MODELLING OF INCREASED CO_2 IMPACT ON MAIZE YIELD

MODELOVÁNÍ DOPADU ZVÝŠENÉ KONCENTRACE CO_2 NA VÝNOS KUKUŘICE

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Abstract

The crop growth model CERES-Maize was used to estimate the effects of increased CO_2 and the related climate change on grain yields of maize. The analysis was based on comparison of the model yields obtained in multi-year crop simulation experiments run with weather series representing present and changed climate conditions. The synthetic weather series, representing a changed climate, were obtained by means of a stochastic weather generator (WG approach). The crop simulations were run under two environmental settings: stressed yields were simulated in water and nutrients limited conditions, potential yields were simulated in water and nutrients unlimited conditions. The direct (through increased fertilization effect of ambient CO_2) and indirect (through changed weather related to an enhanced greenhouse effect) effects of increased CO_2 on both stressed and potential yields in the simulated WG approach are assessed. The climate change scenario is based on the daily output from the equilibrium GCM experiment (ECHAM3/T42). The scenario includes changes in variability. Prior to the analysis, the crop model validation was performed showing very good fit between the observed and modelled yields of maize.

The results of the analysis show: (i) The stressed yields would increase by 36 - 41 % in a present climate and 61 - 66 % in $2\times CO_2$ climate due to the direct effect of doubled CO_2. Since the improved water use efficiency (WUE), which reduces the water stress, only insignificantly affects the yields in water and nitrogen unlimited conditions, the direct effect on potential yields is manifested only by 9-10 % increase. (ii) The model stressed yields are expected to decrease by 27-29 % at present concentration of ambient CO_2 (by 14-16 % in $2\times CO_2$ atmosphere) due to the indirect effect of doubled CO_2. The results of the sensitivity analysis suggest that the negative contributions come from changes in all individual weather characteristics for stressed yield. (iii) If both direct and indirect effects are considered, the

stressed grain yields should increase by 17-18 %, and the potential yields by 5-14 %. (iv) The magnitude of the indirect effect on the stressed yields may be reduced from −27 % to −17 % by applying earlier (1 month sooner compared to the present climate) planting dates.

Introduction

It is generally expected that the increasing concentration of greenhouse gases in the atmosphere will affect the climate in the forthcoming. The question stands what will be the effect of the climate change on various terrestrial ecosystems, e.g. agriculture, forestry, grasslands and water resources.

Increased CO_2 concentrations can affect crop growth in two ways. Firstly, the crop is directly affected by the presence of CO_2 in the ambient air. As atmospheric CO_2 is the primary source of carbon for the plants and its present concentration is suboptimal, the increased CO_2 concentration stimulates photosynthesis. Simultaneously, the transpiration intensity is reduced by partially closing the stomata which leads to improved water use efficiency (WUE) and thereby to lower probability of water stress occurrence. These physiological responses are known as the CO_2-*fertilisation effect* or the *direct effect* of increased CO_2. The experiments made in controlled environment indicate that crop growth should increase by about 14-11% for C_4 plants (e.g., maize) at doubled CO_2 (Kimball, 1983; Porter, 1992; Dhakhwa *et al.*, 1997). If the water is a limiting factor, the yields may increase much more than in non-limiting conditions due to additional effect of improved WUE.

The second effect of increased CO_2 is through changed climate and is referred to as the *indirect effect* or the *weather effect*. The weather variables that determine crop yield directly are solar radiation, precipitation and temperature. If no management response (e.g., other cultivar or shift of the planting date) is not applied, the maize yields typically decrease with increasing temperature due to shortening of the phenological phases. This paper aims to estimate the effect of expected climate change (induced by an increase of greenhouse gases concentration) on grain maize yields in the most fertile area of the Czech Republic. Crop model CERES-Maize is used in this study to simulate crop growth in present and changed climate conditions.

Methodology

Assessment of the climate change impacts on crop yields was made with the use of crop growth model run with weather series representing present and changed climates. In order the findings obtained by comparing model yields for the different climates have a statistical significance, multi-annual crop model simulations were run for each scenario and the descriptive statistics, such as means and standard deviations, or quantile characteristics, were determined and used for the impacts assessment. This approach is considered more resolute (in a statistical meaning) than using single values related to individual years. Although the quantiles are more robust and might be more appropriate (since the distribution of the yields may be far from normal and symmetrical), the usage of the averages and standard deviations may be more suitable in case the time series is not long enough (estimates of the quantiles are loaded by greater error).

Weather generator approach was created for climate change impact assessment. The input to the crop model consists of pedological, physiological and cultivation data taken from a single "representative" year and 99-year synthetic weather series created by the stochastic weather generator Met&Roll (Dubrovský, 1997). The representative year is defined by the typical values of all non-meteorological parameters (including the planting date, soil profile and details on the fertilisation regime) needed to run the model. Parameters of the weather generator derived from the observed series are used to generate weather series representing present climate, parameters of the generator are modified in accordance with climate change scenario to generate series representing changed climate. This method will be referred to as the weather generator (WG) approach.

In either approach, the yields in both limiting conditions (stressed yields) and non-limiting conditions (potential yields) were calculated, and both direct and indirect effects of increased CO_2 were assessed. The sensitivity of grain yields to changes in individual weather characteristics, and the relationship between the yields and the planting date were analysed .

Crop model

Crop growth model CERES-Maize version 3.0 (Jones and Kiniry, 1986) was used in this study. This model was developed within the frame of IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) project and was run within the DSSAT [Decision Support System for Agrotechnology Transfer, Hoogenboom *et. al.* (1994)] environment. The choice of the model follows its ability to simulate the real yield which is limited by the genetic potential of the crop, temperature, solar radiation, and available water and nutrients, and the potential yield which is limited only by the genetic potential of the crop, temperature and solar radiation. Moreover, the crop models from the CERES series are among the few crop growth models which allow to modify the environmental concentration of CO_2.

The model input data were based on the field experiments made during 1980-96 in Žabčice experimental station operated by the Mendel Agricultural and Forest University. The station is situated in the southeast of the Czech Republic (49°01′ N, 16°37′ E, 179 m above sea level), which belongs to the warmest and driest regions of the country. The 1961-90 mean annual temperature is 9.3 ºC and the mean annual precipitation during the same normal period is 480 mm (Rožnovský and Svoboda, 1995). Most of the parameters required as an input to the crop model simulation were measured and archived in this site.

The cultivar used in this study is Dea (origin PIONEER 3839, licensed from 1982), which is a middle early, two line hybrid with a FAO number of 300. The soil type of the experimental field is described as Oxyaquic Cryofluvents according to the classification of the US Department of Agriculture (Soil Survey Staff, 1975). The soil parameters were determined by Karpíšek and Prax (1989).

Observational weather data (daily series of *TMAX*, *TMIN* and *RAIN*) required for the crop model simulations were measured in Žabčice station, located approximately 1 km from the experimental field. Daily sums of global solar radiation were taken from the nearby (40 km apart) station in Kuchařovice. Based on analysis of one year measurements made in both stations parallely, it was found that the systematic deviation between the daily solar radiation sums measured in the two stations is 0%, and the standard deviation is about 10%. This is considered to be a sufficient accuracy for using the surrogate radiation data.).

Planting details, management factors and fertilisation regime were set a) individually for each year in the validation experiment b) constant for all simulation years in experiments. In both approaches, all these input data (except for the planting date in experiments) were the same for all climate change and CO_2 scenarios. In WG approach, the planting date was May 6, and four fertilisation dosages were applied (total amount of N was 110 kg/ha). Details on the previous crop, residue, tillage, rotation and chemical application were set according to the historical records. No irrigation was applied.

Results

Validation of CERES-Maize Model

In order the crop growth model may be used in the climate change impact study, proper validation must precede. This means that the model yields simulated with input data, which are based on the set of site-specific input parameters, satisfactorily fit the observed yields.

The grain yields simulated by the crop growth model with use of measured pedological, physiological, cultivation and meteorological data are compared with observed grain yields in Figure 1. Observational data from 17 years were available. The figure shows that the simulated maize yields well fit the observed yields for most of the years. On average, the model yields overestimate the observed yields by 17% and the standard deviation of the ratio of model to observed yield is 32%. The systematic overestimation could be caused by the occurrence of the non-simulated factors, such as harvest losses, pest and diseases, or by the occurrence of extreme weather events. Overall, the fit between simulated and observed yields is considered satisfactory and corresponds to studies by other authors (Hunkár, 1994; Iglesias, 1995; Guevara et al., 1999).

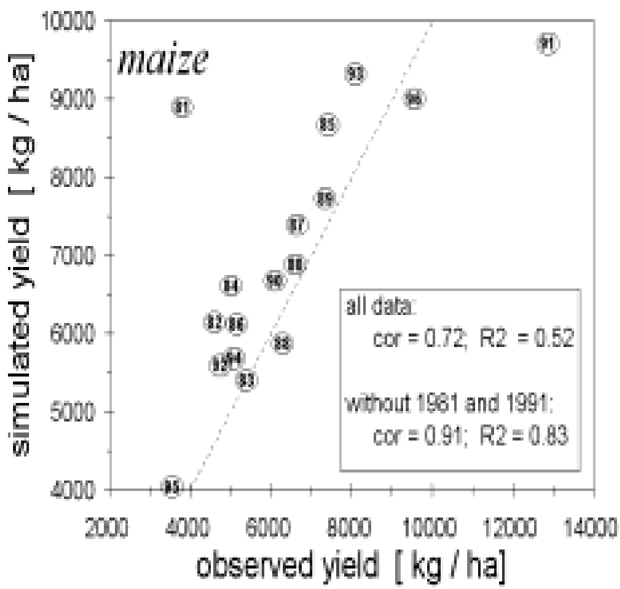

Fig.1. Validation of CERES-Maize model

Climate Change Scenario and Daily Weather Series

Regarding the limited availability and reliability of GCM data, the climate change scenario was constructed in a mixed way (Nemešová *et al.*, 1999). The scenario consists of coefficients which prescribe changes of the means of *SRAD*, *TMAX*, *TMIN* and *RAIN* and changes in standard deviations of *TMAX* and *TMIN*. The coefficients relate to individual months. The changes in the means and standard deviations of daily extreme temperatures are defined as the differences between the means and ratios of the standard deviations of respective characteristics derived from GCM [model ECHAM, version 3/T42, described in DKRZ (1993)] simulations of 2×CO_2 and 1×CO_2 climates. In the sensitivity analysis, seven subscenarios derived from the 2×CO_2 scenario were used.

Weather generator Met&Roll (Dubrovský, 1997) was used. The set of parameters [which includes (i) means and standard deviations of *SRAD*, *TMAX* and *TMIN*, determined separately for wet and dry days for each day of the year, (ii) lag-0 and lag-1 correlations among the standardised (conditionally on wet day occurrence) values of *SRAD*, *TMAX* and *TMIN* (annual cycle is not considered), (iii) probability of wet day occurrence and probability of wet day following a dry day (monthly), (iv) parameters of the Gamma distribution for modelling daily precipitation amount (monthly)] is derived from the observed series in the first step. The set of unmodified parameters is then used to generate series for present climate conditions. To generate series representing changed climate conditions is generated, the parameters of the generator are modified according to the climate change scenario.

The direct, indirect and combined effects of CO_2 change

It seems the positive effect on the yields of the better WUE due to increased CO_2 will be greater in 2×CO_2 weather conditions. The magnitude of the direct effect of increased CO_2 is greater than the magnitude of the indirect effect, so that the superposition of both effects implies positive change in maize yields in increased CO_2 conditions. The mean model stressed yields increase by 17-18% in 2×CO_2 conditions. The potential yields increase by 5-14% in 2×CO_2 conditions (figure 2)

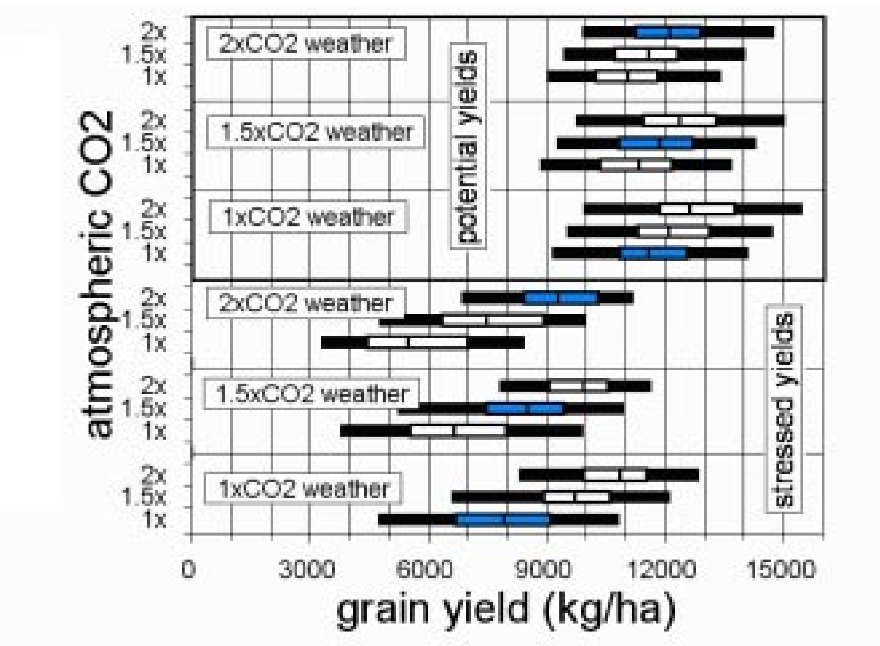

Fig. 2: Potential and stressed yields simulated with stochastically generated weather. Bars represent quantiles (5th, 25th, median, 75th, 95th) from 99-year simulations.

Stressed vs. potential yields

Effects (both direct and indirect) of varying CO_2 on potential yields are much less pronounced than those in water and nitrogen limited conditions (stressed yields). For example, the direct effect of doubled CO_2 on potential yields is 9-10% (compare with 36-66 % in stressed conditions) and the indirect effect is −4% (compare with minus 14 to minus 27% in stressed conditions). In contrast with the stressed conditions, the direct and indirect effects on potential yields are mutually additive (the percentage magnitude of direct (or indirect effect) is same for all weather regimes (all CO_2 levels). This is explained by the water stress which causes unlinearities in trends of the stressed yields but misses in simulating the potential yields. For further interpretation, the index of production potential, *Z* (Žalud 1999), will be introduced. The value of the index will be defined as a ratio of stressed and potential yields under given weather conditions and ambient CO_2 concentration

$$Z(w,c) = Y_S(w,c)/Y_P(w,c) \times 100\% \quad (1)$$

This index may serve as a measure of impacts of limiting factors on the grain yields. The value of *Z* is always greater than 0% and lower than 100%. The zero value of *Z* would mean that the stress totally inhibits the growth, *Z*=100% would mean that no stress affects the yields. It is seen from figure 2, that *Z* increases with increasing intensity of the direct effect but decreases with increasing intensity of the indirect effect. If the both effects are combined, the index of production potential slightly increases with increasing CO_2.

Sensitivity of Model Yields to Changes in Individual Climatic Characteristics

Since the prognosed changes in individual climatic characteristics are affected by different errors, the sensitivity analysis was made to estimate impact of separate components of the climate change scenario.

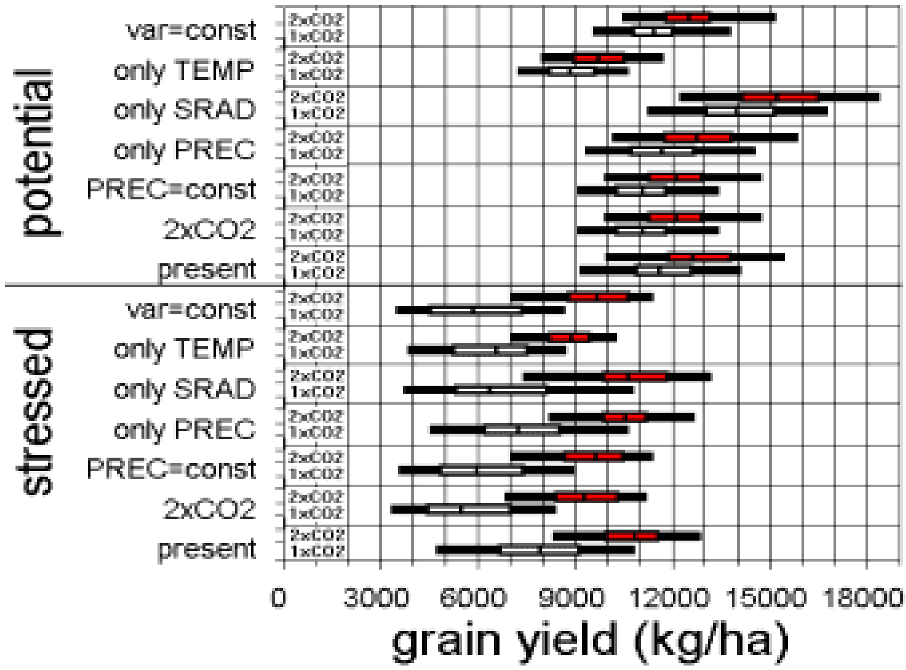

Fig. 3: Effect of changes in individual weather characteristics on model grain yields *[The bars are 5th, 25th, 50th, 75th, 95th) quantiles from 99 years],* the scenarios are described in Dubrovský *et al*., 2000, this volume) in detail.

In each climate sensitivity scenario, only selected climatic characteristic(s) was (were) modified and the 99-year crop model simulation was run for both potential and stressed conditions, and for both $1\times CO_2$ and $2\times CO_2$ concentration in the atmosphere. The results are displayed in figure 3.

Adaptation to climate change by shifting the planting date

Up to now, it was assumed that all input parameters except for the weather series and ambient CO_2 concentration are constant. However, the yields may apparently be modified by various management responses, such as adjustments in fertilisation and irrigation regimes, shifting the planting date, or using other cultivar. Only the shift of the planting date (PD) is considered in the present study.

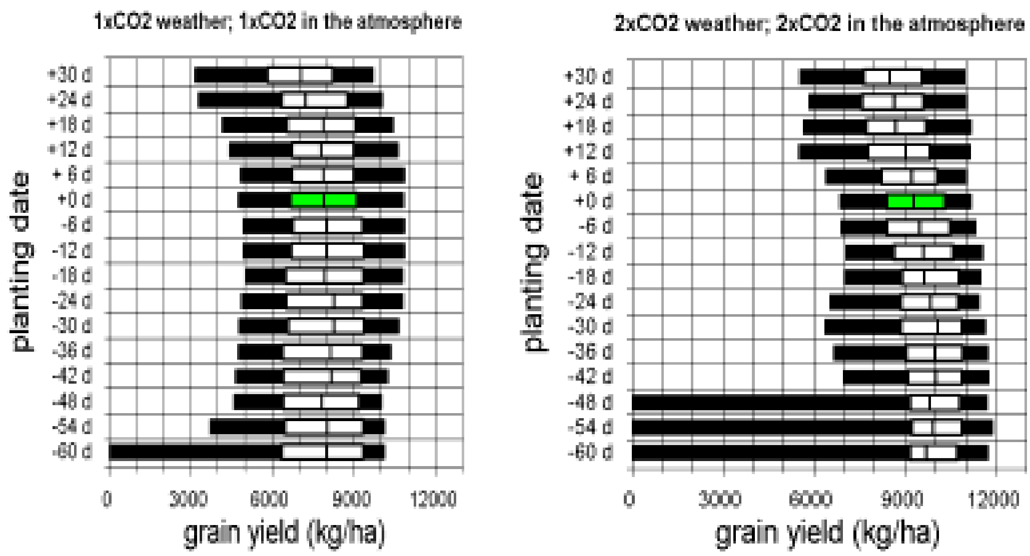

Fig. 4. Effect of the planting date on maize yield

The 99-year crop model simulations were run for two CO_2 levels and two climates (present climate and $2\times CO_2$ climate), at water and nitrogen limited conditions. The value of PD was varied within interval $<D_0 - 60$ days, $D_0 + 30$ days$>$, where $D_0 = 126$ (May 6) is the planting date of the “representative year”. The results displayed in figure 4 show: (i) The model grain yields simulated in present climate conditions are rather insensitive to small changes in PD. Specifically, the median of the yields remains nearly constant if PD varies within $<D_0 - 60$ days, $D_0 + 18$ days$>$. In case of the earlier PD, the probability that the yield is damaged by a spring frost increases: one zero yield occurs in the 99-year series if PD = D_0, but three (six) zero yields occur if PD = D_0-36 (D_0-60). On the other hand, if the planting date is delayed beyond D_0, the grain yields tend to decrease due to the occurrence of the autumn frosts which precociously terminate the grain filling phase. In case of the planting date delayed by 1 month, the average grain yield decreases by 11%. (ii) The decreases of the yields resulting from the changes in daily weather conditions in $2\times CO_2$ climate, especially from the increased temperature, might be partially compensated by applying earlier planting terms.

Conclusion

The impact of climate change related to increased CO_2 concentration was studied in this paper. Two effects of increased CO_2 were distinguished. The direct effect is related to the functioning of increased CO_2 concentration in the ambient air and is manifested by increased rate of photosynthesis and improved water use efficiency. The indirect effect is related to changed weather conditions in the $2\times CO_2$ climate. While the indirect effect is closely related to the crop and location and cannot be easily compared with studies by other authors, the direct effect is much less site-dependent and may be compared to other studies. As the model yields are affected by water and nutrient stresses which depend on weather conditions in a rather complex manner, and, moreover, may be mitigated by adjustments in regime of irrigation and fertilisation, the yields were simulated in two model settings. The stressed yields were modelled with water and nutrient routines switched on, and the potential yields were modelled with the water and nutrient routines switched off. In the latter settings, the crop is given as much water and nutrients as it needs. The analysis of results obtained in both settings allows to better reveal the role of changes in individual weather characteristics and ambient CO_2 on the crop growth and development.

Abstrakt

Dlouhodobý polní experiment kukuřice na zrno byl využit pro kalibraci a validaci růstového modelu CERES-Maize. Experimentální místo je situováno do lokality Žabčice polní pokusné stanice školního zemědělského podniku MZLU v Brně. Modifikací meteorologických údajů naměřených na stanici a jejich využitím pro simulace růstovým modelem byl posouzen přímý, nepřímý a kombinovaný efekt změny klimatu na výnos kukuřice. Statistické parametry meteorologického generátoru byly odvozeny z pozorovaných meteorologických dat a upraveny podle scénáře změny klimatu. Byla provedena citlivostní a adaptační analýza pro posouzení významu jednotlivých meteorologických prvků, koncentrace CO_2 a doby setí. na výnos kukuřice. Výsledky naznačují, že pozitivní efekt zvýšení koncentrace CO_2 bude vyšší než negativní vliv změny meteorologických parametrů, který může být dále zmírněn posunem doby setí k začátku roku.

Key words: maize; simulation; yield; climate change; sensitivity and adaptation analysis

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