Climate Change Impacts on Czech Agriculture

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1. Introduction

Chapter summarizes the major impacts of changing climatic conditions in the Czech agriculture. Specific case studies are performed for the whole country (arable land) and are processed through GIS in the spatial grid 500 x 500 m respectively 1 x 1 km if middle Europe is considered. Contribution presents the impacts of climate change on the production of two major field crops (winter wheat and spring barley) in the Czech Republic for different future time horizons (2030, 2050 and 2100). The yield study includes not only the effect of climatic conditions but also the fertilization effect of carbon dioxide. Study is completed by effects of rising temperatures on the spread of temperature-depending biotic factors (selected pests) and changes in agroclimatic conditions for field crops. The basic data which are needed and used are long-term database of the national meteorological service and agricultural organizations which was used for evaluation of growth models (e.g. CERES). Other used tools are models which allow describe the evolution of pests in new climate conditions (e.g. CLIMEX or ECAMON) and various meteorological indieces. Description of expected weather conditions are based on two emission scenarios, according to the IPCC (mostly SRES-A2 and -B1) and three GCM models (NCAR-PCM, ECHAM5 and HadCM3). Their open access monthly outputs are published for the individual time horizons (e.g. 2030, 2050 and 2100) and are prepared in the daily time step by stochastic weather generator. The impacts of climate change are determined by comparing the current and expected state observed phenomena.

2. Climate change scenarios for the Czech Republic

In assessing impacts of the climate change on agriculture, various models (e.g. crop growth models) are used. These models need for their simulations multivariate weather series

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representing present and future climates. As the presently available climate models [either solely Global Climate Models (GCMs) or Regional Climate Models (RCMs) driven by selected GCM)] used to project the future climate do not satisfactorily reproduce the structure of the required surface weather series (in terms of probability distribution functions of individual variables, as well as in terms of correlations and lag-correlations among the variables), alternative approaches are employed to create the surface weather series with a real-world statistical structure: statistial downscaling (Benestad et al., 2008) and weather generators (Beersma & Buishand, 2003; Dubrovský et al, 2004; Wilks, 2009; Semenov et al., 1998) Both methodologies rely on statistical approaches. In case of the statistical downscaling (SDS), the surface weather series is modelled conditionally (using, e.g., regression-based relationships) on the larger-scale characteristics (e.g. circulation indices, weather types, and upper-air atmospheric characteristics). Once the SDS model is calibrated with the present climate data, the future-climate weather series is created by applying the SDS model to GCM-simulated future-climate predictors. In our experiments, we use the latter approach - the weather generators (WGs). Specifically, we use the stochastic daily weather generator M&Rfi (more advanced follower of the earlier Met&Roll generator [Dubrovský et al., 2004]), which models the multivariate surface daily weather series using the mixture of statistical models: in the first step, precipitation is simulated using Markov chain for precipitation occurrence and Gamma distribution for daily precipitation amount. In the second step, solar radiation (SRAD), and daily temperature extremes (TMAX and TMIN) are simulated using the first order autoregressive model. To generate weather series representing the future climate, the WG parameters are modified according to the GCM-based climate change scenario (Dubrovský et al., 2000; Žalud & Dubrovský, 2002), which consists of the changes in monthly climatic characteristics (means and variabilities of the surface weather characteristics) and is derived from latest available GCM simulations.

The development of the climate change scenario is affected by various uncertainties (Dubrovský et al., 2005). Of these, we account for uncertainties in climate sensitivity (CS), emission scenario (ES) and inter-GCM uncertainty. This is done by using the pattern scaling method (Santer et al., 1990), in which the changes in individual climatic characteristics (ΔX) are defined as a product of standardized changes ($\Delta_s X$) and change in global mean temperature (ΔT_G):

$$\Delta X = \Delta T_G \times \Delta_s X \tag{1}$$

The standardised scenarios are derived from the GCMs (we used GCMs from IPCC-AR4 database), the ΔT_G values are determined by the simple climate model MAGICC (Harvey et al., 1997; Hulme et al., 2000) assuming user-selected emission scenario and climate sensitivity. To account for the above uncertainties, we use 3 GCMs to represent uncertainty in the standardized scenario (~ inter-GCM uncertainty), and 3 values of ΔT_G to represent uncertainty in the scaling factor.

The choice of the triplet of the GCMs was based on assessing the fit between the observed and GCM simulated annual cycles (Dubrovský et al., 2005). Based on the results of these validation tests, we chose ECHAM5, HadCM3 and NCAR-PCM models (ECHAM, HadCM, NCAR in next text). The standardized climate change scenarios derived from the three selected GCMs are shown in Fig.1. To represent uncertainty in ΔT_G, we use the low, middle

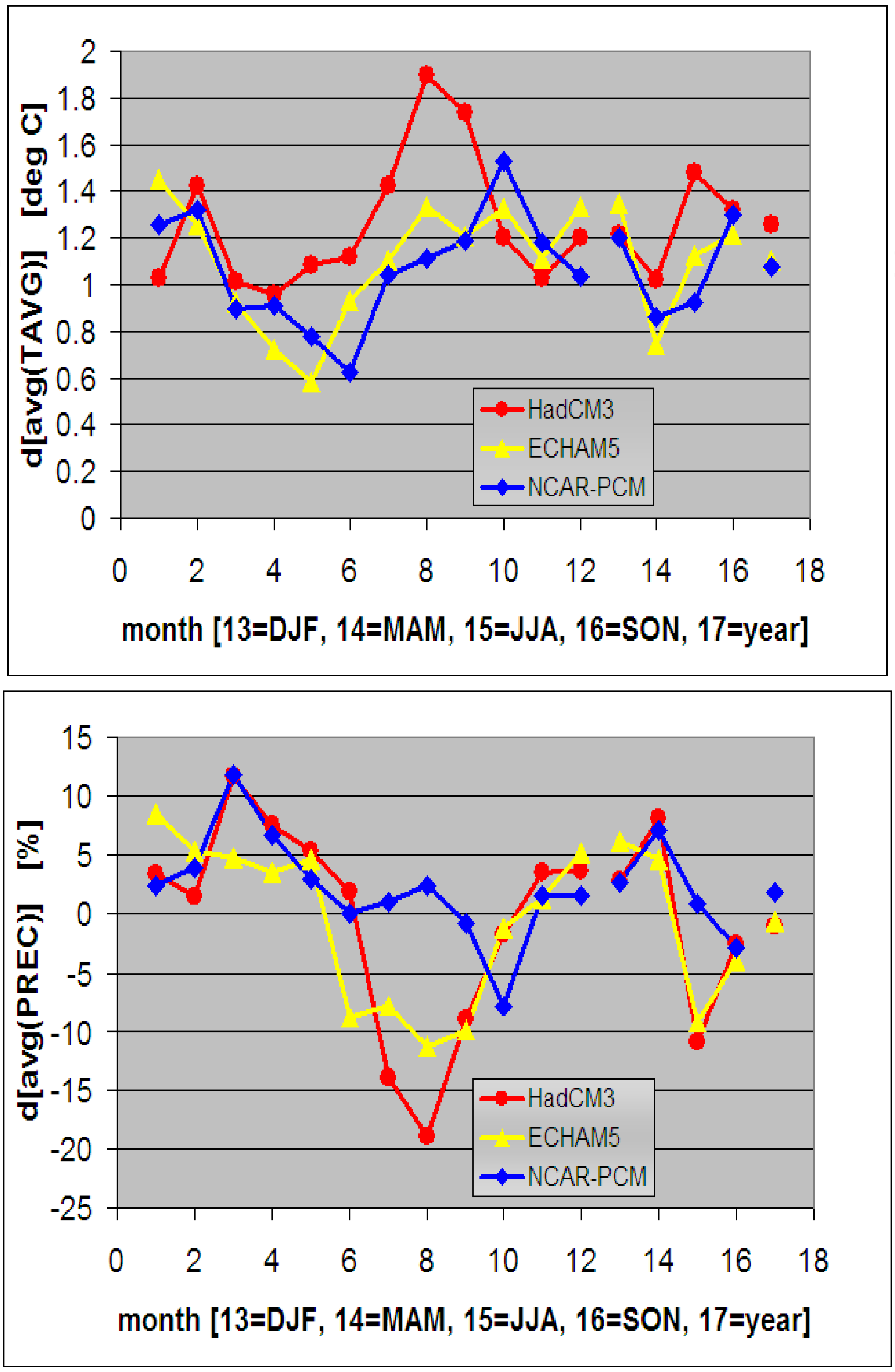


Fig. 1. Standardized scenarios of changes in monthly, seasonal (month = 13 to 16) and annual (month = 17) means of temperature (top) and precipitation (bottom)

and high values, which represent combined uncertainty in emission scenario and climate sensitivity (Fig.2): The low value is defined as a minimum of ΔT_G related to 4 emission scenarios (SRES-A1b, -B1, -A2, -B2) and low climate sensitivity (1.5 K), the high value is

defined as a maximum of ΔT_G related to the 4 emission scenarios and high climate sensitivity (4.5 K), and the middle value relates to the average of two middle values related to the four emission scenarios and middle climate sensitivity (2.6 K).
In modifying the parameters of the WG, the above scaling equation (1) is applied differently to individual WG parameters: To modify annual cycle of mean temperature (both *TMAX* and *TMIN*) values, the standardized scenario values $\Delta_s T$ are identical with the temperature changes expressed in terms of Kelvin degrees, which implies additive modification of the annual temperature cycle:

$$<T_{\text{future}}> = <T_{\text{present}}> + \Delta T, \text{ where } \Delta T = \Delta T_G \times \Delta_s T \quad (2)$$

In modifying the mean precipitation cycle, we assume the multiplicative modification:

$$<P_{\text{future}}> = <P_{\text{present}}> \times (1 + \Delta P/100) \quad (3)$$

where ΔP is a percentage change in precipitation. When the pattern scaling method (eq.1) is used to determine ΔP, the problem arises how to define the standardised change $\Delta_S P$ and how to apply the scaling procedure. In a most straightforward way and in accordance with eq.1, we may assume that ΔP is linearly proportional to ΔT_G:

$$\Delta P = \Delta T_G \times \Delta_S P \quad (4)$$

which may work for small values of ΔT_G. However, in case of the larger values of ΔT_G (for example, it takes value of about 5 for SRES-A2 and high climate sensitivity) and modest standardised decrease of precipitation $\Delta_S P$ (say -25%), the above equation would imply senseless $\Delta P < -100\%$. In result, we apply a different formula when applying the pattern scaling method for precipitation changes. Instead of the above assumed linearilty between ΔT_G and ΔP we assume $dP / P = k \times \Delta T_G$, where dP indicates an infinitesimal change, which in turn implies a linear relationship between $\ln P$ and ΔT_G and thereby an exponential dependence of P on ΔT_G:

$$\ln P_{\text{future}} = \ln P_{\text{present}} + k \times \Delta T_G \quad \rightarrow \quad P_{\text{future}} = P_{\text{present}} \times \exp(k \times \Delta T_G) \quad (5)$$

where k is, in fact, a standardised (related to 1K rise in global mean temperature) change in $\ln P$ and may be determined by applying linear regression to [$\ln P$, ΔT_G] data. In applying the pattern scaling equation, another problem arises: if the standardised change is positive ($k > 0$) and ΔT_G is close to the high end of or even beyond the calibration interval (values simulated by the given GCM) of ΔT_G, we deal with a problem of extrapolation. Also considering the not-so-high correlation between P and T_G, which implies relatively high errors in estimating the regression parameters, we must be very careful in this extrapolation. To address this problem, we use a linear (instead of the exponential) rise when k is positive and ΔT_G rise beyond 1:

$$\Delta P = [\exp(k \times \Delta T_G) - 1] \times 100 \, [\%]; \quad \text{for } \Delta T_G < 1 \quad (6)$$

$$\Delta P = [1 + k \times (\Delta T_G - 1)] \times [\exp(k) - 1] \times 100 \, [\%]; \quad \text{for } \Delta T_G > 1 \quad (7)$$

The relationships between ΔP and ΔTG for both positive and negative values of k are shown in Fig.3. If k is negative, the curves shown in Fig.3 are mirror-symmetric with curves for positive k along the x = 0 line and therefore the exponential dependence is used for ΔTG > −1 and the linear relationship for ΔTG < −1. The changes in the mean global solar radiation

(SRAD) and in variabilities of SRAD, TMAX and TMIN (if applied) are determined in the same way as the changes in the precipitation amount.

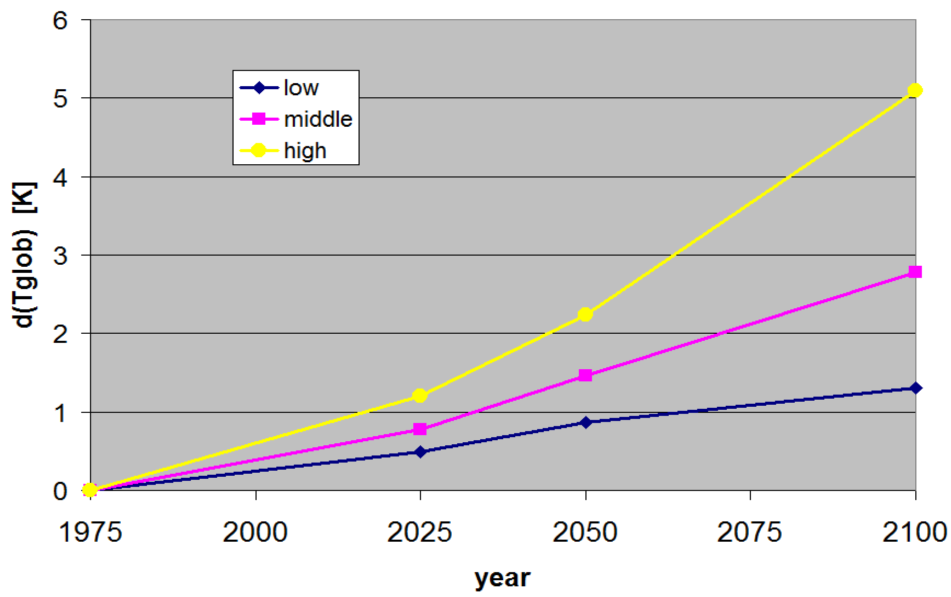


Fig. 2. Low, middle and high values of change (with respect to 1975, which is the center of the common reference period 1961-1990) in global mean temperature for 2025, 2050 and 2100 according to MAGICC (v.5.3) model. The low value relates to minimum of ΔT_G related to 4 emission scenarios (SRES-A1b, -B1, -A2, -B2) and low climate sensitivity (1.5 K), the high value relates to maximum of dTglob related to the 4 emission scenarios and high climate sensitivity (4.5 K), and the middle value relates to the average of two middle values related to the four emission scenarios and middle climate sensitivity (2.6 K).

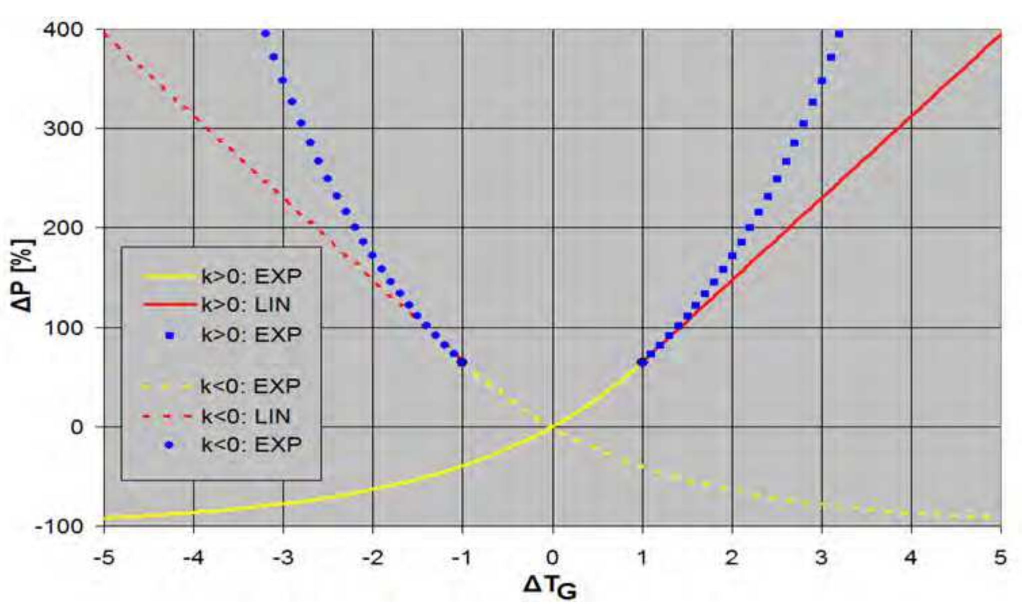


Fig. 3. The dependence of ΔX on ΔT_G according to the pattern scaling method. The solid lines represent the dependence for k>0, the dashed lines for k<0 The blue dots indicate the exponential dependence, which is rejected for dTG>1 AND k>0 and dTG<−1 AND k<0 to avoid the extrapolation problem.

3. Using growth models for climate change impact assessment on crop yield

Crop growth models are widely accepted tools for plant production assessing (under various conditions or management strategies) and have been used since the 1960s. They are designed as a set of algorithms on various bases for assessing agricultural potential, crop development and yield forecasting (Perdigão & Suppit 1999). They could be applied at local (field), regional or wider spatial level and used for analysis and optimization of agricultural practices, such as various sowing date, nitrogen fertilization (e.g., Rinaldi 2004) or within climate change impact assessment (e.g., Alexandrov & Hogenboom 2000; Trnka et al., 2004a; Wolf et al., 1996). The effect of expected future climatic conditions (namely changes of solar radiation, air temperature and precipitation) and higher concentration of carbon dioxide are analyzed by this way. Generally, the direct influence of higher carbon dioxide (as a crucial source of carbon) is connected with photosynthesis stimulation (Mitchel et al., 1999). Simultaneously, the higher concentration of CO_2 influences the stomata activity (causing its higher resistance) and the water use efficiency (WUE). The experiments with higher CO_2 concentration confirmed the biomass production increase within C_3 plants (Amthor, 2001). On the other hand, according to some of recent studies the influence of CO_2 in real conditions will be lower (Ainsworth & Long, 2005). Moreover, the conducted studies usually neglected the influence of CO_2 concentration within higher air temperature and some yields increase could be expected also due to agro-technological improvement and breeding (Berntsen et al., 2006). If only temperature increase is assumed (without adaptation measures such as breeding or sowing date shift), than the expected yields (e.g. winter wheat) will be lower as a consequence of shorter growing period (e.g. Batts et al., 1997).

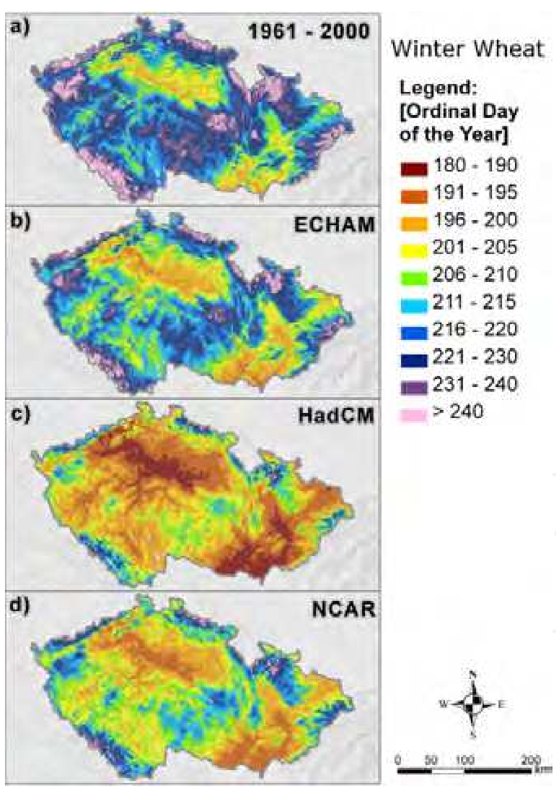
For the purpose of presented study the CERES-Wheat (Godwin et al., 1989) and CERES-Barley (Otter-Nacke et al., 1991) models were selected as they were successfully used within several studies through the central Europe (e.g. Hlavinka et al., 2010; Eitzinger et al., 2004) including the analysis of climate change impact on yields (Trnka et al., 2004a, b). They are process-oriented varieties of crop models and works within the framework of the DSSAT - Decision Support System for Agrotechnology Transfer (Hoogenboom et al., 1994). Phenological development and growth in the CERES models are directed by cultivar-specific genetic coefficients depending on the photoperiod, thermal time, temperature response and dry matter partitioning. CERES models calculate dry matter accumulation as a linear function based on intercepted photosynthetically active radiation. Potential dry matter accumulation depends on the amount of biomass already produced and the actual leaf area index. This is then corrected for actual daily biomass by applying factors for water and/or nitrogen stress and non-optimal temperature.

For the spatial analysis the Czech Republic was divided into grids 500 x 500 m with information about altitude, landuse, soil type and texture and hydrolimits. The present climatic conditions were represented by daily measured maximum and minimum temperatures, precipitation and global radiation from 125 stations during the period 1961-2000. If the pyranometer was missing than the sunshine duration in combination with Angström method was used for global radiation estimates.

For the future climatic conditions the measured weather data were replaced by the data derived from selected GCM models (ECHAM, HadCM, NCAR) in combination with SRES-A2 and SRES-B1 emission scenarios. Moreover SRES-A2 was connected with high climate sensitivity to increased CO_2 concentration and SRES-B1 with low climate sensitivity. Consequently, the daily weather data were prepared using stochastic weather generator Met&Roll (Dubrovský, 1997) and the spatial analysis was conducted using ArcGIS software.

3.1 Climate change and winter wheat (case study)

The basic task for the assessment of future climatic conditions within selected crops is the analysis of the expected changes of plant development (i.e. start and duration of selected phenological stages) and attainable yields (influenced by the water stress and nutrient concentration). For the purpose of presented study the cultivar Hana was selected as it was successfully calibrated and verified within seven various locations through the Czech Republic by Trnka et al. (2004b). Within submitted study the expected terms of sowing, anthesis and physiological maturity (for selected scenarios of future climatic conditions) were predicted. Generally, the later term of winter wheat sowing (as it is driven mainly by available soil moisture) could be expected due to increasing drought. The last two of mentioned phases were simulated by the CERES-Wheat model. Based on HadCM model the anthesis within South-Eastern part of country could be expected about 25 days earlier for the year 2050 (for ECHAM 7-8 days earlier). The similar situation is apparent also for physiological maturity (see Fig.4). The conditions according to HadCM will lead up to 23 days (for warmer regions) and 36 days earlier maturity (for colder regions). This is in accordance with results of Olessen et al. (2000), that 1°C air temperature increase during the grain filling phase reduced its duration by 5%. The total duration of growing period (from sowing to physiological maturity) could be up to 6 weeks shorter (according to SRES A-2 for 2050 as the most pessimistic scenario) within the numerous Czech Republic districts. Similar results were reported by number of other studies (e.g. Harrison et al., 2000; Tubiello et al., 2000).



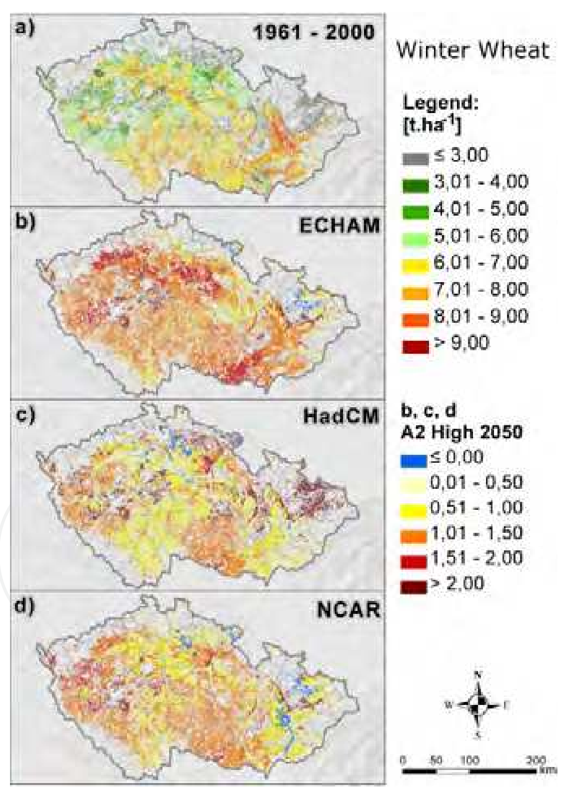


Fig. 4. (left) The term (described by the day of year/ Julian day – JD) of physiological maturity of winter wheat (a) for present climatic conditions and (b, c, d) for the year 2050 according to SRES-A2 and three selected GCM (as a median of 99 simulations).

Fig. 5. (right) The yields ($t.ha^{-1}$) of winter wheat simulated by the CERES-Wheat at arable land (a) for the present climatic conditions (1961-2000) and (b, c, d) expected differences for the period around 2050 according SRES-A2, high climatic sensitivity and three selected GCM.

For the combined effect of increased carbon dioxide (i.e. changed meteorological conditions and fertilization effect of CO_2) positive trend within winter wheat yields could be expected. From the conducted analyses is apparent that winter wheat will prosper from the new climate conditions and attainable yields could be about 14% higher within 2050 according to SRES-B1 and over 20% according SRES-A2 (Fig. 5). Also in the conditions of Slovakia (neighboring country) the increased yields of winter wheat and spring barley are expected according to CGCM and all SRES scenarios (Takáč & Šiška, 2008). On the other hand, the selected GCM and SRES scenario has a big influence on achieved results (Olesen et al., 2007). The extend of combined influence in the conditions of the Czech Republic is also dependent on the particular soil and climatic conditions.
The highest relative increase of yields could be expected in the regions with high quality of soils and sufficient precipitation. The increased yields could be achieved also with conditions Czech-Moravian Highlands, Northern Moravia and Bohemia where are presently suboptimal (lower) temperatures, higher precipitations and sufficient soil quality. Generally, the winter crops show lower susceptibility to the negative impacts of climate change against to the spring crops.

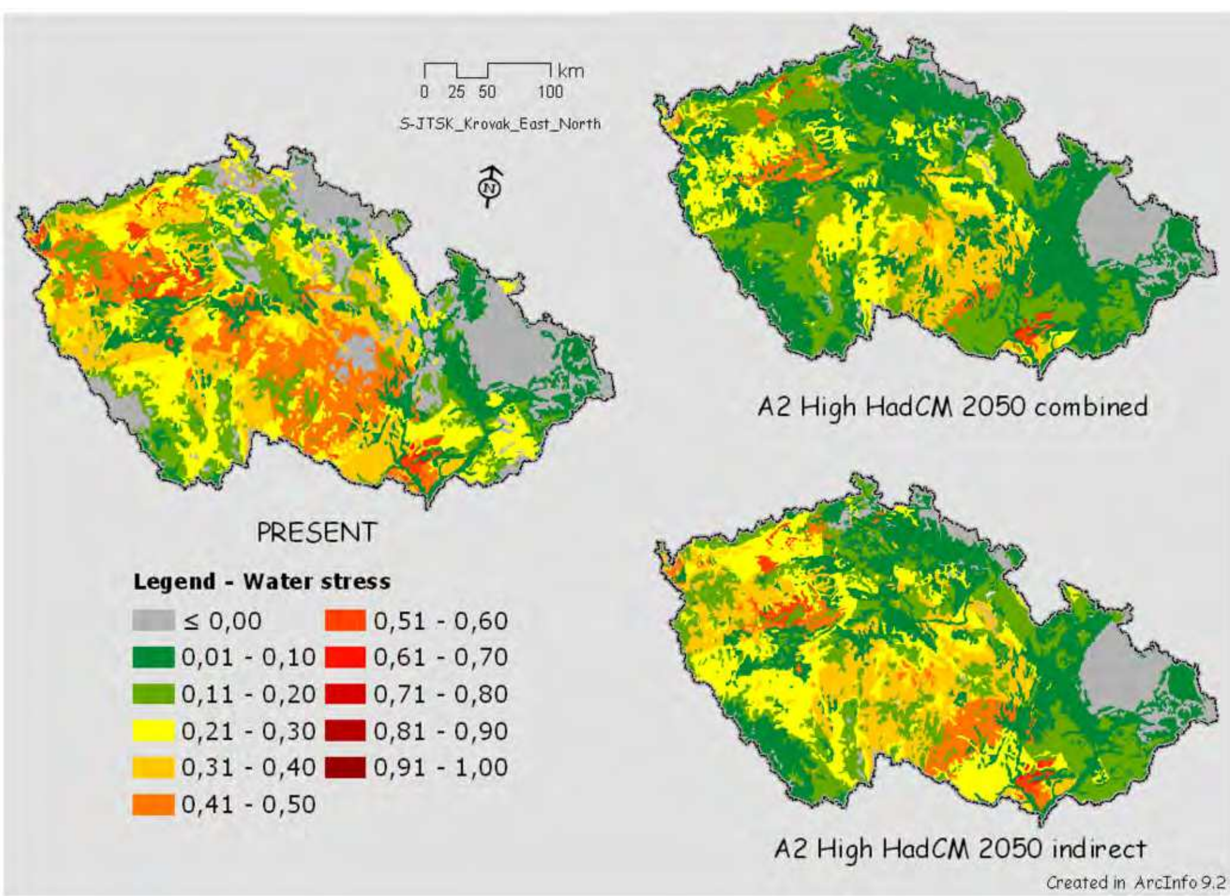


Fig. 6. Spatial distribution of water stress with 20 year return probability based on SWDF2 parameter (CERES-Wheat) for winter wheat under present and expected (HadCM, SRES-A2 and high climate sensitivity) conditions. The indirect effect of higher greenhouse gases concentration and combined effect were assessed. The higher number in legend indicates the higher value of water stress (1 equals 100% stress and 0 is without any water stress).

The CERES models also offer the methods for crop specific water stress quantification (during the various parts of vegetation) through the set of parameters. One of the CERES models advantages for drought impact assessment under future climate is the incorporation of direct effect of increased CO_2 concentration leading to higher WUE.

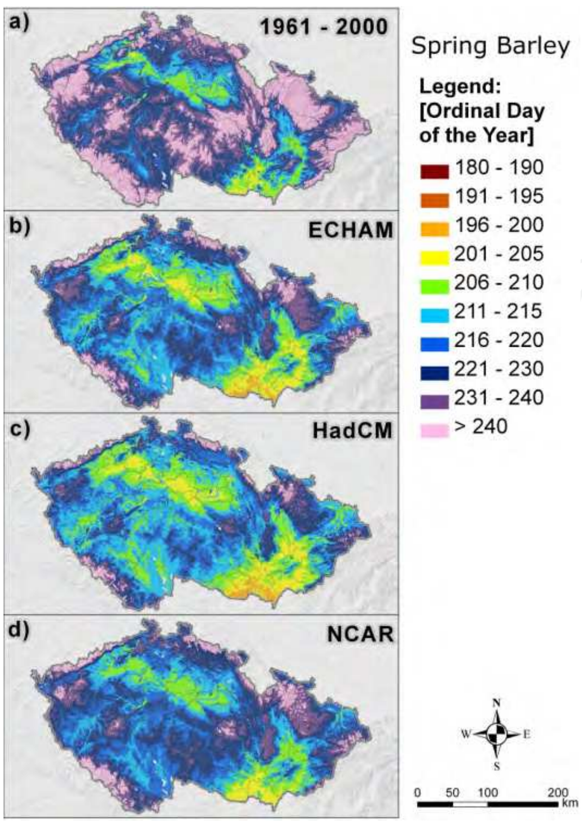
The results regarding 20 years return probability of drought was investigated by CERES-Wheat through the Czech Republic (HadCM model, SRES A2 scenario and high climate sensitivity). This analysis was based on SWDF2 parameter (describes water deficit effects on plant physiological processes) assessed from anthesis to maturity. The results indicate reduced water stress in most regions of the Czech Republic around 2050 both for combined effect (connected indirect impact of higher greenhouse gases concentration and direct fertilization effect of increased CO_2) and even for solely indirect effect (see Fig. 6). The lower water stress within combined effect could be explained by the higher WUE, shorter vegetation season and its partial shift from drought occurrence periods. The water stress reduction under isolated indirect effect could be explained only by the last two mentioned reasons.

3.2 Climate change and spring barley (case study)

For the climate change impact assessment within spring barley development and cultivation, the analogical approach as in the case of winter wheat was applied. The cultivar Akcent was used as it was validated within three localities through the Czech Republic with various soil and climatic conditions (Trnka et al., 2004a). The expected higher temperatures will lead to earlier sowing date and the shorter phenological phases (especially for the model HadCM). These changes partly enable to avoid the vegetation during the period with negative water balance (i.e. drought stress). The present and expected date of physiological maturity according to the SRES-A2 and three GCM for the period around 2050 is depicted within Fig. 7. This shortening of vegetation phases (without the assumption of CO_2 direct fertilization effect) is mostly negative for yields. On the other hand, when also fertilization effect was included, the positive trend within attainable yields could be expected for the period around 2050 (see Fig. 8). The highest yields under present conditions are achieved (as well as simulated) within lowlands. The spatial distribution of expected trends within yields is very similar through various regions and altitudes. According to ECHAM and NCAR the yield increase could be about 1000 $kg.ha^{-1}$ for majority of our country. The driest scenario (using HadCM model) will lead to the lowest yield increase together with the highest variability. It could be explained by the higher negative influence of extreme years. The aim of this study is not accurate prognosis of yields in future, but to assess possible impact of future conditions according to selected scenarios. For this purpose the attainable yields were estimated. It is clear that it will be influenced also by the breeding, technological improvement or economic situation and priorities. According to presented results the attainable yields of these two investigated crops will be higher. On the other hand the future climate conditions will lead to the various changes such as higher pest and diseases occurrence which together with higher probability of extreme weather events such as drought or rainstorms will lead to the attainable yields reduction in some years.

4. Pest development in climate change conditions

Productivity of crops grown for human consumption is at risk due to the incidence of pests, especially weeds, pathogens and animal pests: for instance, without crop protection almost



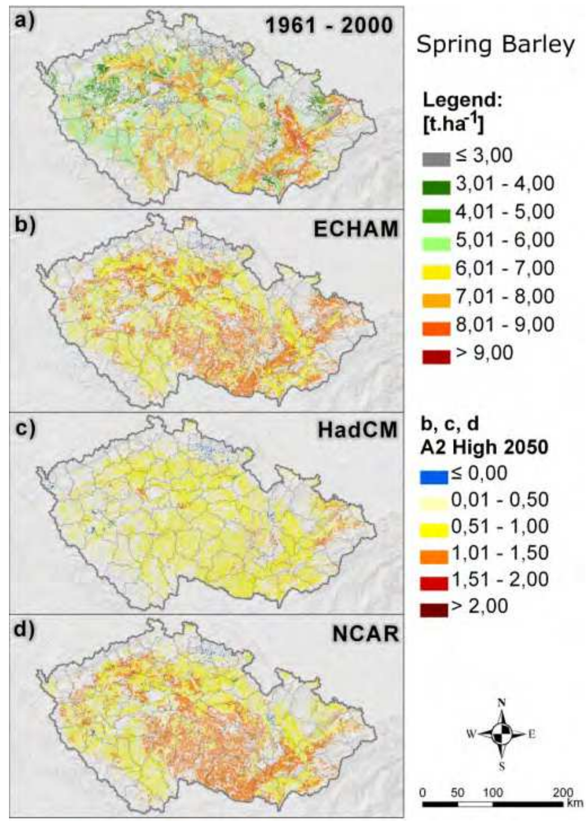


Fig. 7. (left) The term (described by the day of year/ Julian day – JD) of physiological maturity of spring barley (a) for present climatic conditions and (b, c, d) for the year 2050 according to SRES-A2 and three selected GCM (as a median of 99 simulations).

Fig. 8. (right) The yields ($t.ha^{-1}$) of spring barley simulated at arable land (a) for the present climatic conditions (1961-2000) and (b, c, d) expected differences for the period around 2050 according SRES-A2, High climatic sensitivity and three selected GCM.

75% of attainable potato production would be lost to pests (Oerke, 2006). Climatic conditions have a significant influence on the population dynamics, life-cycle duration, infestation pressure and overall occurrence of the majority of agricultural pests and diseases. This is particularly true for pest species whose development is directly linked with the climatic conditions and for whom a shift in their climatic niche or their infestation capability is expected during changing climate. In climate warming the number of insect species per unit area tends to decrease with increasing latitude, a similar trend is usually found with increasing altitude (Gaston & Williams, 1996). Climatic warming will allow the majority of temperate insect species to extend their ranges to higher latitudes and altitudes. Species which currently have wide latitudinal ranges, already encounter considerable temperature variation and are preadapted to cope with temperature change (Bale et al., 2002). Except the changes in geographical distribution of the species climate change may result in alterations in the overwintering, changes in population growth rates, increases in the number of generations per season, extension of the development season, changes in crop-pest synchrony, changes in interspecific interactions and increased risk of invasion by migrating pests (Porter et al., 1991). An increase in the number of generations per season means an increase in the number of reproductive events per year. If the mortality per generation does not change, then the population of thermophile insects will potentially become larger under global warming (Yamamura & Yokozawa, 2002). This could play an important role in the case of multivoltine species (Pollard & Yates, 1993). A higher survival rate during the overwintering period could result in an increase in the overwintering population and consequently a greater abundance of insects on crops in the summer. At the same time, the increasing temperature could probably support an earlier diapauses termination of overwintering species which will consequently appear earlier. This will influence the intensity of crop–insect interactions (Yamamura & Yokozawa, 2002).

Following case study estimates the impact of climate change on two pests: the Colorado potato beetle (*Leptinotarsa decemlineata* Say) and the European corn borer (*Ostrinia nubilalis* Hübner). According to Hare (1990), *L. decemlineata* is one of the most important insect pests of potato crops around the world; it is present and widespread in the countries covered in the present study (European and Mediterranean Plant Protection Organization (hereafter EPPO) 2007). The occurrence of *O. nubilalis* across some of the regions in the present study has also been recorded by the EPPO (2007). These two species are expected to gain new territory and lead to an increase in infestation pressure under climate change because their survival is closely related to climate conditions and, in particular, temperature.

4.1 Modelling as the estimation method of climate change impact on the pests' distribution

Modelling the life stages of insect species is most often done using accumulated degree-days, while socalled climate matching is a common modelling tool for estimating the impact of climate change on the extension of the range of a species. Climate matching identifies locations currently not invaded that could be colonized by a potential invasive species on the basis of similarity to climates found in the species' native range (Rodda et al., 2007). Several models that belong to the group of climate matching tools have been developed and applied in the past. For example, BIOCLIM (Nix, 1986) is a general model for the assessment of the favourability of a given climate for the occurrence of a species. HABITAT is a model for the analysis of the environmental conditions related to the distribution of plants and animals (Walker & Cocks, 1991). DOMAIN is a flexible tool for the modelling of the potential distribution of plants and animals (Carpenter et al., 1993). ANN and SPECIES are used for the estimation of the impact of climate change on plant species in the UK (Berry et al., 2002; Pearson et al., 2002, 2004). The assessment of climate favourability for univoltine and bivoltine population of the European corn borer is performed by ECAMON (Trnka et al., 2007). Régnière & Sharov (1998) used the stochastic generator BioSIM in the model of the geographical distribution of the gypsy moth to obtain the daily temperature data (Régnière et al., 1995).

Mechanisms by which climate conditions affect the development of a species can also be analysed with the CLIMEX software tool. CLIMEX is a world renowned software that has recently been applied in various scientific studies considering the potential distribution and spread of animal or plant species (Sutherst, 2000a, b; Bell & Willoughby, 2003; Kriticos et al., 2003; Lockett & Palmer, 2003; Pethybridge et al., 2003; Rafoss & Sæthre, 2003; Zalucki & Furlong, 2005; Olfert & Weiss, 2006, among many others).

4.2 Potential distribution of Colorado potato beetle and European corn borer (case study)

The climate-matching software program CLIMEX estimates the geographical distribution of a species based on the climate conditions of a given location. CLIMEX is based on the assumption that if you know where a species lives you can infer what climatic conditions it can tolerate (Sutherst et al., 2000a). The CLIMEX model is designed to extract maximum information out of minimal field data on the response of a species to climate. It derives weekly and annual indices that describe the responses of a nominated species to temperature and moisture, and, in the case of plants, light (Sutherst, 2003). Knowing the climatological requirements of a given species allows us to assess the suitability of a particular area for population growth and to determine the stress induced by unsuitable climate conditions. These are expressed in terms of the ecoclimatic index (EI), which describes the overall suitability of climate conditions for the establishment and long-term presence of a pest population at a given location:

$$EI = GI_A \times SI \times SX \quad (8)$$

where GI_A is the annual growth index describing population growth under favourable conditions, SI is the annual stress index describing survival during unfavourable periods, and SX represents stress interactions. The calculation of GI_A and stress indices is based on the ranges of threshold parameters for species development adjusted by the user (Table 1).

Temperature parameters include the lower and upper thresholds and optimal range of air temperature for development, and similar parameters are used for soil moisture. In the present study, soil moisture thresholds were set to values representing the optimal moisture conditions for the pest species' development. In the model validation procedure, we found that this approach was most appropriate because it prevented the incorrect estimation of high dry/wet stress, which would cause an undesirable decrease in EI. In addition to temperature and moisture limitations, CLIMEX also takes into account the process of diapause, which is driven by temperature (initiation and termination temperature) and day-length thresholds. The number of generations is calculated based on the number of degree-days above the lower temperature threshold per generation. Generally EI ranges from 0 to 100, where EI = 0 indicates climate conditions unfavourable for long-term species occurrence and EI > 30 represents very suitable climate conditions for species occurrence (Sutherst & Maywald, 1985; Sutherst et al., 2001). Hoddle (2004) considers locations with EI > 25 as very favourable for species occurrence, 10 < EI < 25 as favourable, and EI < 10 as limiting for species survival and occurrence. CLIMEX models use input data on a monthly scale (minimum and maximum temperature, relative humidity at 09:00 and 15:00 h, and precipitation), which are readily available.

Model validation was carried out by comparing the modelled range of a particular pest to the current area of occurrence obtained from field observations for the period from 1961 to 1990 (weather series prepared by a weather generator, Dubrovský et al., 2000, 2004). In the present study, the CLIMEX models were first validated using observed occurrence data for ECB and CPB in the Czech Republic. The validated model was applied within the domain of the regional climate model (RCM) ALADIN, which covers the Central European area between 45° and 51.5°N and 8° and 27°E and includes Austria, the Czech Republic, Hungary, Poland, and parts of Germany, Romania, Slovakia, Switzerland, and Ukraine, Slovenia and northern parts of Serbia, parts of Croatia and northern Italy. The ALADIN model was run at a resolution of 10 km over the whole domain and the final maps were interpolated to 1 km resolution using a digital terrain model. The input weather series for the CLIMEX model was prepared by a weather generator (Dubrovský et al., 2000, 2004), which was calibrated with the RCM-simulated weather series (for the period of 1961–90). To generate weather series representing possible climate conditions in 2050, the WG parameters were modified according to climate change scenarios (Dubrovský et al., 2005) (more detailed description in Kocmánková et al., 2011).

Development thresholds	**CPB**	**ECB**
Lower temperature threshold (°C)	12	10
Optimum range of temperatures (°C)	15 – 28	18 – 28
Higher temperature threshold (°C)	33	38
Diapause induction temperature (°C)	13	12
Diapause induction daylength (h)	10	10
Diapause termination temperature (°C)	13.5	14.5
Degree-days per generation	400	726

Table 1. Parameters of the CLIMEX model for the development of Colorado potato beetle (CPB) and European corn borer (ECB)

4.2.1 Colorado potato beetle's (*L. decemlineata*) geographical distribution

The current climate conditions in the European region allow for the occurrence of one to four pest generations. Four generations currently occur in a small area in the north of Italy (Fig. 9), while only one generation is found in the northern and eastern part of the region, mainly in Poland and Ukraine. Populations in the lowlands of Germany, the Czech Republic and Slovakia can produce a partial second generation. The main areas with the climate conditions suitable for the development of three generations include Hungary, northern parts of Serbia, Croatia, Italy and the eastern part of Romania.

In altitudes higher than 600 m a.s.l, the number of degree-days for the completion of one generation of the pest is not reached, which makes these areas unfavourable for the development and survival of a viable pest population.

The results of the simulations for the expected climate scenarios show an apparent widening of the pests' climatic niche and an increase in the number of generations per year based on the temperature increase predicted by various scenarios. Fig. 10 shows the change in the number of *L. decemlineata* generations according to the HadCM-high scenario in 2050. In this scenario, there is an increase of about one generation per year in the northern part of Europe up to an altitude of 800 m a.s.l. In addition, there is a marked increase of about two generations per year in the lowlands, with a significant occurrence of three generations per year. In contrast, a marked decrease in the climate conditions favourable for *L. decemlineata* development under ECHAM-high is simulated in northern Serbia (Vojvodina region), where the significant temperature increase, according to this scenario, causes the high-temperature limitation for the pest's development and subsequent decrease of about one generation per year. A similar trend in the increase of the high temperature limitation is also seen in the NCAR-PCM-high and HadCM-high scenarios, which show all of Hungary, Croatia and the north of Italy having a decrease in the number of generations per year. Detail figures depicting results of ECHAM-high and NCAR-PCM-high scenarios see in Kocmánková et al., 2011).

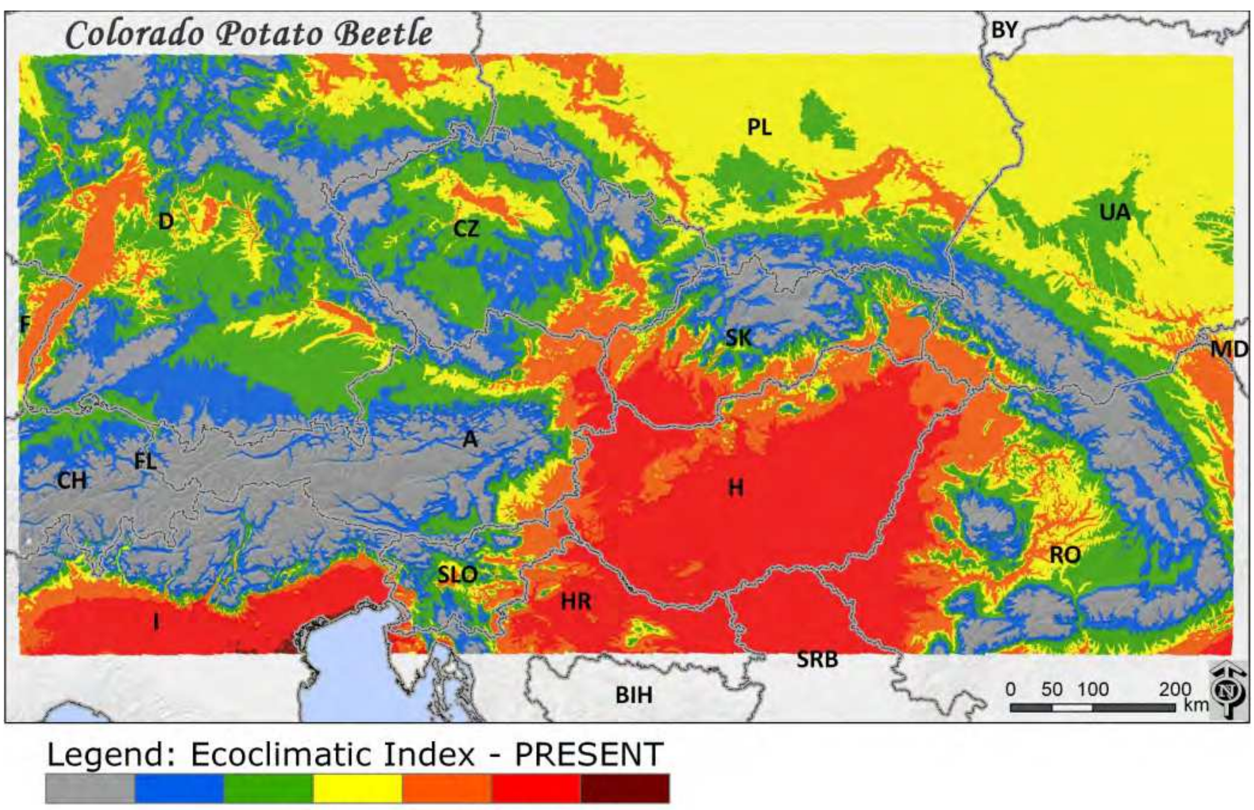


Fig. 9. Potential geographical distribution of the Colorado potato beetle (*L. decemlineata*) in current climate conditions expressed by meteorological data between 1961 and 2000. The yellow grey colour (EI 23.9–26.9) represents the area occupied by first generation of the pest, orange (EI 26.9–32.9) is the second generation, red (EI 32.9–38.9) third generation and dark red (EI>38.9) indicates the fourth generation. Abbreviations: D, Germany, CZ, Czech Republic, PL, Poland, UA, Ukraine, SK, Slovakia, Moldova, BY, Belarus, R, Romania, H, Hungary, A, Austria, CH, Switzerland, F, France, I, Italy, SLO, Slovenia, HR, Croatia, BIH, Bosnia and Herzegovina, SRB, Serbia.

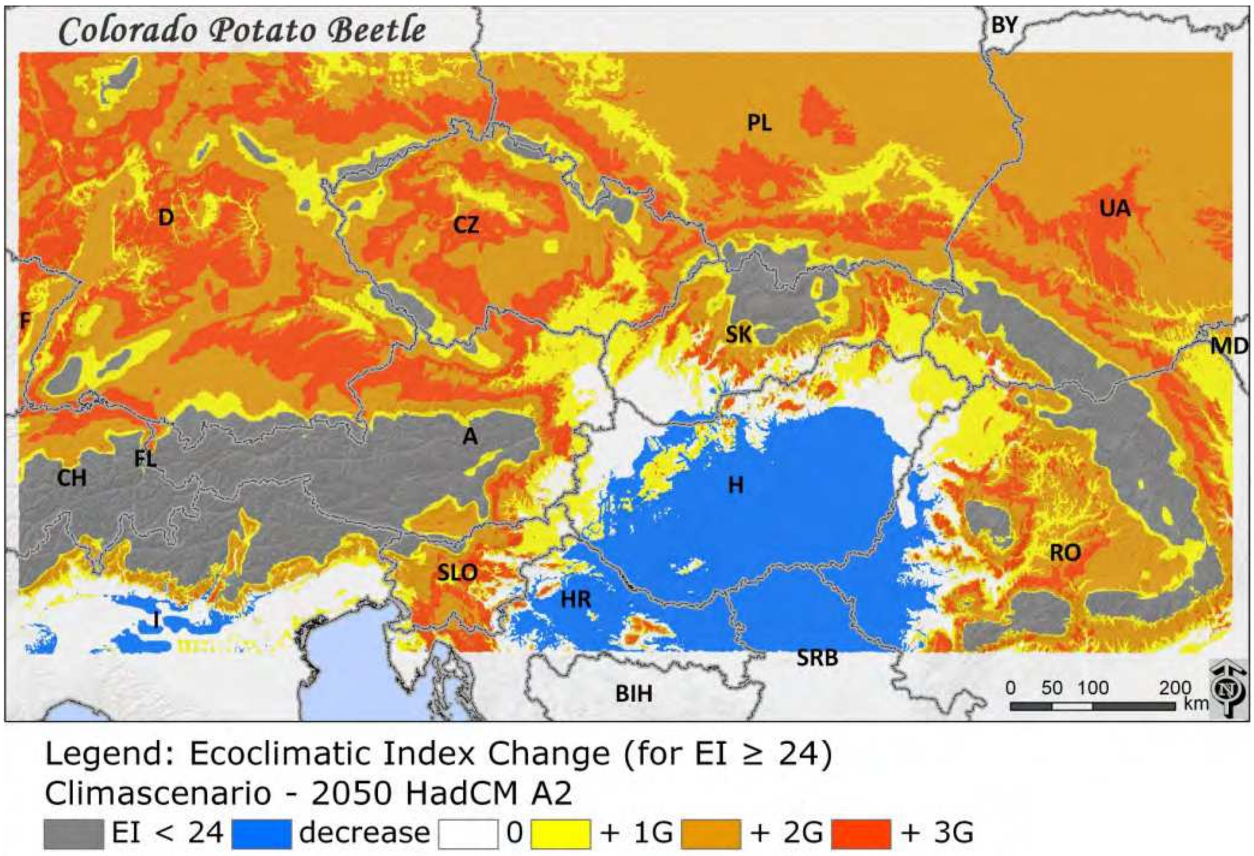


Fig. 10. Potential geographical distribution of the Colorado potato beetle (*L. decemlineata*) in the expected climate conditions expressed by meteorological data according to the HadCM-high scenario in 2050. Grey areas represent the area without an occurrence of the pest due to the incomplete first generation, blue areas show a recorded decrease in EI, i.e., the shift to less favourable climate conditions for the pest development, white colour marks the areas without any change and the colour scale (yellow to orange) points the increase in the number of particular generations. Abbreviations as in Fig. 9.

4.2.2 European corn borer's (*O. nubilalis*) geographical distribution

In the European region examined in the present study, the model indicates the presence of one or two generations per year of *O. nubilalis* under the reference climate conditions (1960–90). A higher number of generations are found in the southern part of the domain, in areas more climatically favourable for the development of *O. nubilalis* (Hungary, the northern part of Croatia, Serbia and Italy and the eastern part of Romania) (Fig. 11). Under future climate conditions, with their expected temperature increase and prolonged vegetative season, the widening of the area of univoltine population is simulated. Areas occupied by the univoltine population are likely to be replaced by a bivoltine population, which only slightly exceeds the original areal of univoltine one. At the same time, the emergence of bivoltine populations and a further increase to a third generation per year in the warmest areas is indicated. Fig. 12 depicts the expected change in the number of generations according to the HadCM-high scenario in the 2050s. It clearly shows that the pest would, for example, colonize areas recently unoccupied by the univoltine population, up presently. HadCM-high presumes a prevailing increase of about one generation, which will probably result in the presence of a third generation in the eastern part of Austria, the north of Italy and the western part of Germany (Rhine valley), where there are currently two generations per season. The NCAR-high climate sensitivity scenario (see in Kocmánková et al., 2011) assumes a wider spread, covering a major part of Hungary, Croatia and the whole simulated part of Italy.

Under the expected future climate conditions in Central and Eastern Europe, as expressed by selected climate change scenarios, crop damage by both the Colorado potato beetle (*L. decemlineata*) and European corn borer (*O. nubilalis*) is likely to increase. The increase in temperature will relocate the pests' development limitations and enable the pests to colonize higher altitudes, thus widening the area over which they occur. In the case of *L. decemlineata*, there will probably be a decrease in the number of generations per year in the warmest areas, due to the limitations of high temperature, which negatively influence the pest population.

The method presented here plays an important role in estimating species' occurrence depending on their climate requirements, but the method is limited by its lack of field- or population-level interactions. Climatic mapping may therefore be a very useful tool in pest risk analyses under changing climate because it allows us to estimate the risk of introduction, colonisation, and spread of various pest species and their economic impacts. However, the present case study also demonstrates, using two pest species as examples, that any long-term pest risk analysis must take climate change into account because of the possible changes in climatic niches.

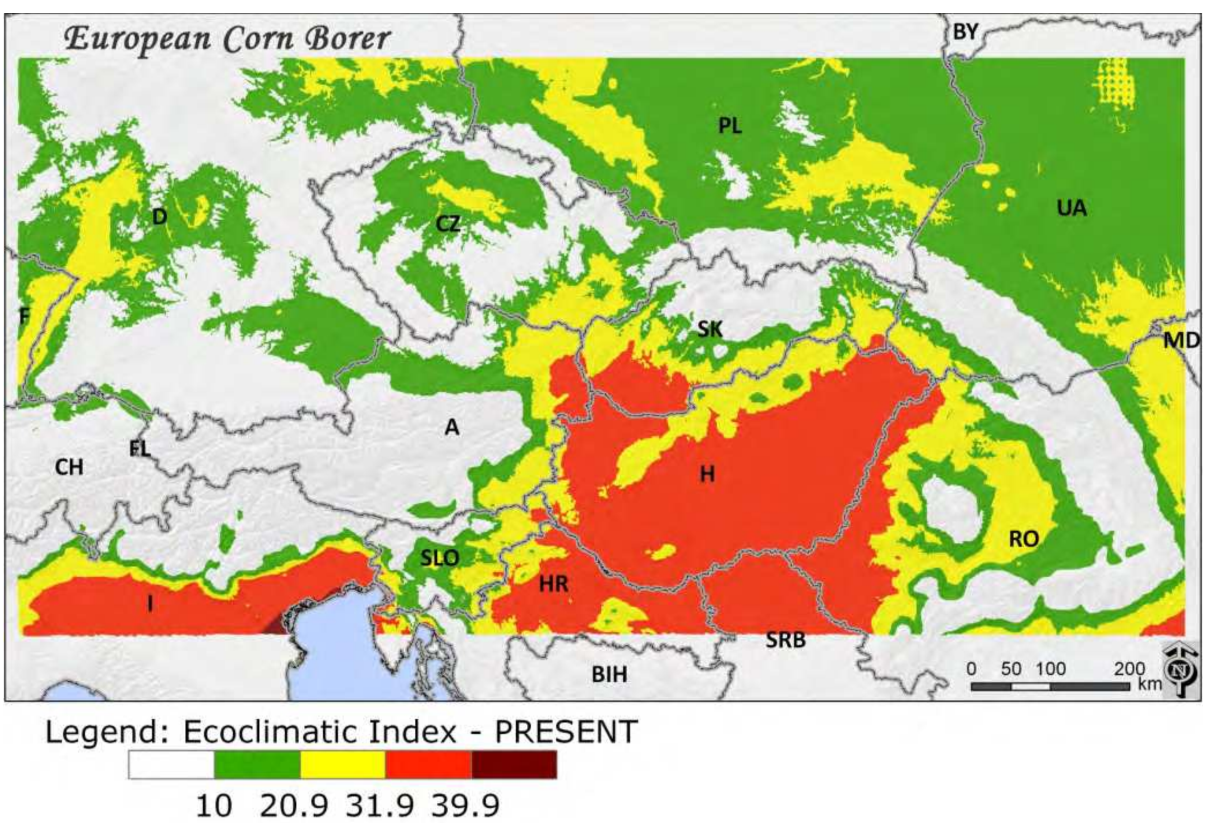


Fig. 11. Potential geographical distribution of the European corn borer (*O. nubilalis*) in current climate conditions expressed by meteorological data of the period 1961–2000. Yellow (EI 20.9–31.9) corresponds to first generation, red (EI 31.9–39.9) the second generation and dark red (EI>39.9) represents third generation of the pest. Abbreviations as in Fig. 9.

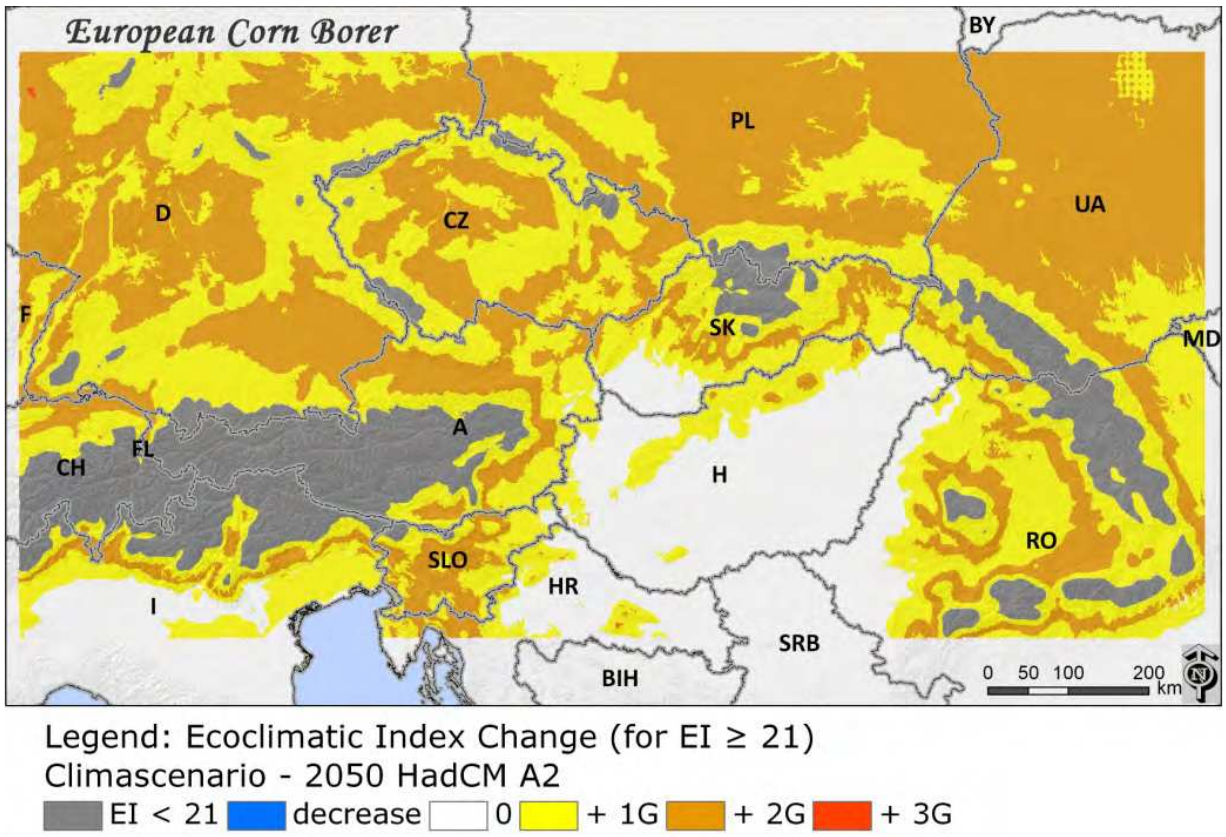


Fig. 12. Potential geographical distribution of the European corn borer (*O. nubilalis*) in the climate conditions according to the HadCM-high scenario in 2050. Grey areas indicate a lack of occurrence of the pest due to an incomplete first generation, blue areas represent a decrease of EI, i.e., the shift to less favourable climate conditions for the pest's development, white colour marks the areas without any change and the colour scale points the increase in the number of particular generations. Abbreviations as in Fig. 9.

5. Estimation of effects of climate change on agroclimatic conditions

Agroclimatic indices attempt to describe complex relations existing between climate and crops (their development and/or production) as well as the agrosystems as a whole (Orlandini et al., 2008). In order to describe agroclimatic conditions, a total of nine agroclimatic indicators were selected. The goal was to use a set of key indices that would be relevant for various aspects of crop production and complement other tools (e.g. process-based crop models).

The selected indicators include: **(a)** sum of effective global radiation, **(b-c)** water balance during the climatological spring (March-May) and summer (June-August), **(d)** thermal conditions as a proxy determing suitable areas for producing particular wine varieties based on the Huglin index and **(e)** conditions during winter in particular number of days with snow cover and **(f)** number of days with potential for severe frost damage.

All agrometeorological parameters described above were calculated with a software package, *AgriClim* (Trnka et al., 2011). The software uses daily inputs of global radiation, maximum and minimum temperatures, precipitation, air water vapor pressure and mean daily wind speed to calculate a whole range of indices as presented. When calculating actual soil water content, we assumed homogenous soil conditions and a soil water-holding capacity of 20 mm in the top 0.1 m to estimate the number of days suitable for sowing and harvest operations. The soil profile necessary for calculating effective global radiation and proportion of sowing/harvest suitable days assumed maximum rooting depth of 1.3 m and soil water holding capacity of 270 mm.

To allow grid-to-grid comparability, the same soil profile was used at all sites. While calculating evapotranspiration, an adjustment for the increased CO_2 concentration was always made using the method proposed by Kruijt *et al.* (2008), and the CO_2 ambient air concentration for the time horizon of the study (i.e. 2050) was set at 536 ppm with the "baseline" calculations set at 360 ppm. As the reference surface is defined as spring C_3 crop, accounting for the CO_2 effect resulted in a considerable decrease in reference evapontranspiration rates compared to runs not considering increase in the CO_2 levels. The whole set of agroclimatic indicators were calculated for all 99 years in each grid for the horizon of 2050. In most cases, the median value of the parameter was analyzed as well as the 5^{th} and 95^{th} percentile in order to determine 20-year extremes of the given agroclimatic index. The values in the 10 x 10 km grids were re-gridded at 1x1 km resolution using co-kriging techniques with altitude used as an additional parameter.

Effective global radiation for crop growth

The sum of the effective global radiation was calculated as the sum of global radiation during the period with mean air temperature continuously above 5°C (and without snow cover or frost occurrence) and with sufficient soil water available for evapotranspiration

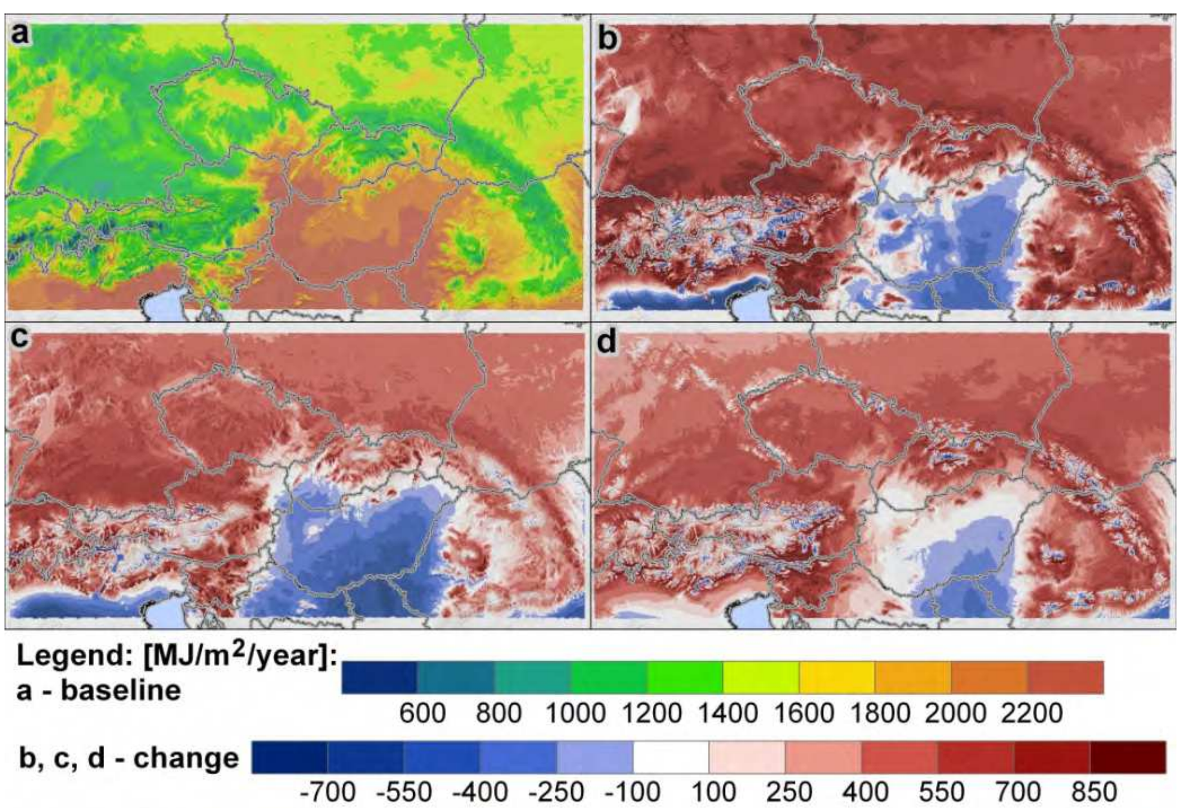


Fig. 13. Sum of effective global radiation in Central-Eastern Europe for a) baseline (1961-1990) and for increase of global mean temperature by 2.3°C with three standardized scenarios based on HadCM, ECHAM and NCAR global climate models (b-d).

(ratio between the actual and potential evapotranspiration had to be above 0.4). The temperature thresholds used followed suggestions by Brown (1976), Chmielewsky and Köhn (2000), Mitchell & Hulme (2002), and Larcher (2003). The direct effect of drought stress on crop growth is often expressed as the ratio between actual and potential transpiration (van Ittersum et al., 2003). However, in situations where evaporation from soil is not a large component, the use of evapotranspiration values will provide reasonable results. According to a number of studies (e.g. Eliasson et al., 2007), growth of the crop on a given day is not considered water limited if the ratio of daily actual and potential evapotranspiration exceeds 0.5. For this study we deliberately chose a lower threshold (0.4), to limit over-reporting drought by the used indices.
According to the applied climate scenarios the annual sum of effective global radiation will increase through increases in the duration of the potential growing period (i.e. with mean air temperatures continuously above 5°C). Additionally, the effective annual global radiation would be affected in some cases by the increase in global radiation as a result of decreased cloudiness associated with precipitation decreases, especially during the summer months. Although these changes may increase crop production potential the decrease in precipitation also increases the probability of water deficit, leading to a lower overall value of this key parameter. As shown in Fig. 13a under present conditions the southern and south-eastern parts of the domain have the highest values of effective global radiation, indicating the potential productivity of rainfed agriculture. It is the western and northern parts of the domain that would benefit most from the changed climate conditions, with areas in Germany, Poland, parts of Austria, Slovakia and Czech Republic showing sustained increase in the values of this parameter (Fig. 13b-d). The largest decreases are to be expected within the Pannonia lowland, which includes almost all of Hungary, northern Serbia and Croatia as well as parts of southern Slovakia, eastern Austria and western parts of Romania. The most marked changes (both positive and negative in regard to growing conditions) within the regions are to be expected under HadCM-driven scenarios, while the NCAR-based results indicate a much lower rate of change. The overall spatial pattern of these changes remains the same regardless of the scenario used.

Drought intensity

As an indicator the availability of water was assessed with the help of climatological water balance (i.e. difference between reference evapotranspiration ETr and the precipitation) during the spring i.e. period from March to May (MAM) as well as during the summer (JJA) when this deficit is usually the highest.

The spatial patterns of 20-year drought intensity during spring (MAM) and summer (JJA) months are similar (Fig. 14a-b) with the highest water deficit being found in Pannonian region and lowest in the Alps and mountain regions in general. The climate change (presented here by HadCM based scenario) shows an increase in the present spatial gradients during spring (i.e. dry areas become drier and wet wetter), while in summer months significant changes are to be expected over the whole region (Fig. 14c-d). The magnitude of the changes has a south-east gradient, where the arable land in the Czech Republic would be affected least, and Hungary and Slovenia show the most marked changes. On the other hand, in the NCAR scenario a slight easing of the 20-year drought intensity in the Czech Republic, Austria, Slovakia and Slovenia is shown, leaving only the arable lands in Hungary worse off.

Wine growing conditions

The Huglin index (HI) enables different viticultural regions to be classified in terms of the sum of temperatures required for vine development and grape ripening (Huglin, 1978). The HI value was calculated for the period from April 1 until September 30 using the following formula:

$$HI = \sum_{i=0}^{n}((T_{max} - 10) + (T_{mean} - 10) * K))/2 \tag{9}$$

where Tmax corresponds to maximum daily temperature, Tmean to mean daily temperature and K represents the coefficient for latitude that changes linearly from 1.02 at 40°N to 1.06 at 50°N. Different grape varieties are thus classified according to the minimal thermal requirement for grape ripening. The minimal Huglin index for vine development is defined between 1500 - 1600. As the HI considers only thermal conditions during the growing season, the results must be interpreted with caution especially in the eastern part of the domain where continental climate is predominant as wine growing is prevented by frequent occurrence of winter temperatures below -20°C. The attribution of the particular variety to thermal conditions estimated with the use of Huglin index was based on Schultz et al. (2005) and should be treated as an approximation.

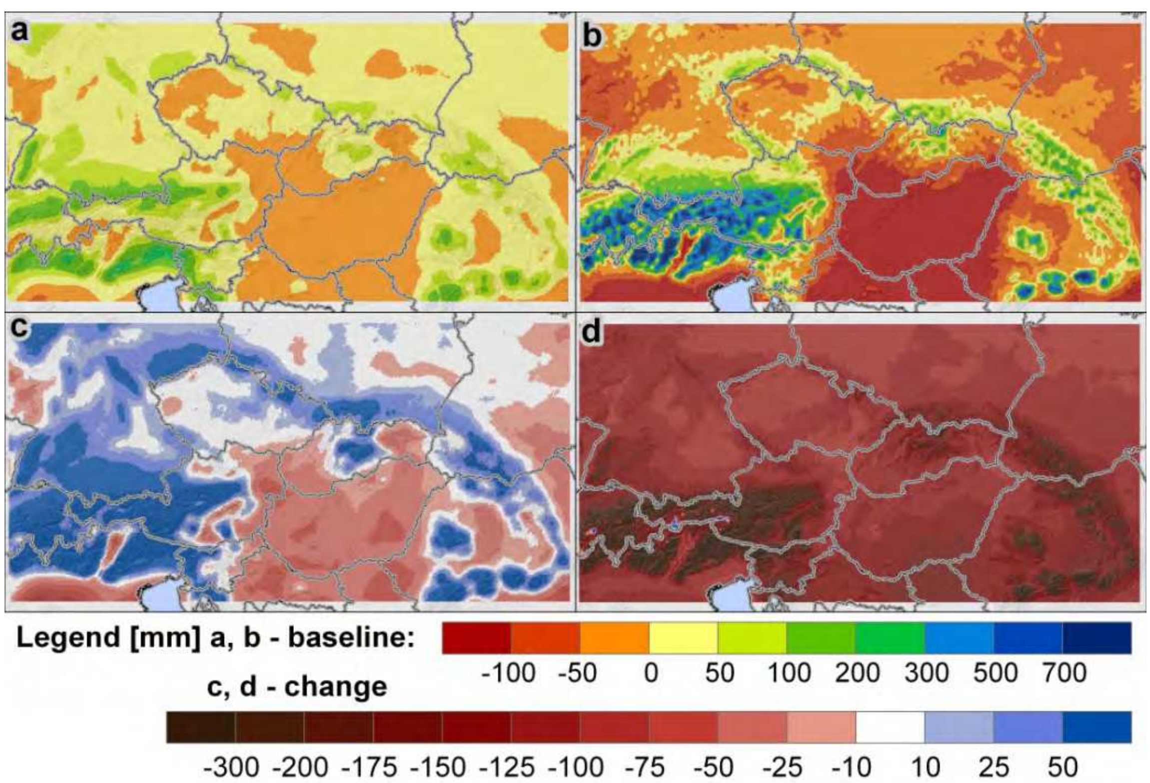


Fig. 14. Water deficit with 20-year return period for spring i.e. March-May (a,c) and summer i.e. June-August (b,d) in Central-Eastern Europe for baseline i.e. period between 1961 and 1990 (a,b) and for increase of global mean temperature by 2.3°C with HadCM standardized scenario.

The Huglin index indicates growing degree day changes for wine. Significant increase in the Huglin index value across the whole domain (Fig.15) is a direct consequence of the expected temperature increase according to climate projections used. Fig. 15 shows that the present mean value of Huglin index would not allow a permanent successful production of grapes across most of the domain except in areas established as wine growing regions already and those very good thermal conditions for wine growing are to be found especially in the southeastern part of the domain. Under the changed climate, the potential wine growing area would increase substantially, providing Huglin index values sufficient for wine production across much of the region with the exception of mountainous areas (however, other limitations such as soil conditions and small scale local climatic variations based on terrain effects such as the slope effects on temperature or cold air lake conditions are not considered in this study). It must be stressed that the Huglin index takes into account only temperature requirements during the summer period, which is not by any means a sole factor affecting wine production. The results clearly show that the present wine growing regions in Central Europe will be faced overall with much warmer conditions, requiring in some cases different cultivars than those grown nowadays. They also indicate that there is a prospect of wine growing even in the northern latitudes where wine production is off limits due to the present climate.

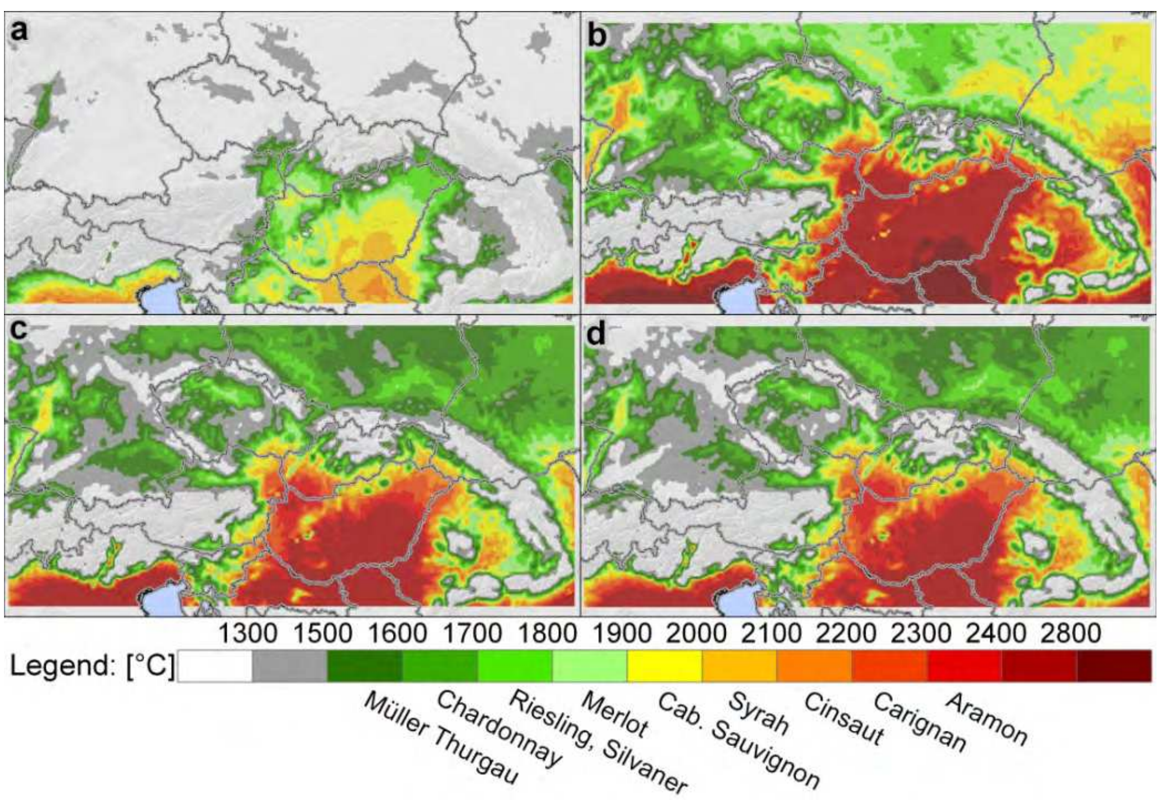


Fig. 15. Value of HUGLIN index serving as a proxy for wine cultivar suitability in Central-Eastern Europe for a) baseline (1961-1990) and for increase of global mean temperature by 2.3°C with three standardized scenarios based on HadCM, ECHAM and NCAR global climate models (b-d).

Agroclimatic conditions during winter

The number of days with snow cover was estimated with the help of SnowMAUS model (Trnka et al., 2010) that estimates snow cover absence/presence using daily temperature and precipitation total.

The days between September-April during which minimum daily temperature (at 2 m height) decreased below -10 °C and there was no snow cover were evaluated as period with likely frost damage to field crops using also approach described in more detail by Trnka et al. (2010).

The effect of changed climate on the number of days with the snow cover (Fig. 16a,c) indicates that by 2050 more than 80% of the domain will have on average snow cover on less than 50 days while at one third of the domain it is going to be less than 25 days. The related risk of severe frost damage to field crops by low temperatures (less than -10°C) is likely to decrease (Fig. 16b,d) as well across most of the domain despite the reduction of snow cover that acts as quite reliable protection in these events. On the other hand the occurrence of late frost (especially radiation type frost) is likely not to altered so significantly that will pose different sort of risk to field (but especially to perennial crops such as orchards) that will tend to start their growing season earlier and as a consequence will lose their frost tolerance.

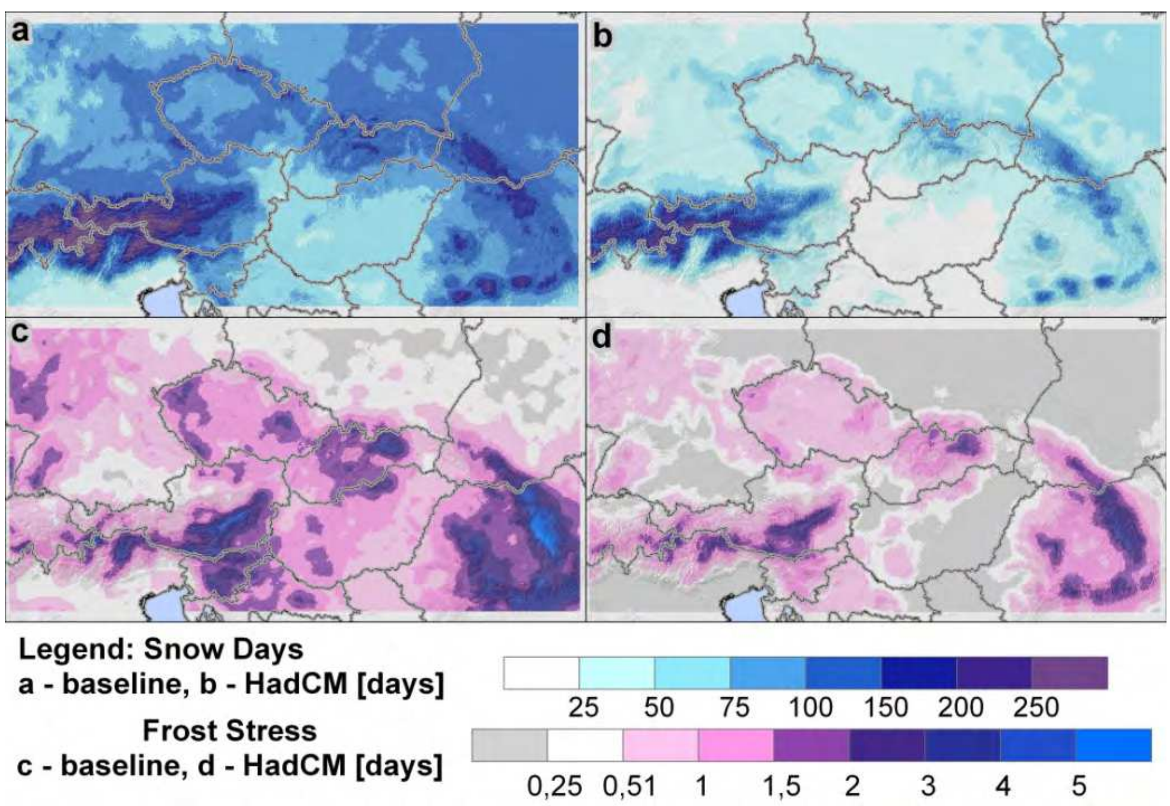


Fig. 16. (a) Mean number of days with snow cover in Central-Eastern Europe for baseline i.e. period between 1961 and 1990 and (b) expected change for increase of global mean temperature by 2.3°C with HadCM standardized scenario; (c) number of days with high risk of frost damage with 20-year return period for the baseline period and (d) expected change for increase of global mean temperature by 2.3°C with HadCM standardized scenario

6. Conclusions

It can be concluded that rainfed agriculture in Czech Republic as representative of Middle Europe region may face higher climate-related risks. However, the analyzed agroclimatic indicators will likely remain at levels that permit acceptable yields in most years.

Concurrently, our findings also suggest that the risk of extremely unfavorable years, resulting in poor economic returns, is likely to increase in many years. This projected increase in the variability of climatic suitability for crop production is particularly challenging for crop management and for agricultural policy, which aims to ensure stable food production and viable conditions for farmers. This therefore suggests that agricultural policy should encourage the adoption of both agroecological techniques and a diversification of production

To increase crop resilience to climatic variability as well as the implementation of various instance schemes (e.g. strategic grain stocks, farmer drought and flood insurances) and improvements in the efficiency of agricultural water use. An analysis of yield development, agrometeorological conditions in combination with agroclimatic projections under different climate-change scenarios across Europe offers the possibility of supporting early decision-making with regard to opportunities and risks. The analysis presented here should be conducted at regional and local levels to better reflect how specific localities may be affected.

7. Acknowledgement

We gratefully acknowledge the support of the Research plan No. MSM6215648905 "Biological and technological aspects of sustainability of controlled ecosystems and their adaptability to climate change and National Agency for Agricultural Research project No. QI91C054, CzechGlobe – Centre for Global Climate Change Impacts Studies, Reg. No. CZ.1.05/1.1.00/02.0073, project KONTAKT LH11010 (Integrated system for drought surveillance), 7th FP EU project CLIMSAVE Climate Change Integrated Assessment Methodology for Cross-Sectoral Adaptation and Vulnerability in Europ (contract no. 244031), which helped to execute the presented study.

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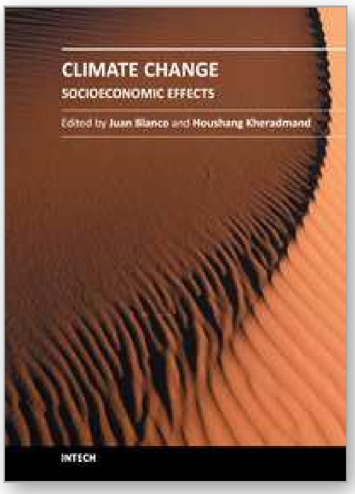

Climate Change - Socioeconomic Effects
Edited by Dr Houshan Kheradmand

ISBN 978-953-307-411-5
Hard cover, 454 pages
Publisher InTech
Published online 09, September, 2011
Published in print edition September, 2011

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