forestry and Fisheries), Institute of Biodiversity,
38116 Bundesallee 50, D-Braunschweig, Germany

(Manuscript received in final form December 5, 2008)

Abstract—In regional studies the effect of elevated CO_2 level on crop biomass and yield had not been considered in most cases, although several approaches were described in literature. Different algorithms describing CO_2 response on crop growth and crop water use efficiency have been integrated in the soil-crop model HERMES. The approaches are different in complexity and parameter requirement. Their suitability to explain crop growth responses and soil water dynamics observed in a six-year agricultural crop rotation (winter barley, sugar beet, winter wheat) under elevated atmospheric CO_2 level in a FACE experiment was tested. All algorithms were able to describe an observed increase in above-ground dry matter for all crops in the rotation. Increasing water use efficiency with rising CO_2 was also reflected. A combination of a semi-empirical Michaelis-Menten approach describing a direct impact of CO_2 on photosynthesis and a Penman–Monteith approach with a simple stomata conduction model for evapotranspiration yielded the best simulation result expressed by model performance indicators. Scenario simulations with and without CO_2 effect were performed for different sites in Germany for the present situation and the SRES-A1B scenario using statistically downscaled climate change scenarios from the WETTREG model. Results show that without consideration of the CO_2 effect mostly negative impacts on crop yields were simulated. Considering the CO_2 effect compensated the negative trend in most cases and turned yield effects to a positive impact.

Key-words: climate change, CO_2 effect, FACE experiment, crop yield, water use

---

[*] Corresponding author; E-mail: ckersebaum@zalf.de

1. *Introduction*

Climate change impact on food production is one of the key concerns of policy and research. Impact assessment usually requires spatial and temporal resolutions smaller than provided by the global climate models (GCM), since crop growth is temporary very sensitive, e.g., to radiation, temperature, soil moisture. Regional climate models *(Jacob et al.*, 2007*)* downscale the GCM results to a meso-climate level that can be used to assess climate effects on regional agriculture.

Climate change is expected to affect crop growth mainly by increasing temperatures, shifting distribution of precipitation, changing amount of precipitation, and rising atmospheric carbon dioxide concentration.

Describing the interactions of crop growth, soil processes, and weather variables in a simulation model is current state-of-art methodology to interpret downscaled GCM outputs for yield predictions. The effect of CO_2 on crop growth was recently implemented in agro-ecosystem models. Mainly two processes are affected: (i) in C3 plants, an increasing CO_2 would directly increase the photosynthesis rate (*Gaastra*, 1959) and (ii) a higher CO_2 would also lead to a decrease in stomatal conductance and thus to a higher water use efficiency *(Manderscheid* and *Weigel*, 2007*)*.

The impact of CO_2 on photosynthesis has been included in simulation models in different ways (*Tubiello* and *Ewert*, 2002). More simple approaches use an empirical relation between CO_2 and a crop specific radiation use efficiency (RUE) factor (e.g., *Bindi et al.*, 1996), others employ a CO_2 dependency of the photosynthesis-light response curve (e.g., *Porter*, 1993; *Goudriaan* and *van Laar*, 1994). Only few leaf-level biochemical algorithms are used, which require an extensive parameterization restricting their application to biochemical process research.

In this study, we integrated a number of selected algorithms into the soil-crop model HERMES to test their suitability to describe CO_2 impact on crop growth against data of a Free Air Carbon Enrichment (FACE) experiment (*Weigel* and *Dämmgen*, 2000). The best algorithm was then used in combination with downscaled climate change scenarios for simulations at different sites in Germany under the SRES-A1B scenario. Site selection considered locations with different climatic situations to demonstrate the combined climate change and CO_2 effect on crop yields of winter wheat.

2. *Material and methods*

2.1. *The FACE experiment*

At the experimental station of the von Thünen-Institute (vTI) at Braunschweig, Germany (52°18’N; 10°26’E), a three-year crop rotation (winter barley, sugar beet, winter wheat) was grown over two cycles at normal (~374 ppm) and elevated (~550 ppm) CO_2 levels. The crops were grown under optimum nutritional and moisture conditions. A FACE system, consisting of six rings with 20 m diameter was set up. Treatments included two rings equipped with blowers and enriched with CO_2, two rings operated with blowers and ambient air only and two rings without blowers. Subplots within the rings with 50% (N50) of the adequate nitrogen supply (N100) were established to study interactions between C and N. A detailed description is given by *Weigel* and *Dämmgen* (2000).

The soil is a loamy sand with 1.4% organic carbon (SOC) in the top soil. Soil texture allows a volumetric plant available water content (PAWC) of about 18% in the plough layer, which decreases slightly with increasing profile depth. Rooting depth is about 60 cm. During the experiment, soil moisture contents were determined gravimetrically. Fresh and dry weights of individual plant organs (culm, leaves, and ears, or tubers, respectively) were measured at intermediate harvests. At the final harvest, cereal grain yield was additionally quantified. Daily weather data were recorded at a nearby weather station.

2.2. The model framework

We tested the different CO_2 response algorithms within the HERMES model, which was designed to simulate crop growth, water and nitrogen uptake, and the nitrogen dynamics in the soil for applied purposes. This implies simple and robust model approaches, which are able to operate under restricted data availability. A more detailed description of the model is provided by *Kersebaum* (2007). Therefore, the characteristics of the model are described only briefly.

A capacity approach was used to describe soil water dynamics. The reference evapotranspiration was calculated using the Penman-Monteith method according to *Allen et al.* (1998). Crop specific potential evapotranspiration is calculated using crop specific factors (*kc*) during the growing season, which were linked to the developmental stages of the crops, and bare soil factors between harvest and crop emergence. Nitrogen mineralization and denitrification are simulated depending on temperature and soil moisture and nitrate content respectively.

Crop growth follows a generic approach, which is based on the SUCROS model. Daily net dry matter production by photosynthesis and respiration is driven by global radiation and temperature. Assimilates are partitioned depending on crop development stage, which is calculated from a thermal sum (degree-days) and modified, if applicable, by day length and vernalization. Root dry matter is distributed exponentially over depth with the rooting depth increasing with the thermal sum. Water and nitrogen uptake is calculated from potential evaporation and crop N status, depending on the simulated root distribution, and water and N availability in different soil layers. Crop growth is limited by water and N stress. Water and nitrogen stress accelerates crop ontogenesis for specific development stages. Crop yield was estimated at harvest from the weight of the storage organ.

The HERMES model was calibrated to the data of the control treatment of the FACE experiment, using the output variables soil moisture (sum of 0 – 60 cm soil depth), above-ground crop dry matter, and yield. Willmott's index of agreement (IoA) was used as a goodness-of-fit criterion (*Willmott*, 1981).

2.3. The CO_2 response algorithms

In order to equip the model with a suitable approach to describe CO_2 impact on crop growth, three algorithms were selected. The mechanistic and partly empirical character of the HERMES model determines the range of complexity the response algorithms have to match. The following approaches were selected:

(I) The Mitchell approach (*Mitchell et al*., 1995) used a set of algorithms based on the ideas of *Farquhar* and *von Caemmerer* (1982) and *Long* (1991), calculating the maximum photosynthesis rate

$$A_{\max} = \frac{(C_i - \Gamma^*) \cdot V_{c\max}}{C_i + K_c \cdot \left(1 + \frac{O_i}{K_o}\right)}, \tag{1}$$

where C_i and O_i are the intercellular CO_2 and O_2 concentrations, respectively, Γ^* is the CO_2 compensation point of photosynthesis in absence of dark respiration, $V_{c\max}$ is the maximum Rubisco saturated rate of carboxylation, and K_c and K_o are Michaelis-Menten constants for CO_2 and O_2. The calculation of the latter four parameters is carried out according to *Long* (1991). Some modifications were applied to simplify the algorithms for suboptimal light conditions and light use efficiency.

(II) The Nonhebel approach is a much simpler approach extracted from the SUCROS87 model (*Nonhebel*, 1996). Here, *RUE* is directly affected by CO_2 as

$$RUE_{\mathrm{CO}_2} = \left(\frac{C_a - \Gamma}{C_a + 2\Gamma}\right) \cdot E_0, \tag{2}$$

where C_a denotes CO_2 and E_0 the quantum use efficiency. Additionally, the maximum photosynthesis rate is influenced by CO_2 using

$$A_{\max(\mathrm{CO}_2)} = \frac{C_a - \Gamma}{350 - \Gamma} \cdot A_{\max(350)}. \tag{3}$$

(III) The Hoffmann approach (*Hoffmann,* 1995) was similar to *Nonhebel* (1996) based on his own work with sugar beet and tree species, and on data previously obtained by *Gaastra* (1959). He adjusted $A_{\max}$ by the factor

$$K_{CO_2} = \frac{\dfrac{C_a - \Gamma *}{k_1 + C_a - \Gamma *}}{\dfrac{C_{a0} - \Gamma *}{k_1 + C_{a0} - \Gamma *}}, \tag{4}$$

where C_{a0} denotes the ambient CO_2 and C_a the elevated CO_2. Furthermore, $k_1 = 220 + 0.158 \cdot I_g$ and $\Gamma * = 80 - 0.0036 \cdot I_g$, with I_g being the global radiation.

These three approaches were combined with a mixed Allen/Yu approach describing the CO_2 impact on crop transpiration. Evapotranspiration was calculated using the Penman and Monteith formula according to *Allen et al.* (1998) using the stomata resistance calculated as suggested by *Yu et al.* (2001) as

$$r_s = \frac{C_s\left(1 + \dfrac{D}{D_0}\right)}{a \cdot A_g}, \tag{5}$$

where a is a constant, A_g denotes the gross photosynthesis rate, D/D_0 describes the air water vapor deficit, and C_s is the ambient CO_2 concentration at leaf level, which was set equal to C_a in this case. D_0 and a were used for parameter calibration.

2.4. Model behavior under climate change scenarios

To demonstrate the combined effect of climate change and elevated CO_2 on wheat production, we selected 4 weather stations across Germany to cover the different climatic and soil conditions. The climate change scenarios were based on the SRES-A1B scenario and the output of the global climate model (GCM) ECHAM5/MPI-OMT63L31. The GCM output was downscaled using a statistical generation of classified weather situation sequences based on a data analysis of long term historical data of single meteorological stations by the WETTREG model (*Enke et al.* 2005). We selected 3 realizations (normal, wet, dry) for wetness for the period from 1961 to 2050. We used the time slice 1970–1989 as reference period and the time slice 2031–2050 for the projected future.

For each site, a typical soil profile was used. The characterization of the sites including the soil class, elevation, and the climatic conditions of the reference, as well as projected period are given in *Table 1.*

Table 1. Site characteristics and climatic changes estimated for the A1B scenario using the WETTREG model (*Enke et al.,* 2005) for selected locations across Germany. Numbers in parenthesis are changes in %

Station	Period	Hannover	Müncheberg	Hof	Weihenstephan
Latitude		52°28’N	52°52’N	50°19’N	48°24’N
Longitude		9°42’E	14°07’E	11°53’E	11°42’E
Altitude (a.s.l.)		55 m	62 m	567 m	470 m
Annual mean temperature (°C)	1970–1989	9.3	8.8	6.8	7.8
		(+8.8)	(+7.3)	(+10.8)	(+10.9)
	2031–2050	10.1	9.4	7.5	8.6
Annual precipitation (mm)	1970–1989	628	533	739	726
		(–5.1)	(–5.1)	(–3.5)	(–6.5)
	2031–2050	596	506	713	679
Precipitation winter (DJF) (mm)	1970–1989	156	131	182	118
		(+1.4)	(–7.6)	(+7.3)	(+12.9)
	2031–2050	158	121	195	133
Precipitation spring (MAM) (mm)	1970–1989	195	166	221	202
		(–3.4)	(–0.9)	(+3.6)	(+5.6)
	2031–2050	188	165	229	213
Precipitation summer (JJA) (mm)	1970–1989	181	165	230	272
		(–7.9)	(–3.0)	(–4.4)	(–5.8)
	2031–2050	167	160	220	229
Precipitation autumn (SON) (mm)	1970–1989	146	113	166	174
		(–9.1)	(–13.5)	(–8.8)	(–6.2)
	2031–2050	133	98	135	146
Soil		sandy loam	sand	sandy loam	silty loam

DJF = December, January, February; MAM = March, April, May; JJA = June, July, August; SON = September, October, November

3. Results and discussion

The Braunschweig FACE experiment showed two important results: increased CO_2 (i) enhanced crop growth for all investigated species and (ii) decreased evapotranspiration rate of the canopies resulting in higher soil moisture content (*Weigel et al.*, 2006). All algorithms tested within the HERMES model framework were able to describe the observed crop growth and soil moisture dynamics sufficiently under ambient and elevated CO_2 levels (*Table 2*). Since the Nonhebel and Mitchell approaches also affected the way of calculating photosynthesis under ambient CO_2 conditions, the simulation of the control treatment process yielded different results for all selected approaches. IoA yielded values of between 0.93 and 0.99 for the calibrated simulation of above ground dry matter (including tubers for sugar beet) and yield at sufficient N supply. *Fig. 1* shows the results using the combined Hoffmann/Yu/Allen approach. However, under limited N supply and under elevated CO_2 level the simulation performance was similar. For these variables, the Nonhebel approach performed slightly less satisfyingly than the others (*Table 2*). Such a performance is often found for single season crop growth simulations. However, for a six years rotation with three different crops this result is satisfying.

Table 2. Index of agreement IoA (*Willmott*, 1981) as a goodness-of-fit criterion for the simulation of the crop rotation experiment, using different approaches for the description of CO_2 impact on crop growth

CO_2 level	**ppm**	**Ambient**		**550**		**Ambient**		**550**	
N level	**%**	**100**	**50**	**100**	**50**	**100**	**50**	**100**	**50**
		Hoffmann				**Hoffmann + Allen/Yu**			
Above ground dry matter		0.99	0.98	0.99	0.99	0.99	0.99	0.99	0.99
Yield		0.98	0.96	0.97	0.94	0.98	0.98	0.97	0.97
Leaf area index		0.61	0.55	0.57	0.54	0.57	0.55	0.61	0.56
Soil moisture (0-60 cm)		0.77		0.76		0.79		0.82	
Mean IoA		**0.83**				**0.84**			
		Nonhebel				**Nonhebel + Allen/Yu**			
Above ground dry matter		0.95	0.94	0.98	0.96	0.95	0.99	0.98	0.98
Yield		0.93	0.94	0.95	0.93	0.93	0.94	0.95	0.92
Leaf area index		0.66	0.58	0.55	0.52	0.66	0.59	0.55	0.54
Soil moisture (0-60 cm)		0.77		0.77		0.85		0.85	
Mean IoA		**0.82**				**0.83**			
		Mitchell				**Mitchell + Allen/Yu**			
Above ground dry matter		0.99	0.95	0.99	0.99	0.99	0.95	0.99	0.99
Yield		0.98	0.98	0.97	0.96	0.97	0.97	0.97	0.96
Leaf area index		0.52	0.49	0.51	0.49	0.52	0.50	0.52	0.50
Soil moisture (0-60 cm)		0.78		0.78		0.80		0.83	
Mean IoA		**0.81**				**0.82**			

The simulation of soil moisture was compared to aggregated data (0 – 60 cm soil depth) and showed an IoA of 0.82 for calibrated conditions and 0.79 – 0.80 under elevated CO_2. When the CO_2 effect on transpiration was taken into account additionally, the overall performance improved slightly (*Table 2*) due to the better performance of the soil moisture simulation for all approaches (*Fig. 1c*). On the basis on above ground dry matter, yield, and soil moisture simulation, the Hoffmann approach in combination with the Allen/Yu approach performed best. However, the differences were marginal. *Fig. 1c* shows the measured and simulated soil water content under winter wheat in 2005 for ambient and elevated CO_2 level. The difference between the two CO_2 treatments expressed as the sum over six years corresponded well with the observed mean difference of approximately 20 mm water per year.

Application of the model with and without the combined Hoffmann/Yu/Allen approach for 4 selected sites in Germany shows different responses of crop yield to the projected climate change (*Fig. 2*). Without consideration of the CO_2 effect, only the site at Hof shows a beneficial trend for the wheat yield, because this elevated site is presently temperature limited. Therefore, crops would benefit from warming since precipitation is still sufficient. At the other sites, climate change without CO_2 would have a negative impact on crop yield mainly due to decreasing summer precipitation. Introducing the CO_2 effect in the model simulations in most cases leveled out the negative trend. Only at Müncheberg, the combination of poor sandy soil and very low precipitation could not be compensated completely by the CO_2 effect. Similar results for sites in Austria were published by *Alexandrov et al.* (2002). Separating the indirect from the direct CO_2 effect by switching off only the indirect effect shows, e.g., for the site at Hannover, that the indirect effect through the modified transpiration accounts for 2/3 of the total CO_2 effect simulated by the combined approach. The sites were selected exemplarily and neither represent wheat production areas in Germany nor give a representation of the whole specific regions, since they are only examples of one selected typical soil of the region.

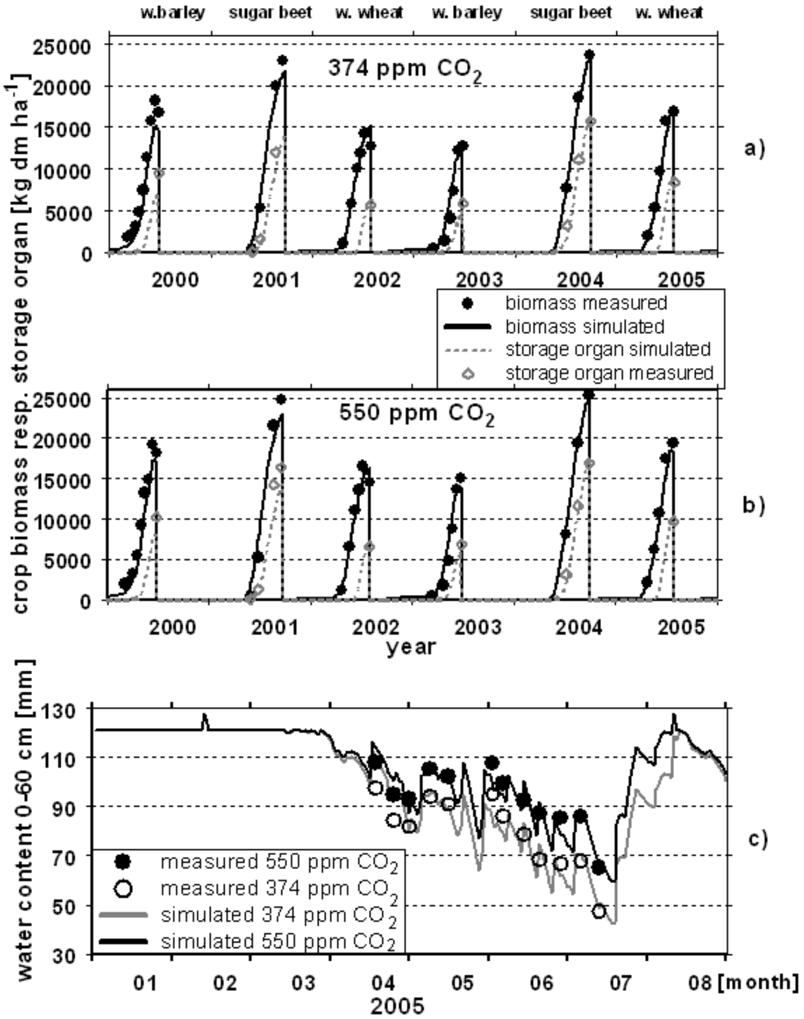

Fig. 1. Measured and simulated crop biomass (excluding root biomass) and storage organ mass of the Braunschweig FACE experiment for (a) 374 ppm CO_2 concentration, (b) 550 ppm CO_2 concentration, and (c) soil water contents (0 – 60cm) under winter wheat in 2005 in the 374 and 550 ppm plots (100% N treatment, simulation using the combined Hoffmann/Yu/Allen approach).

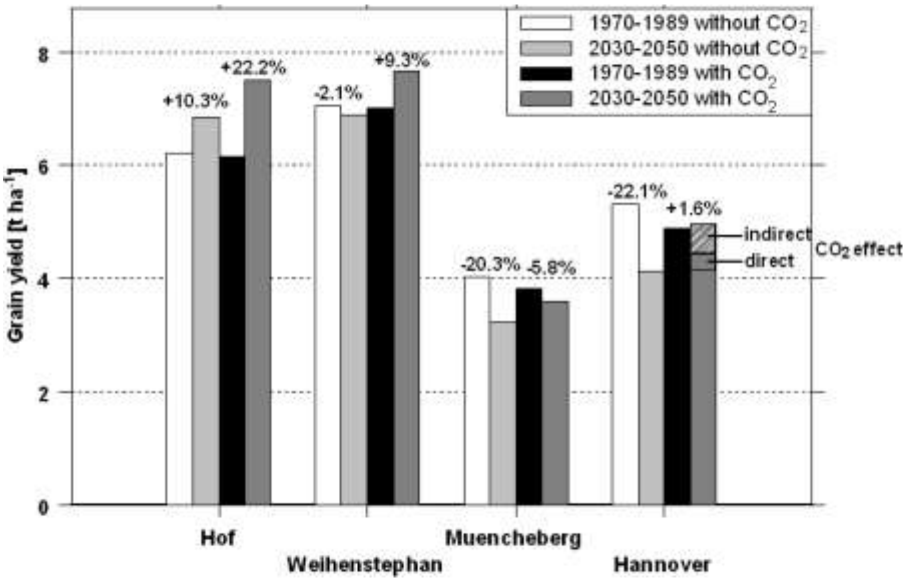

Fig. 2. Simulated impact of climate change scenario SRES-A1B on grain yield of winter wheat on selected sites across Germany with and without consideration of the CO_2 effect (combined Hoffmann/Yu/Allen approach).

4. Conclusions

For the simulation of expected climate change effects on regional agriculture an algorithm was found to successfully describe combined effects CO_2 levels, temperature, and moisture regime in a typical agricultural crop rotation in Germany. Application for 4 selected sites across Germany revealed that the simulated negative effect due to decreasing summer precipitation can be compensated in most cases if the combined CO_2 effect is considered. While sites at high elevation will benefit from global warming, the combination of poor sites and summer drought conditions resulted in yield reduction, which cannot be leveled out by the CO_2 effect.

Acknowledgement—The authors gratefully acknowledge funding from the German Federal Ministry of Education and Research (BMBF) within the “klimazwei” research program and from COST 734.

References

Alexandrov, V., Eitzinger, J., Cajic, V., Oberforster, M., 2002: Potential impact of climate change on selected agricultural crops in north-eastern Austria. *Glob. Change Biol. 8*, 372-389.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998: *Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper 56, Roma.

Bindi, M., Fibbi, L., Gozzini, B., Orlandini, S., Miglietta, F., 1996: Modelling the impact of future climate scenarios on yield and yield variability of grapevine. *Climate Res. 7*, 213-224.

Enke, W., Schneider, F., Deutschländer, Th., 2005: A novel scheme to derive optimized circulation pattern classifications for downscaling and forecast purposes. *Theor. Appl. Climatol. 82*, 51–63.

Farquhar, G.D., von Caemmerer, S., 1982: Modelling of photosynthetic response to environmental conditions. In *Encyclopedia of Plant Physiology* (eds.: *O.L. Lange*). *New series. Vol. 12B*. Physiological plant ecology. II. Water relations and carbon assimilation, 549-587.

Gaastra, P., 1959: Photosynthesis of crop plants as influenced by light, carbon dioxide, temperature, and stomatal diffusion resistance. *Mededel. Landbouwhogesch. Wageningen 59* (13), 1-68.

Goudriaan, J., van Laar, H.H., 1994: *Modelling Potential Crop Growth Processes.* Kluwer Academic Publishers, Dordrecht, The Netherlands.

Hoffmann, F., 1995: Fagus, a model for growth and development of beech. *Ecol. Model. 83*, 327-348.

Jacob, D., Barring, L., Christensen, O.B., Christensen, J.H., de Castro, M., Deque, M., Giorgi, F., Hagemann, S., Lenderink, G., Rockel, B., Sanchez, E., Schar, C., Seneviratne, S.I., Somot, S., van Ulden, A., van den Hurk, B., 2007: An inter-comparison of regional climate models for Europe: model performance in present-day climate. *Climate Change 81*, 31-52.

Kersebaum, K.C., 2007: Modelling nitrogen dynamics in soil-crop systems with HERMES. *Nutr. Cycl. Agroecosys. 77* (1), 39-52.

Long, S.P., 1991: Modification of the response of photosynthetic productivity to rising temperature by atmospheric CO2 concentrations – Has its importance been underestimated. *Plant Cell Environ. 14*, 729-739.

Manderscheid, R., Weigel, H.J., 2007: Drought stress effects on wheat are mitigated by atmospheric CO2 enrichment. *Agron. Sust. Dev. 27*(2), 79-87.

Mitchell, R.A.C., Lawlor, D.W., Mitchell, V.J., Gibbard, C.L., White, E.M., Porter, J.R., 1995: Effects of elevated CO_2 concentration and increased temperature on winter-wheat – Test of ARCWHEAT1 simulation model. *Plant Cell Environ. 18*, 736-748.

Nonhebel, S., 1996: Effects of temperature rise and increase in CO_2 concentration on simulated wheat yields in Europe. *Climate Change 34*, 73-90.

Porter, J., 1993: AFRCWHEAT2: a model of the growth and development of wheat incorporating responses to water and nitrogen. *Eur. J. Agron. 2* (2), 69-82.

Tubiello, F.N., Ewert, F., 2002: Simulating the effects of elevated CO_2 on crops: approaches and applications for climate change. *Eur. J. Agron. 18* (1-2), 57-74.

Weigel, H.J., Dämmgen, U., 2000: The Braunschweig Carbon Projekt: atmospheric flux monitoring and free air carbon dioxide enrichment (FACE). *J. Appl. Bot. 74*, 55-60.

Weigel, H.J., Manderscheid, R., Burkart, S., Pacholski, A., Waloszczyk, CK., Frühauf, O., Heinemeyer, O., 2006: Responses of an arable crop rotation system to elevated CO_2. In *Managed Ecosystems and CO_2 Case Studies, Processes, and Perspectives* (eds.: *J. Nösberger et al.*). *Ecol. Stud. 187*, 121-137.

Willmott, C.J., 1981: On the validation of models. *Phys. Geogr. 2*, 184-194.

Yu, Q., Goudriaan, J., Wang, T.D., 2001: Modelling diurnal courses of photosynthesis and transpiration of leaves on the basis of stomatal and non-stomatal responses, including photoinhibition. *Photosynthetica 39* (1), 43-51.