Comparison of Two Mapping Methods of Potential Distribution of Pests under Present and Changed Climate

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Abstract

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The study compares two methods for modeling the potential distribution of pests when applied to the European corn borer (*Ostrinia nubilalis* Hubner). The development of the European corn borer (ECB) is known to be closely correlated with daily air temperature as well as other climate variables. The climatic parameters are, therefore, used to predict the potential geographical distribution using tested tools such as CLIMEX or ECAMON. These models consider the climatic suitability of a given site/region for the pest's development and, thus, the possible establishment of a population at a given location. In this study, meteorological data from 1961 to 2000 and from 45 meteorological stations were used to characterise the current climate conditions in the Czech Republic. Validation was based on available field data of the occurrence of ECB in the same period. The climate parameters were later modified according to the estimates based on the combination of three SRES emission scenarios and three global circulation models. Under all climate change scenarios, we noted a marked shift of the pest's potential niches to higher altitudes, which might lead to an increase in the infestation pressure during the first half of this century. The present area of the univoltine population will increase due to temperature increases even above 800 m a.s.l. In addition there is a risk of the establishment of a bivoltine population in the main agricultural areas and 38% of arable land in the Czech Republic before 2050.

Keywords: *Ostrinia nubilalis;* ECB; ECAMON; CLIMEX; geographical distribution; climate change; climate niche

There are major gaps between the actual and maximum attainable yields of crops. These gaps are largely attributable to pests, diseases and weeds. The main factors determining the intensity and occurrence of pests are the overall climate conditions of the locality and the course of weather within the given season, in addition to the abundance of host plants. While inter-seasonal weather variability and consequent fluctuations of individual pest species are well-known phenomena,

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the changes in the overall climate conditions and associated shifts in ranges of particular taxa have received increasing attention, as this is perceived by some recent reports to be a threat to managed ecosystems (McCarhy *et al.* 2001). The present study will demonstrate the methodology and benefits of climate-driven modeling tools using the example of the European corn borer (*Ostrinia nubilalis,* Hübner 1796). This model species was selected as it is one of the most important pests of corn (*Zea mays* L.) and also because European corn borer (ECB) development closely correlates with meteorological conditions during a given season. It was possible to concurrently acquire a sufficient database from past field experiments as well as reports on ECB occurrence and damage within the 1961–2000 period. Pest species, ECB in particular, may also be considered as model species representing the possible behavior of other *Lepidoptera* species with similar environmental requirements.

The number of generations of ECB during one vegetation season varies from one to six, depending on the climate conditions (Capinera 2001). In the Czech Republic, the ECB population is thought to be univoltine (Bírová 1984), as partial bivoltine populations are present only occasionally in Slovakia during unusually warm vegetative seasons (Cagáň 1998). According to one of the first studies focused on the impact of climate change on ECB populations in Europe (Porter *et al.* 1991), a temperature increase associated with ongoing climate change would lead to a shift of the area of ECB occurrence to the north, and possibly to the occurrence of a second generation in areas with presently univoltine populations. However, the biological cycle of the pest is also affected by day length, scotophase (defined here as that part of a night when the sun is less than 6° below the horizon) and latitude (e.g. Onstad & Brewer 1996), as well as particular pheromone types (so-called Z and E strains). The Z strain is closely associated with corn as a host plant, whereas the E type is also found on other crops (Mason 1996). According to Hrdý *et al.* (1986), both Z and E strains are present in southeast Moravia where most of the validation data were collected. In the Czech Republic at present, the onset of the diapause of the whole larval population is probably determined by the combination of photoperiod and temperature, as observed in a number of studies (Bírová 1984; Onstad & Brewer 1996; Cagáň 1998; Cagáň *et al.* 2000; Tancik & Cagáň 2004; Trnka *et al.* 2007).

The aim of this study is to illustrate the present range of ECB occurrence in the current climate and compare it with the observed data and also to estimate the expected time horizon for the appearance of a second generation of the ECB. In order to demonstrate the possibilities of climate-driven modeling tools, the results of two models, ECAMON (Trnka *et al.* 2007) and CLIMEX (Sutherst & Maywald 1985; Sutherst *et al.* 2001), will be compared.

MATERIAL AND METHODS

ECAMON is a semi-quantitative model used in assessing the occurrence of ECB based on climate conditions. This model integrates into a complex framework the results of multiple studies that describe the relationships between seasonal weather conditions and ECB occurrence. It consists of two modules providing data on (*i*) phenology of the pest, and (*ii*) environmental stresses encountered by the ECB population within a given season. ECAMON can estimate the date of initiation, 25%, 50%, 75% and termination (100%) of each developmental stage using a degree-day calculation method that was adjusted according to Apple (1952) and Mason (1996), and has a base temperature of 10°C. The degree-day calculation in ECAMON also takes the presence of a snow cover into account, and the initiation procedure is fully autonomous and climate-driven (i.e. no arbitrary starting date is needed). ECAMON also estimates the extent of environmental stresses during sensitive periods of the development of ECB, ranging from excessive dryness during egg laying and hatching to the occurrence of heavy rain during early larval stages or of frost during the active life cycle (i.e. outside of diapause). The model then calculates the proportion of the population that terminated during development up to a certain stage, using only the daily meteorological data (e.g. minimum and maximum temperature, rain, daily sum of global radiation, precipitation, mean water vapor pressure and wind speed) in the individual season. Thus, the climate suitability (CS) index is determined for univoltine (CS_I) and bivoltine (CS_{II}) populations (Trnka *et al.* 2007). The CS_I and CS_{II} are defined as ratios of seasons with successful completion of the 1st (or 2nd) generation of the pest and the overall number of evaluated seasons. A year was marked as suitable when it enabled the development of 95% of the population, and the value of CS_I was calculated as:

$$CS_I = X_{suitable}/n$$

where:

$X_{suitable}$ – number of suitable seasons based on the criteria defined above

n – total number of years

While ECAMON is based on the observed daily data and is rather detailed, CLIMEX version 2.0 is much simpler, though it is still a dynamic model operating with input data on a monthly scale (minimum and maximum temperature, relative humidity at 09:00 h and 15:00 h, precipitation), which are generally more readily available. Knowing the climatological requirements of the given species allows us to assess the suitability of a given area for population growth and determines the stress exposure due to unsuitable climatic conditions. These are expressed in terms of the Ecoclimatical index (EI), which describes the climate, and enables us to draw conclusion on the possible prospect of development and survival of ECB (Sutherst & Maywald 1985; Sutherst *et al.* 2001):

$$EI = GIA \times SI \times SX$$

where:

GIA – annual growth index describing the population growth during favorable conditions

SI – annual stress index describing survival during unfavorable period

SX – stress interactions

Both models of the potential geographical distribution of ECB in the current climate conditions assessment were run for two sets of conditions in order to verify the functionality of the models in comparison with the observed data. First, the meteorological data of the reference period 1961–1990 were used, followed by analysis of the response of ECB to the unusually warm period of 1991–2000. During the latter period, the mean annual temperature at 30 representative Czech weather stations increased by 0.2–0.9°C compared to the 1961–1990 baseline (e.g. Květoň *et al.* 2001; Chládková *et al.* 2007). These studies also showed that the 1990's were the warmest decade of the 20th century in the Czech Republic.

The potential geographical distribution of ECB, as estimated by both models, was compared with the observed occurrence of ECB in the same period. The observed data set was gathered from light and pheromone traps in the period from 1977 to 2005 (furnishing records of the initiation, 50% and termination of the ECB flight), supplemented by data published by the SPA (State Phytosanitary Administration) in their annual reports and also those obtained through personal contacts with individual research stations and farmers during the period of 1961 to 2003. The database consists of almost 900 reports on the occurrence of ECB from more than 200 sites spanning the entire Czech Republic. Even though this database is not complete and comprehensive, it allows us to determine those regions where crop damage caused by ECB has been extensive (Figure 2). Meteorological data used in the study originated from the 45 climatologic stations in the period of 1961–2000, and were provided by the Czech Hydrometeorological Institute.

Following the validation and the calibration of the model, the input meteorological data were altered according to a set of three Global Circulation Models (ECHAM, HadCM and NCAR), which were driven by three SRES emission scenarios (A2, B1 and A1T) based on the work of Dubrovský *et al.* (2005). The projected temperature increase

Table 1. Expected rise in daily mean temperature of individual months according to the scenarios ECHAM B1 and ECHAM A2 for 2025 and 2050 (Dubrovský *et al.* 2005)

Month	ECHAM B1		ECHAM A2	
	2025	2050	2025	2050
1	0.624	0.968	1.490	2.649
2	0.628	0.975	1.500	2.667
3	0.602	0.934	1.437	2.555
4	0.742	1.150	1.771	3.147
5	0.443	0.688	1.060	1.885
6	0.717	1.111	1.711	3.041
7	0.835	1.296	1.995	3.546
8	0.945	1.466	2.256	4.012
9	0.868	1.348	2.075	3.688
10	0.660	1.024	1.576	2.802
11	0.614	0.953	1.467	2.608
12	0.660	1.024	1.576	2.802

according to scenario ECHAM is shown in Table 1. The outputs of the models for the current and expected climate conditions were visualised by GIS (Geographical Information Systems), using a digital landscape model (grid layer with resolution of 1 × 1 km), which for each grid section included information on suitability of the area for maize production (e.g. land use type, mean annual temperature, altitude, soil type, maximum available soil water capacity in the rooting zone etc.).

RESULTS AND DISCUSSION

The simulation outputs of the potential geographical distribution models for ECB for the current climate conditions derived from using ECAMON and CLIMEX modeling are presented in Figure 1. The simulated geographical distribution represents the potential occurrence of infestations by the pest, or the area with conditions suitable for the occurrence of ECB with viable populations that are usually associated with economically significant densities. The study did not take presence of the host into account because of the wide range of possible host species for ECB; this is not thought to be a severely limiting factor, although it may significantly slow down developmental rates (Anderson *et al.* 1982). Both models demonstrated very good agreement with the observed series of data during two different periods (1961–1990 and 1991–2000). Both models also properly recorded the expansion of ECB based on the higher temperatures of the last decade of the 20th century, which seems to support the hypothesis that this expansion was at least partly climate driven. All maps constitute the GIS visualisation of the output climate suitability based on the selected indices (CS_I, CS_{II} and EI). The interpolation method took the altitude into account, using a detailed digital elevation model. The recorded field occurrence

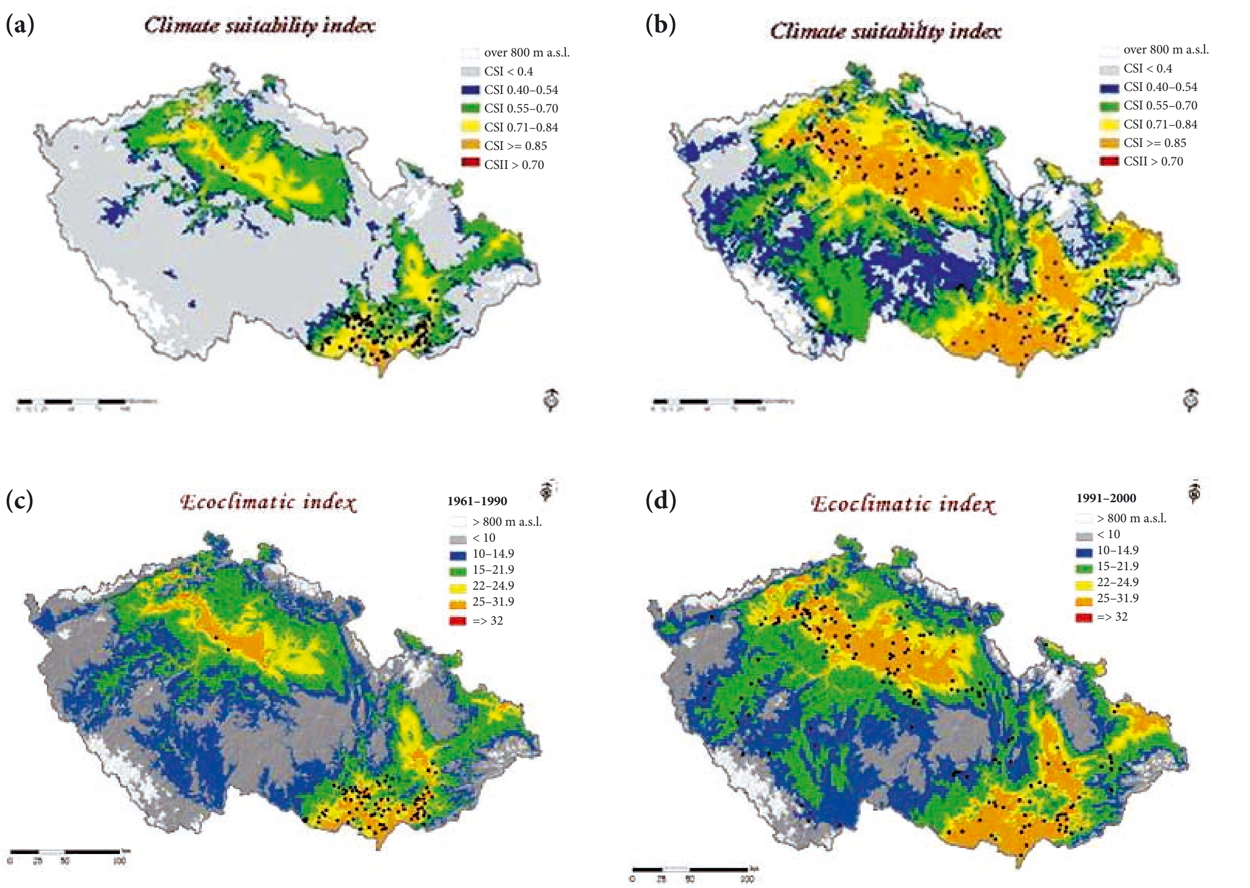

Figure 1. Occurrence of ECB (*Ostrinia nubilalis*) in the Czech Republic according to ECAMON (a, b) and CLIMEX (c, d). Figures (a) and (c) correspond to the estimated range under climate conditions of 1961–1990, while (b) and (d) correspond with those between 1991 and 2000

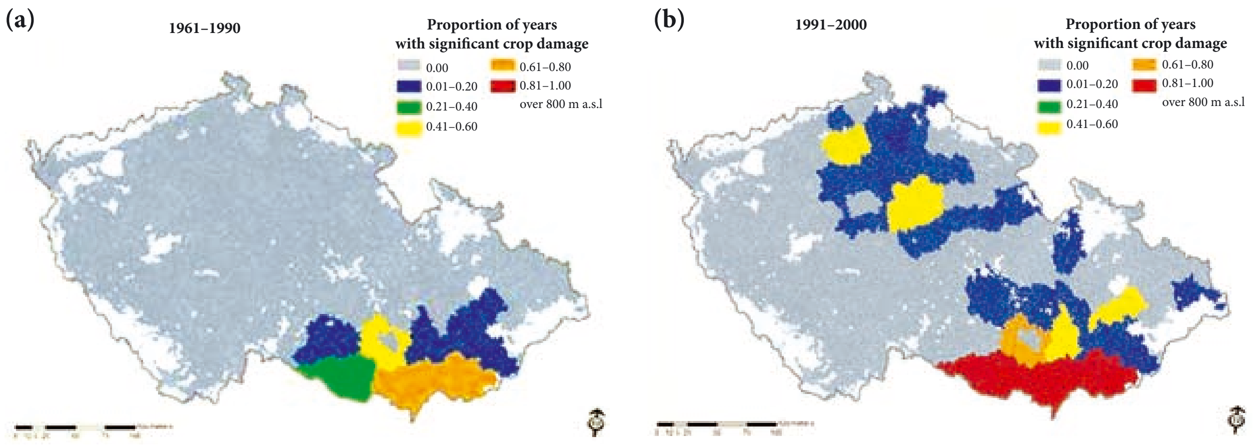

Figure 2. Areas where ECB caused economic losses expressed as the proportion of years when treatment against ECB in the region was reported during the periods of 1961–1990 (a) and 1991–2000 (b)

of ECB with resulting economic losses during the two periods 1961–1990 and 1991–2001 are shown in Figure 2.

Figure 3 shows the comparison between estimated potential niches for ECB according to both models (ECAMON and CLIMEX). The green area represents regions where both models indicated the potential for establishment of an ECB population, while no color indicates where no long-term ECB population was possible during each of the two periods according to both models. The areas in red and yellow indicate the regions of disagreement between the two models. Figure 3b shows that CLIMEX is likely to underestimate the potential geographical distribution assessment compared to ECAMON, which seems to be a more sensitive tool for estimating ECB occurrence and also shows a better fit with the observations (Figure 1). This superiority of ECAMON over CLIMEX is due to its very detailed developmental module and the use of the daily time step as compared to the crude climatology used in CLIMEX. Given that a detailed evaluation of the model has proven ECAMON's capability to accurately estimate the initiation and persistence of crucial phenological stages, and the fact that the CS index corresponds with the occurrence of the real pest, the main advantage of CLIMEX is that it has far lower input data requirements and still yields relatively reliable results.

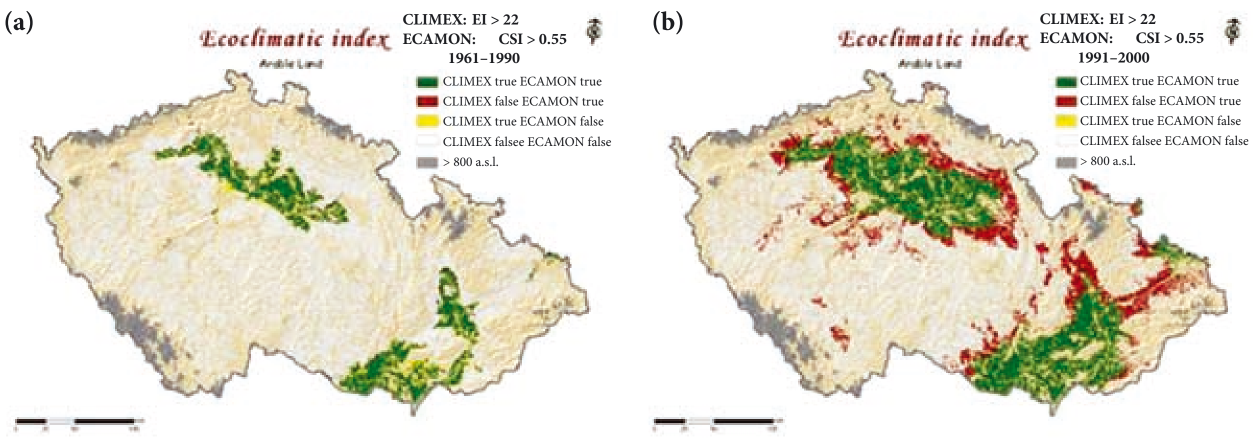

Figure 3. Comparison of potential climate niches for ECB under the current climate conditions and on the arable land, as estimated by CLIMEX and ECAMON during 1961–1990 (a) and 1991–2000 (b). Green color marks those regions that are considered suitable for ECB establishment by both models, while no color is assigned to regions that are not suitable. Yellow and red colors mark the regions where the outputs of the models do not correspond

The relatively good agreement between simulated and observed data (Figure 1), and the ability to determine the shifts in the potential niche in the 1990's enabled us to use both models to estimate the extension of the potential niche in the future. In the case of an expected increase in temperature and seasonal shift (Dubrovský *et al.* 2005), both models estimated an expansion of ECB into higher altitudes (Figures 4 and 5) according to chosen SRES scenarios. The scenario ECHAM B1 for 2025 in the ECAMON model shows the presence of the ECB univoltine population in the Czech Republic comparable to its actual occurrence in the last decade of the 20th century. However, the scenario ECHAM A2 for 2025, which projects a more pronounced temperature increase, predicts a significant spread of the univoltine ECB area that should be expected as this expansion proceeds from the central areas of the Elbe river basin, southern Moravia, and the Silesian region to remaining low- and mid-lying agricultural areas of the Czech Republic, including 95% of the arable land (Trnka *et al*. 2007). Simultaneously, the ECAMON model indicates a possible occurrence of a ECB bivoltine population in a relatively small part of southern Moravia (0.02% of the arable land). The trend toward widening of the pest's climatic niche is even more pronounced in ECHAM B1 and A2 model maps for 2050 (Figures 4 and 5). During the next 25 years, ECB could potentially become established as a significant maize pest in large numbers throughout the whole area of the Czech Republic, with bivoltine populations in the main production regions which encompass 38% of the arable land, and possible univoltine populations in areas above 800 m a.s.l.

Both models demonstrated that climate is a significant factor determining the development and

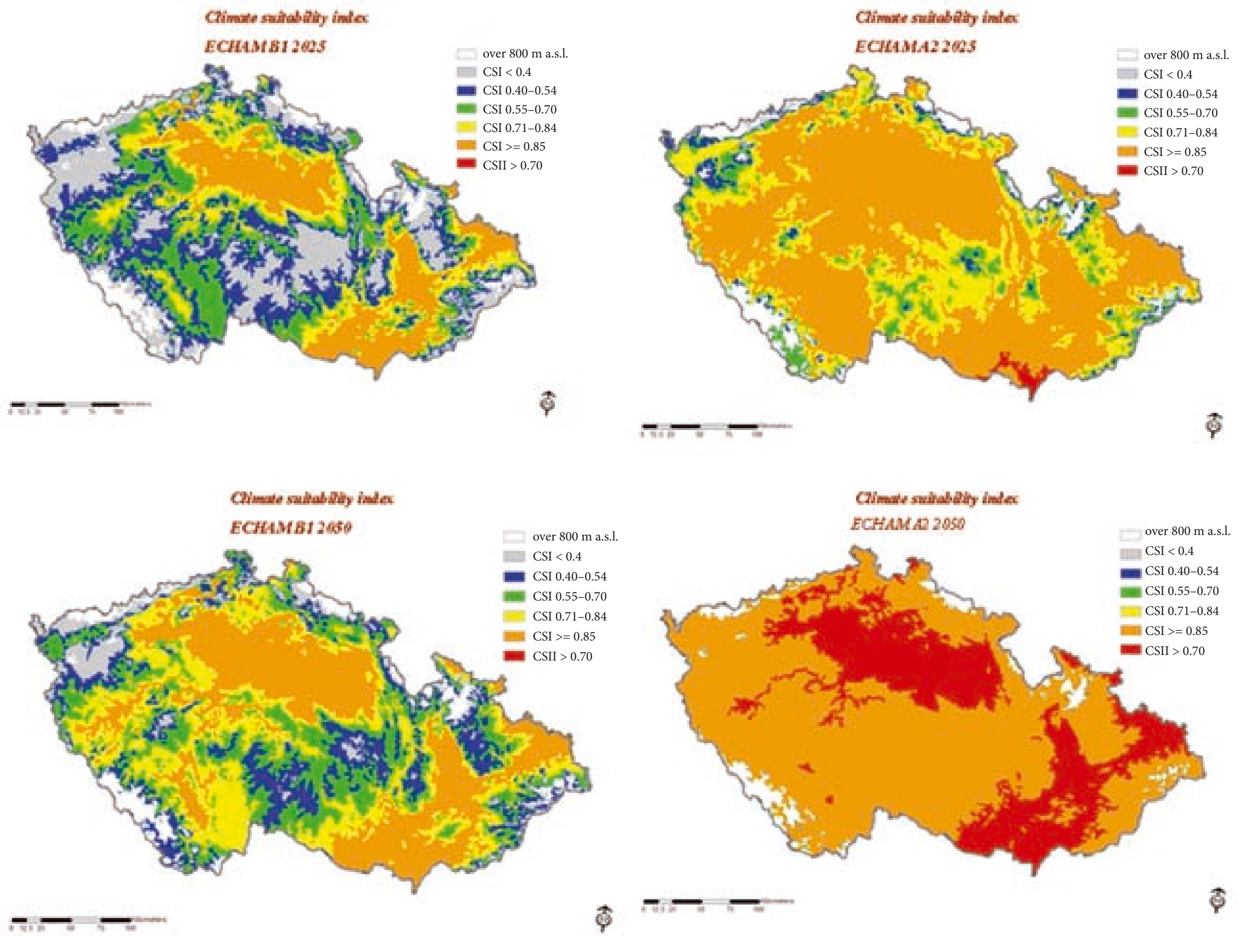

Figure 4. Development of the climatically suitable areas for the 1st and 2nd generations expressed in terms of CS_I and CS_{II} based on ECAMON calculations for 2025 and 2050. The estimates are based on the ECHAM GCM model with a combination of the B1 SRES scenario and the low sensitivity of a climate system (ECHAM LOW) and A2 SRES scenario and high climate sensitivity (ECHAM HIGH)

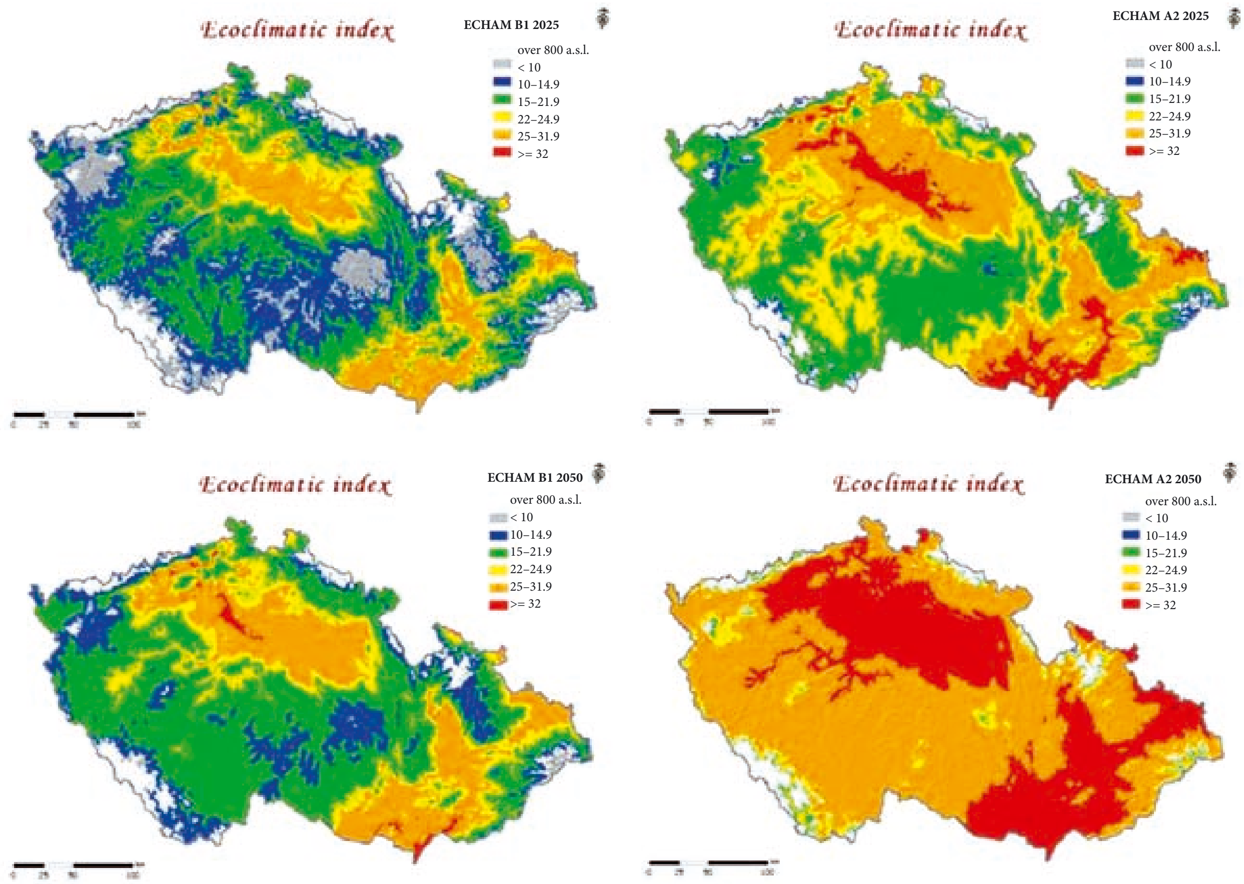

Figure 5. Development of the climatically suitable areas expressed in terms of Ecoclimatic index for 2025 and 2050 based on CLIMEX calculations. The estimates are based on the ECHAM GCM model with a combination of the B1 SRES scenario and the low sensitivity of a climate system (ECHAM LOW) and A2 SRES scenario and high climate sensitivity (ECHAM HIGH)

survival of ECB. According to the estimates, the area of established univoltine populations could significantly widen over the next 20–30 years, until in 2050 it could cover most of the area suitable for agriculture. The threat of an expanding ECB bivoltine population is not imminent in the next decade, although this is likely to change during the period of 2025–2050, at least in the warmest areas of the Czech Republic.

Similar results have been acquired in the simulations of the potential geographical distribution of Colorado potato beetle (*Leptinotarsa decemlineata*, Say 1824; CPB) in the Czech Republic for both the present and expected climate (Kocmánková *et al.* 2007). In this case the results also indicated a widening of the area suitable for CPB development, its shift to higher altitudes and an increase in the number of generations. Under the present climate, the pest has established both univoltine and in the warmest areas also bivoltine populations. However, under the conditions expected according to GCM ECHAM A2 for 2050, a partial third generation on 45.1% of the country is likely. During this time horizon the conditions suitable for the complete third generation will be fulfilled on up to 0.2% of the arable land.

Climatic mapping is a tool for estimating the potential distribution of organisms under the current and expected conditions (Baker *et al.* 2000). This method plays an important role in estimating the occurrence of species depending on their climate niche requirements, but is limited by its lack of field- or population-level interactions. Climatic mapping may be a very useful tool in the pest risk analyses as it allows us to estimate the risk of introduction, colonisation and spread of various pest species and their economic impacts. In addition, it is also very promising in cases of seasonal monitoring and forecasting (e.g. http://ume.zedx-inc.com/cgi-bin/site.cgi?location=1&user=ume# 2007). This study demonstrates, through an example species, that any pest risk analysis must take global change into account because of the possible changes in the climate niche of the species in question.

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