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A simulation study of the effect of soil water balance and water stress on winter wheat production under different climate change scenarios

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Abstract

The effect of water balance parameters and water stress on winter wheat production in a specified environment and under different climate change scenarios using the CERES (Crop Environment REsource Synthesis)-Wheat model is presented. For our study, two test sites with similar climatic conditions and soil water storage potential but with (site B) and without (site A) groundwater impact in a semi-arid agricultural area in central Europe (southeast of the Czech Republic and northeast of Austria) were chosen. For the current climatic conditions, the impact of groundwater to the rooting zone at site B caused a rain-fed yield level close to the potential yield (6772 kg ha^{-1}), whereas at site A the rain-fed yield reached only 49% of the potential yield level of 6552 kg ha^{-1}. Although potential yields also increased at both sites in the range of 17–24%, rain-fed yields came closer to potential yields under all applied climate scenarios (47–61% of potential yield at site A and 55–75% of potential yield at site B, depending on the climate scenario). The most yield-sensitive simulated growing stage at both sites was found during the grain filling period. Despite higher yield levels, crop transpiration and water stress dropped significantly compared with current conditions through the simulated increase in water use efficiency and reduced total potential evapotranspiration (caused by shortened growing period) under the applied 2× CO_2 climate scenarios. Up to 42% (194 mm) of evapotranspiration was provided by groundwater at site B under present climate and only 126 mm was used for the worst case scenario ECHAM. For both locations, however, the availability and management of soil water reserves will remain an important influence on the attainment of the

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potential yield level of winter wheat under climate change scenarios, especially when extreme events such as droughts occur more frequently and annual soil and groundwater recharge decrease.

Keywords: Water stress effect; Soil water balance; DSSAT crop model; Climate change scenarios; Winter wheat; Groundwater uptake

1. Introduction

Numerous studies have been carried out on the impact of climate variability and change on crop production as a function of water balance (Alexandrov et al., 2002; Bacsi and Hunkár, 1994; Eitzinger et al., 2000; Mearns et al., 1992; Semenov and Porter, 1995; Xie et al., 2001). Climate change impact studies on crop production are affected by uncertainties, however, which can be caused by several factors (Carter et al., 1999). One of the most important factors is the uncertainty in global climate model scenarios, particularly with regard to climate variability. It is therefore advisable to use several state-of-the-art climate scenarios (IPCC–TGCIA, 1999) in impact studies. Soil characteristics such as soil water storage capacity (Eitzinger et al., 2001) and long-term changes in soil fertility (Sirotenko et al., 1997) can significantly alter the impact of climate change on crop production. Other sources of uncertainty are the wide range of crop sensitivities to a change in climatic parameters and enhanced atmospheric CO_2 levels as well as other factors and their short- and long-term interactions (Amthor, 2001). Impact models such as crop models, which deal with these complex bio-physical interactions by using different methods are another source of uncertainty and have to be tested in advance to verify their applicability for the relevant application and location.

A change in climate can accelerate the hydrological cycle, which is affected by a change in precipitation, evapotranspiration, the magnitude and timing of run-off, and by any change in the intensity and frequency of floods and droughts (Watson et al., 1996). The physiological responses of increasing atmospheric CO_2 concentration known as CO_2 fertilization effect can produce larger and more vigorous plants, higher total dry matter yields and, often, greater quantities of harvestable product (Acock and Acock, 1993). Water stress and drought, however, are the most important limiting factors in crop productivity in semi-arid agricultural areas (Wilhite, 1993). Under drought conditions transpiration decreases significantly. When transpiration is reduced, heat loss from leaves slows down and leaf temperature increases. Water stress on plants is increased by low humidity, high temperatures, strong winds and high light intensity. Increased CO_2 concentrations affect plant growth directly through stimulation of photosynthesis and reduction of transpiration and, as a result, can improve water use efficiency (Rosenberg et al., 1990) and hence soil water availability. Another factor is the effect of soil nitrogen on water use efficiency of wheat under elevated CO_2, as reported by Hunsaker et al. (2000) and Jamieson et al. (2000). Simmelsgaard (1976) and Gottschalck et al. (2001) reported that decreases in transpiration were always significantly less than stomatal resistance increases, and transpiration may not decrease significantly under 2× CO_2 climates. From another point of view, similar studies (Curtis, 1996; Gifford, 1979; Kimball et al., 1995; Manunta et al., 2002) have shown that plant growth increases more with CO_2 under water limited conditions and that canopy mass and energy exchange depends on soil water availability. A significant correlation between the amount of CO_2 in the atmosphere and water stress with respect to the final wheat grain yield has been found, with elevated CO_2 causing a 10% increase in well-watered plots and a 20% increase in water-stressed plots (Kartschall et al., 1995). Water stress during certain growth stages may have a greater impact on grain yield than similar stress at other growth stages, and crop cultivars differ in their sensitivity to drought. The sensitivity of wheat under different levels of water stress has been investigated. For example, Singh et al. (1990) observed significant differences in water potential among wheat genotypes under water stress. Significant differences in water stress sensitivity have also been confirmed for wheat cultivars in Austria (Kastelliz and Ruckenbauer, 2000) and the United Kingdom (Foulkes et al., 2002) and other studies (Morgan and Condon, 1986; Blumm et al., 1999). Although uncertainties remain on account of lack of knowledge crop simulation models can reasonably estimate and quantify the impact of specific water stress conditions on crop productivity provided that they are well calibrated and validated in field experiments (Grossman-Clarke et al., 2001; Hanks, 1974; Howel and Hiler, 1975; Wolf et al., 1996). They permit variation of environmental inputs such as the water regime and temperature and simulate the crop response through several calculated growth parameters such as crop yield. Because of the complexity of the problem, research continues and improvements are constantly being made to models, e.g. for drought impact assessments. For example, Jamieson et al. (1998) compared the models AFRCWHEAT2, CERES (Crop Environment REsource Synthesis)-Wheat, Sirius, SUCROS2 and SWHEAT with measurements from wheat grown under drought. CERES-Wheat, which is also used in our study, has proved to be useful for evaluating drought effects on crops at specific locations (the uncertainty of yield prediction was found to be below 10%). CERES-Wheat is well documented and has been successfully tested in numerous studies (Ritchie et al., 1998; Šťastná et al., 2002), particularly for climate change effects on growth (Tubiello et al., 1999; Zalud et al., 1999).

Agricultural land with groundwater impact plays an important role in central and eastern European regions (Hartig et al., 1997). Climate change may also have important consequences for agricultural land use and sustainable use of agricultural soil water resources in this continental climate region (Downing et al., 2000). As crop-soil water balance under a changed climate is regarded as a significant source of uncertainty our study was carried out to provide new results for the specified environment. To highlight the role of groundwater and soil water storage at specified sites in this region for an important crop such as winter wheat, we compared two locations with similar climatic conditions but significantly different soil water balance characteristics (including the effect of groundwater on soil water balance) using the CERES-Wheat growth model modified for four different climatic scenarios. The simulated critical water balance parameters and water stress situations on crop yield for two selected winter wheat cultivars under the present climatic conditions (1× CO_2 weather) and the changes obtained under climate scenarios (2× CO_2 weather) are analyzed. Results are presented in relation to available soil water and phenological growth stages during the winter wheat growing period.

2. Material and methods

2.1. Locations

2.1.1. Field and crop description

The first experimental field in Gross-Enzersdorf (Marchfeld) is located in the northeastern part of Austria (latitude 48°12′N, longitude 16°34′E, altitude 153 m). It is an area with low groundwater and precipitation. The mean annual precipitation is 577 mm and the mean annual temperature is 9.9 °C. This site is referred to as site A.

The second experimental field in Žabčice (latitude 49°01′N, longitude 16°037′E, altitude 179 m) is located within the same climatic region in the southeast of the Czech Republic. The long-term mean annual precipitation is 480 mm, the mean annual temperature is 9.3 °C. This site is referred to as site B.

Winter wheat (*Triticum aestivum* L.)—cultivar ‘‘Perlo’’ at site A and cultivar ‘‘Hana’’ at site B—was grown to obtain experimental data for model validation. Both varieties are often used in the selected regions and adapted to the same climatic conditions. The crops at both experimental locations were managed with optimum fertilization (80 kg ha^{-1} of nitrogen at site A and 90 kg ha^{-1} at site B) and plant protection. No major diseases or damage occurred during the growing period. Sowing density was 300 kernels/m^2 at site A and 350 kernels/m^2 at site B. Sowing dates for the climate change impact simulations were set on 10 October for site A and 2 October for site B according to the mean in current practice. Primary soil cultivation at both experimental sites was the same, i.e. ploughing at 30 cm depth in autumn. The course of precipitation and air temperatures (used as model inputs) were very similar at both locations.

2.1.2. Soil description

The soil at site A (in Austria) according to the FAO Soil Classification (FAO–UNESCO, 1988) is calcic chernozem. It is described as chernozem on fine calcareous sediments over gravel and sand. The soil type of the mineral soil surface layer at this site is loamy sand and sandy silt loam with a very deep groundwater table (below 6 m depth), which is typical of the Marchfeld region. There is no groundwater impact on the rooting zone of winter wheat, but there are large spatial variations in soil water storage capacity. The arable soil has a deep layer (about 1 m) of the mineral soil surface and is well cultivated. Water saturation is 36% by volume, field capacity 27% by volume and wilting point 14% by volume in the top soil layers (Table 1).

The soil at site B (in the Czech Republic) is a calcaric fluvisol (FAO–UNESCO, 1988). Water saturation is at 40% by volume, field capacity 38% by volume, and wilting point 21% by volume (Table 1). The soil of the mineral soil surface is clay loam and has a thickness of more than 1 m with a high groundwater level (annual mean at about 1.7 m depth) resulting in continuous impact of groundwater on the rooting zone of crops. The soil depth considered for simulation of soil water balance was 1.5 m at both locations with similar soil water storage capacity for both soils (240–260 mm for the rooting depth of 1.5 m).

Table 1
The main soil characteristics of the soil profile used by CERES-Wheat model for the experimental sites

Soil depth (cm)	Wilting point (vol.%)	Field capacity (vol.%)	Soil saturation (vol.%)	Clay (%)	Sand (%)	Silt (%)
Site A—loamy sand						
25	14	27	36	16	47	37
75	15	28	37	20	41	39
150	9	28	32	10	60	30
Site B—clay loam						
25	21	39	40	32	21	47
75	21	38	40	34	27	39
150	21	39	40	29	37	34

2.2. *CERES-Wheat model*

2.2.1. *Overview*

The CERES-Wheat model (Ritchie and Otter, 1985) was designed to simulate the effects of cultivar, planting density, weather, soil water and nitrogen on crop growth, development and yield. The primary purpose was to predict potential alternative management strategies and tactics that affect yield and intermediate steps in the yield formation process. The model, however, was also adapted for climate change impact studies in view of rising atmospheric CO_2 levels in the atmosphere for photosynthesis and evapotranspiration (Rosenzweig and Iglesias, 1998). Ratios were calculated between measured daily photosynthesis and evapotranspiration rates for a canopy exposed to a range of high CO_2 values. In the crop model, the photosynthesis ratios were applied to the maximum amount of daily carbohydrate production. To account for the effect of elevated carbon dioxide on stomatal closure and increased leaf area index and hence on potential transpiration, the evapotranspiration formulation was changed to include the ratio of transpiration under elevated CO_2 conditions to that under ambient conditions. Various types of input data are required to prepare and run the model simulation. The minimum weather data set (comprising daily maximum and minimum temperatures, global radiation, and precipitation) and management data were obtained from the field experiments. Crop parameters were derived partly from literature sources and partly from experimental data from test sites. Genetic coefficients used in CERES-Wheat describe the specific growth and development of the crop cultivar. They were adjusted during model calibration using an optimizing procedure (Alexandrov et al., 2002). CERES-Wheat uses nine different development stages which can be related to the Zadoks et al. (1974) stages (Table 2). Soil input data were derived from soil pits at the experimental sites (Table 1).

2.2.2. *Calculation of water balance and water stress effects in the CERES-Wheat model*

The simulation of soil water balance depends on the ability of water from rainfall or irrigation to enter soil through the surface and be stored in the soil reserve. Other elements in the soil water balance include drainage of water out of the root zone by the forces of gravity, run-off and interception that does not enter the surface, water lost from the surface

Table 2
Growth stages of wheat as defined by Zadoks classification in CERES-Wheat model

CERES-Wheat	Zadoks	Event
7		Fallow or pre-sowing
8		Sowing to germination
9		Germination to emergence
1	10–29	Emergence to terminal spikelet initiation
2	30–49	Terminal spikelet to end of leaf growth and beginning of ear growth
3	50–59	End of leaf growth and beginning of ear growth to end of pre-anthesis ear growth
4	60–69	End of pre-anthesis ear growth to beginning of grain filling
5	70–90	Grain filling
6		End of grain filling to harvest

by evaporation, and water absorbed by plant roots and used via transpiration (Ritchie, 1998). The soil water content of vertical soil layers is calculated by distributing total infiltrated water among various soil layers using a simple cascading principle. The slowest draining layer controls drainage of the water from the soil profile. The calculations require knowledge of soil water content (volumetric fraction) for the lower limit of plant availability (wilting point), for the upper limit, where capillary forces are greater than gravity forces (field capacity), and for field saturation. When the soil dries and the potential root water uptake decreases to a value lower than the potential transpiration rate, the actual transpiration rate is reduced because of partial closing of the stomata to potential root uptake rate. When this happens, the potential biomass production rate is assumed to decline in the same proportion as the transpiration. The potential transpiration and biomass production rates are reduced by multiplying their potential rates by a soil water deficit factor calculated from the ratio of the potential uptake to the potential transpiration. This value is set at 1 when the ratio exceeds 1. A second water deficit factor is calculated to account for water deficit effects on phytophysiological processes that are more sensitive than the stomata-controlled processes of transpiration and biomass reduction. Reduced turgor pressure in many crop plants will slow down processes such as leaf expansion, branching and tillering before stomata-controlled processes are reduced. Values for the second factor are assumed to fall below 1 when potential root uptake relative to potential transpiration falls below 1.5. They are assumed to reduce linearly from 1 to 0 in proportion to this ratio (Ritchie, 1981). In our study, the impact of groundwater was significant for soil water input and storage in the rooting zone. As the CERES-Wheat model does not consider capillary rise from groundwater or a shallow water table, this effect was indicated by setting saturated soil water content at the beginning of the simulated wheat growing period.

2.3. Model validation

Validation is an important step in model verification (Addiscot et al., 1995; Power, 1993). It involves a comparison between independent field measurements (data) and outputs created by the model. Grain yield and phonological development were considered as the evaluation parameters for the CERES-Wheat model at both localities, which is shown in the results. The model validation for the experimental sites is based on successful calibration and validation (deviation in annual yield predictions below 20%) of both wheat cultivars on independent data sets in preliminary studies (for cultivar "Hana" in Štastná, 2000; for cultivar "Perlo" in Alexandrov et al., 2002; Dufková et al., 2002). However, additionally, a re-validation using 9 years of experimental data from the experimental sites was carried out, whereas the crop management, soil characteristics and crop parameters remained the same as given for the impact study.

2.4. Modifications by scenarios

Recent transient runs of general circulation models (GCMs), provided by the IPCC DDC (Intergovernmental Panel on Climate Change Data Distribution Centre), were used to develop climate change scenarios for the considered region (Fig. 1a and b). The three GCMs that best reproduced the present climate of the Czech Republic (several scores were used to measure the fit between the annual cycles of observed climatic characteristics and GCM—simulated climatic characteristics) were selected to define the scenarios: ECHAM4/OPYC3 (ECHAM), HADCM2 (HAD) and NCAR DOE-PCM (NCAR). All three models are coupled atmosphere–ocean GCMs. In addition, the AVG scenario obtained by averaging scenarios from seven individual GCMs was included to show the resulting simulated differences of the impact models to the considered single scenarios. The final scenarios were defined by pattern scaling (Santer et al., 1990), which consists of multiplying the standardized scenario by the simulated increment of the global mean temperature, ΔT_G. The value of $\Delta T_G = 2.33\,^{\circ}\mathrm{C}$ for doubled CO_2 climate was estimated using the MAGICC one-dimensional climate model (Harvey et al., 1997; Hulme et al., 2000) assuming IS92a emission scenario (SRES scenarios were not available when starting analysis described in this paper) and average climate sensitivity. The standardized scenario gives changes in individual climate characteristics for 1 °C increase in global mean temperature. It was determined as a weighted average of the scenarios for nine consecutive 10-year segments within the 2010–2099 run for the GCM in question. The scenarios differed in the magnitude of the changes in mean annual climate characteristics and in the shape of the annual cycle of changes (Fig. 1a and b). ECHAM: mean annual temperature (T) increases by 3.6 °C, precipitation (P) decreases by 2.9%; HAD: $\Delta T = 2.7\,^{\circ}\mathrm{C}$, $\Delta P = -0.7\%$; NCAR: $\Delta T = 2.5\,^{\circ}\mathrm{C}$, $\Delta P = 8.7\%$; average scenario (AVG): $\Delta T = 3.0\,^{\circ}\mathrm{C}$, $\Delta P = 3.9\%$.

Daily weather series representing the present climate conditions were produced by the Met&Roll stochastic weather generator (Dubrovský, 1997) using parameters derived from the observed weather series. To generate series representing changed climate conditions based on the years 1985–1993 (used as crop model input in our study), the generator parameters were modified according to the GCM-based $2\times\ CO_2$ climate change scenarios. The weather generator has been validated in detail (Dubrovský, 1997). The good fit of the means and variances of the crop model (CERES-Maize, CERES-Wheat) yields obtained with use of observed weather series and synthetic weather series indicates that the generator is satisfactory for use in crop growth modeling (Dubrovský et al., 2000, 2003).

Winter wheat growth and development were simulated for: (a) present conditions ($1\times\ CO_2$ weather, 330 ppm), representing no change in used weather input files (present

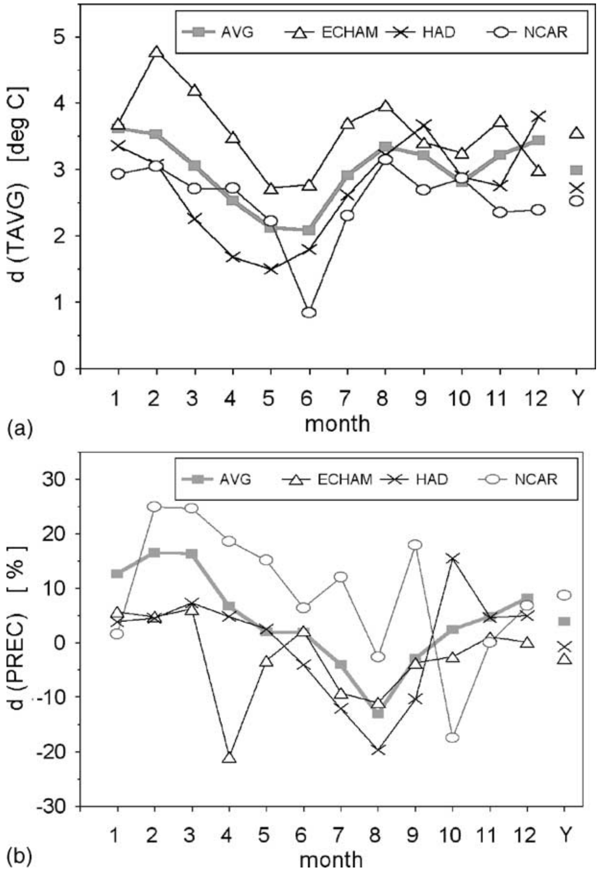

Fig. 1. (a) Changes in daily average temperature projected for 2× CO_2 climate according to four climate change scenarios: ECHAM = ECHAM4/OPYC3; HAD = HADCM2; NCAR = NCAR DOE-PCM; AVG = scenario averaged over seven GCMs. Y relates to the whole year. (b) Changes in precipitation projected for 2× CO_2 climate according to four climate change scenarios: ECHAM = ECHAM4/OPYC3; HAD = HADCM2; NCAR = NCAR DOE-PCM; AVG = scenario averaged over seven GCMs. Y relates to the whole year.

climate) and in CO_2 concentration in the atmosphere (330 ppm); (b) combined effect (2× CO_2 weather, 660 ppm), representing a change in weather input compared with the present climate (according to scenarios) and in CO_2 concentration in the atmosphere (660 ppm); (c) climate effect (2× CO_2 weather, 330 ppm) representing a change in weather input compared with the present climate (according to scenarios) but no change in CO_2 concentration in the atmosphere (330 ppm); (d) CO_2 effect (1× CO_2 weather, 660 ppm) shows no change in weather input but doubled CO_2 concentration in the atmosphere (660 ppm), representing an increased fertilization effect from ambient CO_2. Results of climate and combined effect were processed for all scenarios (ECHAM, NCA, HAD and AVG) at both locations.

3. Results

3.1. Model validation

CERES-Wheat was re-validated for our study using observed and simulated grain yields for the years 1985–1993 (Fig. 2a and b). The results show a standard deviation of 551 kg ha^{-1} for site B (“Hana” winter wheat cultivar) and a standard deviation of 1284 kg ha^{-1} for site A (“Perlo” cultivar). Simple linear regressions were computed to determine the R^2 value between observed and simulated yield data. The mean validation difference over 9 years between measured and simulated yield was 318 kg ha^{-1} (5.1% compared with the measured yield) at site B and 164 kg ha^{-1} (2.5% compared with the measured yield) at site A. At site A was obviously a larger difference between interannual simulated yields than at site B, which was partly caused by frequently observed water stress at site A. Water stress is in general a source of uncertainty in crop growth simulation as an accurate simulation of crop available soil water is difficult and becomes crucial. In contrast to site B the regression line between observed and simulated yields was not parallel to the 1:1 line, but all yields were within 20% deviation and only 4 years exceed 10% deviation. The model especially underestimated years with relatively low yields (1993 and 1986) and overestimated years with high yields (1988 and 1992). The deviations, however, seem not to be related to simulated water stress only (significant water stress during grain filling period was simulated only in 1993), but to other unknown factors, which are not considered by the model. A maximum deviation of about 20% has therefore to be assumed as the range of uncertainty of simulated annual yields in the climate change scenario analyses especially under conditions with high annual yield variability such as at site A. At site B all yields were slightly underestimated (a maximum of 16% for 1992), although with the exclusion of yields obtained under significant water stress as at site A. The annual yields at site B lay in a relatively small range but showed the same tendency of underestimation at lower yield levels.

3.2. Impact of climate change scenarios

The four climate scenarios described above (ECHAM, NCA, HAD and AVG) were applied for the years 1985–1993 (9 years, which represent the current conditions in our case) and run for the “combined effect” and “climate effect” at both locations. Additionally, the cases of “present conditions” and “CO_2 effect” were applied, as shown above. Tables 3 and 4 show the impact on crop development and simulated water stress levels for the different phenological stages of winter wheat (Table 2) for the defined cases, the AVG climate scenario being applied at both sites (average of 9 years). In Table 5 the results of simulated potential and actual yields are presented. To highlight the significant effect of groundwater to the rooting zone on crop yield and soil water balance a simulation without groundwater impact was carried out at site B (the initial soil water content of winter wheat in autumn was set at the wilting point). No groundwater impact on the rooting zone at site A and groundwater impact at site B reflect the real conditions.

(a) *Present conditions (1× CO_2 weather, 330 ppm)*: Simulated rain-fed winter wheat yield was 3225 kg ha^{-1} at site A and 2604 kg ha^{-1} at site B (Table 5) if no groundwater

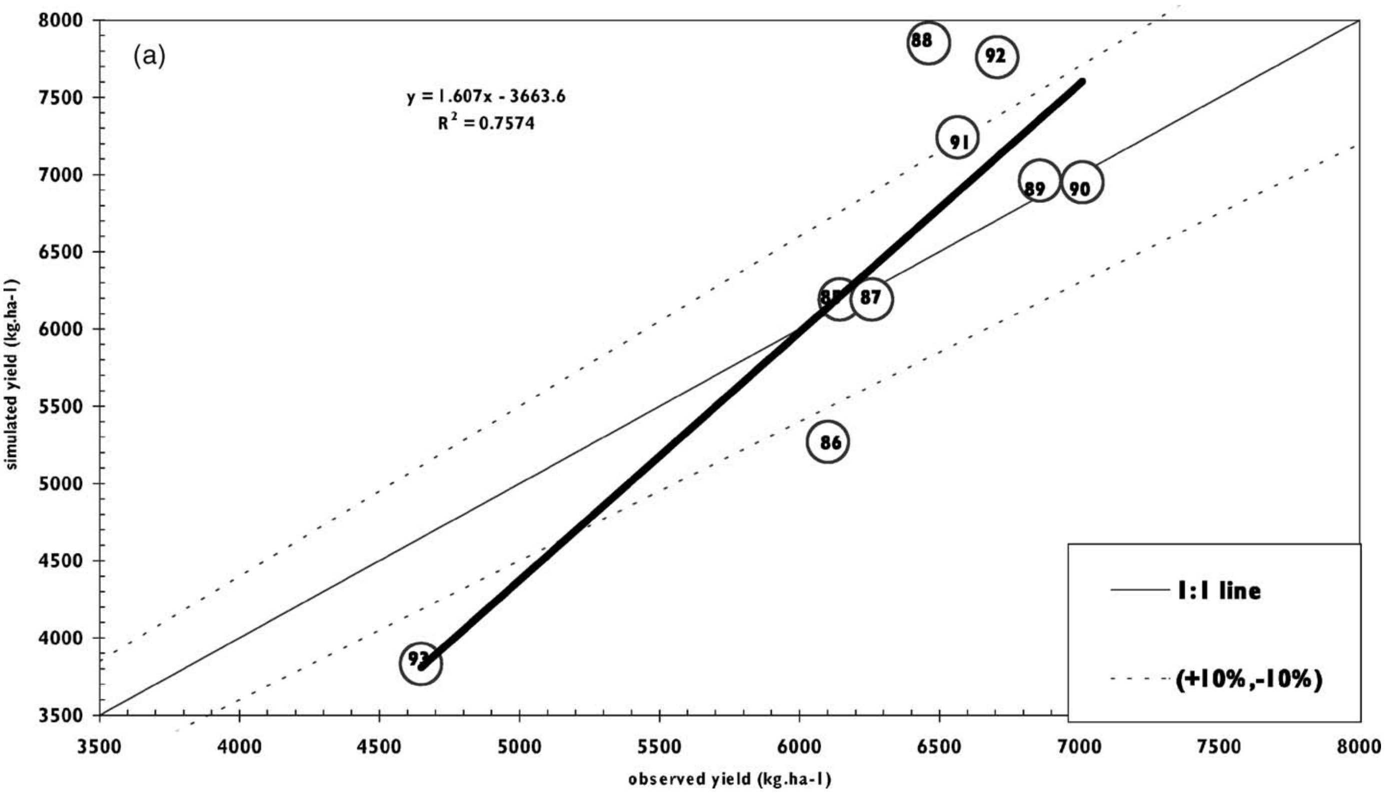

Fig. 2. (a) Validation of winter wheat grain yield in site A (1985–1993); (b) Validation of winter wheat grain yield at site B (1985–1993); the straight lines represent the linear regression function relating the observed and simulated water limited grain yield; dash lines represent the percentage of simulated yields within 10% of the observed yield, the years are marked by numbers inside the circles.

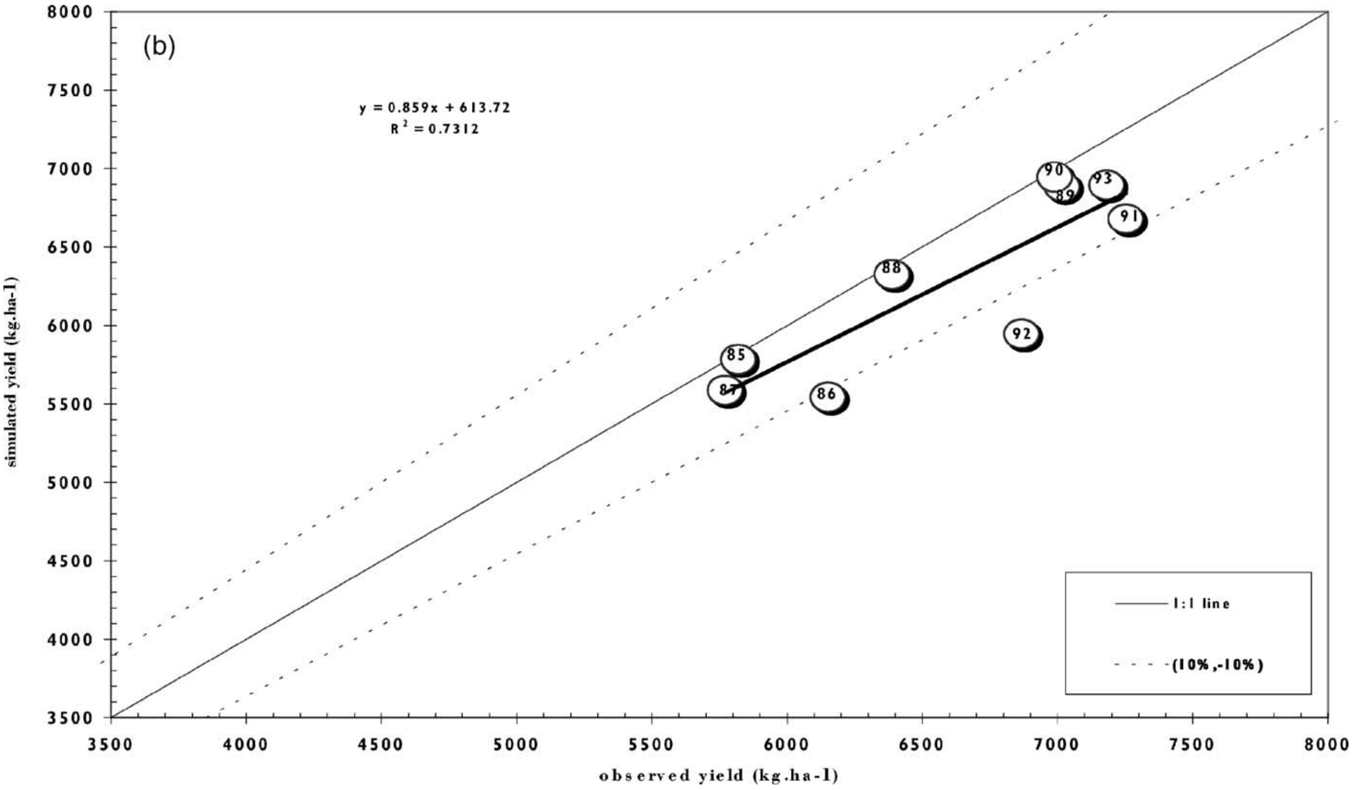

Fig. 2. (*Continued*).

Table 3
Water stress values indicated by CERES-Wheat for growth in particular Zadoks stages at site A, with no groundwater impact (average of 9 years, based on 1985–1993 weather); AVG = scenario averaged over seven GCMs

Site A		Present conditions (1× CO_2 weather, 330 ppm)		Combined effect (AVG, 2× CO_2 weather, 660 ppm)		Climate effect (AVG, 2× CO_2 at weather, 330 ppm)		CO_2 effect (1× CO_2 weather, 660 ppm)	
CERES-Wheat	Zadoks	Duration (days)	Water stress (0–1)	Duration (days)	Water stress (0–1)	Duration (days)	Water stress (0–1)	Duration (days)	Water stress (0–1)
1	10–29	163	0.03	155	0.02	155	0.03	163	0.01
2	30–49	24	0.18	24	0.13	24	0.21	24	0.11
3	50–59	14	0.31	14	0.14	14	0.19	14	0.23
4	60–69	14	0.29	14	0.19	14	0.28	14	0.25
5	70–90	25	0.31	25	0.21	25	0.23	25	0.24
Total		240		232		232		240	

impact was assumed, which is less than half of the simulated potential yield (no water stress) of about 6600 kg ha^{-1} at both sites. Such low yields occurred because of significant water stress during most growing stages (see Table 3 for site A). When groundwater impact was simulated at site B, the yield under rain-fed conditions (6571 kg ha^{-1}) came close to the potential yield for that site as a result of only very low water stress during all development stages (Table 4). The duration of the simulated total growing period differed by 37 days between the two sites (Tables 3 and 4), caused only by the difference during winter dormancy period (CERES-Wheat development stage 1). Additionally, the sowing date in autumn was set 10 days earlier at site B.

Table 4
Water stress values indicated by CERES-Wheat for growth in particular Zadoks stages at site B with groundwater impact (average of 9 years, based on 1985–1993 weather); AVG = scenario averaged over seven GCMs

Site B		Present conditions (1× CO_2 weather, 330 ppm)		Combined effect (AVG, 2× CO_2 weather, 660 ppm)		Climate effect (AVG, 2× CO_2 weather, 330 ppm)		CO_2 effect (1× CO_2 weather, 660 ppm)	
CERES-Wheat	Zadoks	Duration (days)	Water stress (0–1)	Duration (days)	Water stress (0–1)	Duration (days)	Water stress (0–1)	Duration (days)	Water stress (0–1)
1	10–29	198	0.10	155	0.04	155	0.11	163	0
2	30–49	24	0	24	0.02	24	0.01	24	0
3	50–59	15	0	14	0.02	14	0.02	14	0
4	60–69	15	0	14	0	14	0	14	0
5	70–90	25	0.02	25	0	25	0	25	0
Total		277		232		232		240	

Table 5

Simulated water limited and potential winter wheat yield (kg ha^{-1}) in present and modified conditions for each scenario at sites A and B (average of 9 years, based on 1985–1993 weather)[a]

Cases	Climate scenario	Site A			Site B				
		ISW = WP		Potential	ISW = WP		ISW = SAT		Potential
		Water limited	Percentage of potential		Water limited	Percentage of potential	Water limited	Percentage of potential	
Present conditions (1× CO_2 weather, 330 ppm)		3225 (d)	49	6552 (d)	2604 (d)	38	6571 (d)	97	6772 (d)
CO_2 effect (1× CO_2 weather, 660 ppm)		744	47	1940	1302	44	1465	90	2127
Climate effect (2× CO_2 weather, 330 ppm)	ECHAM	−690	43	−669	−191	42	−942	98	−1054
	NCA	497	62	−547	829	60	−1082	96	−1055
	HAD	581	61	−355	1135	63	−860	96	−843
	AVG	30	54	−501	509	55	−1022	97	−1068
Combined effect (2× CO_2 weather, 660 ppm)	ECHAM	469	47	1255	1777	55	925	95	1155
	NCA	1646	61	1462	3327	74	903	93	1289
	HAD	1729	61	1562	3553	75	888	91	1399
	AVG	1201	56	1351	2909	69	821	93	1199
Standard deviation from validation		1284					551		

[a] Standard deviation shows the range of uncertainty at both localities. ISW: initial soil water; WP: wilting point and no groundwater impact; SAT: soil saturation and groundwater impact; d: absolute yield differences to present conditions.

(b) *Combined effect (2× CO_2 weather, 660 ppm)*: Rain-fed yield was simulated for the four different climate scenarios (Table 5). There was almost no indication of water stress at site B due to the impact of groundwater and the highest absolute yields were obtained in this case (7392 kg ha^{-1} average of all scenarios), almost the level of potential yield. It increased 12.5% compared with the present conditions. The best results in terms of absolute yield were obtained with the ECHAM scenario (7496 kg ha^{-1}). The total growing period at site B decreased 31 days on average for all scenarios compared with present conditions (Table 4), but this was caused only by the shortened winter dormancy period. Assuming no groundwater impact at site B, the rain-fed yield increased 112% to 5513 kg ha^{-1} on average for all scenarios compared to present conditions. At the Austrian location (site A, no groundwater impact) rain-fed yield was lower than for the same case (without groundwater impact) at site B. Water stress at site A occurred regularly during the growing period and the yield increased 37.2% with a reduction in winter dormancy period of 8 days on average for all scenarios. The highest yield was achieved by the HAD scenario with 4954 kg ha^{-1}. Except for the ECHAM scenario at site A, the highest increases in yield compared with current conditions were found for the combined effect at both locations without groundwater impact.

(c) *Climate effect (2× CO_2 weather, 330 ppm)*: The results obtained for all applied scenarios produced higher water stress levels compared with the combined effect. The ECHAM model in particular produced very low simulated grain yields compared with the other cases at both locations without groundwater impact (Table 5). In the case of groundwater impact, all scenarios at site B showed very strong decreases in yields compared with current conditions, which were already close to the potential yield level. The yield under the ECHAM scenario decreased 14.3% (with groundwater impact) and 7.3% (with no groundwater impact) at site B compared with the present conditions. At site A it decreased 21%. However, except for ECHAM, the scenarios showed an increase in rain-fed yields for the cases without groundwater impact compared with current conditions. This was caused by higher precipitation under changed climate, outweighing the negative temperature effect. However, the yield in absolute terms was still much lower than in the case with groundwater impact and no water stress at site B. Taking all scenarios together, the yield decreased on average by 15% (groundwater impact) and increased 19.5% (no groundwater) at site B and 3.5% at site A (no groundwater). The potential yields were reduced at both locations, but to a greater extent at site B than at site A.

(d) *CO_2 effect (1× CO_2 weather, 660 ppm)*: The highest rain-fed yield (8036 kg ha^{-1}), which corresponds a yield increase of 22% compared with current conditions, was simulated for the case of groundwater impact at site B. The rain-fed simulated yield increase with no groundwater impact, however, was lower than for the combined effect scenarios at both locations. At site A, this case showed a yield increase of 744 kg ha^{-1} (+23%), where the yield increase at site B reached 1302 kg ha^{-1} (+50%). The increase in potential yields was around 2000 kg ha^{-1} (about +30%) at both locations because of the pure fertilization effect of CO_2.

3.3. Crop water stress and soil water balance

Yields and water stress levels 0–1 (0 indicates no water stress, 1 the highest water stress level) for 1985–1993 simulated by the CERES-Wheat model with the modified weather files from the ECHAM scenario (combined effect) were chosen to show the impact of soil water balance and water stress during the different development stages (Table 2) on wheat yield (Fig. 3a and b). ECHAM was selected because it shows a strong decrease in precipitation in April of about 20% (Fig. 1b), which causes potential water stress effects under changed climate during this critical month for crop growth. During the first development stage only low water stress (less than 0.1) occurred at either locality, and this stress level did not influence the final wheat yield, although site B recorded this stress every year except for 1990. During the second stage, very high water stress occurred in 1989 and 1991 at site A compared with site B, where only low stress occurred in 1988. However, high values at this stage did not have a significant impact on the grain yield as well (e.g. high water stress level, but also high yield in 1991). Simulated water deficit also appeared during the third stage at site A, where the water stress values reached 0.7 in 1989 and 1993. The most yield-sensitive growing stage was during the grain filling period at site A (the fourth and especially the fifth development stage), which can be seen by comparing the yield and water stress levels in 1990 and 1991. The highest water stress indicators correspond directly with the lowest yields (1990 and 1993) for the whole 9-year period.

Table 6 shows the significant reduction of canopy transpiration and potential evapotranspiration for the combined effect (ECHAM) over the considered time period. In spite of higher yield levels (Table 5), canopy transpiration dropped by 16% at site A and by 32% at site B (with groundwater), where evaporation decreased only a little, as a result mainly of the shortened growing period compared with the present conditions. Beside crop water use efficiency the amount of canopy transpiration is strongly related to biomass production as shown for the ECHAM scenario in Fig. 4a. Years with low yields, caused by water stress, also showed the lowest transpiration rates and full use of available soil water at site A (Fig. 4b). At site B, available soil water was not limited by the impact of groundwater, permitting additional mean

Table 6
Simulated crop growing season (winter wheat) water balance components of the plant stand (9 years, ECHAM scenario, the amount of water in mm)[a]

	Site A		Site B		
	Present conditions	ISW = WP (ECHAM)	Present conditions	ISW = WP (ECHAM)	ISW = SAT (ECHAM)
Soil water balance	−7	18	−194	−30	−126
Precipitation	371	342	337	328	328
Drainage	0	0	52	0	75
Run-off	9	9	19	15	23
Evaporation	177	165	173	157	160
Transpiration	179	150	288	127	195
Evapotranspiration (ET)	355	316	461	283	355
Potential ET	503	469	506	435	428
Available soil water storage capacity	240	240	259	259	259

[a] The negative values for soil water balance at site B represent the potential water supply from groundwater during the growing period of winter wheat. ISW: initial soil water; WP: wilting point and no groundwater impact; SAT: soil saturation and groundwater impact.

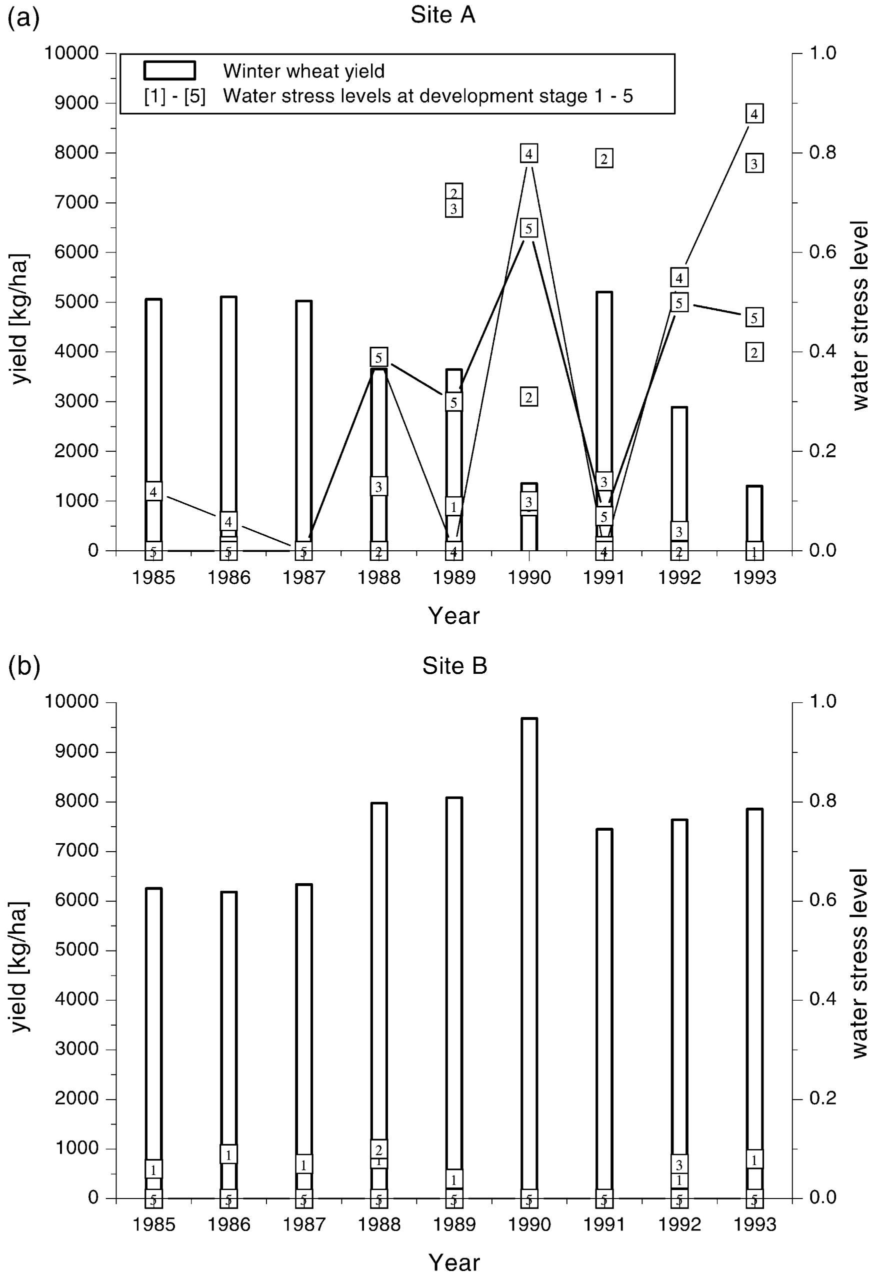

Fig. 3. (a) and (b) Water stress levels of winter wheat related to simulated rain-fed yield and development stages of site A (no groundwater impact to rooting zone) and site B (groundwater impact to rooting zone) for the years 1985–1993 under the ECHAM scenario (combined effect).

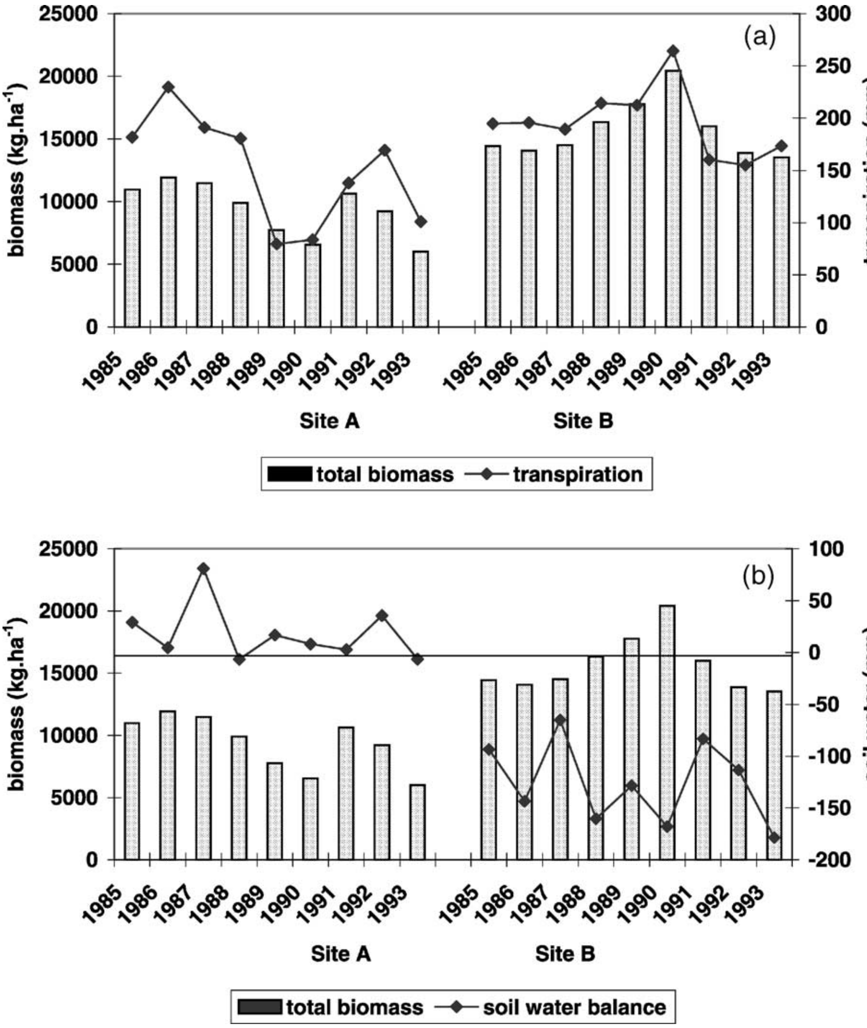

Fig. 4. Relation between simulated total biomass and transpiration (a) and soil water balance (b) of the winter wheat growing period for the ECHAM climate scenario.

input of 126 mm to the soil water balance under ECHAM (compared to 194 mm for present conditions), varying between 60 and 180 mm during the 9 years under review.

4. Discussion

4.1. Yield sensitivity and water stress

The simulated winter wheat yield increase for the CO_2 effect of between 22 and 50% in our study lies within the range as reported by field studies (Amthor, 2001) and other simulation studies (Eitzinger et al., 2001; Ewert et al., 2002). The CO_2 effect is also mainly responsible for the strong increase in yields in the case of the combined effect in our study. The yield increase for the combined effect scenarios reached 14–54% at site A (without groundwater) and as 68–135% (without groundwater) and 12–14% (with groundwater) at site B. The highest yields were still simulated at site B with groundwater impact. The results show that except under ECHAM the climate effect of the climate scenarios has a positive impact on winter wheat yield for the locations without groundwater impact, because of increase in precipitation. The ECHAM scenario (Fig. 1a and b) represents the most aggressive change of mean annual temperature (increase of 3.6 °C) as well as precipitation (decrease of 2.9%) compared with others scenarios, which results in more severe droughts during the growing period together with an increase in water stress in all growth stages (Fig. 3a). The low yields under the ECHAM scenario appear to have been caused mainly by the considerable drop in rainfall in April accompanied by very high temperatures (Fig. 1), when the crop is very sensitive to water stress (Fig. 3a), as also demonstrated experimentally (Aiguo et al., 2001; Kastelliz and Ruckenbauer, 2000), where the most sensitive stages are observed during the grain filling period. The reduction in potential and actual yields in this climate scenario was obvious at both locations without groundwater impact, however, we have to keep in mind that the model tended to underestimate yield levels below approximately 6000 kg ha^{-1} as shown in validation results. As for the potential yields the yield reduction was caused by the effects of higher temperatures on biomass accumulation. As winter wheat can start growing any time in spring, depending on weather and temperatures, the simulated active growing period in spring did not vary significantly between the $2\times$ CO_2 weather scenarios, although the winter dormancy period was shorter, leading to earlier maturity in spring. At site B with groundwater impact, actual yields came closest to the potential yields for all cases (Table 5), where values between 91 and 98% utilization of potential yield were reached. In contrast, at both sites without groundwater, values between 38 and 75% utilization were obtained, with site B showing slightly better results for the combined effect. This results confirm that availability of soil water and groundwater for crop growth and yield level and their changes under the applied climate scenarios is crucial as several other studies have reported (Mejia et al., 2000; Morgan and Condon, 1986). The reason for the strong increase at site B without groundwater is not fully clear, but it could result partially from a weak model calibration for drought conditions at this site (model validation for cultivar “Hana” was possible only for the real case of groundwater impact as shown in Fig. 1b; the trend of underestimation of yields at low yield levels). Similar yield increase results under the combined effect for the case without groundwater for site A have been found in previous studies for comparable scenarios (Alexandrov et al., 2002; Eitzinger et al., 2001). In general, we found that the yield increased much more under conditions without groundwater under the combined effect than under conditions without water stress compared with the present case, especially at site B. We may argue that the CO_2 effect may increase yields relatively more under arid conditions than under humid conditions because of increased crop water use efficiency. This is supported by other studies, such as in south Australia, where elevated CO_2 increased yields by 13–52% (atmospheric CO_2 concentrations of 700 ppm in combination with warmer temperatures and reduced rainfall), with the greater responses occurring in combination with drier climates, most likely the result of CO_2-induced enhancements of water use efficiency (Reyenga et al., 2001) and hence reduced transpiration. Volk et al. (2000) also concluded in a study for grassland that the CO_2-induced soil moisture effect was larger than the primary CO_2 effect. In any case, at both localities a significant increase in winter wheat production with increased CO_2 level in the atmosphere can be expected compared to the current conditions (1985–1993) with allowance made for the existing uncertainties (climate scenarios, crop model validation) and limitations (management and soil conditions, different cultivar sensitivities to water stress).

4.2. Yield sensitivity and water balance

The continuously higher water stress levels at the Austrian location compared with site B (with groundwater impact) can be explained by differences in the soil water balance during the winter wheat growing period (Fig. 4a and b and Table 6). There was no drainage, low run-off, higher evaporation and lower transpiration through less vegetative ground cover at site A than at site B. Site B, by contrast, had higher soil water storage in the rooting zone through the impact of groundwater, which can act as a buffer during drought periods. Total biomass accumulation and yield was therefore significantly higher at site B for rain-fed conditions as no water shortage occurred in spite of increased soil water use. In several studies the importance of groundwater for crop water use has been investigated, mostly in semi-arid regions and for water table management. Mejia et al. (2000) reported that subirrigation water table management can improve soil water availability and significantly raise the yield for corn and soybean. Other authors have pointed out several limitations in groundwater use by crops, which are important for the validity of the results of this study for different conditions. For example, the impact of groundwater salinity on root water uptake of various crops and the impact of soil physical properties on capillary rise or root growth has to be considered. Hopmans and Van-Immerzeel (1988) have pointed out that the capacity of the subsoil to transport water from the groundwater to the root zone can be an important factor for groundwater use of crops. Zhang et al. (1999) showed that the salinity of groundwater played a key role of water uptake by lucerne. In cotton, groundwater contributed up to 42% of water to seasonal total evapotranspiration, depending on salinity (Hutmacher et al., 1996), which is comparable with the simulated 9-year average obtained in our study of 42% (194 mm) under present conditions for the winter wheat growing period at site B. Compared with 126 mm groundwater input under the most “dry” scenario ECHAM (Table 6) it is shown that for the combined effect less groundwater is used for the winter wheat growing period under the given conditions in our study. The simulated hypothetical case of no groundwater impact at site B highlights the importance of groundwater (or irrigation) for crop yields in this climatic region. With no groundwater impact or decreasing groundwater table, rain-fed yield levels at site B would decrease to levels similar to those at site A. Table 6 also clearly shows the simulated increase in crop water use efficiency under the 2× CO_2 scenario ECHAM: despite higher yield levels, crop transpiration and evapotranspiration dropped compared with current conditions. However, because of rising temperatures the annual potential and actual evapotranspiration may further increase under expected climate scenarios (Riedo et al., 2001; Xu, 2000) and cause rising soil water shortages (McCabe and Wolock, 2002). Additionally, as reported in several case studies on locations in central Europe, a long-term decrease in groundwater tables or a decrease in groundwater recharge is predicted under climate change scenarios (Kruger et al., 2001; Lasch et al., 2002). On the other hand, a change in climate variability and in extreme weather events such as the frequency and timing of droughts related to crop development, as indicated in our study by the ECHAM scenario, could cause increasing water losses and highly negative impacts on crop yields (Downing et al., 2000), all the more so in cases when the effect of decreasing canopy transpiration under increased atmospheric CO_2 is less than was assumed in crop models used in the past, as recent research results suggest (Gottschalck et al., 2001).

5. Conclusions

Both agricultural sites with similar climatic conditions showed a simulated decrease in water stress, lower transpiration and an increase in winter wheat yields under future climate scenarios (combined effect of $2\times$ CO_2 weather) under the model assumptions and study limitations. The impact of groundwater to the rooting zone considerably affected water balance and yield level at site B and was the main reason for the difference in yield levels between the two locations. The winter wheat growing period for both sites was also shorter under all scenarios with unchanged production technique. The actual yields came closer to the potential yield level at site B (especially for the case with groundwater impact) under $2\times$ CO_2 climate for all scenarios than at site A. There is strong evidence that, especially for soils with low soil water storage capacity or no groundwater impact to the rooting zone, irrigation or water-saving production techniques (mulching systems, crop rotation) will remain important requirements under future climates in central European agricultural regions for the attainment of the yield potential of winter wheat, especially if the frequency and duration of droughts will increase or soil- and groundwater reserves decrease. Summer crops will be even more vulnerable and dependent on soil water reserves, as the soil water or higher groundwater tables during the winter period cannot be utilized as much as by winter crops and evapotranspiration losses during summer due to higher temperatures could increase significantly. Although there is still a considerable range of uncertainty related to changes in climate variability in future climate scenarios, the study shows that factors that have an impact on soil and crop water balance will play a major role in sustainable crop production and use of soil- and groundwater resources in agriculture.

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