A local simulation study on the impact of climate change on winter wheat production in north-eastern Austria

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Eine lokale Simulationsstudie über den Einfluss einer Klimaänderung auf die Winterweizenproduktion im Nordosten Österreichs

1. Introduction

The methodology of dynamic modeling allows a quantitative and qualitative approach to simultaneous and interacting processes in natural systems and is therefore often used in studies of the impact of climate change on ecosystems (CURRY et al., 1990). Theories about processes in the soil-crop-atmosphere system that have emerged from experimental work can be integrated into mechanistic crop simulation models, so that the consistency of the theory can be tested (VAN KEULEN and WOLF, 1986). Such models are necessarily simplified representations of natural processes (DE WIT, 1986; HANKS and RITCHIE, 1991; PENNING DE VRIES et al., 1989) and cannot fully describe the behaviour

Zusammenfassung

Das WOFOST Pflanzenwachstumssimulationsmodell wurde für eine Winterweizensorte an einem Standort im Nordosten Österreichs (Marchfeld) evaluiert. Um den Effekt einer Klimaänderung auf das Wachstum und den Ertrag von Winterweizen abzuschätzen wurden die jeweiligen potentiellen und aktuellen Erträge simuliert. Der Effekt der Bodenwasserspeicherfähigkeit wurde durch eine Sensitivitätsanalyse bestimmt. Die Ergebnisse zeigen, dass der kombinierte Effekt einer Klimaänderung bei unveränderter Produktionstechnik und in Abhängigkeit der in dieser Studie definierten Bodenwasserspeicherfähigkeiten bei Winterweizen eine Ertragssteigerung um 30–55 % verursachen wird. Das Produktionspotenzial zeigt, dass trotz der bei höheren Temperaturen verkürzten Vegetationsperiode des Winterweizen ein signifikanter Einfluss der Bodenwasserverfügbarkeit gegeben ist. In Kombination mit dem insgesamt höheren Verdunstungspotenzial unter zukünftigen Klimaszenarien werden wassersparende Produktionsverfahren im Pflanzenbau in Zukunft eine wichtige Rolle spielen.

Schlagworte: Winterweizen, WOFOST Modell, Klimaänderungsauswirkungen, Pflanzenwachstumsmodellierung, Produktionspotenzial.

Summary

The WOFOST crop model was evaluated for a winter wheat cultivar at a location in north-eastern Austria (Marchfeld). Water-limited (rainfed) and potential yields were simulated in order to estimate the effect of climatic change scenarios on crop growth and yield. The effect of soil water storage capacity was estimated by a sensitivity analysis. The overall results show that the combined effect of climatic change will lead to an increase in winter wheat grain yield of 30–55 % based on the current production technique and depending on the defined available soil water storage capacity of the soils used in our study. The production potential shows the significant impact of soil water availability on yields even under a shortened vegetation period of winter wheat, which is caused by higher temperatures. In general, water-saving techniques in plant production will be very important under future climatic conditions through higher evapotranspiration potential.

Key words: winter wheat, WOFOST crop model, climatic change impact, crop modelling, production potential.

of the real system (SPITTERS, 1990), which means that there is a certain degree of uncertainty in the model results. Uncertainties in model outputs are also caused by the model input parameters themselves, especially by their spatial representativeness (AGGARWAL, 1995; BOUMAN, 1994; EITZINGER und DIRMHIRN, 1994; NONHEBEL, 1993). However, when assessing the uncertainties and limitations of climate change impact studies as a whole, a number of other factors have to be taken into account, since the application of crop models in these studies is just one of the causes of uncertainties (CARTER et al., 1999).

The evaluation of ecological models such as crop models is an important precondition for their use for various applications (ADDISCOT et al., 1995; PENNING DE VRIES, 1977), especially in climate change impact studies, in order to reduce the related uncertainties. It involves validation, in other words verification through comparison of model predictions with results from independent field experiments (HAMILTON, 1991; DE KONING et al., 1993; POWER, 1993). A sensitivity analysis illustrates the response of a model to systematic variations in model inputs (HAMBY, 1994; IMAN and HELTON, 1988; JANSSEN, 1994) and shows us how the validation process might be extended to a broader range of environmental conditions, if model results are unrealistic. However, it also shows us how the simulated system, including crop growth, may react to a change in certain environmental parameters such as a changed climate (EASTERLING et al., 1992a, b; GOUDRIAAN and HUNT, 1995; MEARNS et al., 1996).

Crop simulation models are therefore used frequently to estimate the impact of climate change on agricultural production and crop growth and to assess vulnerability of agro-ecosystems in different regions. Several related studies have been published for different regions in Europe taking into account a number of important crops (e.g. ALEXANDROV, 1997; EITZINGER and ŽALUD; 1995; HARRISON et al., 1995; VAN DIEPEN et al., 1990; ŽALUD et al., 1999). As cereals are among the main agricultural crops in Europe, several impact studies have been carried out especially for winter wheat, taking into account a number of climate change scenarios for different regions and environments, crop models, crop cultivars and management practices. Although there are significant regional variations, in general an increase in simulated water-limited and potential winter wheat yields using different crop models on different scales in Europe has been reported (DOWNING et al., 2000; SEMENOV et al., 1993; WOLF, 1993). For example, a continental scale simulation study showed an increase in water-limited (rainfed) wheat yields of 0.1 to 4.5 t ha^{-1} under most of the available climate change scenarios (DOWNING et al., 2000). Most of the simulations were based on current management practices, defined cultivars and soil conditions, and considered the 'combined effect' which includes both the direct (impact of CO_2 fertilization) and indirect (impact of climatic parameters) effect on crop growth. These results therefore reflect the positive effects of elevated CO_2 on photosynthesis and water use (GOUDRIAAN and UNSWORTH, 1990; PINTER et al., 1996), which generally outweigh any negative effects from higher temperatures reducing the length of vegetation period and especially the length of the grain filling period. Nevertheless, some of the studies predict significant decreases in simulated water-limited winter wheat yields at some locations such as Hungary (HARNOS et al., 2000). This could be explained by several factors, such as the available soil water storage capacity, which can have a marked effect on simulation results, depending on the model itself and the simulated occurrence of water stress (BROOKS and SEMENOV, 2000; EITZINGER et al., 2000a). However, recent impact studies using the CERES wheat crop growth model have confirmed increasing winter wheat yields under the combined effect and for different climate change scenarios for north-eastern Austria (ALEXANDROV et al., 2000). In our study this regional trend was further investigated using a different crop model and focusing on the impact of soil water storage capacity (in a range representing main arable soil types of the selected region) on predicted yields under potential future climates.

2. Aims and methods

The aim of the study was to evaluate and validate the WOFOST crop model for a representative site in north-eastern Austria (Marchfeld). The crop model was used to assess the impacts of elevated CO_2 concentration and the related change in climatic conditions predicted from different global circulation models (GCMs) on grain yield and length of vegetation period of winter wheat. A sensitivity analysis of simulated winter wheat yields for available soil water retention capacity and initial available soil water content using the WOFOST model was carried out to relate the results to a certain range of soil conditions in the region. Finally, the production potential, which is defined as the relationship between simulated water limited yield and potential yield, for present and changed future conditions was estimated.

2.1 Location and database

The study site is located in Marchfeld plain (48°12' N, 16°34' E), an area of intensive arable agricultural production north-east of Vienna. The site is 153 m above sea level. The long-term yearly average air temperature is 9.9 °C and the yearly average precipitation is 527 mm. The agroclimatic conditions of this region were described in detail by MÜLLER (1993). Daily meteorological input data for the WOFOST model (global radiation, air temperature, vapour pressure, wind speed and precipitation), measured at the standardized station in Gross-Enzersdorf for the period of 1960 to 1999 were provided by the Central Institute for Meteorology and Geodynamics, Vienna, Austria. The soil at this site is loamy sand and sandy silt loam, which is typical for the Marchfeld region. However, there are large spatial variations in soil water storage capacity and no groundwater impact on the top soil layers in most of the region. Based on the data on measured grain yield and length of vegetation period from field experiments in Marchfeld, which were available for the whole period of 1985 to 1999, the Austrian registered winter wheat variety 'Perlo' was selected for model validation. 'Perlo' is a well established cultivar, adapted to relatively dry and warm regions such as eastern Austria. The annual nitrogen input for the wheat field experiments during the whole period was 80 kg/ha.

2.2 Climate change impact assessment methods

Most climate change studies use estimates of regional climate change from GCMs (IPCC, 1997; TEGAERT et al., 1990, WATSON et al., 1996). The major advantage of using GCMs as the basis for creating climate change scenarios is that they are the main tool for estimating changes in climate due to increased greenhouse gases for a large number of climate variables in a physically consistent manner (e.g. IPCC-TGCIA, 1999). At least three GCMs should be used for creating regional climate change scenarios. If only one GCM scenario is used, the results look as if they are predicative. Where two CGMs are used, there are sometimes only minor variances between scenarios (ANL, 1994). The Data Distribution Centre (DDC) of the Intergovernmental Panel on Climate Change (IPCC) was established to facilitate the distribution of a consistent set of up-to-date scenarios of changes in climate and related environmental and socio-economic factors for use in climate impacts assessments (IPCC DDC, 1999). The 30-year averaged GCM monthly meteorological outputs in this study were provided by the IPCC DDC for the period 2070–2099, referred to as the 2080s. The GCMs used in the study include the models from the Max-Planck Institute for Meteorology (ECHAM4), UK Hadley Centre for Climate Prediction and Research (HadCM2), Canadian Centre for Climate Modeling and Analysis (CGCM1) and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO-Mk2b). The simulated results from the "business as usual" scenario, greenhouse gas and sulphate aerosol forced GCM experiments were used in the study (IPCC DDC, 1999). The ECHAM4 outputs included only a greenhouse gas experiment, without assuming the cooling aerosol effect. Monthly air temperature, precipitation and solar radiation values for the future climate in the region of north-east Austria (Marchfeld) were calculated by linear averaging using the inverse of distances between the specific points and the nearest four GCM grid points (ANL, 1994). According to the GCMs used in the study, annual temperatures in the selected region of Marchfeld are expected to rise between 3 °C and 4.8 °C in the 2080s (Fig. 1a). Most of the GCMs show higher increases of air temperature during winter and summer than in the spring. In general, precipitation is expected to increase during the cold half of the year and to decrease slightly during the warm half of the year. The CSIRO-Mk2b model even simulated a decrease in precipitation only in August (Fig. 1b). The changes in monthly solar radiation are expected to be mainly in the range of –10 % to 10 % at the end of the 21st century.

The 2080s GCM scenarios were applied to the baseline climate, which is the normal period of recorded weather data from 1961 to 1990, and to which all differences were related. All four GCMs provide monthly mean output data. As the WOFOST crop model requires daily weather input data, the GCM outputs were converted into daily data using the incremental approach (ANL, 1994). Each of the 30 years from the normal weather period (1961–1990) were modified according to the monthly outputs of the GCM models used in our study (ECHAM4, HadCM2, CGCM1 and CSIRO-Mk2b). The modified 30-year weather series, representative for the 2080's, were then used as the input weather data for the crop model in combination with a representative year input data. The representative year contained fixed crop management, crop cultivar and soil type and was used for both present and changed weather conditions.

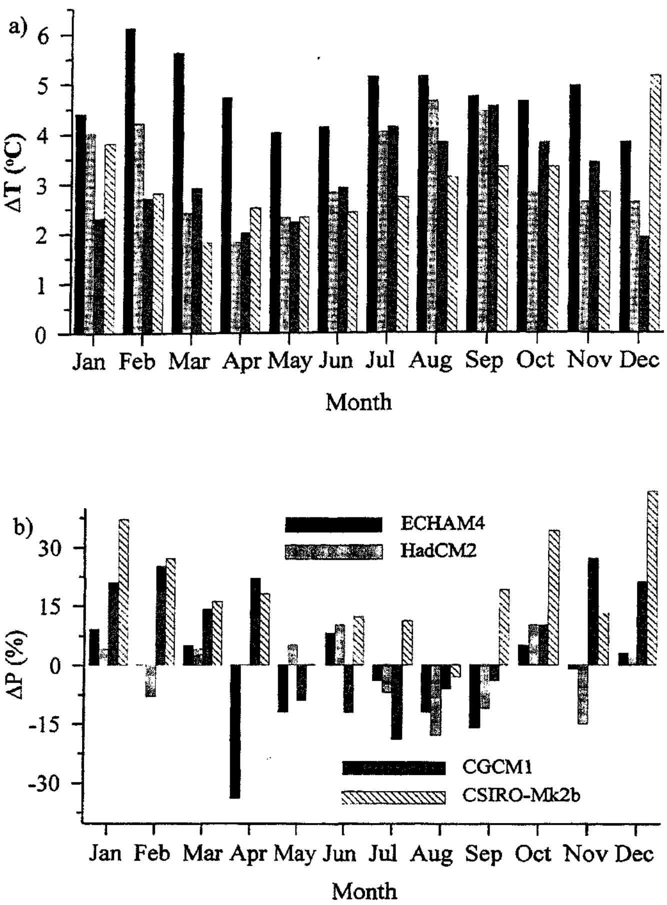

Figure 1: GCM climate change scenarios for a) air temperature (ΔT) and b) precipitation (ΔP) in the 2080s for the region Marchfeld, north-eastern Austria

Abbildung 1: GCM Klimaänderungsszenarien für a) Lufttemperatur (ΔT) und b) Niederschlag (ΔP) der 2080er Jahre in der Region Marchfeld, nordöstliches Österreich

2.3 The WOFOST crop model

The WOFOST (WOrld FOod STudies) explanatory and dynamic crop model, Ver. 6.0 was used in our study (SUPIT et al., 1994; VAN DIEPEN et al., 1989). This model was developed by the DLO-Winand Staring Centre and Research Institute for Agrobiology and Soil Fertility in Wageningen and has been frequently evaluated and used in European climate change impact studies on agricultural crop production (e.g. EITZINGER et al., 2000b; VAN DIEPEN et al., 1990; WOLF and VAN DIEPEN, 1991). WOFOST is a member of the family of models developed in Wageningen by the school of C.T. de Wit. It is designed to simulate the growth and development of annual field crops and grass during the growing season, from sowing to maturity or harvest in daily increments. It simulates a cropping system defined by crop, the weather conditions and the soil parameters, including the plant and soil water balance. Outside the crop-growing period the soil water balance can be calculated for bare soil conditions. The major processes taken into account are phenological development, assimilation, respiration and evapotranspiration. WOFOST uses parameters and functions describing the effects of temperature, radiation and water stress on important physiological crop processes as a function of the development stage and crop status. For example, the photosynthesis response curve is limited by a maximum leaf CO_2-assimilation rate and initial light use efficiency of a single leaf. These parameters are further related to temperature at a specified carbon dioxide concentration. Biomass partitioning is a function of the development stage of the crop, while temperature determines the development rate of the crop.

The model is designed for simulation of three production levels. The potential yield production level is limited only by temperature, solar radiation and the specific physiological plant characteristics. Such conditions are possible in greenhouses or in very intensive agricultural production systems (e.g. under field conditions with optimum irrigation and nutrition). At the water-limited production level (for rainfed conditions), the soil and plant water balance is also included in the simulation of crop growth with the interactions between transpiration, stomata opening, CO_2 assimilation and water uptake being considered. The third production level is also limited by nutrients. Only two production levels (potential and water-limited) were considered in our study. WOFOST uses only one homogeneous soil profile for calculating soil water balance, as it is designed to be used for climate change impact studies of wide regions, where only limited soil data are available (using average soil characteristic data). However, the most important related soil parameter for the model, the available soil water capacity, can be described in this manner easily. Calculation of evapotranspiration is based on Penman-Monteith and is taking into account the effect of increased evaporation under higher temperatures as well as the effect of enhanced water use efficiency of plants under elevated CO_2-levels. Interception is calculated as a function of Leaf Area Index.

2.4 Crop model evaluation and sensitivity analysis

The model was evaluated for our location by adapting soil and crop model input parameters. The closest matching soil type from the original model data set was modified according to measured soil profile characteristics of the location. Crop input parameters were adapted through model calibration using measured grain yield and length of vegetation period of the winter wheat cultivar 'Perlo'. The model was validated on an independent data set for the period 1985 to 1999.

After evaluation of the crop model using the local soil profile data designated as 'medium' soil, two other virtual soil profiles, called 'light' and 'heavy' soil with significantly different soil water storage capacities (Table 1) were defined as inputs for a sensitivity analysis on winter wheat production under current and changed climatic conditions. These three defined soil types should reflect the range of available soil water capacities of the most important soils in the region. The model sensitivity to another important parameter, the initial available soil water at the beginning of the simulation, was evaluated for the CGCM1 scenario only.

3. Results and discussion

3.1 Crop model validation

The results of the WOFOST model validation, based on observed data from 1985 to 1999, were as follows. The calculated length of vegetation period correlated well with the real observed data, but in some years (1986, 1992 and 1993) larger differences (11–14 days) were noted (Fig. 2). In the years 1986, 1991, 1992, 1993 and 1996 the observed growth duration was clearly shorter than the simulated growth duration. This may be attributed to accelerated maturing caused by disease or drought. 1986 was a rather wet year, 1993 was a very dry year. In 1990 and 1994 the observed duration was longer than the simulated duration. This may be caused by mild winters, leading to continuing phenological development according to the model, while in reality the development is halted, because of winter dormancy. However, the mean difference was only 1 day and in an acceptable range of 0 to 8 days excluding the three extreme years. Detailed and reliable experimental data on crop growth and development are important as shown by the fact that phenological development is closely related to biomass production and final yield, which has to be represented well by the model (e.g. COLSON et al., 1995).

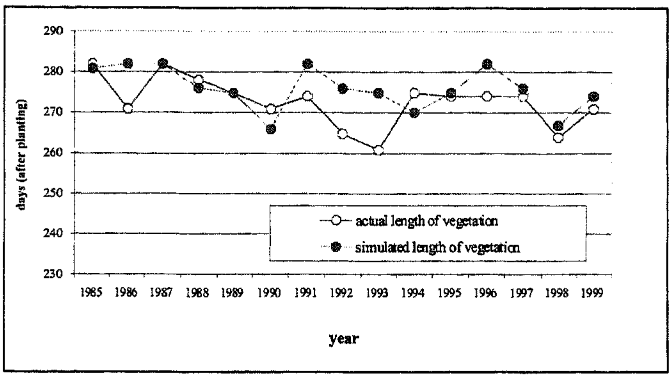

Figure 2: The comparison of the actual and simulated (WOFOST) length of vegetation (winter wheat cultivar 'Perlo' on medium soil, Obersiebenbrunn, Marchfeld 1985–1999)

Abbildung 2: Vergleich der beobachteten und simulierten (WOFOST) Länge der Vegetationsperiode (Winterweizensorte 'Perlo' auf mittelschwerem Boden, Obersiebenbrunn, Marchfeld 1985–1999)

Potential and water-limited (rainfed conditions) simulated yields compared with actual yields of winter wheat from 1985 to 1999 are shown in Fig. 3. The statistical comparison of measured and simulated yields (Table 2) shows that the calculated potential yield level was higher and the variation coefficient of the potential yearly grain yield was much smaller than for the actual yield. The lowest yields and highest

Table 1: Basic soil physical parameters of the three defined soil types used as model inputs in our study. Data represent mean values for the maximum rooting depth (only one homogeneous soil layer is considered in the WOFOST model).

Tabelle 1: Charakterisierung der wichtigsten bodenphysikalischen Parameter der in der Studie definierten Böden. Angaben sind mittlere Werte über den maximalen Wurzelraum (Modelleingabedaten, da im WOFOST Modell nur eine homogene Bodenschicht berücksichtigt wird).

soil type[1]	Water content at wilting point (%Vol.)	water content at field capacity (%Vol.)	water content at saturation (%Vol.)	bulk density (g/ccm)	maximum potential rooting depth (cm)	maximum available soil water storage capacity (mm)
medium soil	11	28	46	1.45	150	260
heavy soil	11	38	44	1.51	150	405
light soil	12	28	46	1.45	75	120

[1] Medium soil data are based on real soil profile data from the region, the other two soils are constructed to cover a wider range of available soil water storage capacity representing other important soils in the region.

variability in grain yields are shown for the measured actual yields from the field experiments, which correspond well with the literature (e.g. WOLF, 1993). One reason for this is that in simulations of potential yields all conditions are assumed to be optimal. Simulated actual yields are limited only by water shortage, and no diseases, damage or other limitations are considered by the model. However, the variability of the simulated water-limited yields in comparison with actual data was very similar, confirming optimum growth conditions in most of the years. In years where drought periods caused plant water stress, as in 1993, there was an obvious and significant difference between actual and potential yields. In some years (1985, 1986 and 1996) there was a large difference between actual yield and simulated water-limited yield, which was the result of a growth limitation (AGGARWAL et al., 1994) not considered by the model. However, the average for all the years showed that the actual yield level was 15.1 % lower than the mean simulated water-limited yield. The model validation can therefore be regarded as good, especially since the yearly trends are also represented well, as shown in Fig. 3. The remaining differences can be explained by non-representative input data (for example the initial soil water content or crop coefficients) or by other factors not considered by the model (shortage of nutrients, diseases, pests, high intensity rains and other damage).

Table 2: Basic statistical yield data for simulated and measured winter wheat grain yield on medium soil in Obersiebenbrunn, Marchfeld (Austria) during 1984–1999

Tabelle 2: Statistik des simulierten und gemessenen Winterweizenertrages auf mittelschwerem Boden in Obersiebenbrunn, Marchfeld (Österreich) von 1984–1999

	Observed yields	Simulated – water limited yield	Simulated – potential yield
Mean *(kg/ha)*	6202	7137	7969
standard deviation *(kg/ha)*	1389	1200	547
variation coefficient *(%)*	22,4	16,8	6,9

3.2 Local climate change impact assessment

The impact assessment study on winter wheat was based on the local conditions for the 'medium' soil type (Table 1). The representative year for the crop management input

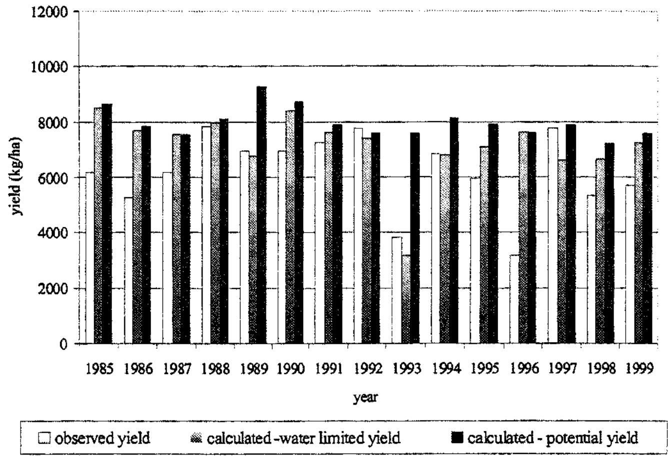

Figure 3: Simulated potential and water-limited yield compared to actual grain yield (winter wheat cultivar 'Perlo' on medium soil, Obersiebenbrunn, Marchfeld 1985–1999)

Abbildung 3: Simulierte potentielle und aktuelle Erträge im Vergleich zum gemessenen Ertrag (Winterweizensorte 'Perlo' auf mittelschwerem Boden, Obersiebenbrunn, Marchfeld 1985–1999)

data was defined on the basis of field experiment data. The winter wheat sowing date was set between 7 to 17 October. The initially available soil water (as a function of maximum rooting depth) at sowing date was calculated from available data and previous simulations and set at 100 mm for the local (medium) soil type. The simulation results for the direct effect ('fertilizing' effect of CO_2), the indirect effect (change in weather characteristics only) and the combined effect of a changed climate according to the different GCM scenarios for the 2080s are presented in Fig. 4 and 5. It should be emphasized that the following results simulated by the crop model are valid for the winter wheat cultivar 'Perlo' or for cultivars with similar characteristics only.

All considered GCM scenarios predict an increase in temperature (Fig. 1a) which is the main factor influencing the phenological development. Increasing temperatures raise the development rate of the crops, resulting in a shorter vegetation period. Normally in such cases, the total sum of carbon assimilation is also reduced, resulting in declining biomass production for annual crops (e.g. PENNING DE VRIES et al., 1989; ZHANG, 1993). According to our results a significant shortening of the vegetation period can be expected (Fig. 4). In all the scenarios the vegetation period was shortened by 28 to 37 days, with the yearly variation of this important value being twice as high as under present conditions. On average, our simulations showed that winter wheat would mature 242 to 253 days after sowing depending on the scenario, i.e. in mid-June.

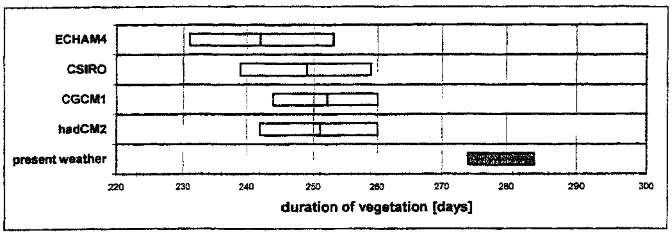

Figure 4: Duration of vegetation (average and standard deviation) of winter wheat cultivar 'Perlo' modelled by WOFOST in 30 years simulation with incremental weather series for 2080's based on HadCM2, CGCM1, CSIRO-Mk2b and ECHAM4 global circulation models. The combined effect of doubled atmospheric CO_2 and related changes of climate (see Fig. 1 for the scenarios) is displayed

Abbildung 4: Dauer der Vegetationsperiode (Mittelwert und Standardabweichung) der Winterweizensorte 'Perlo', simuliert durch WOFOST für 30 Jahre aufgrund direkter Änderung der Wetterdaten basierend auf den prognostizierten Klimaszenarien für die 2080er Jahre der globalen Zirkulationsmodelle HadCM2, CGCM1, CSIRO-Mk2b und ECHAM4. Der kombinierte Effekt eines zukünftigen veränderten Klimas und einer verdoppelten atmosphärischen CO_2-Konzentration wird gezeigt (Klimaänderungsszenarien in Abb. 1)

The most important and overall information provided by our results was the significant increase in winter wheat grain yield at the selected location in all climate scenarios considering the combined effect which included the direct effect of about double the ambient CO_2 concentration. The ECHAM4 scenario caused the lowest increase in water-limited yields as a decrease in spring precipitation is predicted (Fig. 1b). The highest water-limited grain yields and also the lowest yield variabilities were predicted by the CSIRO-Mk2b and CGCM1 scenarios (38 % and 43 % yield increase, respectively in comparison with the present weather) (Fig. 5). However, the difference between the highest and lowest yield values in the scenarios was 12 % on average and the mean increase of all 2080's scenarios for water-limited yield was 35 % (9506 kg/ha vs. 7047 kg/ha) (Table 3, Fig. 5). If only the indirect effect is considered, it can be seen that the main reason for the yield increase was the direct effect of CO_2, which had a positive effect on crop assimilation and transpiration efficiency. Simulated wheat yields decreased in all scenarios by at least 20 % compared with the present level if they were not compensated by the direct effect of CO_2. The combined effect of the changed climates would also shift the potential winter wheat yields upwards. The potential yield level of the location would increase from a mean 7800 kg/ha at present to about 10350 kg/ha (+33 %) under the changed conditions (Table 3). This increase would be accompanied by a higher yield variability, especially under the ECHAM4 scenario, as a result of significant changes in global radiation, particularly temperature.

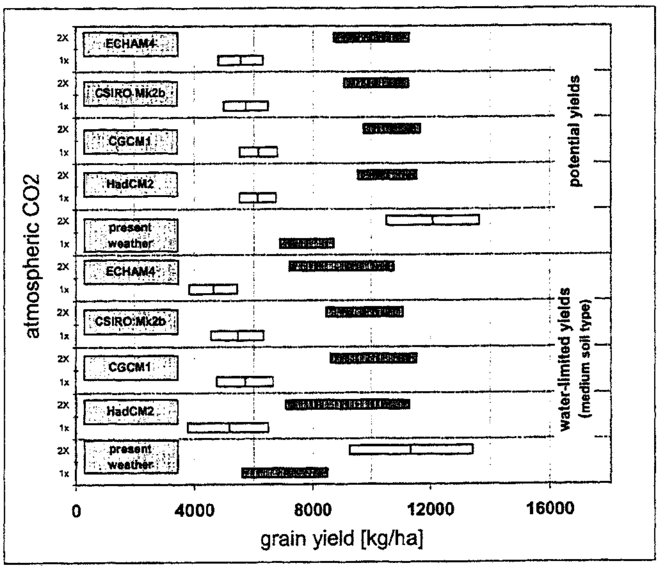

Figure 5: Potential and water-limited winter wheat grain yields (average and standard deviation) on medium soil modelled by WOFOST in 30 years simulation with incremental weather series for 2080's based on HadCM2, CGCM1, CSIRO-Mk2b and ECHAM4 global circulation models. The direct (effect of atmospheric CO_2) and indirect effect (through changed climate; see Fig. 1 for the scenarios) of increased CO_2 is displayed. The $2xCO_2$ level represents the 2080's ambient CO_2-concentration and the combined (direct and indirect) effect is shown in grey bars

Abbildung 5: Potentielle und aktuelle Winterweizenerträge (Mittelwert und Standardabweichung) auf mittelschwerem Boden, simuliert durch WOFOST für 30 Jahre aufgrund direkter Änderung der Wetterdaten basierend auf den prognostizierten Klimaszenarien für die 2080er Jahre der globalen Zirkulationsmodelle HadCM2, CGCM1, CSIRO-Mk2b und ECHAM4. Der direkte (Effekt erhöhter Kohlendioxidkonzentration) und indirekte (Effekt des veränderten physikalischen Klimas) Einfluss eines zukünftigen veränderten Klimas wird gezeigt. Der $2xCO_2$ Level repräsentiert die erwartete atmosphärische CO_2-Konzentration der 2080er Jahre und die graugefärbten Säulen zeigen den kombinierten (direkten und indirekten) Effekt

Our results in general confirm the trend results of another climate change impact study carried out for winter wheat in that region, using the CERES-wheat crop model (ALEXANDROV et al., 2000). In this previous study an increase in air temperature of between 0.5° and 2.0 °C resulted in a grain yield decrease of 1 to 6 %. Precipitation also increases projected grain yield reductions. The only positive grain yield changes were simulated through warming by 1.0 °C, combined with precipitation decreases. All transient GCM climate change scenarios for the 21st century, including the adjustment for air temperature, precipitation and solar radiation only, predicted reductions of winter wheat yield in the selected region of north-eastern Austria. However, when the direct effect of an increased CO_2 level was assumed, all GCM climate change scenarios projected an increase in water-limited winter wheat yield in the range of 10 % to 30 %.

3.3 Sensitivity analysis on soil water storage capacity

The sensitivity analysis was used in this study to quantify the effect of soil water storage capacity on the predicted yield levels under changed climatic conditions. Three soil types were considered (Table 1), covering the main range of soil water storage capacities in the region. The 'medium' soil type was defined as standard and corresponded to the actual soil characteristics at the experiment site used in the impact study. Additionally a 'light' soil with low water storage capacity and a 'heavy' soil with high water storage capacity were defined for the sensitivity analysis, in accordance with the real soil conditions in the Marchfeld region. The 'heavy' soil type had a deep potential rooting zone (150 cm) and increased water storage capacity (Table 1) resulting in a high level of potentially available water in the soil profile (405 mm). The initially available soil water content at the sowing date was set at 180 mm in accordance with previous soil water balance simulations and measured data. The potential rooting depth of the 'light' soil type was set at half of the previous soil types (75 cm), assuming sandy subsoil layers. Compared to the 'medium' soil type it can be seen therefore as a more shallow medium textured soil. The potentially available water in the soil profile is only 120 mm and the initially available soil water content at the beginning of the simulation was set at 75 mm.

The simulated potential yields increased significantly in all climatic scenarios and for all soil types. The simulated water-limited yield on the 'heavy' soil (Fig. 6) was slightly lower under present climatic conditions than the yield on the 'medium' soil type, and the yield variability was smaller due to the higher water-holding capacity, which acted as a buffer. Conversely, the 'light' soil showed the lowest yields and highest variabilities, both under present and changed climatic conditions. For example, the water-limited grain yield on the 'light' soil under present weather conditions was only 72 % of the yield on the 'medium' soil with very high variability (Table 3). However, the combined effect of climatic change yielded a 55 % increase in grain yield on average with the yield variability remaining high. Like the results of the 'medium' soil type (Fig. 5) the combined effect of climatic change on the 'heavy' soil type increased water-limited yield by 32 % on average (Table 3, Fig. 6). Unlike the 'medium' and 'light' soil type, the best results on the 'heavy' soil were obtained in the HadCM2 and CGCM1 scenario. The CSIRO-Mk2b scenario, which predicted the highest increase in precipitation of the considered scenarios (Fig. 1b), yielded the relatively lowest yield increase and the highest variability. The number of days when the crop was stressed by excessive amounts of soil water was in this case the highest of all simulations. The HadCM2 and CGCM1 scenarios, which showed only a moderate increase in precipitation, had the lowest yield variability and the highest yield level on the 'heavy' soil. The results correspond well with the assumption that under the predicted climatic changes the

Table 3: Mean water-limited and potential winter wheat grain yields (kg/ha) modelled by WOFOST in 30 years simulation with incremental weather series for 2080's for HadCM2, CGCM1, CSIRO-Mk2b and ECHAM4 global circulation models. The direct (effect of atmospheric CO_2) and indirect effect (through changed climate) of future climate is displayed. The 2xCO_2 level represents the 2080's ambient CO_2-concentration. Bold numbers represent the combined effect on yield of the 2080's

Tabelle 3: Durchschnittliche aktuelle Winterweizenerträge (kg/ha), simuliert durch WOFOST für 30-Jahre aufgrund direkter Änderung der Wetterdaten basierend auf den prognostizierten Klimaszenarien für die 2080er Jahre der globalen Zirkulationsmodelle HadCM2, CGCM1, CSIRO-Mk2b und ECHAM4. Der direkte (Effekt erhöhter Kohlendioxidkonzentration) und indirekte (Effekt des veränderten physikalischen Klimas) Einfluss eines zukünftigen veränderten Klimas wird gezeigt. Der 2xCO_2 Level repräsentiert die erwartete atmosphärische CO_2-Konzentration der 2080er Jahre. Die fettgedruckten Zahlen zeigen den kombinierten Effekt auf den Ertrag der 2080'er

	all soils		medium soil		heavy soil		light soil	
	potential yields		water limited yields					
	direct effect (ambient CO_2 concentration)							
indirect effect	1xCO_2	2xCO_2	1xCO_2	2xCO_2	1xCO_2	2xCO_2	1xCO_2	2xCO_2
present climate	7798	12076	7047	11339	7325	11704	5073	8713
future climate	5888	**10352**	5223	**9506**	5364	**9681**	4501	**7865**

crops would be increasingly dependent on precipitation distribution over the season (PARRY, 2000). Therefore, soil water storage capacity becomes more important, acting as a buffer and water reserve for drought periods.

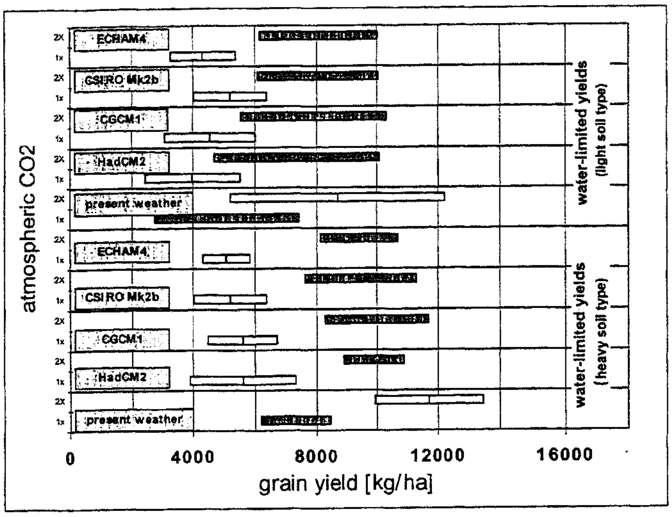

Figure 6: Potential and water-limited winter wheat grain yields (average and standard deviation) on heavy and light soil modelled by WOFOST in 30 years simulation with incremental weather series for 2080's based on HadCM2, CGCM1, CSIRO Mk2b and ECHAM4 global circulation models. The direct (effect of atmospheric CO_2) and indirect effect (through changed climate; see Fig. 1 for the scenarios) of increased CO_2 is displayed. The $2xCO_2$ level represents the 2080's ambient CO_2-concentration and the combined (direct and indirect) effect is shown in grey bars

Abbildung 6: Potentielle und aktuelle Winterweizenerträge (Mittelwert und Standardabweichung) auf schwerem und leichtem Boden, simuliert durch WOFOST für 30 Jahre aufgrund direkter Änderung der Wetterdaten basierend auf den prognostizierten Klimaszenarien für die 2080er Jahre der globalen Zirkulationsmodelle HadCM2, CGCM1, CSIRO-Mk2b und ECHAM4. Der direkte (Effekt erhöhter Kohlendioxidkonzentration) und indirekte (Effekt des veränderten physikalischen Klimas) Einfluss eines zukünftigen veränderten Klimas wird gezeigt. Der $2xCO_2$ Level repräsentiert die erwartete atmosphärische CO_2-Konzentration der 2080er Jahre und die graugefärbten Säulen zeigen den kombinierten (direkten und indirekten) Effekt

The second part of the sensitivity analysis focused on the importance of the initial available soil water in autumn and the role of the soil type. Soil water conservation techniques are an increasingly important tool for keeping ample soil water available. The available soil water in autumn in particular can have an important impact on the soil water status of the following year and the following crop (LOPEZ et al., 1996; LYON et al., 1998). As different crops use different amount of water from the soil water reservoir, a number of simulations with potential pre-crops to winter wheat were carried out. Based on these simulations, six initially available soil water values were chosen between wilting point and field capacity for each of three soil profiles. As the results show (Fig. 7a–c), grain yields of winter wheat under the changed conditions on

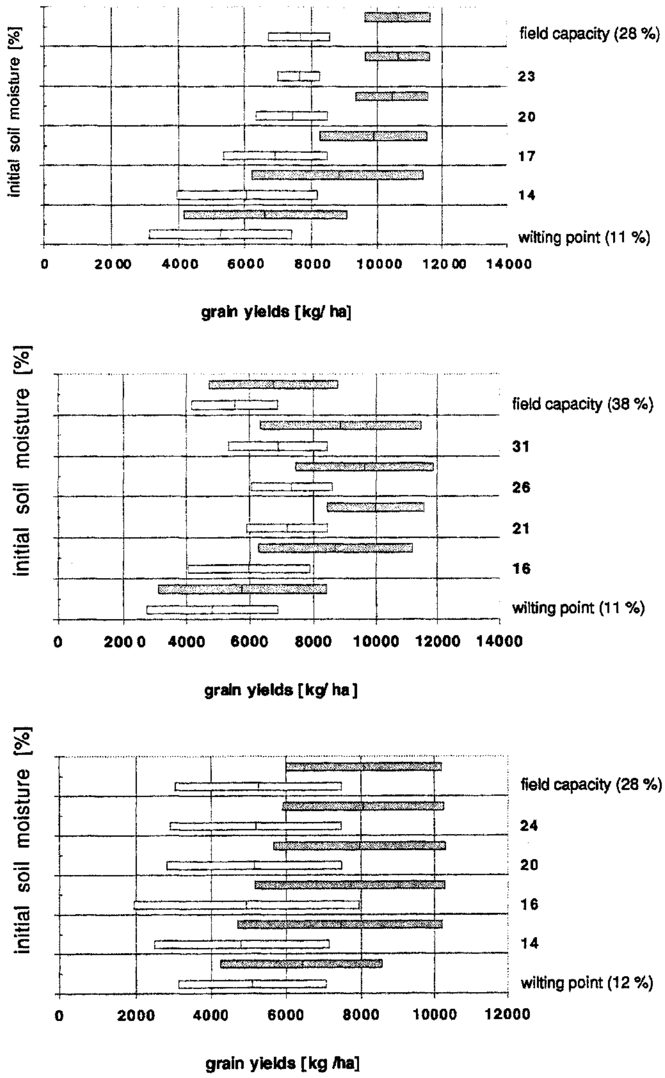

Figure 7a–c: Sensitivity analysis for a) medium b) heavy and c) light soil on the effect of the initial available soil water content on the yield of winter wheat (mean and standard deviation, white bars represent present weather, grey bars represent changed weather under $2xCO_2$ concentration). Weather series modification is based on CGCM1 global circulation model only

Abbildung 7a–c: Sensitivitätsanalyse des verfügbaren Anfangsbodenwassergehaltes auf den Winterweizenertrag für den a) mittelschweren b) schweren und c) leichten Boden (Mittelwert und Standardabweichung, weisse Säulen repräsentieren derzeitiges Klima, graue Säulen repräsentieren das zukünftige veränderte Klima bei verdoppelter CO_2-Konzentration). Nur das CGCM1 Szenario wurde verwendet 'light' and 'medium' soils were directly dependent on soil water content in autumn. With higher soil water levels in autumn the final yield increased because the crop suffered less water stress during the vegetation period. On the other hand, on the 'heavy' soil the optimum initial soil water content was found in the relatively small range of 21 to 26 % volumetric water content within the soil profile. Below and above this value the yield decreased rapidly. However, the direct CO_2 effect of climate change remained the most important factor affecting winter wheat yields under expected changed climate for the 2080's.

3.4 Production potential

The production potential index (PPI) is defined as the relationship between simulated water-limited and potential yield levels, which can be also an expression of the effectiveness of water-saving production techniques. To compare current and future conditions, we related water-limited yields under current and future climate to potential yield levels in various combinations. The relative change in PPI of the different combinations between current and future climatic conditions is shown in Table 4. It can be seen that the direct effect only causes an increase of PPI of 3 % on the 'medium' and 'heavy' soil and 10 % on the shallow (light) soil, which means that water-limited yields get closer to potential yields. In case 'A' in Table 4 there is an increase of PPI on the light 'soil' type under future climatic conditions compared to the current scenario (116 vs. 110 %), whereby on the 'heavy' and 'medium' soil type PPI decreased as a result of the negative influence of the 'indirect effect'. By relating future water-limited yields to the current potential yield level with doubled ambient CO_2 concentration (case 'B' in Table 4), it is shown that PPI decreases for all soils except for the 'light' soil. This is suggesting that current production technique on 'light' soils becomes more effective under future climate conditions. However, the reason for this is that there is less potential yield and water stress under future climatic conditions due to the significantly shortened vegetation period. As winter wheat is using most water resources in spring, the largest positive effect is obtained on soils with low water storage capacity. For spring crops with longer vegetation period, this pattern might be significantly different.

4. Conclusions

The results of this study confirm the overall trend of increasing winter wheat yields in Central Europe under different climate change scenarios based on the greenhouse effect. For north-eastern Austria, a region with intensive agricultural crop production, in our simulation study with the WOFOST model winter wheat yields are expected to rise 30 to 55 % for the climate of the 2080s, especially through the direct CO_2 fertilization effect. Rising temperatures, however, will shorten the winter wheat growing period as increasing temperatures enhance the development rate of the

Table 4: The production potential index (PPI) based on the values in Table 3 and its relative change as average from all climate scenarios depending on the direct and indirect effect of changed climate and the soil type

Tabelle 4: Der Produktionspotentialindex (PPI) errechnet aus den Werten der Tabelle 3 und seine relative Änderung im Mittel aller verwendeten Klimaszenarien in Abhängigkeit zum direkten und indirekten Effekt einer Klimaänderung und zur Bodenart

	medium Soil		heavy Soil		light Soil	
	direct effect (ambient CO_2 concentration)					
indirect effect of climatic conditions	$1\times CO_2$	$2\times CO_2$	$1\times CO_2$	$2\times CO_2$	$1\times CO_2$	$2\times CO_2$
present climate	**0.90**	0.94	**0.94**	0.97	**0.65**	0.72
future climate – case A	0.89	**0.92**	0.91	**0.94**	0.76	**0.76**
future climate – case B	0.67	**0.79**	0.69	**0.80**	0.58	**0.65**
present climate	**100.0 %**	103.9 %	**100.0 %**	103.2 %	**100.0 %**	110.9 %
future climate – case A	98.1 %	**101.6 %**	97.0 %	**99.6 %**	117.5 %	**116.8 %**
future climate – case B	74.1 %	**87.1 %**	73.2 %	**85.3 %**	88.7 %	**100.1 %**

Calculation procedure of PPI:
present climate: PPI = Water limited yield of present climate/Potential yield of present climate
future climate – case A: PPI = Water limited yield of future climate (e.g. 9506 kg/ha for medium soil and 2 x CO_2 direct effect)/Potential yield of future climate including 2 x CO_2 direct effect (10352 kg/ha)
future climate – case B: PPI = Water limited yield of future climate/Potential yield of current climate and 2 x CO_2 direct effect (12076 kg/ha)

crop (e.g. PENNING DE VRIES et al., 1989) and reduce yield potential if they are not compensated by the direct CO_2 fertilization effect. From other impact studies including the climate scenarios from the 2020's as well as 2050's (e.g. ALEXANDROV et al., 2000) it is shown that the positive yield trend is already obvious in the coming decades, however, on a lower level in accordance with the changed climate and CO_2 level. A sensitivity analysis showed that soil water storage capacity plays an important role in yield levels and yield variability under current climate as well as expected climatic change, where 'light' soils show a lower increase in winter wheat yields and higher yield variability than the standard 'medium' and the 'heavy' soil types. Additionally, yields and yield variabilities were significantly different between the climate scenarios as a result of the differently predicted amount and distribution of precipitation over the vegetation period, which therefore remains a main source of uncertainty. A change in extreme weather events in future climates such as the pattern of drought periods, which are not considered in the climate change scenarios, could significantly reduce the predicted yield levels. Crops grown on soils with low soil water storage capacity, such as sandy soils and soils with shallow potential rooting depth, or crops with shallow rooting systems are much more vulnerable to changes in precipitation patterns. The change in potential production index, which is the relationship between simulated potential and water-limited yield, shows that the current production technique will have a similar effect under future climatic conditions for achieving potential yield levels for winter wheat on 'heavy' and 'medium' soils. However, water-limited yields will come closer to potential yields on 'light' soils, but the difference is still larger than on the other two soil types. Also the soil water content in autumn is shown to have a significant impact on final yield on all soil types. The results confirm that the importance of water-saving production techniques will be important especially under future climatic conditions, even when the crop growing period is shortened significantly by higher temperatures. Methods used could include crop cultivation techniques, irrigation scheduling, mulching systems and crop rotation to enable the available soil water to be exploited more effective.

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