CLIMATE CHANGE IMPACTS AND ADAPTATION STRATEGIES IN SPRING BARLEY PRODUCTION IN THE CZECH REPUBLIC *

MIROSLAV TRNKA [1], MARTIN DUBROVSKÝ [2] and ZDENĚK ŽALUD [1]

[1] *Institute of Landscape Ecology, Mendel University of Agriculture and Forestry Brno,*
Zemědělská 1, 613 00 Brno, Czech Republic
E-mail: mirek_trnka@yahoo.com
[2] *Institute of Atmospheric Physics, AS CR, Praha, Czech Republic*

Abstract. The crop model CERES-Barley was used to assess the impacts of increased concentration of atmospheric CO_2 on growth and development of the most important spring cereal in Central and Western Europe, i.e., spring barley, and to examine possible adaptation strategies. Three experimental regions were selected to compare the climate change impacts in various climatic and pedological conditions. The analysis was based on multi-year crop model simulations run with daily weather series obtained by a stochastic weather generator and included two yield levels: stressed yields and potential yields. Four climate change scenarios based on global climate models and representing 2 × CO_2 climate were applied. Results: (i) The crop model is suitable for use in the given environment, e.g., the coefficient of determination between the simulated and experimental yields equals 0.88. (ii) The indirect effect related to changed weather conditions is mostly negative. Its magnitude ranges from –19% to +5% for the four scenarios applied at the three regions. (iii) The magnitude of the direct effect of doubled CO_2 on the stressed yields for the three test sites is 35–55% in the present climate and 25–65% in the 2 × CO_2 climates. (iv) The stressed yields would increase in 2 × CO_2 conditions by 13–52% when both direct and indirect effects were considered. (v) The impacts of doubled CO_2 on potential yields are more uniform throughout the localities in comparison with the stressed yields. The magnitude of the indirect and direct effects ranges from –1 to –9% and from +31 to +33%, respectively. Superposition of both effects results in 19–30% increase of the potential yields. (vi) Application of the earlier planting date (up to 60 days) would result in 15–22% increase of the yields in 2 × CO_2 conditions. (vii) Use of a cultivar with longer vegetation duration would bring 1.5% yield increase per one extra day of the vegetation season. (viii) The initial water content in the soil water profile proved to be one of the key elements determining the spring barley yield. It causes the yields to increase by 54–101 $kg.ha^{-1}$ per 1% increase of the available soil water content on the sowing day.

1. Introduction

The increasing concentration of greenhouse gases and aerosols in the atmosphere is assumed to affect the climate in the forthcoming decades. The most straightforward question stands: what will be the effect of the increased CO_2 and related climate change on crop production?

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Direct and indirect effects of increased ambient CO_2 concentration are usually distinguished. Direct effects are those affecting the crops by the presence of CO_2 in ambient air. Atmospheric CO_2, which is the primary source of carbon for the plants is, in its present concentration, sub-optimal for C_3 type plants (Hall, 1979) and therefore the increased content of CO_2 in the air stimulates photosynthesis even though some experiments seem to suggest that the increase of photosynthesis rate vary with phenological phase (e.g., Mitchell et al., 1999). At the same time, higher ambient CO_2 will allow to reduce the transpiration rate through decreased stomatal conductance especially under higher temperatures (Bunce, 2000). This should lead to improved water use efficiency (WUE) and thereby to a lower probability of water stress occurrence (Kimbal, 1983). These physiological responses are known as the CO_2-*fertilisation effect* (Dhakhwa et al., 1997) or the *direct effect* of increased CO_2. The experiments made in a controlled environment indicate that the crop growth and biomass production should increase up to 33 ± 6% for C_3 plants (e.g., spring barley or winter and spring wheat) at doubled ambient CO_2 (Kimbal, 1983; Porter, 1992; Kostrej et al., 1998; Ewert et al., 1999; Amthor, 2001) even though some of the field open chamber experiments show lower (10–20%) biomass increase under double CO_2 conditions (e.g., Sæbø and Mortensen, 1996). If water is a limiting factor, which is the case of rain dependent agriculture systems in the Central Europe region, the yields seem to increase more due to the additional effect of improved WUE.

On the other hand, an impact of the changed weather regime brought about by the CO_2 increase is referred to as the *indirect effect* or the *weather effect*. The most important weather variables that directly determine the crop yield are solar radiation, precipitation and air temperature. If no management response (e.g., other cultivars, change in the planting date or soil water conserving practices) is applied, spring barley (and all cereals in general) yields typically decrease with increasing temperature due to a shortening of phenological phases (Nonhebel, 1996; Batts et al., 1997; Brown and Rosenberg, 1997) but the crop response to the high temperature clearly depends on the character of the temperature increase as well as the developmental stage of the crop (Porter and Gawith, 1999). Increasing solar radiation stimulates leaf assimilation (Wolf and van Diepen, 1995), thereby increasing the yields (Hall, 2001; Brown and Rosenberg, 1997). However, as both increased temperature and solar radiation stimulate evapotranspiration, the yields may decrease due to a deepened water stress if the water supply is under its critical level (Trnka, 2002). The effect of precipitation may be either positive if precipitation reduces water stress, or negative, which may be related, e.g., to intensified nitrogen leaching by excessive water or by decrease of soil oxygen content below a critical threshold.

Impacts of climate change on crop growth and development may be estimated by crop models, which simulate the development of individual parts of the plants, commonly in daily steps. The crop models frequently used to simulate the growth and development of spring barley include CERES-Barley (Otter-Nacke et al. (1991), used, e.g., by Travasso and Magrin (1998)), WOFOST (Hijmans et al. (1994), used, e.g., by Alexandrov and Eitzinger (2002)) or SHOOTGROW (McMaster (1993), used e.g., by Žalud et al. (2003)). The input to the crop model incorporates the parameters of the cultivar (genetic coefficients), the field and soil characteristics, the agrotechnological management details (the most important are planting, fertilization and irrigation), and environmental conditions (concentration of CO_2 and time series of daily weather characteristics). The effect of climate change is estimated by comparing model crop yields simulated with use of weather series representing the present climate and the changed climate. The weather series for the changed climate conditions can be prepared by stochastic weather generator parameters of which were derived from the observed weather series and then modified according to the climate change scenario (Semenov and Porter, 1995; Riha et al., 1996; Semenov and Barrow, 1997; Dubrovský et al., 2000). The model simulations are performed under two sets of conditions. In unlimited conditions, the plant is given as much water and nutrients as it needs. In this case, no water stress and nitrogen stress may occur, and the resultant yields are referred to as the *potential yields*. In limiting conditions, water and nutrients supplies are limited and the *stressed yields* are simulated. Climate change impact studies focus on (i) impacts of an increased CO_2 concentration on the crop growth and development (ii) possible adaptations through changes of the cultivar and sowing dates. The latter issue is addressed, e.g., by Alexandrov and Eitzinger (2002), Cuculeanu et al. (1999), Wolf and van Diepen (1995), Bacsi and Hunkár (1994), Easterling et al. (1993), Žalud and Dubrovský (2002).

However all of these studies deal almost exclusively with wheat and maize and therefore do not include spring barley, which is without doubt essential for most of the crop rotation schemes as well as important commodity. At the same time it is the second (after winter wheat) most significant cereal in the Czech Republic as well as in many countries of the European Union both in acreage and production quantity. The arable area used for spring barley production in the Czech Republic in 2000 was 352,892 ha, i.e., 11.5% of the total acreage (www.czso.cz, 2001) with mean national yield 3030 $kg.ha^{-1}$. Total barley acreage in the European Union in 2000 equaled to 8.7% (europa.eu.int/comm/agriculture, 2002), which represents 10,773,000 ha, with significant differences among individual EU members (e.g., Germany 12.9%, Austria 7.2% etc.). Average barley yield in 15 EU member countries in 2000 equaled to 4790 $kg.ha^{-1}$, when the range of national yields in 2000 was within 1430–6800 $kg.ha^{-1}$ interval.

The CERES-Barley crop model is used in this study as a tool for assessing the effect of doubled ambient CO_2 concentration and related climate change on spring barley yields in three regions that represent major agriculture areas of the Czech Republic and results might be applied to vast regions of Central Europe with similar environmental characteristics.

2. Methods and Data

2.1. METHODOLOGY

Climate change impacts on crop growth, development and yield characteristics and the effects of possible adaptation measures were assessed with use of the crop growth model run with weather series representing present and 2 × CO_2 climates and present (350 ppm) and doubled (700 ppm) ambient air CO_2 concentrations. Multi-annual crop model simulations were run for each scenario and the descriptive statistics, such as means, standard deviations, and quantile characteristics, were determined and used for impact assessment. The input to the crop model consists of pedological, physiological and cultivation data taken from a single 'representative' year and the 99-year synthetic weather series created by the stochastic weather generator Met&Roll (Dubrovský, 1997). The representative year is defined by the region-typical values of all non-meteorological parameters (including the planting date, soil profile, initial soil water content and details on the fertilization regime) needed to run the model. The parameters of the weather generator derived from the observed series are used to generate weather series representing the present climate. Parameter values of the generator are modified in accordance with the climate change scenario to generate series representing the changed climate. Both levels of grain yield, i.e., stressed and potential, were calculated and both direct and indirect effects of increased CO_2 were assessed. In the adaptation analysis (Section 5), the effects of changes in the planting date, cultivar and soil water conserving practices are studied.

2.2. CROP MODEL

The crop growth model CERES-Barley version 2.1 (Otter-Nacke et al., 1991) is used in this study. This model was developed within the framework of IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) project and is run within the DSSAT 3.5. (Decision Support System for Agrotechnology Transfer, Hoogenboom et al., 1994) environment. This model was chosen because of its ability to simulate both the stressed and the potential yields and possibility to introduce multiple soil-layer subroutines. Moreover, the crop models from the CERES series are among crop growth models that allow easy modification of the ambient concentration of CO_2 and because of it, they are frequently used in climate impact studies (e.g. Hunkár, 1994; Brázdil and Rožnovský, 1995).

The CERES-Barley model is a mechanistic process-based model, which increments crop growth in daily steps. Modeled processes include (i) phenological development, (ii) extension of leaves, stems and roots, (iii) biomass accumulation and partitioning, (iv) soil water balance and water use by crop, (v) soil nitrogen transformation, uptake by the crop, and partitioning among plant parts (Ritchie et al., 1998). Details on the characteristics of models included in the CERES

Table I

Characteristics of the three experimental sites representing main production regions in the Czech Republic. Climatic characteristics relate to 1961–1990 period

Site	Region 1	Region 2	Region 3
Latitude	49°01′ N	49°18′ N	49°32′ N
Longitude	16°37′ E	17°23′ E	16°15′ E
Elevation (m a.s.l.)	179	234	560
Primary crop	maize	sugar beet	potato
Soil type	Fluvisol	Chernozem	Cambisol
Soil depth (cm)	105	115	100
Underground water table (cm)	80–160	under 300	under 300
Mean annual temperature (°C)	9.2	8.6	6.5
Mean temperature Apr–Sept (°C)	15.7	15.1	12.8
Mean annual precipitation (mm)	480	599	651
Mean precipitation Apr–Sept (mm)	312	389	396
Mean accumulated global radiation per year (MJ.m^{-2})	3948	3914	3528

group may be obtained, e.g., in Otter-Nacke et al. (1991), Hunkár (1994), Iglesias (1995a,b), Maytín et al. (1995) or Ritchie et al. (1998).

2.3. INPUT DATA TO THE CERES-BARLEY MODEL

Relatively high relief and soil heterogeneity of the Czech Republic enabled us to choose three geographically close experimental sites with different environmental conditions that represent three different production regions of the country (Table I). These sites might be considered representative even for much larger areas of Central Europe. The study was based on the results of extensive field experiments that were carried out on these sites. In all experiments the same spring barley cultivar (Akcent) and same methodology of field trials was used. Such selection of the experimental sites enabled us to test whether the climate change impacts and adaptation strategies will significantly differ in individual environmental conditions.

2.3.1. *Crop Cultivar*

The genetic characteristics of the crop cultivar are expressed in terms of seven genetic coefficients, which describe the physiological processes (photosynthesis, respiration, and others) for an individual crop (Tsuji et al., 1994). The cultivar used in this study is Akcent, which is a two-row semi-late spring barley cultivar of the dwarfed type. It is suitable to all spring barley growing altitudes and is characteristic by high yields and lodging resistance. The cultivar is, however, sensitive to drought conditions as well as to *Rhynchosporium cerealis* and *Pyrenophora teres* (Jurečka and Beneš, 2000). The cultivar is suitable for malt production but it can be also grown under less favorable environmental conditions for feed grain. Based on the experimental results following values of the genetic coefficients were calculated for the cultivar: (i) P1V-vernalisation sensitivity (0.5), (ii) P1D-photoperiod sensitivity (2.4), (iii) P5-relative grain filling duration (2.3), (iv) G1-kernel number per unit weight of stem (2.0), (v) G2-kernel growth rate in mg.day^{-1} (10.0), (vi) G3-standard stem weight in grams (2.0) and (vii) PHINT-phylochron interval in degree days (65.0).

2.3.2. *Weather Data*

Observational daily series of maximum air temperature (*TMAX*), minimum air temperature (*TMIN*) and precipitation (*PREC*) were measured directly at all three test sites. The input solar radiation (*SRAD*) values at Regions 1 and 3 were calculated from sunshine duration measurements using a formula proposed by Angström (1924) while at Region 2 directly measured data were available. Observed weather series were used in calibrating and evaluating the crop model. The meteorological stations are located less than 1 km from the respective experimental fields. Daily weather series for the climate change impact analysis and adaptation analysis were produced by the stochastic weather generator Met&Roll (Dubrovský, 1997). Its parameters were derived from the observed weather series and used to generate series representing the present climate conditions. To generate series representing changed climate conditions, the parameters of the generator were modified according to the climate change scenario. The weather generator was validated in detail in previous studies (Dubrovský, 1996; Dubrovský et al., 2000a; Žalud and Dubrovský, 2002) and was found satisfactory for crop growth modeling.

2.4. CALIBRATION AND EVALUATION OF CERES-BARLEY MODEL

Experimental data sets originating from long-term rainfed field trials were used for calibration and evaluation of the model. The trials were carried out using small area plots (10–15 m^2) in four replicates using routine field trials techniques, e.g., randomization and isolation plots. Fertilizer doses were based on soil analysis and sufficient nutrient levels were attained throughout the trial period. The trials were treated against weeds, pests and diseases and no significant damage of the crop was recorded during the trial period. All field experiments used in this work followed

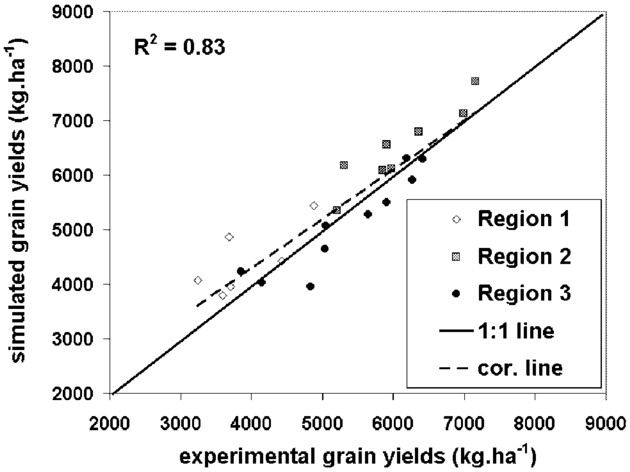


Figure 1. Evaluation of the model yields (cultivar Akcent) simulated by CERES-Barley. The fit between the observed and modeled yields is expressed in terms of the 1:1 line and linear correlation line.

the official methodology for the field trials given by the Czech Central Institute for Supervision and Testing (Jurečka and Beneš, 2000) and were under its constant supervision.

The grain yields simulated by the crop growth model with use of measured pedological, physiological, cultivation and meteorological data are compared with the observed grain yields (Figure 1) and vegetation season duration (from sowing till maturity). The model was calibrated with use of the data from the Region 2 (1993–2000) and then evaluated using the independent data sets from Region 1 (1993–1998) and Region 3 (1989–2000).

The simulated yields fit the observed yields for most of the years with coefficient of determination equaling to 0.83 (Figure 1). On average, the model yields overestimate the observed yields by 7%. The systematic overestimation could be caused by the occurrence of the non-simulated factors, such as harvest losses, pest and diseases. The greatest departures of the model yields from those observed occur in year 1997 in Region 1 (+32%) and Region 2 (+16%) and at Region 3 (+25%) in 1995. Severe flooding during July apparently caused the high difference between simulated and experimental yields at Regions 1 and 2 in 1997. The yield deviation in 1995 at Region 3 was caused by thunderstorm, which occurred two weeks before the harvest. The storm together with strong winds caused lodging followed by fungi infection leading to yield reduction, which could not be anticipated by the model. After omitting these three years, we find that the model yields overestimate those observed by 5% on average and the coefficient of determination between the simulated and observed yields increases to 0.88. The overall fit corresponds with the results of the studies made by other authors (e.g., Wolf et al., 1996; Dhakhwa et

Table II

Multiple treatment field experiment at Region 3 (previous crop was field pea and the spring barley sowing density equaled to 400 seeds.m^2)

Treatment	Cultivar	Sowing date	N-fertilizer (kg.ha^{-1})	Grain yield (1000 kg.ha^{-1})	
				Experiment	Simulated
1	Orbit	10.4.	70	5.40	5.50
2	Orbit	10.4.	90	4.80	5.26
3	Orbit	21.4.	70	4.83	4.91
4	Orbit	21.4.	90	4.51	4.91
5	Akcent	10.4.	70	5.08	5.22
6	Akcent	10.4.	90	4.30	5.20
7	Akcent	21.4.	70	4.14	4.78
8	Akcent	21.4.	90	4.26	4.80

al., 1997; MacRobert and Savage, 1998; Travasso and Magrin, 1998; Alexandrov and Eitzinger, 2002; Šťastná et al., 2002).

To assess the feasibility of adaptation measures the multiple treatment field experiment was set up at Region 3. The results show (Table II) that a significant factor influencing the yields in this experiment was the sowing date, which corresponds also with the simulated results. The difference between the cultivars which was mostly caused by the difference in the vegetation duration period (Orbit's vegetation period duration is on average 1–2 days longer than the one of Akcent) was also apparent both from the simulated and experimental data. Also in this case the model simulated properly the trend in the yield formation.

The final step of the evaluation process was the selection of a representative year for each region. Because the fertilizer doses, tillage practices and sowing density were kept the same at each locality, only the typical sowing and maturity dates had to be determined for each test site. Daily weather series were also examined in order to discard any year, in which an extreme weather phenomenon (especially hail or flood) was recorded. The specifications of the representative years are given in Table III for each locality. All these input data were the same for all model simulations, except those discussed in Section 5.

2.5. CLIMATE CHANGE SCENARIOS

In developing climate change scenarios, outputs from recent transient runs of global climate models (GCMs) were used. Seven GCMs available from the IPCC data distribution center (http://ipcc-ddc.cru.uea.ac.uk) were evaluated in detail to examine their performance for the area corresponding to the Czech Republic. The GCMs were validated in terms of the annual cycle of four climatic characteristics

Table III

Characteristics of representative years at the three test regions

Site	Region 1	Region 2	Region 3
Representative year	1998	1998	1993
Sowing date	20th March	26th March	22nd April
Harvest date	27th July	3rd August	18th August
Dose of N fertilizer (kg.ha^{-1})	90	60	70
Initial available soil water in the soil profile (mm)	260	220	155
Sowing density (seeds.m^{-2})	450	400	400

(global solar radiation, precipitation amount, daily average temperature, daily temperature range). The results showed that: (i) Annual cycles of average temperature and solar radiation are relatively well reproduced in most cases. (ii) Precipitation is generally overestimated, a shape of the annual cycle is poorly reproduced in some models. (iii) Daily temperature range is generally underestimated, but a shape of the annual cycle is mostly satisfactorily reproduced. The performance of the GCMs in the validation tests was mainly measured by the mean square error of the GCM-simulated monthly means (corrected or non-corrected for the systematic deviation) with respect to the observed monthly means. Based on the results obtained, three GCMs for developing 2 × CO_2 climate change scenarios were selected: ECHAM4, HadCM2 and NCAR-DOE. In this selection scenario ECHAM4 predicts higher temperature increase and relatively low precipitation then other scenarios while NCAE-DOE scenario predicts relatively low temperature increase and ample rainfall for the conditions of the Czech Republic under changed climate. The HadCM2 scenario represents ‘conservative’ mean estimate. In addition, the scenario averaged over all 7 GCMs was constructed (in following text these scenarios will be abbreviated as ECHAM, HAD, NCAR and AVG, respectively). The final scenarios were defined by the pattern scaling technique (Santer et al., 1990), which consists in multiplying the standardized scenario by the prognosed increment of the global average temperature, ΔT_G. The standardized scenario is defined as a scenario corresponding to 1 degree rise in global mean temperature. It may be obtained by dividing a climate change scenario for the given period by the increase in mean global surface temperature prognosed for that period. In this study, the standardized scenario was determined as a weighted average of the series of the scenarios for nine consecutive 10-year slices within the 2010–2099 run for a given GCM. The final scenarios derived from individual GCMs differ both in magnitude of the changes of mean annual climate characteristics and in shape of the annual cycle of the changes (Figure 2). The value of $\Delta T_G = 2.33$ °C was estimated with use of the

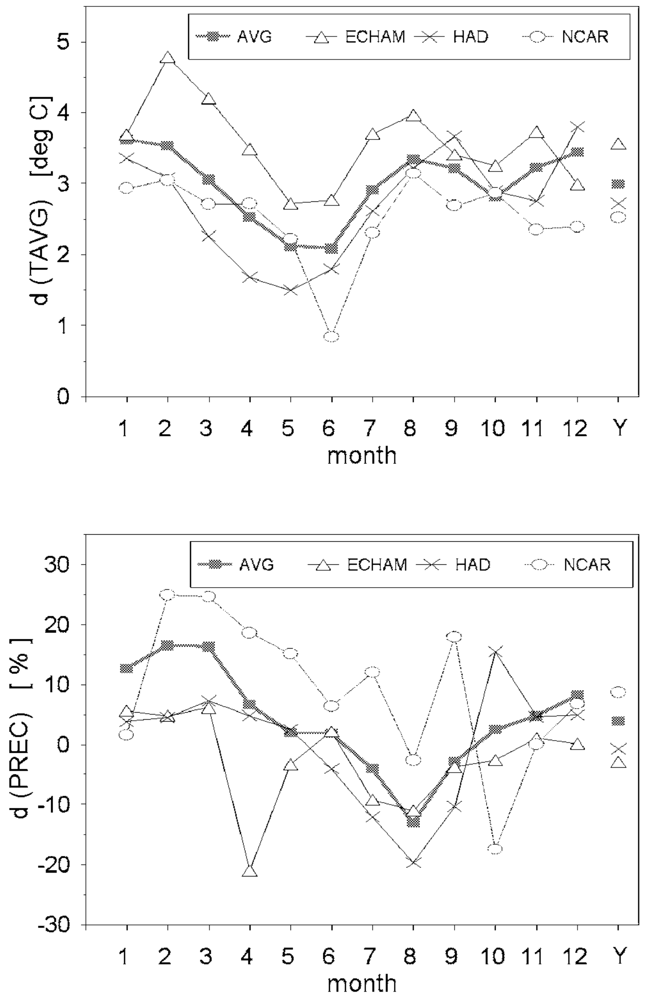


Figure 2. Changes of daily average temperature and daily precipitation amount related to 2 × CO_2 climate according to four GCM-based climate change scenarios. The GCMs are: ECHAM = ECHAM4; HAD = HadCM2; NCAR = NCAR-DOE; AVG = scenario averaged over seven GCMs available from IPCC-DDC. Numbers 1–12 on the x-axis represent mean monthly changes and Y stays for mean annual deviation.

one-dimensional climate model MAGICC (Hulme et al., 2000) assuming IS92a emission scenario, doubled atmospheric CO_2, and the middle climate sensitivity. Scenarios, which were developed using the above-described method, were then coupled with the crop model in order to estimate the direct, indirect and combined effects of increased ambient CO_2.

The climate change scenarios used in this study do not consider changes in weather variability, because the outputs of GCM models available at the IPCC website include only monthly series which do not allow reliable estimates of changes in daily weather variability. This may seem to be a serious limitation regarding the concerns being recently raised that changes in climatic variability might have a greater impact on crop yields than changes in means of climatic variables (e.g., Mearns et al., 1997; Semenov and Porter, 1995). However, results of an analysis made by Dubrovský et al. (2000b) with a previous version of the climate change scenario, which included changes in daily weather variability, have revealed that the prognosed changes in daily variability would decrease the yields of maize but had no significant effect on the yields of spring barley and winter wheat. Therefore, we consider the usage of the present scenarios justifiable for this analysis that deals solely with the spring barley.

2.6. INDEX OF PRODUCTION POTENTIAL

For further interpretation of the simulated results, the index of production potential Z, is introduced (Žalud and Dubrovský, 2002). The value of the index is defined as a ratio of simulated stressed (Y_S), and potential (Y_P) yields under given weather conditions (w) and ambient CO_2 concentration (c):

$$Z(w, c) = \frac{Y_S(w, c)}{Y_P(w, c)} \times 100\% \,. \tag{1}$$

This index may serve as a measure of impacts of limiting factors on the grain yields. In the case of the field experiment, the value of Z is always greater than 0% and lower than 100%. A zero value of Z would mean that the stress totally inhibits the growth, $Z = 100\%$ would mean that no stress affects the yields.

3. Effects of Increased CO_2 on Crop Yields

The direct and indirect as well as the combined effects were evaluated for the four climate change scenarios at the three regions and are presented in Table IV. The summary statistics of the yields from the 99-year crop model runs are given in Table V (only for scenario AVG) and graphically displayed in Figure 3 (all four scenarios). The variability of the grain yields simulated is expressed in terms of quantiles in the figure. The results displayed in the figure and in the tables show the following.

3.1. INDIRECT EFFECT

The indirect effect of increased CO_2 on stressed crop yields at three regions may be seen in Figure 3. The magnitude of the indirect effect is given in Table IV in terms of the ratio of the yield under climatic conditions appropriate to a selected scenario and of the yield under present conditions whilst ambient CO_2 concentration remains unchanged (i.e., doubled). Presented yields and ratios are based

Table IV

Direct, indirect and combined effects of doubled CO_2 on stressed yields of spring barley according to the four climate change scenarios (AVG, HAD, ECHAM and NCAR). The magnitudes of the direct indirect and combined effects are given in terms of the ratios. Direct effect is determined as ratio between yields under doubled ambient CO_2 concentration and yields under present CO_2 level. Indirect effect is defined as ratio between yields attained under changed climatic conditions and yields under present climate without including positive effect of the increased CO_2 on the crop. Combined effect was calculated as ratio between yields calculated for changed climatic conditions with positive influence of doubled CO_2 taken into account and yields attained under present climate and CO_2 level. The ratios are based on the mean values that were calculated from a set of 99 seasonal simulation runs for each option considered. Z(avg) is the index of production potential (see the text for the definition)

	Stressed yields					
Scenario	Present	Present	AVG	HAD	ECHAM	NCAR
ambient CO_2	$1 \times CO_2$	$2 \times CO_2$	$2 \times CO_2$	$2 \times CO_2$	$2 \times CO_2$	$2 \times CO_2$
Region 1						
Grain yield (1000 kg.ha^{-1})	6.90	10.69	9.66	9.81	9.13	10.46
direct effect	–	1.55	1.56	1.59	1.65	1.54
indirect effect	–	–	0.90	0.92	0.85	0.98
combined effect	–	–	1.40	1.42	1.32	1.52
Z(avg)	0.72	0.84	0.82	0.82	0.80	0.86
Region 2						
Grain yield (1000 kg.ha^{-1})	6.71	9.91	8.93	9.09	8.08	10.07
direct effect	–	1.47	1.50	1.52	1.52	1.49
indirect effect	–	–	0.90	0.92	0.81	1.02
combined effect	–	–	1.33	1.35	1.20	1.50
Z(avg)	0.72	0.81	0.76	0.75	0.71	0.84
Region 3						
Grain yield (1000 kg.ha^{-1})	6.70	9.04	8.52	8.12	7.6	9.50
direct effect	–	1.35	1.39	1.41	1.42	1.35
indirect effect	–	–	0.94	0.90	0.84	1.05
combined effect	–	–	1.27	1.21	1.13	1.41
Z(avg)	0.72	0.74	0.73	0.69	0.67	0.79

Table V

Summary statistics of the stressed and potential model yields obtained at the three test regions using the average climate change scenario (AVG). The magnitudes of the direct/indirect/combined effects are given in terms of the ratios as defined in Table IV. Z (avg) is the index of production potential. Means are calculated from set of 99 seasonal simulation runs for each option considered

Locality	Region 1				Region 2				Region 3			
Weather[a] ambient	1×	1×	2×	2×	1×	1×	2×	2×	1×	1×	2×	2×
CO_2 concentration[b]	1×	2×	1×	2×	1×	2×	1×	2×	1×	2×	1×	2×
(a) Stressed yields												
avg (1000 $kg.ha^{-1}$)	6.91	10.69	6.18	9.66	6.71	9.91	5.94	8.93	6.70	9.04	6.13	8.52
std (1000 $kg.ha^{-1}$)	1.51	1.73	1.49	1.75	1.65	1.79	1.42	1.89	1.90	2.06	1.94	2.12
std/avg (%)	21.9	16.2	24.2	18.1	24.6	18.1	24.0	21.2	28.4	22.8	31.7	24.9
direct effect	1.00	1.55	1.00	1.56	1.00	1.48	1.00	1.50	1.00	1.35	1.00	1.39
indirect effect	1.00	1.00	0.89	0.90	1.00	1.00	0.885	0.90	1.00	1.00	0.91	0.94
combined effect	1.00			1.40	1.00			1.33	1.00			1.27
Z (avg)	0.74	0.85	0.70	0.82	0.72	0.81	0.67	0.76	0.72	0.74		0.73
(b) Potential yields												
avg (1000 $kg.ha^{-1}$)	9.60	12.63	8.81	11.76	9.30	12.23	8.80	11.66	9.32	12.18	8.78	11.58
std (1000 $kg.ha^{-1}$)	0.72	0.95	0.59	0.75	0.73	0.91	0.83	1.05	0.74	0.91	0.70	0.91
std/avg (%)	7.5	7.5	6.7	6.4	7.9	7.4	9.5	9.0	7.7	7.5	8.0	7.9
direct effect	1.00	1.31	1.00	1.33	1.00	1.31	1.00	1.32	1.00		1.00	1.32
indirect effect	1.00	1.00	0.92	0.93	1.00	1.00	0.95	0.95	1.00	1.00	0.72	0.95
combined effect	1.00			1.22	1.00			1.25	1.00			1.24

[a] The symbol ‘1×’ stands for present climate while ‘2×’ for climatic conditions expected under AVG scenario.

[b] The symbol ‘1×’ represents present ambient CO_2 level i.e., 350 ppm while ‘2×’ equals to 700 ppm.

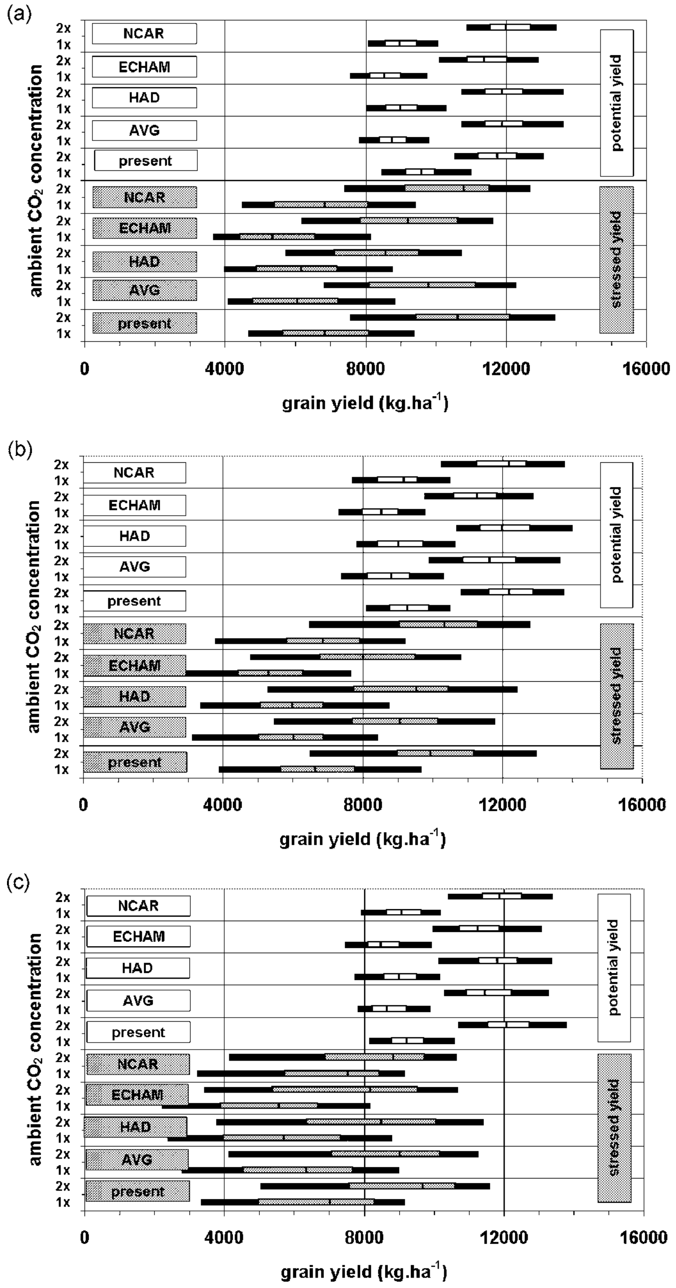


Figure 3. Stressed model yields of spring barley simulated for present climatic conditions and the four climate change scenarios under 1 × CO_2 and 2 × CO_2 ambient air concentration. The horizontal bars represent the 5th, 25th (lower quartile), 50th (median), 75th (upper quartile) and 95th quantiles from set of 99 yields simulated with use of 99-year synthetic daily weather series; the other crop model input data are based on the representative years specific for individual regions (a – Region 1; b – Region 2, c – Region 3).

on the median values of 99 simulation series. According to the AVG and HAD scenarios the stressed yields will decrease due to the indirect effect at all three regions. Simulations based on the ECHAM scenario suggest even stronger negative influence of indirect effect causing up to 19% yield decrease at Region 2. This decrease is assumed to be mainly due to the rise of temperature, which is predicted by all scenarios applied. High temperatures will lead to shorter phenological phases not allowing for an optimal development of the crop. Moreover, the simultaneous decrease of summer precipitation (Figure 2) expected by scenarios AVG, HAD and ECHAM and increase of potential evapotranspiration (mainly due to increased temperature and partly also by increased solar radiation) imply an elevated water stress that contributes to a reduction of the yields at all test sites. In general the ECHAM scenario proved to have the most negative impact on the yield and shortening the vegetation period (Figure 3). It is explained by the fact that the ECHAM scenario predicts the highest monthly temperature increase, which is crucial for spring barley growth and development, and the highest decrease in the precipitation amounts. On the other hand, according to the NCAR scenario, which can be seen as the most favorable for crop growth and development (because of the structure of its temperature and precipitation shifts), slightly positive indirect effect might be seen at Regions 2 and 3.

The indirect effect would cause the potential yield decrease depending on the region and the scenario. The highest potential yield decrease is predicted in the case of ECHAM scenario (which suggests the highest temperature increase). Due to the lack of the effect of increased water stress, the magnitude of the indirect effect on the potential yields is somewhat lower than on the stressed yields. For this reason the differences in potential yields predicted by the four scenarios are insignificant.

3.2. DIRECT EFFECT

An increased concentration of ambient CO_2 implies higher yields. As explained in the introduction, this CO_2 concentration increase contributes to the intensified photosynthesis and (in the case of limited yield only) improved WUE. It is calculated as the ratio of the yields under $2 \times CO_2$ ambient air concentration over yields under $1 \times CO_2$ ambient air concentration attained under the same climatic conditions (e.g., present or AVG). As the magnitude of the latter mechanism depends on available water, the increase of the yields under scenarios with higher precipitation amounts during the vegetation period (NCAR scenario) is 11% less at Region 1 compared to the ‘dry’ ECHAM scenario. The importance of higher WUE is clear when the regions are compared. For the relatively cold Region 3 with ample precipitation the direct effect of doubled CO_2 equals to 39% yield increase (for scenario AVG). For Region 1, which lays in the semiarid region, the yields increase by 56%. As water availability affects only stressed yields, the magnitude of the direct effect on the potential yields (approximately the same values for all three test sites and all four scenarios) is only due to the intensified photosynthesis, and accordingly lower than for the stressed yields. Comparing the magnitudes of the direct effect on the stressed and potential yields it was found that the effect of better WUE is smaller than the effect of intensified photosynthesis, which is caused by spring barley's C_3 photosynthesis mechanism.

3.3. COMBINED EFFECTS OF CO_2 CHANGE

The combined effect of CO_2 change shows a positive trend in spring barley yield development (Table IV), however the size of such increases varies greatly depending both on the region and the applied scenario. It can be expressed as a ratio of the grain yield attained under changed climatic conditions and $2 \times CO_2$ concentration over the yield under present climatic conditions and $1 \times CO_2$ ambient air concentration. The highest yield increase (regardless of region) was recorded when the NCAR scenario was applied. On the other hand, the least favorable scenario ECHAM yielded only a fraction of that increase. The results based on the AVG and HAD scenarios were similar and yield increase due to the combined effect lay between the values of these scenarios. The magnitude of the combined effects is of course affected by region specific conditions. The most significant change in the yields was noted at Region 1, i.e., the region with the lowest precipitation and the highest temperatures, when scenario NCAR that includes precipitation increase during barley vegetation period was implemented.

The magnitude of the direct effect of increased CO_2 is greater than the magnitude of the indirect effect, so the superposition of both effects leads to the positive change in spring barley yields in increased CO_2 conditions. The mean simulated stressed yields increase by 33% on average (by 40% at Region 1, by 33% at Region 2 and by 27% at Region 3) in $2 \times CO_2$ conditions and the trends are almost identical at all three regions.

The potential yields follow a similar pattern as the stressed yields, i.e., the highest yield increase, 25–30%, was simulated when NCAR and HAD scenarios were used. The AVG scenario based yields were slightly lower and the ECHAM scenario gave the lowest potential yield estimate. The influence of the regions on the combined effect on the potential yields was clearly not the same as in the case of the stressed yields. According to three scenarios (all except the ECHAM scenario), the highest potential yield increase through the combined effect was found at Region 2. However the differences between the regions in the magnitude of the combined effect were less than 5% making the region factor less important.

3.4. COMPARISON OF RESULTS OBTAINED USING DIFFERENT SCENARIOS

Based on the simulation results the scenarios AVG and HAD can be treated as 'mean' as far as climate change impact on spring barley grain yield is concerned. Both scenarios yielded similar values of direct, indirect and combined impacts at Regions 1 and 2, and differed slightly in estimates of these values at Region 3. The scenario ECHAM can be used as the least favorable scenario for spring barley impact studies (out of the four scenarios tested) as it predicts the highest temperature increase and precipitation decrease in the period crucial for the spring barley growth and development. It is characterized not only by the lowest yield increase (both stressed and potential) at three regions but also by the highest yield variability. The scenario NCAR, that is characterized by relatively low temperature increment during spring and summer (when compared with the other scenarios), and increase in the precipitation amounts can be used as the most favorable scenario as far as spring barley yields are concerned.

Despite the commonly accepted assumption that the response of the crop growth and development characteristics to changes in climatic characteristics is not linear, it was found that AVG scenario produces more or less average impacts on model barley yields. Specifically, the impact on barley yields based on the AVG scenario is approximately the same as the impacts averaged over the three GCM-based scenarios; the differences lay within ±1.6% interval at the three sites. Averaging of impacts based on all GCM, on which AVG scenario is based, showed even closer convergence with the results attained with AVG scenario. To reduce an amount of the calculations, it was decided to apply this scenario as an exclusive scenario in the adaptation analysis (chapter 5). Due to the above finding on the average impacts, the results obtained with this scenario are therefore expected to indicate the mean responses of the spring barley to individual adaptation options.

3.5. COMPARISON OF RESULTS OBTAINED IN INDIVIDUAL REGIONS

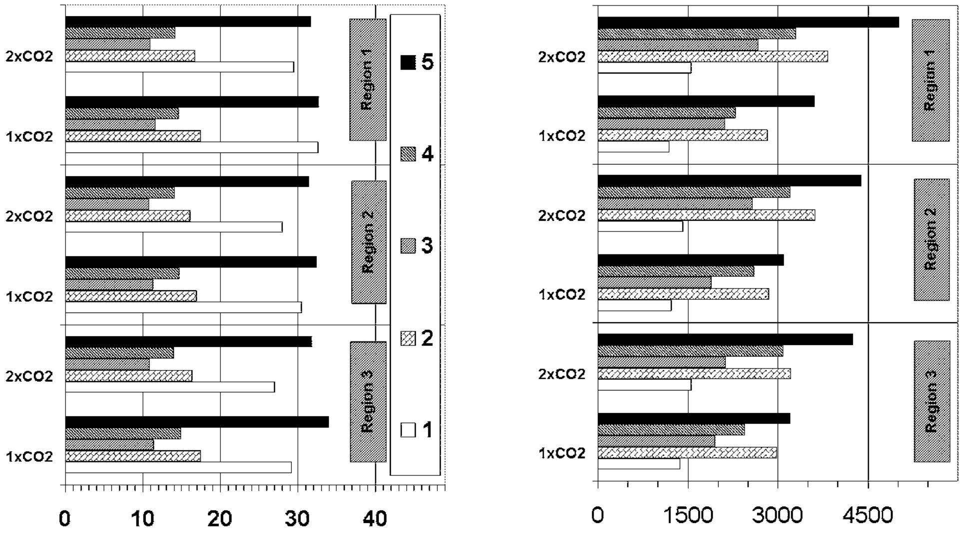
As might be seen in Figures 4a–c and in Table IV the trends of direct, indirect and combined effects of climatic change on stressed yields follow the same trends in all three regions. The magnitude of indirect effect does not vary significantly. The range of differences between the regions under the same scenario is within 0–7%. When the direct effect is quantified we can see significant deviations in individual regions. The highest yield increase (by 54–65%) is attained in warm and dry Region 1, while in Region 3, which is the coldest with highest precipitation; the magnitude of direct effect is by 17–23% smaller. Such significant difference is most likely caused by higher positive effect of increased WUE under dry conditions of Region 1. When both effects are combined the expected yield increase in Region 1 lays within 32–52%, while ‘only’ 13–41% increase is to be expected in Region 3. The same comparison for potential yield show 3–5% differences in combined effect magnitude in individual regions.

4. Effect of CO_2 Change on Other Growth and Development Characteristics

The studies of climate change impact on crops are mostly concerned with yields. However, biomass growth, occurrence of water stress during individual growth phases, duration of these phases, and maximum leaf area index (LAImax), are

(a) duration (days)

(b) biomass (kg.ha^{-1})



(c) water stress

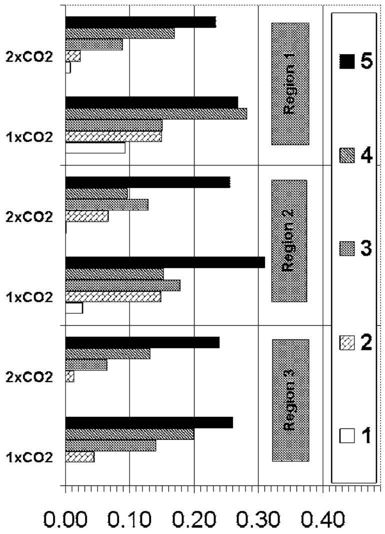


Figure 4. The means of the crop growth characteristics related to the five phenological phases (indicated by numbers 1–5 in the legend box) for each of the three test sites. The characteristics were calculated from the 99-year crop model simulations for doubled CO_2 ($2 \times CO_2$; both direct and indirect effects are considered) and present conditions ($1 \times CO_2$). Three panels relate to (a) duration of the phenological phase, (b) an increment to the biomass and (c) index of the water stress (value within $\langle 0, 1\rangle$ interval).

also worth examining in the impact assessments. The mean values of selected characteristics related to the five growth phases (considered by the CERES-Barley model) and the whole growing period, one climate change scenario (AVG) and two ambient CO_2 levels applied over three test sites are shown in Figure 4. The five phases are: (i) from emergence to the maximum primordium, (ii) from the maximum primordium phase to the beginning of ear growth, (iii) from the beginning of ear growth to the end of ear growth, (iv) from the end of ear growth to the beginning of grain filling, and (v) the linear grain filling phase.

4.1. CHANGES DURING INDIVIDUAL GROWTH PHASES

The first phase shows the most significant changes in duration (Figure 4a) regardless of region. Under the AVG scenario this phenological phase might be shorter by 2 days at Region 3 and up to 3 days shorter at Region 1. The shifts in the phenological phases might be more or less evenly distributed among phases as at Region 3, where the change of remaining phases oscillate around 6% or only one of the phenological phases might be significantly affected as at Region 1, where the shifts in the length of the phases with the exception of the first phase are 2–5% (or less than one day) making it hardly observable under field conditions.

The difference among regions is even clearer for biomass increase under $2 \times CO_2$ ambient air concentration and the AVG climate change scenario (Figure 4b). For Region 3 the first three phases show biomass increase in the range 9–13% and the final two phases increase by 25–30%. However Region 1 shows an increase of more than 25% (up to 44% in the fourth phenological phase).

The projections of water stress alterations under the changed climatic conditions (Figure 4c) can provide a valuable insight into the possible water stress occurrences under such climate. Generally the simulation results suggest a decrease of water stress especially in the first two phenological stages. During this early part of plant development, which takes place from March to May (depending on the region) the higher WUE almost completely diminishes the influence of water stress (under 10% level). However, with the temperature increase without adequate rainfall supply, the positive effect of higher WUE under $2 \times CO_2$ atmosphere is virtually consumed by increasing soil water depletion caused by higher potential evapotranspiration and by crop demands resulting inevitably into water stress. The magnitude of water stress in the final phenological stage is, however, still slightly smaller than under present conditions if the AVG scenario is considered.

4.2. CHANGES OVER THE WHOLE VEGETATION PERIOD

Increasing temperature sums will result in shortening of the crop phenological development resulting in the overall shortening of the vegetation period at all test sites by approximately 9 days. The overall increase of biomass during all phenological stages would lead to a significant 18–36% biomass increase under AVG scenario, which will be most pronounced at Region 1 reaching over 4300 $kg.ha^{-1}$ in absolute terms. The differences among regions in the previously mentioned parameter are almost 100% but the transformation of the above ground biomass into the grain yield somewhat reduces this difference. The expected yield increase at Region 1 equals about to 40% and the yield increase at Region 3 is expected to be 27%. Amount of total above ground biomass is closely interrelated with the maximum LAI value and therefore the increase of the maximum LAI is clear and logical. However, the expected values of the LAI (4.4 at Region 1; i.e., 37% increase in comparison with present conditions) do not exceed the values given by the literature sources (e.g., Kostrej et al., 1998).

5. Adaptation Analysis

Up to now, it was assumed that all input parameters except for the weather data and ambient CO_2 concentration are constant. However, the yields may apparently be modified by various management responses, such as adjustments in fertilization and irrigation regimes, applying soil water conserving management practices (such as mulching, appropriate crop rotation or minimum tillage eventually no-tillage methods), shifting the planting date and sowing density, or using other cultivars (IPCC, 2001; Bindi and Olesen, 2000; Harrison et al., 1995, Watson et al., 1995). The preliminary analysis was based on a field experiment with multiple treatments and also on the detailed sensitivity analysis. It was found that the CERES-Barley model simulates well variations in the sowing date, cultivar adjustments and also in the initial available water content. On the other hand, the model's ability to properly simulate the influence of the different sowing densities or different doses of nitrogen is not very promising under the conditions of the Czech Republic. The use of irrigation was not considered in the study, as it has never been widely used in the Czech Republic in the cereals production because of its high costs. The last frequently proposed adaptation measure, i.e., introduction of more suitable crop, was not considered, as the results did not show any need for such a step. Based on the above-mentioned experimental results, the following adaptation strategies were selected for further evaluation: change in the sowing date, use of the different cultivar and introducing soil water conserving practices. The figures presented in this section show only the results of the analyses at Region 2 as the results in the other two regions followed similar trends.

5.1. CHANGE IN THE SOWING DATE

The 99-year crop model simulations were run for present conditions (present levels of CO_2 and present climate) and for changed climatic conditions (doubled CO_2 concentrations and $2 \times CO_2$ climate according to AVG scenario) at water and nutrient limited conditions at three test regions. The value of the planting date (PD) varied within the interval (D_0 – 60 days, D_0 + 30 days), where D_0 is the planting date of the 'representative year' (Table II). It was assumed that soil and weather conditions would allow for the field operation to be done on the selected date. The main conclusions are:

(i) The model grain yields simulated in the present climate and ambient CO_2 concentration (Figure 5a) are rather insensitive to small changes in PD. Specifically, the median of the yields remains nearly constant if PD varies within (D_0 - 10 days, D_0 + 10 days). In contrast with the similar study carried out for maize (Žalud and Dubrovský, 2002), the probability that barley is damaged by a spring frost does not significantly increase in applying an earlier planting date. The interpretation of the results should be carefully considered as the ability of the model to simulate the frost damage is yet to be experimentally evaluated. On the other hand, if the planting date is delayed beyond D_0, the grain yields tend to decrease due to the shift of the vegetation period into months with higher temperatures and lower precipitation causing higher water stress during the grain filling phase and a shortening of this phase. In the case of the planting date being delayed by one month, the average grain yield decreases by 9.5% at all three regions with significant change in vegetation duration, which shortens by 13 days at Regions 1 and 2 whereas at Region 3 is shortened by 7 days.

(ii) The increase of the yields resulting from the changes in daily weather conditions in the 2 × CO_2 climates can be even enlarged by switching to an earlier planting date (Figure 5b). It is also possible to reduce yield variability (under the changed climatic conditions) by shifting the PD. However, mitigation is only partial, as the high temperatures occurring at the later phases of the crop development cannot be avoided by earlier planting and therefore will cause the adverse effect on the crop yield variability. For example in the case of Region 2 the simulated results suggest planting date shift by 45 days (from the 26th of March to the 9th of February) as the most suitable alternative. This change would lead to the prolongation of mean duration of the growing period from 116 days to 144 days (compare to 125 days in 1 × CO_2 climate) and to the mean yields increase by 3300 kg/ha in comparison with present ambient CO_2 (Figures 5(a,b); note that the graphs display quartile characteristics but the magnitudes of the indirect effect are calculated from the means), and by 1100 kg/ha at doubled ambient CO_2 (Figure 5b).

5.2. USE OF A DIFFERENT CULTIVAR

One of the most influential factors determining yield under the changed climatic conditions is thought to be an increase of temperature. High temperatures generally speed up phenological development of the crop and therefore leave less time for the yield formation. Even though the simulation results presented above suggest that higher WUE together with direct effect of the carbon dioxide will more than eliminate this negative influence, the search for maximum utilization of the climatic

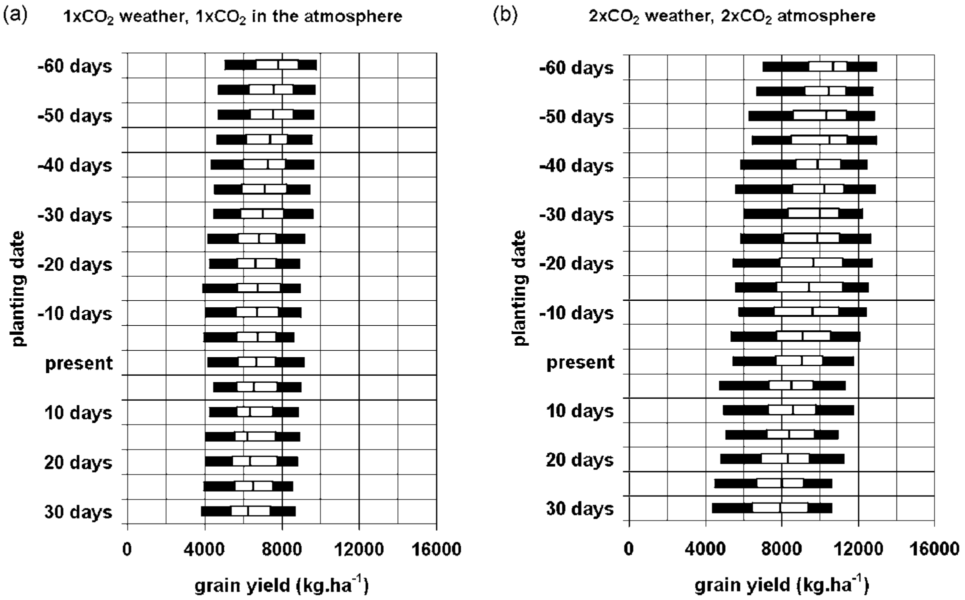


Figure 5. Adaptation to the climate change through the shift in the planting date at Region 2. The shift is given in terms of the deviation (in days) from the representative year's planting date (26th March). The bars represent quantiles (5th, 25th, median, 75th, 95th) of the model yields obtained in the 99-year crop model simulations for present and changed climate. The changed climate is represented by AVG scenario. The shaded bars relate to the representative year's planting date.

conditions in the sense of sustainable agriculture practices should continue. The length of the phenological stage is determined by the number of degree days and therefore the easiest way to encounter the shortening of the phenological phases due to the temperature increase is replacement of the currently used cultivars with those which need higher number of degree days to finish their phenological stages. Therefore, the genetic coefficients of the currently used and calibrated cultivar driving the phenological development were adjusted in such a way that they would prolong (shorten) the vegetation period under present conditions by 2 (5 days respectively). Impact of the modification was than evaluated in three regions based on the simulations for the present and changed climatic conditions (using AVG scenario) with the following results:

(i) The yields simulated in the present climate and ambient CO_2 concentration (Figure 6) show change of yields depending on the length of the vegetation of the cultivar used, showing yield 100 kg.ha^{-1} decrease per each day of shorter vegetation period. The opposite trend of the same magnitude was found when cultivars with a longer vegetation period were used in the simulations. The yield variability (expressed in terms of coefficient of variation) did not show any significant change. These results, especially the negative influence of the

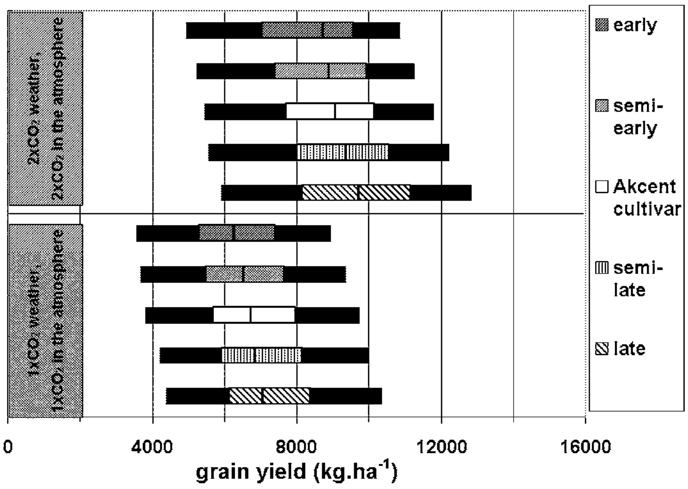


Figure 6. Adaptation to the climate change through the use of cultivars with different length of vegetation. Legend: early = 5 days shorter vegetation period than the presently used Akcent cultivar; semi-early = 2 days shorter; late = 5 days longer; semi-late = 2 days longer). The bars represent quantiles (5th, 25th, median, 75th, 95th) of the model yields obtained in the 99-year crop model simulations present and changed climate. The 2 × CO_2 weather is based on AVG scenario.

shorter vegetation period, correspond in most cases with the long-term results of the State Official Variety Tests (Jurečka and Beneš, 2000)

(ii) The effect of the increasing length of the vegetation period remains positive also under the 2 × CO_2 weather and 2 × CO_2 ambient air concentration adding some momentum to the late and semi-late cultivars yield gains already caused by the direct CO_2 fertilization effect and higher WUE efficiency. The magnitude of the change is higher than under present conditions i.e., about 150 $kg.ha^{-1}.day^{-1}$.

5.3. INTRODUCTION OF SOIL WATER CONSERVATION PRACTICES

The water content in the soil water profile represents the largest storage entity of water in the agriculture system under rainfed conditions. It acts both as source (for the crop) and the sink for (precipitation) and serves as a buffer as it saves water from irregular rainfall events and transforms it into a continuous source for the plants. The amount of water stored depends on physical soil properties (especially on the wilting point and field capacity), depth of the soil profile and on the precipitation regime for rain dependent agriculture system. The model structure respects these experimentally verified facts and the soil water available at the start of each simulation is one of the key predictors influencing crop growth. Careful and well-advised soil water management is therefore one of the key elements in producing high crop yields without the need of additional inputs (e.g., irrigation) under the present climate. A series of simulations were therefore carried out in

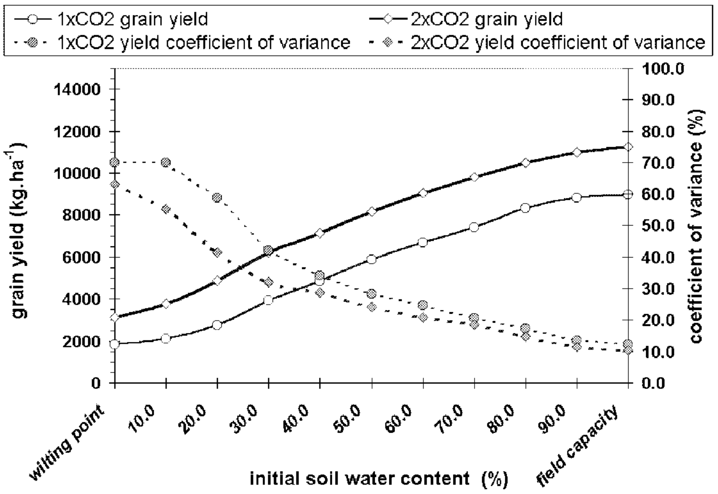


Figure 7. Sensitivity analysis of the water limited spring barley (cultivar Akcent) grain yield to different levels of initial available soil water (ISAW) at Region 2 under present and 2 × CO_2 climatic conditions (only AVG scenario was considered). Each point represents 99-year simulation that is described by the mean and the value of the coefficient of variance.

order to quantify the impact of the initial soil water content on the grain yield under present and changed (using AVG scenario) climatic conditions (Figure 7). The figure shows that the yield increase and their variability (represented by the coefficient of variance) decrease with increasing initial soil water content. These results are mainly due to water stress reduction especially during initial developmental stages. Under present CO_2 conditions, the yield increases by 101, 88 and 54 $kg.ha^{-1}$ per 1% of additional initial soil water content at Regions 1–3. Similar values of soil water relationship and yield were recorded for the changed climatic conditions, making it one of the key parts of any adaptation strategy. The soil water holding ability might increase by using proper soil tillage techniques for the given soil type and climatic conditions (Lampurlanés et al., 2001), straw incorporation (Singh et al., 1998) or mulching (Tolk et al., 1999). Higher soil water reserves can further enhance the production of spring cereals and at the same time eliminate to a certain degree the risk of prolonged drought spells.

All proposed adaptation strategies might be routinely introduced into day-to-day practice either on seasonal basis (as in case of sowing date) or within less than 10–15 years in case of new cultivars and introduction of water-conserving tillage systems (Reilly and Schimmelpfennig, 1999). In accordance with Mendelsohn (2000) these adaptation strategies would belong mostly to the private sector domain and therefore would have to be implemented on farmers not the state funds expense. Only in case of breeding more suitable spring barley cultivars partial involvement of public funds might be necessary.

6. Conclusion

The impacts of increased concentration of atmospheric CO_2 on spring barley growth, development, yield and effects of selected adaptation measures were analyzed in the study. The analysis was based on the multi-year CERES-Barley crop model simulations run with daily weather series created by the stochastic weather generator. The main results obtained in this study may be summarized in the following points:

(i) The evaluation tests show a very good fit between the observed and simulated spring barley yields at all three test regions.

(ii) The magnitude of the indirect effect related to changed weather conditions is negative except for the NCAR scenario at Regions 2 and 3. The differences between the magnitudes of the indirect effect related to individual scenarios are due to differences between the predicted changes of temperature and precipitation. The greatest decrease of the yields by 15–19% is related to the ECHAM scenario. On the other hand, the indirect effect of doubled CO_2 concentration is nearly zero (the yields would change by –2 to +5%) in case of the NCAR scenario that predicts the lowest increase of the temperature simultaneously with the highest increase in the precipitation. According to the remaining two scenarios (AVG and HAD), the stressed yields should decrease by 9–12.5% in the present concentration of ambient CO_2, and by 6–10% in the $2 \times CO_2$ atmosphere depending on the region.

(iii) The magnitude of the direct effect of increased CO_2 on the stressed yields is the result of mutual interactions of two mechanisms: intensified photosynthesis and better WUE. The stressed yields increase by 35–55% due to the direct effect in the present climate and by 25–65% in the $2 \times CO_2$ climates. In both cases the region factor is significantly influencing the magnitude of the yield increase.

(iv) The positive direct effect of doubled CO_2 dominates over the negative effect of changed weather conditions. The stressed yields under $2 \times CO_2$ conditions would increase by about 13–52% if both the direct and indirect effects were considered. The NCAR scenario implies the highest yield increments while the ECHAM scenario implies the lowest ones.

(v) The impacts of doubled CO_2 on potential yields are more uniform throughout the localities and scenarios in comparison with the stressed yields. The higher uniformity of the indirect effect (the yields change by –1 to –9%) is related to the fact that the potential yield simulations do not include influence of the water stress.

(vi) Magnitudes of direct and combined effects depend on both the applied scenario and on the present climatic and soil conditions of the region. Response to the same climate change scenario in individual regions expressed in terms of stressed grain yield might differ by 11–21%.

(vii) The decrease of the mean yields due to the indirect effect of doubled CO_2 may be reduced, and it might be even turned to increase, if the spring barley is planted 45–60 days sooner (compared to the planting date of the representative year). Application of the earlier planting date would result thus in an additional 15–22% increase of the yields in $2 \times CO_2$ conditions.

(viii) Adaptation to climate change through changing the cultivar showed the close positive correlation between the length of vegetation period of the cultivar and the grain yield. The relationship between the two quantities might be quantified by 1.5% yield increase per one extra day of spring barley vegetation season. No more than a 5-day increase of the vegetation period was considered owing to the fact that the difference between the standard and the latest cultivars commonly used in the Czech Republic is only 2 days.

(ix) The initial water content in the soil water profile proved to be one of the key elements determining the spring barley yield under the rainfed conditions: the yield increases by 54–101 $kg.ha^{-1}$ per 1% increase of the available soil water content. The highest sensitivity was found at the locality with the lowest rainfall and vice versa. The issue of the proper soil water management will therefore be important for sustainable production of high spring barley yields, i.e., without the need of additional inputs under the changed climatic conditions.

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