Project No. 037005

CECILIA

Central and Eastern Europe Climate Change Impact and Vulnerability Assessment

Specific targeted research project

1.1.6.3.I.3.2: Climate change impacts in central-eastern Europe

D6.5: Report about the expected changes of occurrence and activity of pests and diseases on selected crops and forest ecosystems

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PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
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Contents

1. Pest and diseases in the crop ecosystems

Pests and plant diseases are relevant biotic factors reducing the yield levels and their presence in agroecosystems can affects also the yield quality parameters. Lifecycle of pests is affected by various factors from which climate conditions are the most significant. Climate can limit distribution of the species directly by influencing survival and fecundity, or indirectly through its effects on interacting species, including food sources, natural enemies and competitors (Gaston 2003). Changes in climate conditions may therefore result in alterations in geographical distribution of the species, changes in overwintering, changes in population growth rates, increases in the number of generations, extension of the development season, changes in crop-pest synchrony, changes in interspecies interactions, and increased risk of invasion by migrant pests (Porter et al. 1991). An increase in the number of generations 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 fact could play an important role in the case of multivoltine species (Pollard & Yates 1993). Most of these species are expected to widen their infestation area to higher latitudes and altitudes, as has been reported for butterflies (Pollard et al. 1995; Hill et al. 1999, 2002; Parmesan et al. 1999). The increasing temperature could likely support the earlier diapause termination of overwintering species, which will consequently appear earlier. This will influence the intensity of crop-insect interactions (Yamamura & Yokozawa 2002).

In current climate conditions the insect species diversity per area tends to decrease with increasing latitude (Gaston & Williams 1996; Wilf & Labandeira 1999). A similar trend is usually seen with increasing altitude (Gaston & Williams 1996). Warmer conditions may be expected to promote a pole ward extension of the range of species which are currently limited by low temperature, or they can shift in altitude at which they can survive. A 2 °C increase of temperature, which is expected in northern temperate latitudes till the 2050´s, is equivalent to a shift of current conditions of approx. 600 km latitude or approx. 330 m in elevation. This is equivalent to approximately 6 km per year latitude or 3.3 m per year elevation (Bale et al. 2002).

Impacts of climate change on pests’ populations in the northern hemisphere will have different character according to geographical position of their current areas. In the northern hemisphere, populations occurring towards the northern margins of species’ ranges will be subject to greater climatic stresses than those occupying more central regions, and as such will be expected to be less stable. In other words organisms near the limits of their ranges are typically most sensitive to change (Archer 1994).

The CECILIA effort was focused on the impact of climate change on two pests: the Colorado potato beetle (*Leptinotarsa decemlineata* Say, 1824) (referred to as CPB) and the European corn borer (*Ostrinia nubilalis* Hübner, 1796) (referred to as ECB). The CPB is one of the most important insect pest of potato crops around the world (Hare 1990) and is widespread in Europe (EPPO 2007). Occurrence of ECB, as the most important pest of grain maize, has also been recorded across the Europe by EPPO (2007). These two species are expected to widen their occurrence area and increase the infestation pressure due to climate change. Development of these species is closely related to climate conditions and mainly to the course of temperature. Mechanisms by which climate conditions affect the development of a species can be analysed with the CLIMEX software tool. CLIMEX is a worldwide renowned software that has recently been applied in various scientific studies considering the potential distribution and spread of animal or plant species (Olfert & Weiss 2006; Zalucki & Furlong 2005; Pethybridge & Wilson 2003; Rafoss & Saethre 2003; Kriticos et al. 2003; Lockett & Palmer 2003; Bell & Willoughby 2003; Sutherst 2000a; and Sutherst 2000b, among many others).

Within the project CLIMEX is used for the estimation of climate limits at in the Czech Republic and northern part of Austria (Lower and Upper Austria and Burgenland) and then the

RCM climatic data are applied and use with the same tool to cover much larger area of Central Europe and demonstrate potential of high resolution RCM data.

Under present climate conditions in the Czech Republic, ECB developes 1 generation, rarely 2 generations only in very warm growing seasons. The occurrence of a second generation of ECB in central Europe has so far been limited by photoperiod as well (Trnka et al. 2007). CPB in the Czech Republic and Austria develops 1–2 generations. The biggest economical losses caused by this pest are recorded in warmer lowland areas of south-east and north-west in the Czech Republic and in the Marchfeld lowland region of north-eastern Austria. In these regions due to favourable climate conditions the pest can create the mentioned two generations. The observed occurrence data obtained from field observations in Czech Republic constitute the base material for the validation of the model of pests' occurrence in recent climate conditions. Following the validation and calibration of the model outputs, the input meteorological data were altered using respective methodologies.

1.1. Regional Study for Czech Republic and Austria (station data)

1.1.1. Material and Methods

Climate-matching model CLIMEX estimates geographical distribution of a species depending on the climate conditions of a given location. CLIMEX can be used for the expression of the suitability of climate conditions for the species survival, further for the comparison of the climate conditions in different locations and for the comparison of the climate conditions of the particular location over time (Samways et al. 1999). Knowing the climatological requirements of the given species allows us to assess the suitability of the given area for the population growth and determine the stress exposure due to unsuitable climatic 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 the pest's population on the given location:

$$\mathbf{EI} = GI_A \times SI \times SX,$$

where GI_A is an annual growth index describing the population growth during favourable conditions, SI is the annual stress index describing survival during unfavourable periods, and SX marks the stress interactions. The calculation of GI and stress indices is based on the intervals of threshold parameters for species development adjusted by user (Table 1.1). Temperature parameters include the lower and upper thresholds and the optimal range of air temperature for development, similarly to soil moisture. In this study, the soil moisture thresholds were set to values representing the optimal moisture conditions for the pests' development. In the model validation, this was determined to be the right approach through the obviation of incorrectly estimated high dry/wet stress, which would cause an undesirable decrease in EI.

In addition to the 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 is in the range of 0–100 where EI = 0 indicates the location with climate conditions unfavourable for long-term species occurrence and EI > 30 represents climate as very suitable for species occurrence (Sutherst & Myawald 1985; Sutherst et al. 2001), whereas Hoddle (2003) considers locations with EI > 25 as very favourable for species occurrence, EI 10–25 as favourable and EI < 10 as limiting for species survival and occurrence. CLIMEX is the model operating with input data on a monthly scale (minimum and maximum temperature, relative humidity at 9 a.m. and 3 p.m, and precipitation), which are generally readily available.

The input weather series were prepared by a weather generator (Dubrovsky et al. 2000; Dubrovsky et al. 2004) for the period of 1961-1990. Model validation was carried out by comparing the modelled and currently observed occurrence of particular pest obtained from field observations both for the period 1961–1990. In this particular study, the CLIMEX model was first validated using data of observed occurrence of ECB and CPB in the Czech Republic. To generate weather series representing climate conditions in 2020 and 2050, the parameters of weather generator were modified according to climate change scenarios (HadCM3, NCAR-PCM, and ECHAM4) (Dubrovsky et al. 2005). The output of the model was at first calculated for 111 weather stations representing climate conditions in the Czech Republic and 17 weather stations representing the climate of northern part of Austria, and then results were interpolated over the whole area. Results of potential geographical distribution of pests both for current and expected climate conditions were visualized in maps interpolated to 1 km resolution using a digital terrain model.

Tab. 1.1 *Parameters of the CLIMEX model for the development of Colorado potato beetle (CPB) and European corn borer (ECB) used in the study.*

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

1.1.2. Results – European corn borer (Ostrinia nubilais Hübner, 1796)

Current climate conditions in the Czech Republic enable the development of one generation of ECB in lowland areas of central Bohemia and south Moravia. The area with presence of complete first generation is depicted in Fig. 1.1 as a grey colour (EI 21–24.9). The area occupied by first generation of ECB in the Czech Republic is in good agreement with the observed occurrence in 1961–1990 as was validated in Kocmankova et al. (2008a). Lowlands, mainly in Lower Austria (Marchfeld region) are established by first generation, and in addition the value of EI 25–31.9 in the lowest altitudes of Burgenland and Lower Austria constitutes the partial second generation of the pest.

Fig. 1.2 demonstrates the change in the number of generations according to selected scenarios (ECHAM4, HadCM3 and NCAR-PCM) combined with A2-high climate sensitivity in 2020’s and 2050’s.

Based on the results, temperature increase clearly leads to the widening of area occupied by first generation of the pest; this event is supported by all scenarios both in 2020’s and 2050’s. Generation increase from 0 to 1 is in Fig. 1.2 marked as a light grey colour. This constitutes the shift in the climate suitability from conditions which doesn´t allow the establishment of the pest to conditions allowing the persistence of viable population. Therefore the pest is likely to colonise recently unoccupied areas by the shifting of first generation to higher altitudes compared to first generation in current climate (hatched area). The widening of the area with one generation is visible in the modest range in maps considering the period 2020’s (a, b, c) while in maps for 2050’s (d, e, f) one generation covers almost the whole area of the Czech Republic except the altitudes above 800 m a. s. l. (HadCM3-high, map e).

Majority of the areas with recent occurrence of one generation in south Moravia and lowlands of Austria might be according to scenario HadCM3-high in the 2020's (Fig. 1.2, map b), affected by generation increase from 1 to 2 generations (dark grey colour). The biggest impact of increased temperatures in the 2020's suggests the scenario HadCM3-high in areas where the pest isn´t recently established and in the expected climate develops two generations. This is the case of boundary and small lowland areas in south Moravia and Lower Austria (black colour, shift from 0 to 2 generations).

As was mentioned above, the first generation in 2050 covers areas up to 800 m a. s. l. According to all scenarios for 2050's areas with recent occurrence of one generation are largely affected by two generations, where the complete substitution by two generations is shown by scenario HadCM3-high (map e). Simultaneously the second generation also covers surrounding areas in higher altitudes where temperature increase constitutes relatively considerable change. This is visible in comparison of generation number in current climate vs. expected climate according to scenario HadCM3-high 2050 which shows relative imbalance in generation increase (Fig. 1.2, map e). In higher altitudes the generation increase is markedly higher than the generation increase in lower areas. This is represented by increase of generation number from 0 to 2 generations (black colour) which appears in higher elevations where the number of degree-days doesn't allow the completion of one generation in current climate but the temperature increase in expected climate fullfills conditions for the development of two generations. This result reflects the hypothesis that in mid higher altitudes climate would lead to more dramatic shifts and that higher altitudes are likely to be more affected by increased temperatures and therefore are probably more vulnerable.

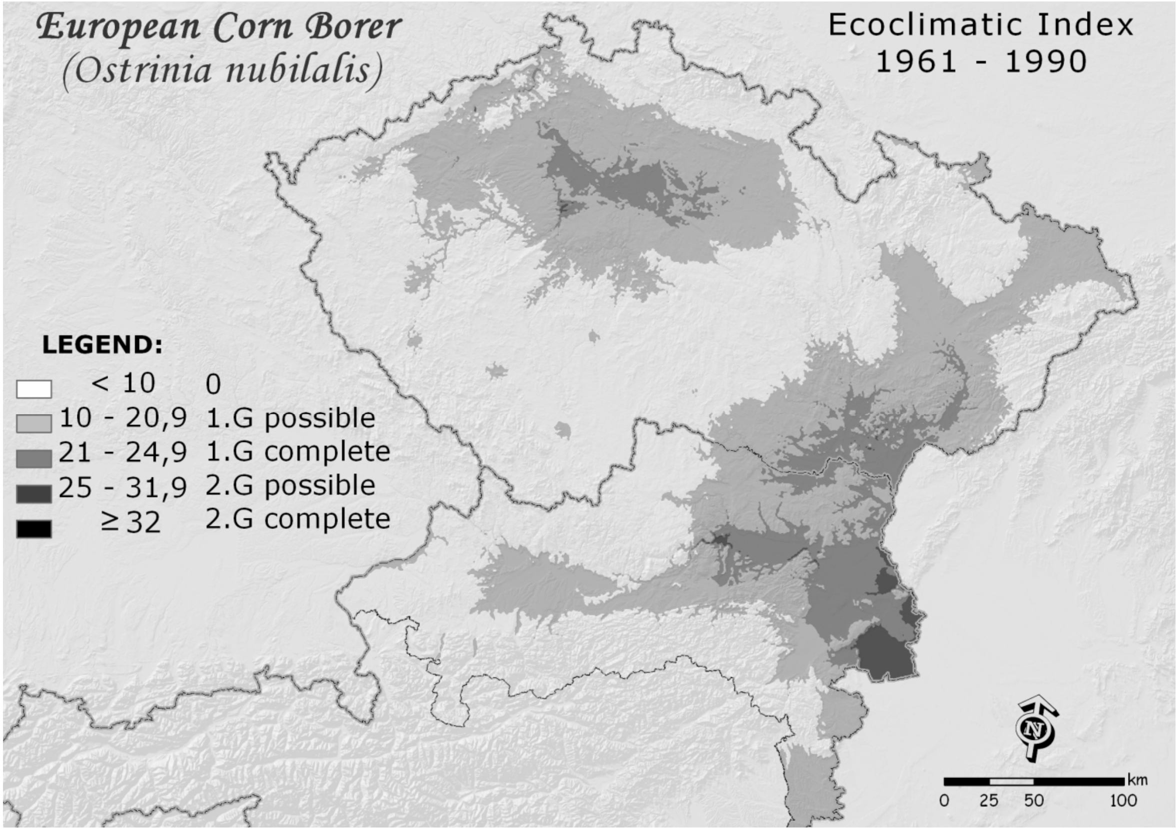

Fig. 1.1 *Potential geographical distribution of the European corn borer under present climate conditions represented by the climatic data for period from 1961 till 1990. Grey colour (EI 21 – 24.9) corresponds to completed first generation of the pest, dark grey colour corresponds to partial second generation, and black colour (EI ≥ 32) to completed second generation.*

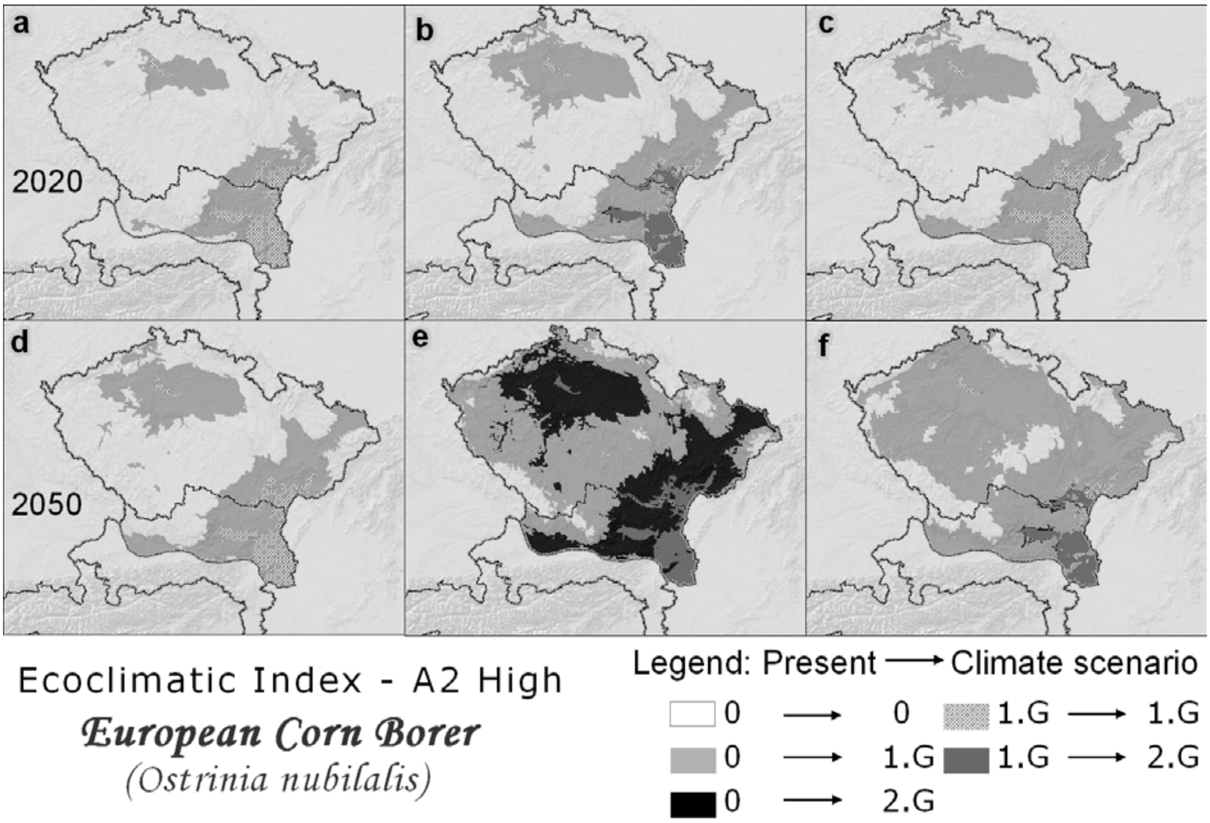

Fig. 1.2 *Increase of number in generations of the European corn borer under expected climate conditions expressed by meteorological data according to scenarios ECHAM4 (a, d), HADCM3 (b, e) and NCAR-PCM (c, f) in 2020's and 2050's. White areas indicate no occurrence of the pest due to an incompleted first generation, hatched colour marks the areas without any change compared to current climate, and the grey scale indicates an increase in the number of particular generations.*

1.1.3. Results – Colorado potato beetle (Leptinotarsa decemlineata Say, 1824)

Currently the occurrence of one generation of CPB in the Czech Republic is observed, but lowlands can be occupied by two generations during particularly warm seasons. Present climate conditions of the period 1961–1990 (Fig. 1.3) allow the development of partial second generation of the pest in lowland areas of the Czech Republic which corresponds to the real occurrence as was validated in Kocmankova et al. (2008b). The area of the establishment of partial second generation is marked by light grey colour (EI 24–26.9). In Austria climate conditions are suitable for the development of partial second generation covering the main lowlands in Lower Austria and Burgenland with added presence of second generation in the lowest altitudes (grey colour, EI 27–29.9).

In expected climate conditions according to the selected scenarios, the temperature increase results in an increase in number of generations depicted in Fig. 1.4. A2-high scenarios for 2020's in order to ECHAM4, HadCM3 and NCAR-PCM (a, b, c) show the widening of the area covered by one generation (hatched area). Areas originally occupied by one generation are substituted by a second generation (HadCM3-high 2020's and NCAR-PCM-high 2020's) (light grey colour).

The significant generation increases suppose scenarios for 2050, which, except the occurrence of second generation in the area of origin first generation, show the more rapid increase in generation number. In lowlands of middle Bohemia, Moravia and in Austria there is marked the increase from 1 to 3 generations (HadCM3-high 2050's, map e, dark dotted areas). Another significant change is shown by the scenarios HadCM3-high 2050's and NCAR-PCM-high 2050's which indicate the emerging of a second generation in recently unoccupied areas in higher altitudes (black colour, HadCM3-high, map e, NCAR-PCM-high, map f). This rapid generation growth (from 0 to 2 generations) in higher elevations is analogical to the generation increase of ECB relative to altitude as described above. Light dotted colour in Fig. 1.4 present in the lowland areas of Lower Austria and Burgenland marks unchanged occurrence of a second generation.

Tab. 1.2 *The ratio of arable land occupied by a particular number of generations of the Colorado potato beetle (CPB) and European corn borer (ECB) in current and expected climate conditions according to the HadCM3-high, NCAR-PCM-high, and ECHAM4-high scenarios in the 2020's and 2050's.*

	CPB	ECB
	1st generation	1st generation
1961- 1990	27.7	9.8
ECHAM-low 2020	35.2	31.0
HadCM3-low 2020	36.1	39.3
NCAR-PCM-low 2020	32.1	25.1
ECHAM-high 2020	7.6	33.0
HadCM3-high 2020	6.7	47.8
NCAR-PCM-high 2020	40.3	52.8
ECHAM-low 2050	40.8	43.7
HadCM3-low 2050	36.8	58.6
NCAR-PCM-low 2050	38.4	40.3
ECHAM-high 2050	39.2	54.7
HadCM3-high 2050	11.7	41.3
NCAR-PCM-high 2050	33.5	92.1
	2nd generation	2nd generation
1961- 1990	1.6	0
ECHAM-low 2020	9.1	0
HadCM3-low 2020	13.5	0
NCAR-PCM-low 2020	5.9	0
ECHAM-high 2020	1.7	0
HadCM3-high 2020	15.4	7.8
NCAR-PCM-high 2020	20.6	0
ECHAM-low 2050	13.4	0
HadCM3-low 2050	30.6	0
NCAR-PCM-low 2050	12.5	0
ECHAM-high 2050	23.4	0
HadCM3-high 2050	44.2	58.1
NCAR-PCM-high 2050	50.2	0
	3rd generation	
1961- 1990	0	
ECHAM-low 2020	0	
HadCM3-low 2020	0	
NCAR-PCM-low 2020	0	
ECHAM-high 2020	0	
HadCM3-high 2020	0	
NCAR-PCM-high 2020	0	
ECHAM-low 2050	0	
HadCM3-low 2050	0	
NCAR-PCM-low 2050	0	
ECHAM-high 2050	0	
HadCM3-high 2050	33.6	
NCAR-PCM-high 2050	0	

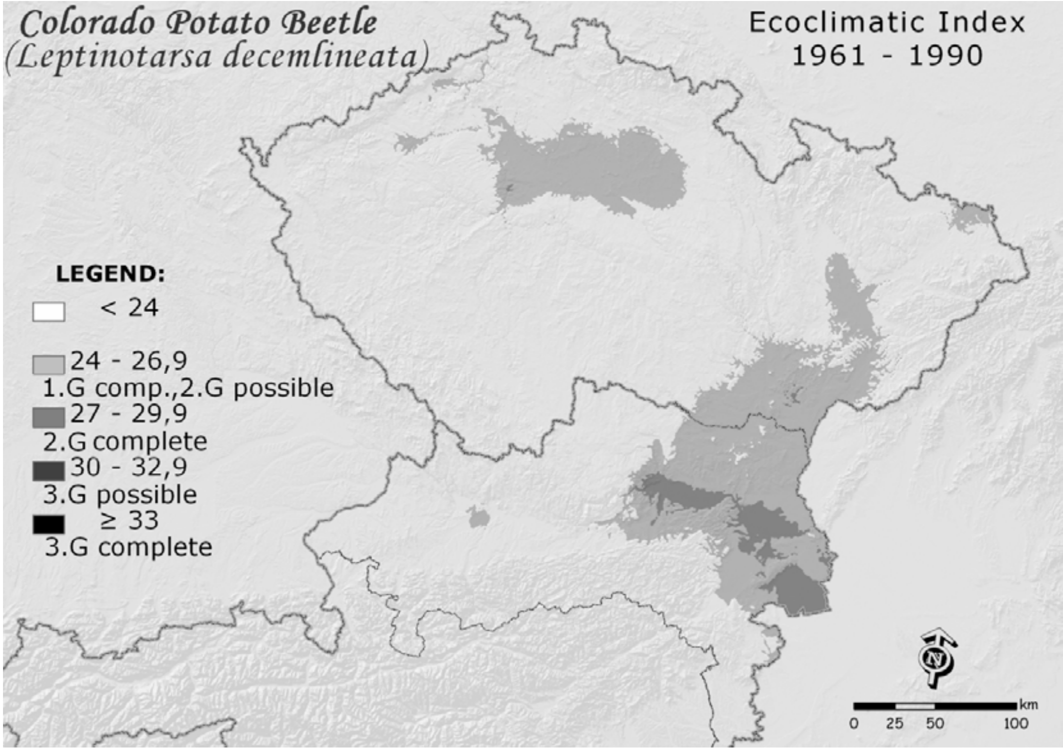

Fig. 1.3 *Potential geographical distribution of the Colorado potato beetle under present climate conditions represented by the climatic data for period from 1961 till 1990. The light grey colour (EI 24 – 26.9) represents the area occupied by first and partial second generation of the pest, grey colour (27 – 29.9) marks the second generation, dark grey colour (EI 30 – 32.9) partial third generation, and black colour (EI >33) indicates the completed third generation.*

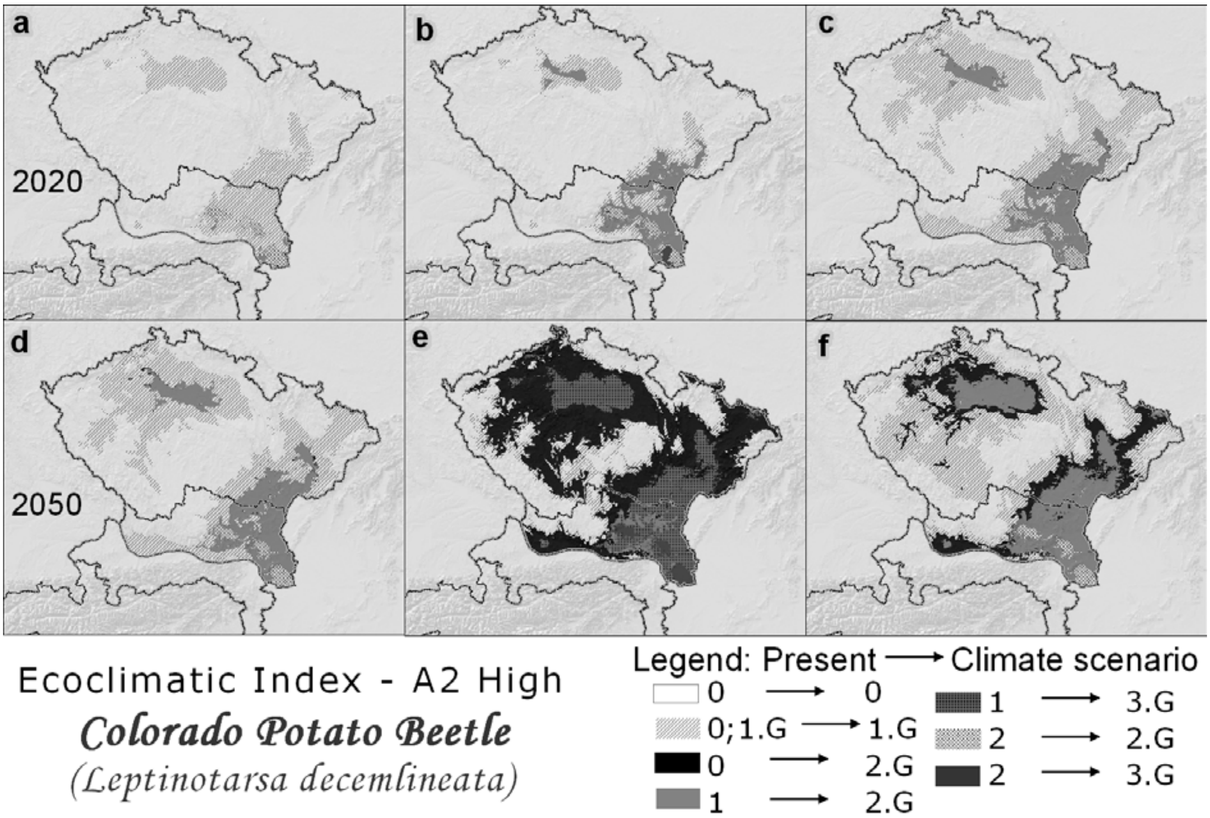

Fig. 1.4 *Increase of number in* generations *of the Colorado potato beetle in expected climate conditions expressed by meteorological data according to scenarios ECHAM4 (a, d), HADCM3 (b, e) and NCAR-PCM (c, f) for the 2020's and 2050's. White areas indicate no occurrence of the pest due to an incomplete first*

generation, hatched colour marks the areas without any change compared to current climate or an increase to one generation, and the grey scale indicates an increase in the number of particular generations.

1.2. Regional Study within the domain of RCM ALADIN

1.2.1. Materials and methods

In the following part of the project validated CLIMEX model was applied within the domain of the regional climate model ALADIN, which covers the Central European area between latitudes 45° and 51.5° N and longitudes 8° and 27° E and includes Austria, the Czech Republic, Hungary, Poland, and parts of Germany, Romania, Slovakia, Switzerland, and Ukraine. The ALADIN model was run at a 10 km resolution over the whole domain and the final maps were interpolated to 1 km resolution using a digital terrain model. The control run used observed boundary conditions (ERA40, ECMWF project, the 45-year re-analysis of the global atmosphere and surface conditions) and covered the period of 1961-2000.

The input weather series for the CLIMEX model was prepared by a weather generator (Dubrovsky *et al.* 2000; Dubrovsky *et al.* 2004), which was calibrated with the RCM-simulated weather series (for the period of 1961-1990). To generate weather series representing climate conditions in 2050, the WG parameters were modified according to climate change scenarios (Dubrovsky *et al.* 2005). In this approach, the scenario is defined as a product of standardised scenario related to a 1 K rise in global mean temperature and change in the global mean temperature (ΔT_G). The standardised scenarios were derived from the outputs of three GCMs from an IPCC-AR4 database (HadCM3, NCAR-PCM, and ECHAM5). The value of ΔT_G was determined by the MAGICC model (Harvey *et al.* 1997, Hulme *et al.* 2000) assuming high climatic sensitivity (4.5 K) and the high emission scenario SRES-A2. The MAGICC estimate for these settings is $\Delta T_G = 2.3$ K, which is slightly lower than the change in global mean temperature for 2100 assuming middle climate sensitivity (2.6 K) and middle emission scenarios ($\Delta T_G = 2.7$ K for SRES-B2, $\Delta T_G = 3.0$ K for SRES-A1b). As a result, the present impact prediction for 2050 (assuming “high” versions of GCM-based scenarios) are about the same as those for the end of 21st century assuming “middle” versions of the climate change scenarios.

The major innovation introduced by this study comes not only with its spatial resolution and the covered area but from the methodology point of view. The study has the advantages of using the Regional Circulation Models as the primary source of weather data (as key inputs for the CLIMEX based pest models that rely on the monthly data). These data are combined with an approach using a weather generator. The methodology enables us to cover a large territory with high spatial resolution, allowing for better regional assessments. The findings are crucial for tailoring the right adaption responses to the expected changes at the regional level.

1.2.2. Results - Colorado potato beetle (CPB)

Current climate conditions in the European region in this study, represented by meteorological data from 1961–1990, result in simulated values of EI that allow for the occurrence of one to four pest generations. Four generations are present in a small area in the north of Italy (Fig. 1.5). One generation is seen 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 area that has climate conditions suitable for the development of three generations includes Hungary, northern parts of Serbia, Croatia, Italy, and eastern part of Romania. Relative to the agricultural production, the simulations of baseline climate conditions suppose that 34.8% of arable land is threatened by the CPB with one complete generation of the pest, 13.5% with two generations, and 23.5% with three generations (Table 1.3). In altitudes above 600 m, the number

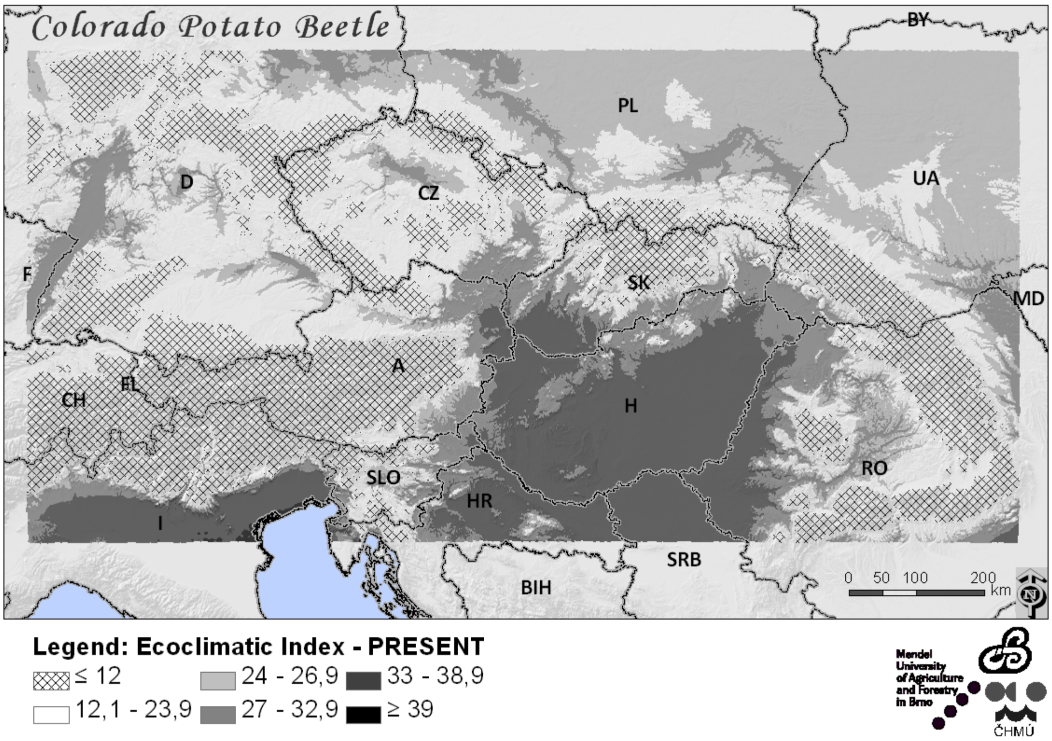

Fig. 1.5 *Potential geographical distribution of the Colorado potato beetle in current climate conditions expressed by meteorological data between 1961 and 2000. The light grey colour (EI 24 – 26.9) represents the area occupied by first generation of the pest, grey colour (27 – 32.9) is the second generation, dark grey colour (EI 33-38.9) third generation, and black colour (EI >39) indicates the fourth generation.*

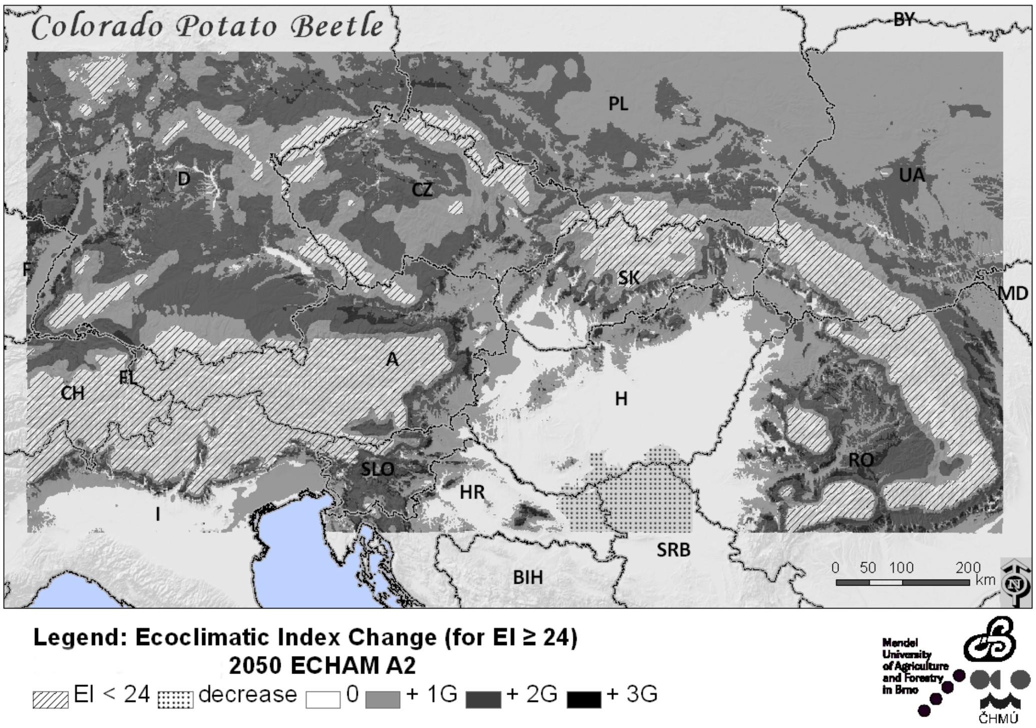

Fig. 1.6 *Potential geographical distribution of the Colorado potato beetle in the expected climate conditions expressed by meteorological data according to the ECHAM-high scenario in 2050. Hatched areas represent the area without an occurrence of the pest due to the incomplete first generation, dotted 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 grey scale points the increase in the number of particular generations.

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 the apparent trend of a widening of the pests' climatic niche and increase of the number of generations based on the temperature increase predicted by various scenarios. Fig. 1.6 shows the change in the number of CPB generations according to the ECHAM-high scenario in 2050. In this scenario, there is an increase of about one generation in the northern part of Europe up to an altitude of 800 m. In addition, there is a marked increase of about two generations in the lowlands, with a rare occurrence of a three generation increase.

According to ECHAM-high scenario in the 2050s (Table III), there is likely to be a decrease of only one full and a partial second generation of the pest to about 7% of arable land (as compared to the 34.8% in the current climate). The decrease of the area established by the univoltine population is caused by a shift of the bivoltine population, which replaces the univoltine one. The complete bivoltine population would occupy 16.8% of arable land, while the area occupied by the third generation increases to 68.5% (HadCM-high). On the other hand, a marked decrease in the climatic favourableness for CPB development under ECHAM-high is simulated in northern Serbia (Vojvodina region), where the significant temperature increase according to the mentioned scenario causes the high-temperature limitation for the pest's development and subsequent decrease of about one generation. 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.

Tab. 1.3 *The ratio of arable land occupied by a particular number of generations of the Colorado potato beetle (CPB) and European corn borer (ECB) in current and expected climate conditions according to the HadCM-high, NCAR-PCM-high, and ECHAM-high scenarios in 2020 and 2050.*

	CPB	ECB
	1. and partial 2. generation	1. generation
1961- 1990	34.8	9.5
ECHAM-high 2050	7.0	3.4
NCAR-PCM-high 2050	6.8	4.8
HADCM-high 2050	1.4	0.9
	2. generation	partial 2. generation
1961- 1990	8.4	8.8
ECHAM-high 2050	16.8	36.8
NCAR-PCM-high 2050	11.4	28.2
HADCM-high 2050	10.8	8.9
	partial 3. generation	2. generation
1961- 1990	5.1	25.1
ECHAM-high 2050	30.5	44.8
NCAR-PCM-high 2050	25.8	46.4
HADCM-high 2050	16.9	86.0
	4. generation	3. generation
1961- 1990	0.4	0.2
ECHAM-high 2050	2.9	13.1
NCAR-PCM-high 2050	6.7	17.8
HADCM-high 2050	1.8	3.8

1.2.3. Results European corn borer (ECB)

In the European region examined in this study, the model indicates the presence of one or two generations of ECB under the reference climate conditions (1960-1990). The higher number of generations is found in the southern part of the domain in areas more climatically favourable for development of the ECB (Hungary, northern part of Croatia, Serbia and Italy, eastern part of Romania) (Fig. 1.7).

Under future climate conditions, with their expected temperature increase and prolonged vegetative season, the widening of the area of univoltine population is simulated. At the same time, the emergence of bivoltine populations and a further increase to a third generation in the warmest areas is indicated. Fig. 1.8 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, colonise areas recently unoccupied by univoltine population, up to an altitude of about 800 m. The lowland areas presently occupied by the univoltine population are likely to be replaced by a bivoltine population, which only slightly exceeds the original areal of univoltine one.

HadCM-high presumes the prevailing increase of about one generation, which will probably result in the presence of a third generation in the eastern part of Austria, north of Italy, and western part of Germany (Rhine valley), where there are currently two generations per season. The NCAR-PCM-high scenario assumes a wider spread, covering a major part of Hungary, Croatia, and the whole simulated part of Italy.

The ratio of arable land endangered by a higher number of generations is expressed in Table 1.3. Table 1.3 shows the simulated depletion of the pest's univoltine areas due to substitution by the bivoltine population (i.e. decrease to 0.9% according to HadCM-high scenario) and the overall increase of the area established by completed bivoltine population (86% HadCM-high). Significantly, a third generation is predicted to emerge in 17.8% of arable land in the domain (NCAR-PCM-high), which has serious implications on production risk.

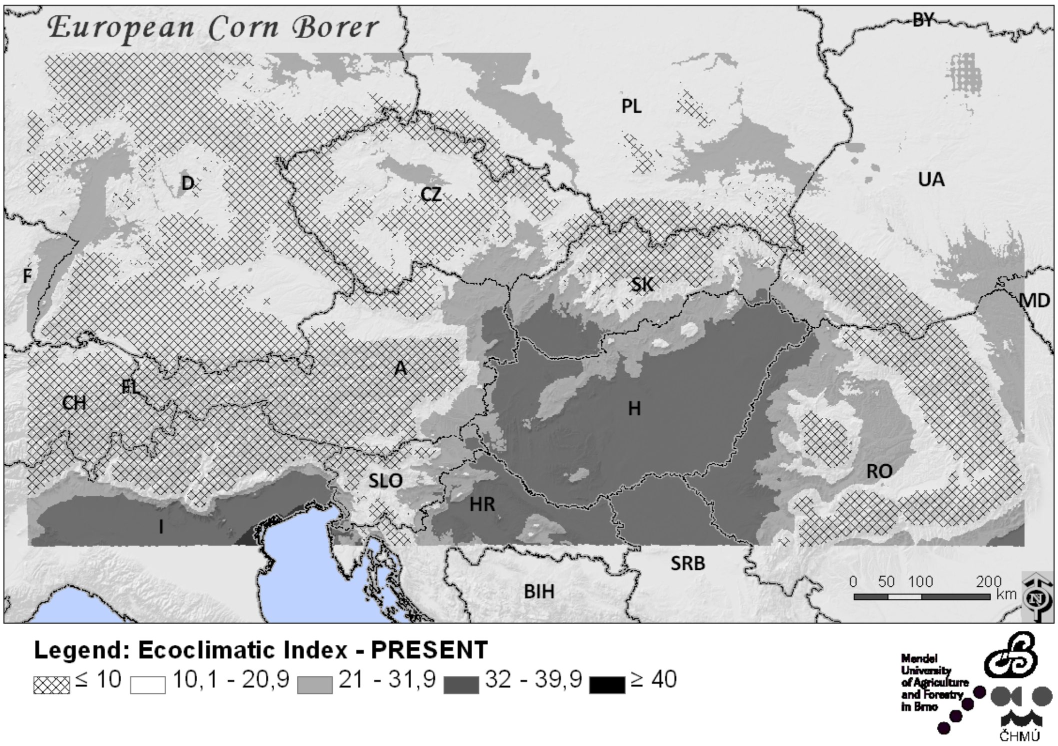

Fig. 1.7 *Potential geographical distribution of the European corn borer in current climate conditions expressed by meteorological data of the period 1961 – 2000. Grey colour (EI 21 -31.9) corresponds to first generation, dark grey (EI 32 – 39.9) the second generation, and black colour (EI >40) represents third generation of the pest.*

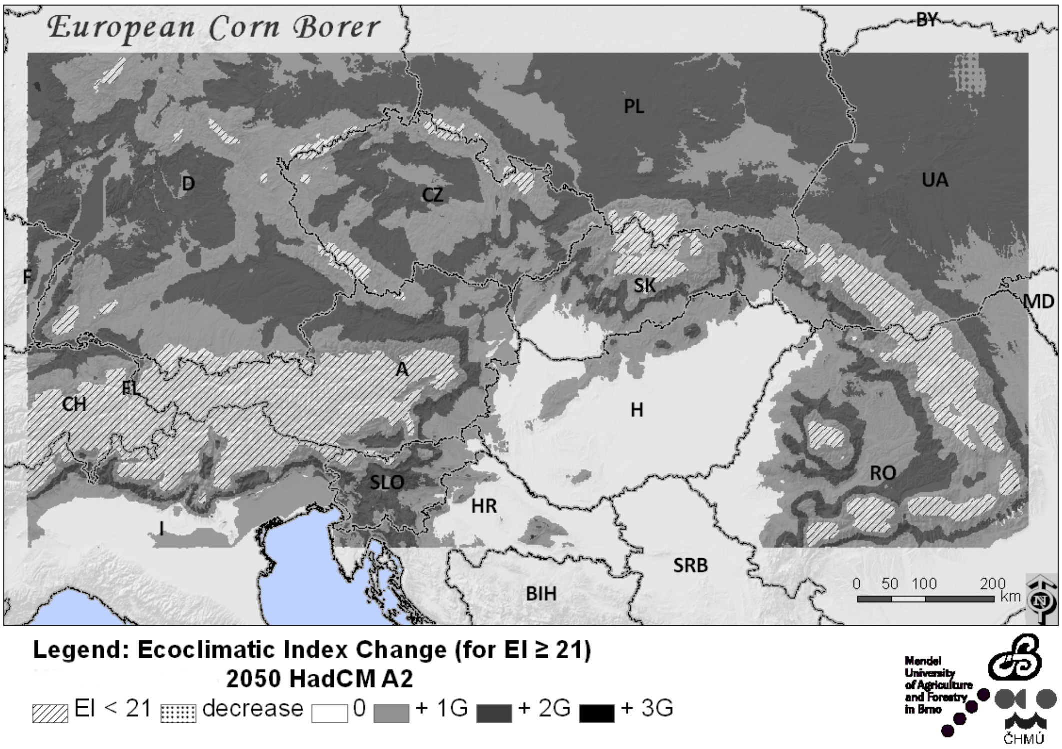

Fig. 1.8 *Potential geographical distribution of the European corn borer in the climate conditions according to the ECHAM-high scenario in 2050. Hatched areas indicate a lack of occurrence of the pest due to an incomplete first generation, dotted areas represent a decrease of EI i.e. the shift to less favourable climate conditions for the pest's development, white colour marks the areas without any change and the grey scale points the increase in the number of particular generations.*

1.2.4. Discussion and Concluding remarks

Under the expected climate conditions in Central and Eastern Europe, as expressed by selected climate change scenarios, there is a likely increase of damage risk in most areas caused by both the Colorado potato beetle (CPB) and European corn borer (ECB), respectively. The increase in temperature will shift the pests' development limitations and allow for a widening of the recent occurrence area simultaneously with shifting to higher altitudes. In the case of CPB, there will likely be a decrease of generations, which would occur only in the warmest areas due to the limitations caused by high temperature, negatively affecting the pest population.

As the regional study focusing on Czech Republic and Austria demonstrated expected increase in temperature will most likely cause shift the pests' development limitations and allow for a widening of the recent occurrence area simultaneously with shifting to higher altitudes. Under these scenarios both pest would be able to complete their development earlier and in higher number of generations. Relative to the agricultural production, the simulations of baseline climate conditions in the Czech Republic and Austria together suppose that 9.8% of arable land is threatened by the occurrence of first generation of ECB (Table 1.2). In future climate conditions there is a significant growth of ratio of arable land indicated for implementation of protective measures connected with the occurrence of first generation, for HadCM3-low 2050's it's an increase about 48.8% and for NCAR-PCM-high 2050's the increase is even 82.3%. Protective measures connected with the presence of second generation likely will be to prove in 58.1% of arable land as is assessed by HadCM3-high 2050's in the considered total area of Austria and Czech Republic.

In the current climate 27.7 % of arable land are affected by one generation of CPB in the Czech Republic and Austria (Table 1.2). In expected climate the area requiring the protection against the first generation of CPB increases about 13.5% (ECHAM4-low 2050's), protection connected with the presence of second generation likely will be necessary in arable land about

48.6% higher (NCAR-PCM-high 2050's) and HadCM3-high in 2050's supposes the occurrence of a third generation in 33.6 % of the total arable land. Most significant changes are expected in higher altitudes recently unoccupied by the pests, as these areas have noted higher increase in the number of generations compared to lowlands. . This is due to the fact that in these regions (cooler conditions at the higher altitudes) the pests are already close to their limit to finish the first generation. However, additional factors for pest occurrences have to be taken under consideration.

Shreeve et al. (1996) point out that the area near the extreme border of species occurrence (in latitude) as marginal, in the sense that environmental factors influencing the probability of population survival and persistence are more intense than in regions to the south, where species are less restricted and occur in a wider habitat range. An increase in temperatures would produce a decrease in marginality, with a coalescence of previously isolated populations and increased stability. If such a scenario also applies to moth pests with similar Palaearctic distributions, then an increase in pest pressure is very likely. For multivoltine species such as *Ostrinia nubilalis*, which are already distributed over a very wide latitudinal range in Europe, successful colonization of northwardly expanded maize crops will depend on factors such as migration ability and the rate at which the climate changes occur (Cannon 1998).

Tobin et al. (2008) applied the phenology degree-day model of temperate moth species (*Paralobesia viteana*). Based on their study, the number of generations of multivoltine insect species is also likely to increase, and such increases can greatly exacerbate the negative ecological and economical costs of insect pest species. Tobin et al. (2008) illustrated that increases in mean surface temperatures > 2 °C can have dramatic effects on insect voltinism by causing a shift in the ovipositional period that currently is subject to diapause-inducing photoperiods. The study of Tran et al. (2007) suggests that cold-limited species may be able to increase their geographic range in the future. In the eastern forests of the United States, several beetles (e. g. southern pine beetle *Dendroctonus frontalis*) are predicted to expand their range northwards.

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 ECB affected area to the north and possibly lead to the occurrence of a second generation in the presently univoltine areas. The results of the presented study are supported by estimates based on the more detailed ECAMON model (Trnka et al. 2007). However, the comparison of the potential occurrence of ECB as assessed by both the ECAMON and CLIMEX models in the study of Kocmánková et al. (2008a) showed that CLIMEX tended to underestimate the potential geographical distribution assessment compared to ECAMON, which seemed to be a more sensitive tool for ECB occurrence estimation which was supported by a better fit with actual observations. This superiority of ECAMON over CLIMEX is caused by a very detailed developmental module and the use of the daily time step compared to the crude climatology used in CLIMEX. The detailed evaluation of the model has proven ECAMON's capability to accurately estimate the initiation and persistence of crucial phenological stages. On the other hand, the main advantage of CLIMEX is that it has far lower input data requirements and yet yields relatively reliable results. In the case of an expected increase in temperature and seasonal shift (Dubrovsky et al. 2005) both models estimated the ECB expansion into higher altitudes according to chosen SRES scenarios. One of the main conclusions was that both models indicated that the climate is a significant factor determining the development and survival of the ECB. However, the CLIMEX results shown in this study could therefore also be seen at the lower side of the potential future risk of this pest.

The simulated geographical distribution represents the potential occurrence of the pest's infestation, or the area with suitable climatic conditions for the ECB occurrence with a viable population, which is usually associated with economically significant densities. The study did not take the host presence 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).

Baker et al. (2000) adopted the CLIMEX approach to study the effect of climate change on the potential distribution of CPB. Their study confirmed the widening of the CPB's area under climate change conditions predicted by the CLIMEX simulation of climate suitability assessment in the UK and Europe. The greatest increases in the suitability for Colorado potato beetle according to Baker´s study lies between the 50°N and 65°N latitudes in northern Europe. The next simulations of the occurrence of the CPB as an exotic pest in Norway made by Raffos & Sætre (2003) indicated that the current climate is not suitable for long-term establishment of this species. The climate change scenarios clearly indicate that a temperature increase could provide a shift in the establishment conditions from non-favourable to favourable for CPB in several regions. The study of Jarvis a Baker (2001) used an insect development model for the Colorado potato beetle coupled with daily temperature to explore the likelihood of this pest becoming established in England and Wales. This sophisticated model has used a daily time step allowed the use of indices included estimates of pest activity and flight potential.

There is an apparent risk of increasing damage caused by pests due to the shifts in the climate conditions. It should be stressed that the study is based on so called potential distribution which means that the expected geographical distribution of the given species is based only on the climate conditions regardless of any other factors determining the species abundance or distribution. Other factors could be also included but it would require extensive integration of CLIMEX model e. g. by growth models of host plants, estimation of drought periods occurrence in the future climate, implementing of the new management strategies and crop varieties feedbacks. Despite the simplifications the study offers valuable data that should be considered for activities dealing with the adaptation to climate change.

Araujo & Luoto (2007) refer to growing evidence for evolutionary shifts in insects exposed to climate change. When predicting direct effects of climate change, phenotypic and genotypic flexibility of herbivores and interactions between species need to be considered.

Levels of heritable variation for traits likely to be involved in adapting to climate change have been investigated in several herbivores. Examples include recent work on variation in the timing of egg hatch in winter moths to counter an increasing mismatch between the herbivore and its host (van Asche et al. 2007) and variation in thermal responses of the Colorado potato beetle (Lyytinen et al., 2008). According to Thomson et al. (2009) thermal thresholds might be plastic as a consequence of acclimation, but there is no allowance for the possibility that thresholds might evolve because of selection imposed by climate change.

The presented method plays an important role in the estimation of the species' occurrence depending on their climate requirements, but the method is limited by its lack of field- or population-level interactions. Climatic mapping may be therefore a very useful tool in pest risk analyses under changing climate as it allows us to estimate the risk of introduction, colonisation, and spread of various pest species and their economic impacts. In general climatic mapping, method plays an important role in the estimation of the species' occurrence depending on their climate niche requirements, but the method is limited by its lack of field- or population-level interactions. For a regional evaluation of potential pest risks under changing environmental conditions additional factors, such as crop and pest management, crop acreage, and land use, have to be considered. This requires expert local knowledge. However, more specific pest models, as already applied or improved for the operational level for pest management decision-making, where data are available, could also be used for long-term assessments. In addition, there is a significant application potential of pest risk monitoring, not only for nowcasting but also for long-term projections, which results in a demand for further research in order to develop more sophisticated models.

2. Insect pests in the forest ecosystems

Climate change is generally agreed to have a profound impact on forest structure and its dynamics (Aber et al. 2001Dale et al. 2000, 2001). As trees can live from decades to centuries, rapid changes of climate are also expressed through alterations of the disturbance regime (Franklin et al. 2002, He et al. 1999). All major disturbances are affected in a certain manner – fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, and landslides (Dale et al. 2001, Aber et al. 2001, Hanson and Weltzin 2000). Although disturbances are an integral part of forests, when such disturbances exceed their natural range of variation the impact on forests may be extreme. Pest organisms have the ability to adapt much faster than their host trees, thereby increasing the likelihood of severe pest impacts (Docherty et al. 1997, Malcolm et al. 2001, Battles et al. 2006).

Pest organisms respond to environmental changes both directly and indirectly, through changes in forest structure and the decreased resistance of trees. A changing climate may also cause those pests that are currently of minor significance (i.e. not forming large-scale outbreaks) to become key species, thereby causing serious damage.

Insects are physiologically extremely sensitive to temperature, and even a small temperature increase may have a severe impact on forests (Lange et al. 2006). In addition to the pest's distributional ranges, climate also influences their voltinism (i.e. the annual number of generations) (Reynolds and Holsten 1994, Hansen and Bentz 2003, Lange et al. 2006). If climate warming extends the vegetation season, multi-voltinism is expected to shift to northern locations and higher altitudes; potentially causing further severe damage to forests.

The impact of climate variability on insect pests' abundance fluctuation is not at all clear (Kendall et al. 1998; Myers 1998; Liebhold & Kamata 2000). The most common hypotheses to explain population oscillations are based on density-dependent biotic interactions, i.e. predator-prey dynamics (Andersson & Erlinge 1977), maternal effects (Rossiter 1994), induced plant defences (Baltensweiler & Fischlin 1988), host–parasitoid interactions (Berryman 1996) and disease dynamics (Myers 1993). However, the concept of climatic release, as a cause of periodic population cycles, has been questioned due to statistical concerns and the lack of periodicity in the climatic deviations that are thought to trigger the outbreaks (Martinat 1987, Turchin & Berryman 2000).

An analysis of potential changes in the distribution of outbreak areas and fluctuation patterns of pests (both indigenous and introduced) is a key task in the assessment of the impact of global change on forest ecosystems. The growing number of recent works on this topic is testimony to this issue's importance (Brasier 1996, Lonsdale and Gibs 1996, Harrington et al. 2001, Gordon et al. 2001, Williams and Liebhold 2002, Logan et al. 2003, Woods 2005, Esper et al. 2007). To contribute to this field, we focused on two key pests in spruce (*Picea abies* L.) and oak-beech ecosystems (*Quercus cerris* L., *Quercus petraea* Liebl. s.l., *Carpinus betulus*, *Quercus robur, Fagus sylvatica* L.) – *Ips typographus* (L. 1758) (hereinafter 'IT') and *Lymantria dispar* (L. 1758) (hereinafter 'LD'). These pest species act in diametrically opposed ways, responding to expected changes of climate differently (Logan et al. 2007, Netherer and Pennerstorfer 2001, Netherer et al. 2004). In particular we focused on:

- the impact of the expected temperature increase on changes in the number of IT generations developed per year (voltinism),
- the impact of the expected temperature increase on future spatial development of LD outbreaks, under the assumption of beech as the alternative host.

To meet these goals, we identify the locations where outbreaks will most probably occur, evaluate changes in voltinism in relation to climate conditions, and assess their development under the climate change scenario.

2.1. Study region

Presented impact studies have been conducted in Slovakia, the Central Europe (Fig. 2.1). Tree species' composition is made up predominantly of spruce (26.1%), fir (4%), pine (7.2%), beech (31.2%), oak (13.4%), and hornbeam (5.7%) (Moravčík et al. 2006). The altitudinal gradient ranges between 94 - 2 655 m a. s. l. The mean annual temperature ranges between 5–8.5°C, mean annual precipitation total is 740 mm. The country belongs to the Temperate Continental Bioclimatic Zone (Rivas-Martínez et al. 2004). Projected temperate increase for this region in 2100 is 3-4°C. Annual mean precipitation is expected to increase by up to 10% mainly in winter, while summer precipitation is expected to decrease up to 10% (Giorgi et al. 2004, Christiansen et al. 2007). Mountainous regions (mainly High Tatras Mts.) are supposed to be faced to even higher temperature increase, while precipitation amounts and patterns are subject to uncertainty. Forest responses to climate change are supposed to be both positive and negative, depending on site conditions and regional variability of climate (Saxe et al. 2001, Geβsler et al. 2007). Forest growth, regeneration and survival are expected to be constrained mainly by water availability. Bark beetles (mainly *Ips typographus* and *Pityogenes chalcographus*) and some defoliators (*Lymantria dispar*, *Lymantria monacha*) are the most important insect pests in this region. Climate change induced impacts on their distributional and outbreak ranges as well as on their population dynamics have already been observed (Hlásny and Turčáni 2009, Csóka and Hirka 2009).

2.2. Used climate data

Climate data used in this study are organized at meteorological stations for the reference climate (1961-1990) and in 10x10 km grid of ALADIN Climate-CZ for the future climate (2021-2050, 2071-2100) (Fig. 2.1). The output of global climate model ARPEGE-Climat (Meteo-France) was used as the driving data of the regional model. A1B emission scenario indicated the expected development of CO_2 emissions.

Fig. 2.1 *Distribution of ALADIN Climate-CZ RCM grid points in Slovakia. The grid is extended approximately 1 point beyond country's borderline to reduce the error of spatial interpolation in edge locations.*

2.3. Climate change impacts on spruce bark beetle

Eight-toothed bark beetle (*I. typographus*) is the most important bark beetle pest in spruce stands. Its lifecycle and population dynamics have long been studied (Christiansen and Bakke 1988, Lieutier et al. 2004), even with various computer simulations (Byers 1993, 1996, 1999, 2000). The species is distributed across the whole of Eurasia, thus it has a very wide niche. It is one of the primary injurious agents in man-made spruce stands at medium latitudes in Europe (Turčáni and Novotný 1998), although large-scale outbreaks have also been reported in northern regions in nature-close forests (Christiansen and Bakke 1988). In normally functioning and balanced ecosystems, IT is not considered to be an aggressive or primary mortality agent of healthy trees. However, under favourable conditions it is able to attack healthy trees and may be the primary tree mortality factor (Hedgren and Schroeder 2004). Once IT populations reach a critical size, they are able to overwhelm almost every mature tree, healthy or otherwise. Outbreaks can last for many years and normally collapse only when every tree within reach has been killed, or when cold weather suppresses the populations (Raffa 1988).

The primary conditions for an outbreak are stand hazard, availability of windthrow, and current beetle population size (Reynolds and Holsten 1994). Windstorms are outstandingly important precursors to outbreaks, because they quickly provide large quantities of breeding material in the form of broken or fallen branches, which eliminates intra- and inter-specific competition (Anderbrant, 1990; Schopf and Köhler, 1995). However, early wood processing and intensive control measures subsequent to such windstorms may reduce such impacts.

The emergence and migration of beetles of monovoltine generations were found to depend on geographical latitude. Northern populations emerged later and migrated less frequently before overwintering than those of southern origin (Forsse 1991). In a bivoltine situation, the overwintering generation was found to disperse more extensively (Furuta et al. 1996).

In warmer areas of Europe, IT is able to emerge from hibernation earlier; and two or – under favorable conditions – even three generations can develop in a single season. The earliest First flight in the history was recorded in the Czech Republic in 2009, when high numbers of adults were captured since April the 8th up to elevation 500 m (M. Turčáni, personal information). In northern Europe, lower temperatures normally constrain the beetles to a single generation (Annila 1969). Increasing temperatures are expected to shift the outbreaks to higher elevation (Baier et al. 2007) and to force more populations per year (Lange et al. 2006, Harding and Ravn 1985). Continued warming trends will increase the risk of spruce bark beetle outbreaks throughout the host's range (Logan et al. 2003).

Several studies have been performed to examine the influence of temperature on the development and reproductive cycles of IT (Vité 1952, Annila 1969, Zumr 1982, Anderbrant 1986, Netherer 2003, Baier et al. 2007). IT limits proposed by Annila (1969) and Wermelinger and Seifert (1998), recently published by Lange et al. (2006), are generally accepted. This topic has also been discussed by Netherer (2003), who conducted extensive research in the High Tatra Mountains. Tab. 2.1 states the stage-specific limits of IT development reported by these authors.

Stadium	**T (C°)**		**D° (dd)**	
Variant	A	B	A	B
Flight of 1st generation	5	—	110.0	—
Egg	10.6	10.3	51.8	54.51
Larvae	8.2	4.07	204.4	246.64
Pupae	9.9	12.81	57.7	39.32
Immature adult	3.2	3.38	238.5	307.00

Table 2.1 *Specific developmental threshold temperatures T (C°) and heat sum requirements (D°) for IT. Variant A is by Annila (1969), and Wermelinger and Seifert (1998); variant B is by Netherer (2003).*

Analysis of IT development was based on the model PHENIPS – a comprehensive phenology model of IT (Baier et al. 2007). Maximum daily air temperature is used to indicate the year day of onset of infestation, while bark temperature determines the development of particular developmental stages of parental generations. The onset of host tree infestation in spring is given by 16.5°C for flight activity coupled with a mean thermal sum of 140 degree days (dd) from the beginning of April 1st onwards. In contrast to other works, a nonlinear function was used to calculate the effective thermal sums, using threshold temperatures of 38.9–8.3°C. The discontinuation of reproductive activity appears at a day length of less than 14.5 hours. Bark temperature is calculated by regression of daily mean air temperature (°C) and solar radiation (Wh m^{-2}):

BTmean = -0.173+0.0008518*SIrel+1.054*ATmean

where BTmean represents daily mean bark temperature, ATmean mean air temperature and SIrel global solar radiation

A thermal sum of 334.2 dd was found to be necessary to complete preimaginal development (egg to pupal stage), and 222.8 dd (i.e. two thirds of the thermal sum for preimaginal development) is required for maturation feeding of the filial beetles (Wermelinger and Seifert 1998, Netherer 2003). Hence, a thermal sum of 557 dd is required for total development. For successful hibernation, the brood must complete preimaginal development (egg–pupae), i.e. it requires 60% of the thermal sum for total development before the onset of the cold period.

2.3.1. Methods

The PHENIPS algorithm was applied spatially by calculating a total sum of degree days for all grid points of used RCM in Slovakia. The calculations were conducted for an average year of the reference (1961-1990), Near Future Climate (2021-2050) and Far Future Climate (2071-2100) (NFC and FFC hereinafter). Degree-day sums obtained at each grid point were interpolated using kriging with external drift) over the whole of Slovakia, using the elevation as the predictor variable. Subsequently, a number of fully developed generations was calculated by the division of interpolated degree-days by 557. Increase in number of generations, spatial variability of such increase and shift of the onset of infestation are analyzed. Changes in other parameters, such as completion of individual developmental stages, were not addressed.

2.3.2. Results

Both spatial modeling and statistical analysis of data distributed in grid points of used RCM were conducted to describe the expected impact of climate change on IT voltinism and distribution. The analysis reveals the basic tendencies in expected development of IT distribution and voltinism as well as provides the starting point for the development of spatially differentiated control measures.

2.3.2.1.Statistical analysis of data on bark beetle development

We analyzed the data calculated using the PHENIPS algorithm distributed in ALADIN Climate-CZ grid points with elevation above 350 m a.s.l. (lower distributional range of spruce in Slovakia). We focused the climate change induced changes in average number of generations developed during a season and the shift of IT 1st Flight (beetles emergence). In both cases, average values during the reference, NFC and FFC have been addressed. Descriptive statistics of both number of developed generations and 1st Flight dates during these periods are given in Tab. 2.2.

	Number of generations											
Period	N	AVG	MED	MIN	MAX	25%	75%	10%	90%	Range	IQR	St. Dev
1961-1990	344	2.49	2.47	0.78	3.45	2.23	2.81	2.04	2.99	2.67	0.58	0.41
2021-2050	344	2.74	2.72	1.07	3.64	2.46	3.04	2.23	3.29	2.57	0.58	0.43
2071-2100	344	3.30	3.32	1.67	4.30	2.98	3.63	2.75	3.90	2.63	0.64	0.45
	1st Flight date											
1961-1990	344	106,98	104,25	91,00	164,00	100,50	110,45	98,40	118,50	73,00	9,95	9,73
2021-2050	344	101,33	99,05	82,40	162,50	93,25	106,85	91,80	115,20	80,10	13,60	12,58
2071-2100	344	95,42	93,35	75,50	160,70	86,95	101,80	82,80	110,20	85,20	14,85	12,19

Tab. 2.2 *Descriptive statistics of number of generations and 1st Flight dates developed at ALADIN Climate-CZ RCM grid points under the reference, NFC and FFC.*

We investigated the development of number of IT generation in all addressed periods in relation to the elevation gradient, which strictly controls IT development (through related climatic processes). We identified generally recognized decreasing tendency of IT development with increasing elevation (Fig. 2.2). The average slope of the regression line between number of generations and elevation during three investigated periods indicated on average 0.18 generation decrease per each 100 m of elevation. The elevation explains from 74-84% of spatial variability of IT development.

Analysis of IT development along the longitudinal and latitudinal gradient (Fig. 2.3) indicated decreasing tendency of number of developed generations from the south to the north. This pattern corresponds to IT response to elevation, because these variables are correlated (elevation of Slovakia increases northward). IT response to longitudinal gradient does not show any interpretable pattern.

We investigated the pattern of differences in number of developed generations between NFC/FFC and the reference climate in relation to elevation (Tab. 2.3, Fig. 2. 2). We found that there is no global tendency in increase of number of IT generation and it is distributed equally over the all elevation gradient of Slovakia. Despite this finding, spatial modeling conducted in the next part of this report allowed for identifying compact *n*-generation increase regions and specifying their altitudinal limits, although with significant altitudinal overlap.

	Differences in number of generations										
Period	N	AVG	MED	MIN	MAX	25%	75%	10%	90%	Range	IQR	St. Dev
2021-2050	344	0,24	0,24	0,11	0,42	0,20	0,29	0,17	0,33	0,31	0,08	0,06
2071-2100	344	0,56	0,57	0,45	0,69	0,53	0,60	0,50	0,62	0,24	0,06	0,05
	Differences in 1st Flight date											
2021-2050	344	-4,55	-4,2	-17,00	4,2	-9,13	-5,35	-14,2	-3,2	21,2	3,78	4,12
2071-2100	344	-11,56	-11,90	-24,00	7,10	-14,60	-8,75	-17,00	-5,80	31,10	5,85	4,43

Tab. 2.3 *Descriptive statistics of differences in number of generations and 1st Flight dates at ALADIN Climate-CZ RCM grid points between NFC/FFC and reference climate. The period 2021-2050 indicates differences of (2021-2050)-(1961-1990) and 2071-2100 of (2071-2100)-(1961-1990).*

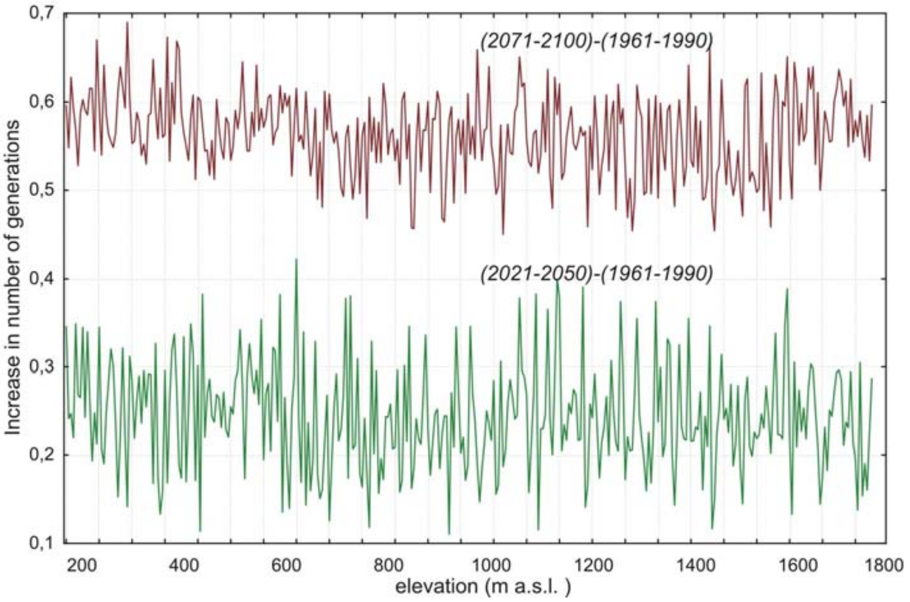

Fig. 2.2 *The average increase in number of IT generations during the NFC and FFC in relation to the reference climate calculated for all grid points of the ALADIN Climat-CZ with elevation above 350 m a.s.l. (given by lower distribution limit of spruce). The values are displayed in relation to elevation.*

IT development reflects the altitudinal arrangement of the country and related climatic gradients. Despite significant altitudinal overlap of regions with *n*-generation regime (Fig. 2.4), generalizing the information on climate change impacts on IT using altitudinal limits of such regions is useful both for practice and for the scientific understanding of IT responses.

Spatial resolution of grid of used RCM (10 km) is rather rough for the identification of altitudinal limit of n-generation regime regions, mainly in the highest altitudes with 0-generation regime, which are covered be this grid very sparsely. Therefore, such vertical limits were identified using data interpolated into a denser grid with resolution of 180 m. Elevation controlled interpolation allowed for more reliable drawing the altitudinal limits of n-generation regime regions than can be reached using RCM`s resolution.

Tab. 2.4 summarizes the altitudinal limits of *n*-generation regime regions for all reference, NFC and FFC. Because of rather long histogram tails of degree-day values within respective regions, we prefer evaluating the shifts of 10-90 percentiles rather than min-max values.

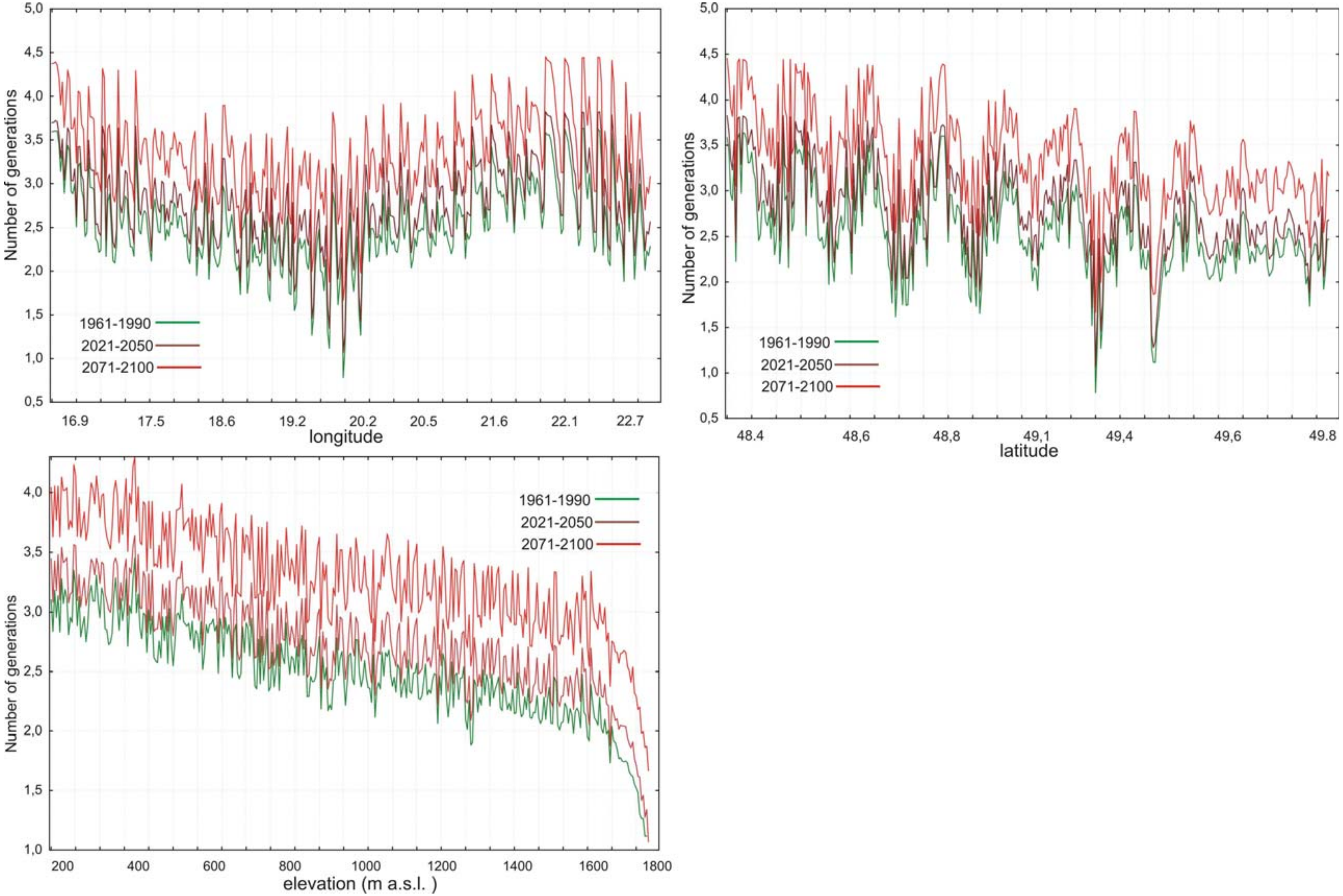

Fig. 2.3 *Development of average number of bark beetle generations along the elevation, longitude and latitude gradient at ALADIN Climate-CZ RCM grid points.*

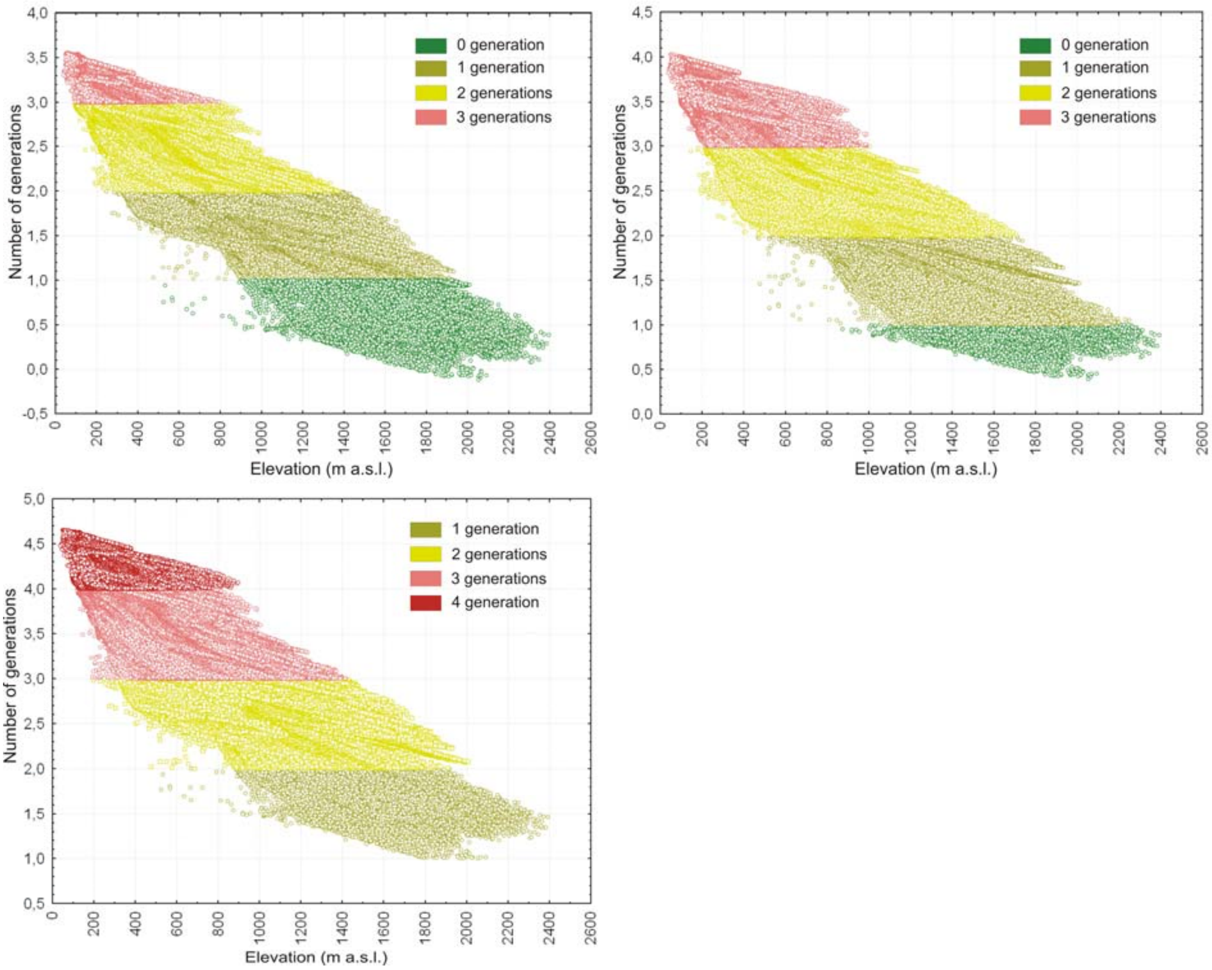

Fig. 2.4. *The changes in distribution of the total area of regions with n generation bark beetle regime in Slovakia in relation to elevation.*

Generation	**Period**	**Min**	**Max**	**25%**	**75%**	**10%**	**90%**
0th generation	1961-1990	524	2393	1472	1877	1270	2029
	2021-2050	874	2393	1605	2019	1378	2149
	2071-2100	–	–	–	–	–	–
1st generation	1961-1990	249	1932	792	1081	691	1274
	2021-2050	467	2249	1096	1522	944	1725
	2071-2100	524	2393	1456	1878	1237	2033
2nd generation	1961-1990	96	1376	381	657	294	789
	2021-2050	146	1706	563	841	462	990
	2071-2100	198	2010	764	1078	657	1285
3rd generation	1961-1990	38	795	121	222	109	281
	2021-2050	38	989	149	354	112	476
	2071-2100	119	1416	408	684	314	827
4th generation	1961-1990	–	–	–	–	–	–
	2021-2050	–	–	–	–	–	–
	2071-2100	38	898	125	244	109	328

Tab. 2.4 *Shifts of altitudinal ranges of n-generation regime regions under ALADINE Climate-CZ climate change scenario.*

Number of generations	0 generation (km^2)		1 generation (km^2)		2 generations (km^2)		3 generations (km^2)		4 generations (km^2)	
Period	Spruce	Country	Spruce	Country	Spruce	Country	Spruce	Country	Spruce	Country
1961-1990	89	332	2503	5726	2708	24266	16	19075	—	—
2021-2050	19	110	678	1142	4163	17287	352	30636	—	—
2071-2100	—	—	85	323	2307	5176	2798	22165	35	21405

Tab. 2.5 *Changes of areas with n-generation regime regions under climate change scenario. Spruce - part of the total extent of spruce stands within the country, Country – part of the total country regardless of spruce distribution*

2.3.2.2.Spatial modelling of climate change impacts on spruce bark beetle

Spatial analysis focuses on the distributional limits of regions allowing for the development of certain number of IT generations under a climate change scenario throughout the all Slovakia and their analysis. Using the spatial interpolation of degree days calculated using the PHENIPS algorithm for each ALADIN Climate-CZ grid point under the reference, NFC and FFC, we produced the maps of degree days for the whole of country. To improve the interpolation accuracy, we used degree-days linear correlation with elevation. Accuracy of produced maps was assessed using the crossvalidation procedure (Fig. 2.5). Normal distribution of residuals indicates properly designed models. A correlation coefficient of predicted vs. observed values ranges between 0.967-0.973 for all variables. It implies the average error of all models be approximately 0.15 of generation.

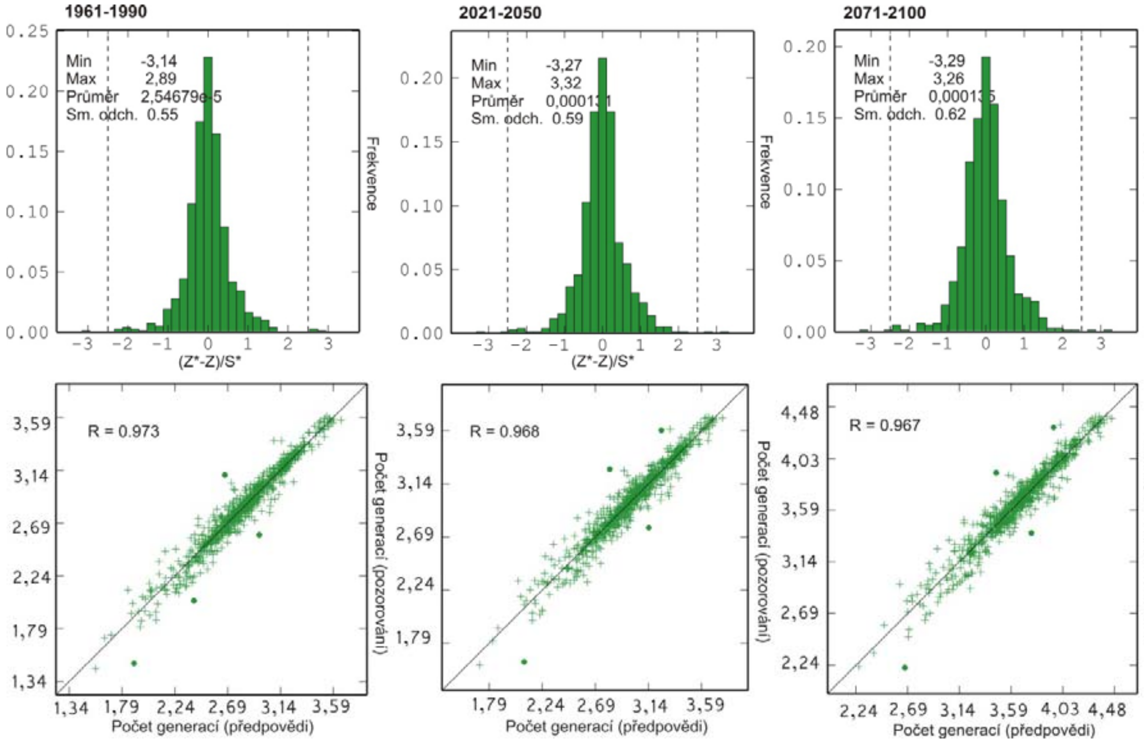

Fig. 2.5 *Results of crosvalidation of maps produced by interpolations of degree-days distributed within the ALADIN Climate-CZ RCM using External Drift Kriging. Histograms describe the residuals distribution (predicted Z* - observed Z) standardized by the standard deviation of the predicted values (S*). The crossplots describe the relation between Z*and Z.*

The interpolated maps of degree days were classified into the discrete disjunctive regions with climate potential allowing for the development of certain number of IT generations during the reference, NFC and FFC (Fig. 2. 6).

The fundamental information on climate change impacts on IT is the change of areas allowing for the development of certain number of IT generations. We calculated the changes of both the proportion of the total country area and of the area of actually distributed spruce stands (Figs. 2.6, Tab. 2.5). Charts in the Fig. 2.7-2.8 shows remarkable differences between these two calculations, which are mainly due to prevailing spruce distribution in the elevations above 350-400 m a.s.l.

Comment: It should be kept in mind that the maps of n-generation regime regions in the Fig. 2.6 indicate the average status during the reference, NFC or FFC. In fact, the boundaries between the regions are fuzzy, reflecting the real/projected climatic variability during the respective period.

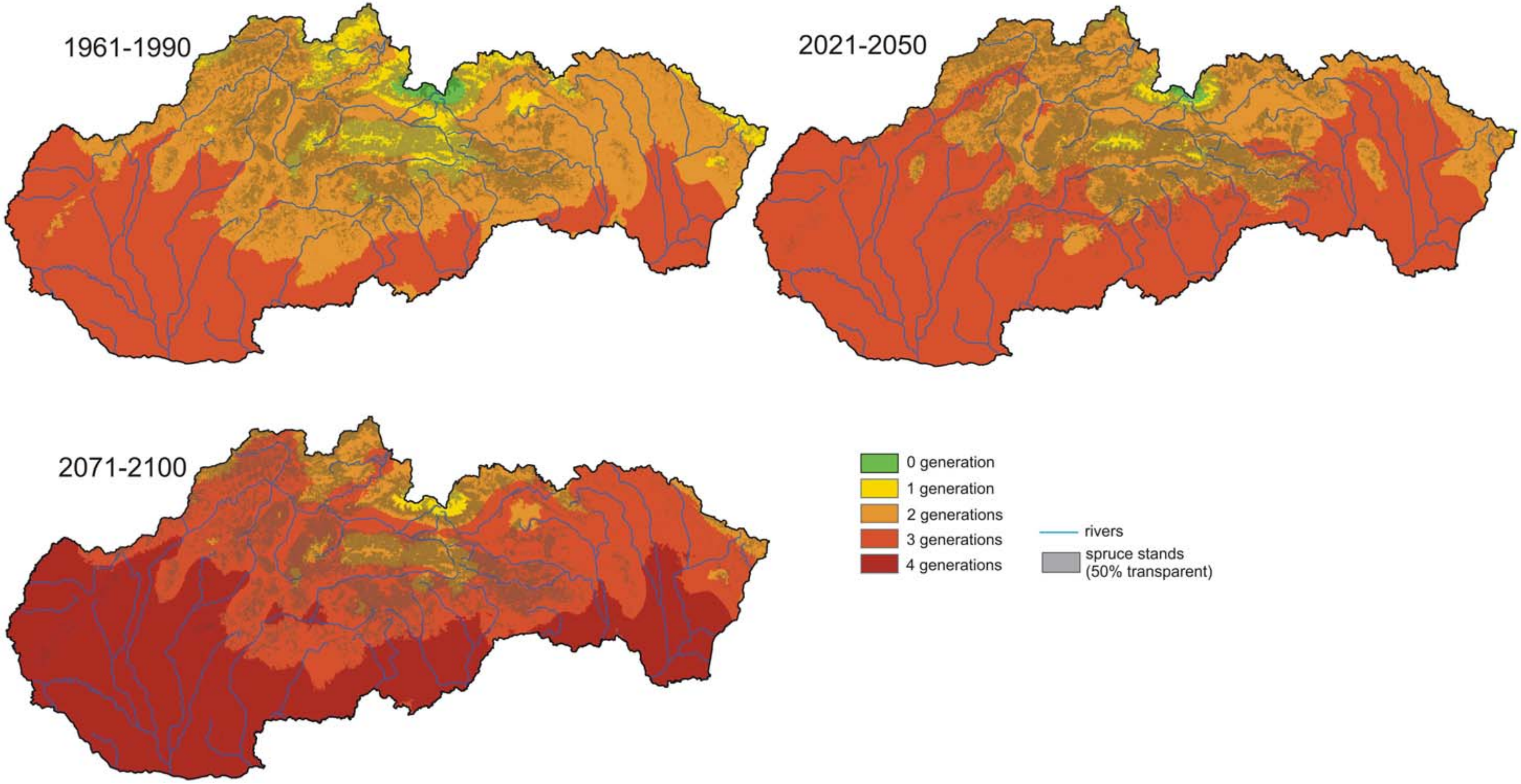

Fig. 2.6 *Maps indicating the shift of n-generation regime regions under climate change scenario ALADIN Climate-CZ.*

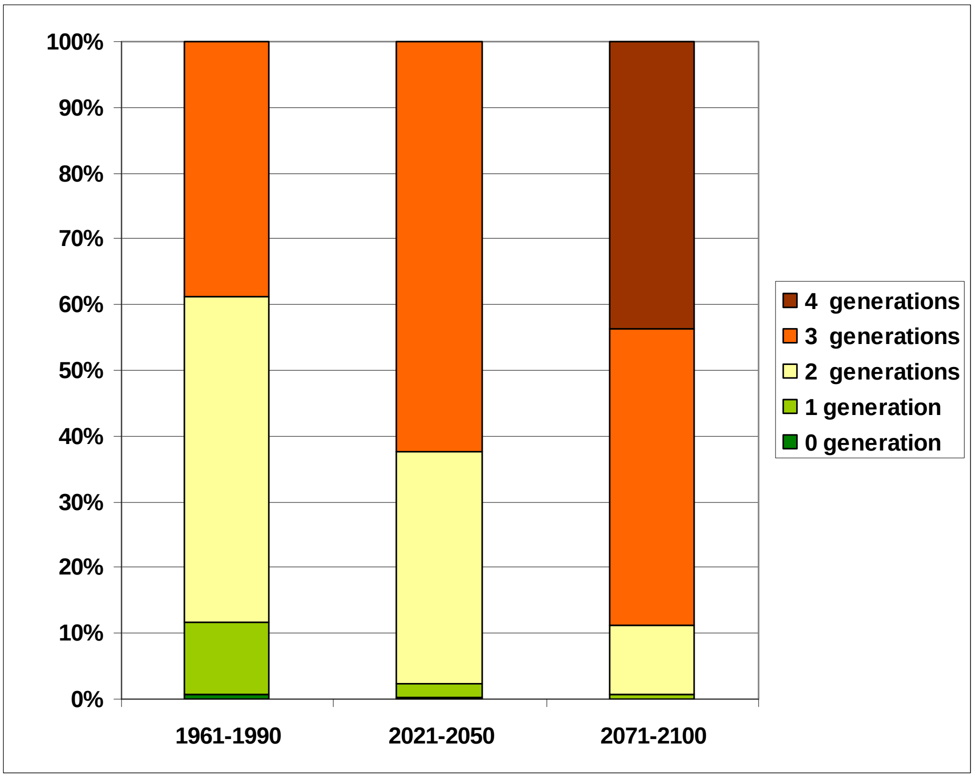

Fig. 2.7 *Proportion of the country allowing for the development of respective number of bark beetle generations under the ALADIN Climate-CZ scenario.*

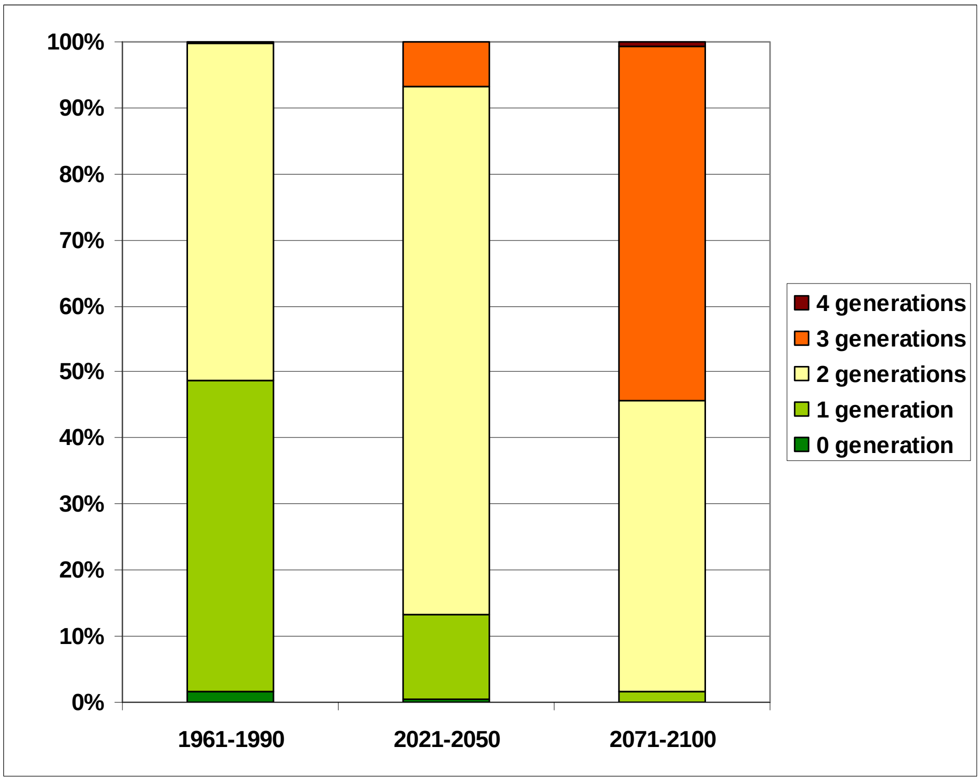

Fig. 2.8 *Proportion of the total area of spruce stands (actual distribution) within the country distributed in regions allowing for the development of respective number of bark beetle generations in the reference, NFC and FFC under the ALADIN Climate-CZ scenario.*

As can be seen in the Figs. 2.7-2.8, two-generation regime of IT was dominating in the country in the reference period 1961-1990, while spruce stands were equally distributed within regions allowing for the development of one and two IT generations (Fig. 2.6). Only the marginally distributed spruce stands at species lower distributional limit were faced to the pressure of three generations. One-generation regime was observed mainly in mountain areas.

In the NFC (2021-2050), two-generation regime was projected to dominate over the 80% of all spruce stands in the country. Three-generation regime will endanger almost 7% of spruce stands (assuming the actual spruce distribution). One generation regime recedes to the elevations above 1100-1200 m a.s.l., where is distributed 13% of spruce stands of the country.

Interpretation of projections to the far future is much more uncertain, because of expected changes in spruce distribution (mainly significant reduction of spruce proportion) due to adaptive forest management. Anyway, three-generation regime will dominate over a great part of the current distribution of spruce (52%), while one-generation regime almost disappears to the highest elevations. Two-generation regime will occur over the 44% of areas currently occupied by spruce. One- and four- generation regimes will be only marginal.

Subsequently, we investigated the spatial variability of differences in the increase of number of developed generations. Such information is an important part of the sensitivity analysis, because mainly the regions where IT related disturbance regime changes are supposed to be extremely vulnerable. Fig. 2.9 describes both changes in the full number of developed generations throughout the country and changes within the actual distribution of spruce stands.

In the NFC the climatic potential for the increase of number of generations remains unchanged over the most of the country, while 42% of spruce stands are faced to 1 generation increase (Tab. 2.6). Increase from 1 to 2 generations dominates. Increase by one generation (either from 1 to 2 or from 2 to 3 generations) occurred at regions forming the belts between the regions without change.

In the FFC, almost all country will be faced to the one-generation increase of IT. In some minor and fragmented areas even the two-generation increase was projected, however we abstracted away from such detailed information. Such areas were merger together with the adjacent one-generation increase regions. Three-generation regime will dominate over half of spruce stands in the country, while two-generation regime will be present in all mountain locations.

Period / generation shift	0–1(ha)	1–1(ha)	1–2(ha)	2–2(ha)	2–3(ha)	3–3(ha)	3–4(ha)	(%)	(%)
1961-1990 –> 2021-2050	70	55 445	176 327	224 187	28 561	1 437	–	42,2	57,8
1961-1990 –> 2071-2100	19	6802	212 834	–	263 227	–	3 094	98,6	1,4

Tab. 2.6. *Extent of spruce stands with specific change of bark beetle development and proportion of the total spruce stands in the country posed to projected 0 and 1 increase of bark beetle generations.*

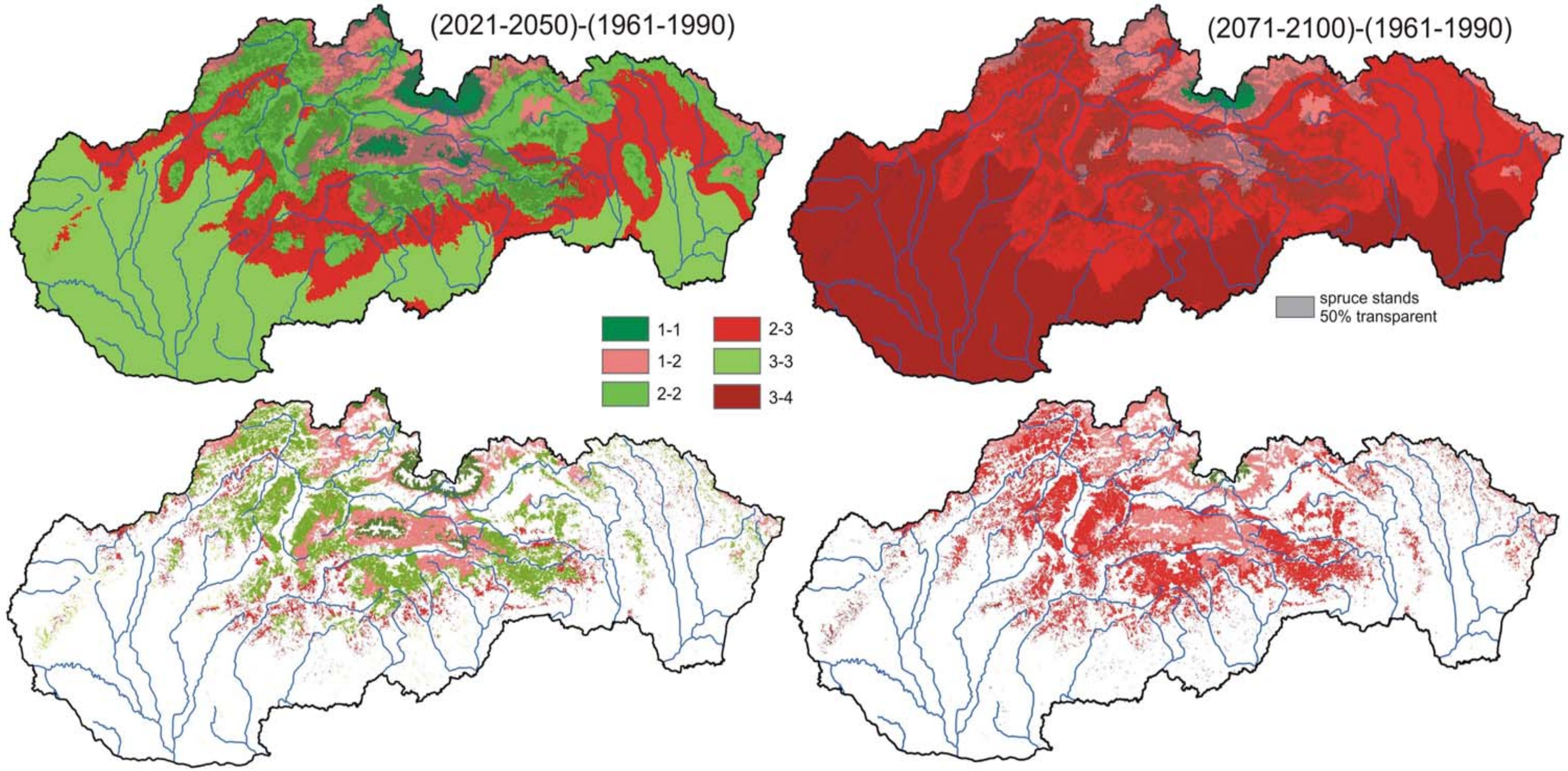

Fig. 2.9 *Differences in number of generations projected to develop in the NFC/FFC vs. the reference climate. The upper row describes the differences in full number of developed generation (Example: 1-2 – number of developed generations increased from 1 to 2) in the whole of country, the bottom row describes the increase in bark beetle generations within the actual distribution of spruce.*

2.4. Climate change impacts on gypsy moth

Gypsy moth (*L. dispar*) is the most important defoliator of broadleaved stands (mainly oak) in Eurasia (native) and North America (introduced). It is characterized by cyclical abundance fluctuations, causing defoliation in large areas across southern, eastern and central Europe, northern Africa, Asia Minor, Central Asia, the Middle East (Villemant and Fraval 1998), and the eastern part of North America (Doane and McManus 1981). Populations with flying females occur from Northern Asia to Japan (Liebhold et al. 2007). Contrary to the previous species, LD is strictly univoltine across all of its distributional territory, and it rarely acts as the primary tree mortality agent. The cyclicity of outbreaks seems to be regular across a wide span of natural conditions (Johnson et al. 2006), fluctuating from 3-4 years in southern Europe, 8-10 years in central Europe, and 20-25 years in northern regions (Johnson et al. 2006). There are indications of altitudinal shifts of outbreaks in warm years (Csoka and Hirka 2006). LD eggs are laid in July-August and the embryo immediately starts developing during the warm days of summer. In a month, the tiny larva is fully formed and ready to hatch. At this point, however, the larva goes into diapause, shutting down metabolic activities and becoming insensitive to the cold. LD can tolerate temperatures as low as - 30° C provided such temperatures do not persist for several days (Doane and McManus 1981). LD caterpillars are thermal conformers (Knapp and Casey 1986). Unlike IT, their growth is independent of temperatures between 25°-30°C. Some newly hatched larvae may be wind-dispersed to new locations. This spring ‘ballooning’ is an important means of dispersal for both Asian and European races, and it is the primary natural means of dispersal for the European race. Although ‘ballooning’ has been recorded over distances of 50 km, it is usually effective from about five to seven km from infestation sites (Doane and McManus 1981).

A specific point is that, under favorable conditions, the species feeds on beech (and occasionally other broadleaves) as alternative hosts. Formerly, this had been observed in isolated beech stands at lower elevations, mainly surrounded by infested oak stands. Recently, this has been observed on larger areas, e.g. in Hungary and Slovakia (Hirka 2006, personal observation). Serious egg mass densities in beech stands were reported in 2004 in Hungary. The 2006 outbreak spread over thousands of hectares of beech stands of different ages at 500-700 meters (Bakony Mts., Bükk Mts., Mátra Mts., Hungary). Observed defoliation was up to 50-70% over large areas. Therefore, the species must be considered an important climate change driven agent in both oak and beech stands.

2.4.1. Methods

We analyzed expected changes in LD outbreak ranges in oak stands, as well as the future danger to beech stands (Fig. 2.10), in the vicinity of identified oak stands outbreak spots. External Drift Kriging was used to produce the underlying temperature maps and their future projections. Long-term data on LD abundance and environmental conditions were analysed using Canonical Correspondence Analysis (CCA) (McCune and Mefford 1999, ter Braak and Šmilauer 2002). CCA allowed us to examine the patterns of the community structure of oak defoliator species (LD among them) in relation to a set of environmental variables, in order to design a regional model of species abundance – environment relationship. The particular steps of the proposed approach are:

1. Identify outbreak spots in oak stands by means of a linear weighted combination of relevant environmental variables.
2. Asses the risk of defoliation to beech stands. Two hypotheses have been followed in this case:
    a. Gypsy moth spreading to beech stands is allowed only from the oak outbreak spots that appear in their vicinity
    b. Gypsy moth spreading to beech stands will be only controlled by species-specific temperature limit
3. Evaluate climate change impact on the size of LD outbreak areas in oak stands, as well as on the extent of potentially endangered beech stands.

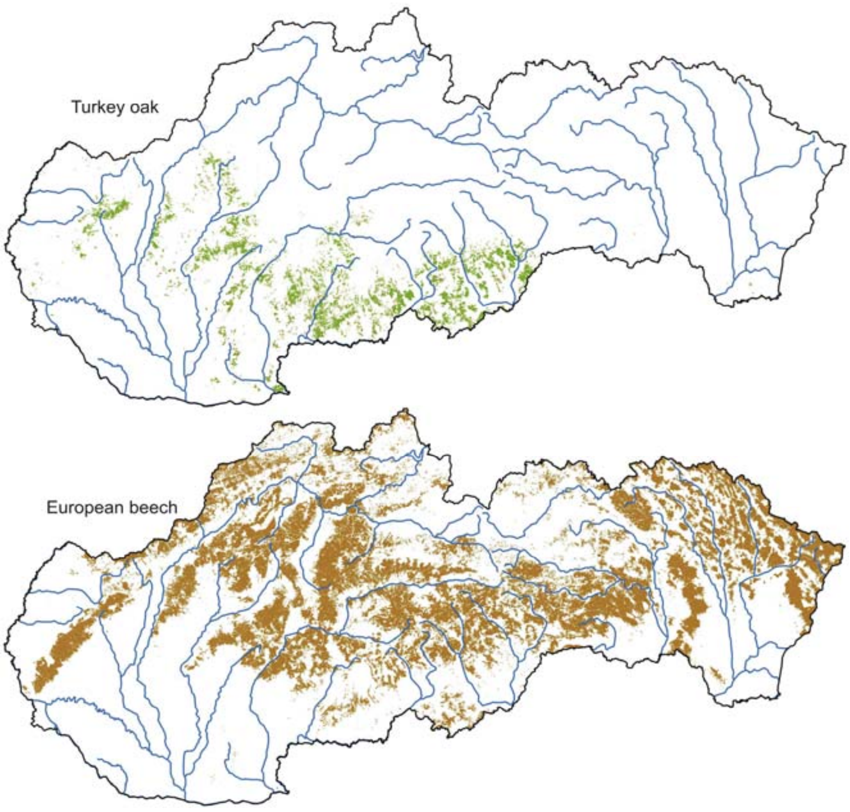

Fig. 2.10 *Distribution of the primary and alternative host trees of gypsy moth*

Canonical Correspondence Analysis was used to identify environmental variables controlling species abundance (Hlásny and Turčáni, 2009). The species–sites matrix consisted of average abundances across 27 years of sampling. The eight environmental variables used for the analysis were elevation, mean annual air temperature, soil moisture, and the proportion of five oak species at a stand (*Q. robur, Q. petrea, Q. pubescens, Q. cerris, Q. rubra*). Statistically significant variables (p=0.01) were air temperature, soil moisture, *Q. petrea, Q. pubescens* and *Q. cerris.* An ordination plot suggested the pest's positive correlation with *Q. cerris* and air temperature. The temperature correlates with the species axis more significantly (r=0.811) than with *Q. cerris* (r=0.576). The weighted combination of these variables (as maps), rescaled to unit range according to Tab. 2.7, was used to identify those stands providing suitable conditions for LD outbreaks under both current and future climate. The respective weights were set to 0.4 (*Q. cerris*) and 0.6 (temperature).

	Q. cerris *(%)*	Temperature (°C)	Outbreak potential (suitability score)
Optimum	>60	>9.5	1
Suboptimum	30-60	8.75	0.5
Pessimum	<30	<8	0

Tab. 2.7 *Criteria used to predict potential LD outbreak areas in oak stands.*

In this way we obtained a surface indicating outbreak potential, taking on values ranging from 0 to 1. The arbitrary threshold of 0.8 was used to identify outbreak spots (Fig. 2.12). This corresponded well with actual observations of defoliation during the recent outbreak. A quantitative analysis of the match of observed and projected outbreak spots has yet to be carried out.

Identified oak outbreak spots were considered as initial spots for pest spreading to beech stands (Hypothesis 1). Parameters used in the prediction were distance from the oak outbreak spots and mean annual average air temperature (Tab. 2.8).

	Dist. from oak outbreak spots (km)	Temperature (°C)	Outbreak potential (suitability score)
Optimum	<2	>9.5	1
Suboptimum	2-5	8.75	0.5
Pessimum	>7	>8	0

Tab. 2.8 *Criteria used to assess the risk of potential LD outbreak spreading to beech stands.*

2.4.2. Results

Following the criteria for the identification of oak outbreak spots (Tab. 2.7) we designed the maps describing their distribution under actual and projected climate (Fig. 2.12). The threshold value used to classify the result of synthesis according to Tab. 2.8 was set in order to reach the maximal compliance of predicted outbreak spots with those observed during the last outbreak in 2004.

Subsequently we calculated the changes of extent of potentially defoliated oak stands. As can be seen, there is a significant increase of defoliated areas between the reference and NFC, while further it remains stable (Tab. 2.9). This is because the upper temperature distributional limit of gypsy moth reached the upper distributional limit of Turkey oak already in 2021-2050.

	OOA (km^2)	Risk to beech (km^2) (H1)	Risk to beech (km^2) (H2)
1961-1990	110	372	645
2021-2050	313	1422	4678
2070-2100	325	1513	6475

Tab. 2.9 *Area of projected oak outbreak areas (OOA) and areas with risk of defoliation to beech stands under ALADIN Climate-CZ climate change scenario. In case of assessment of defoliation risk to beech both Hypothesis 1 and Hypothesis 2 have been considered.*

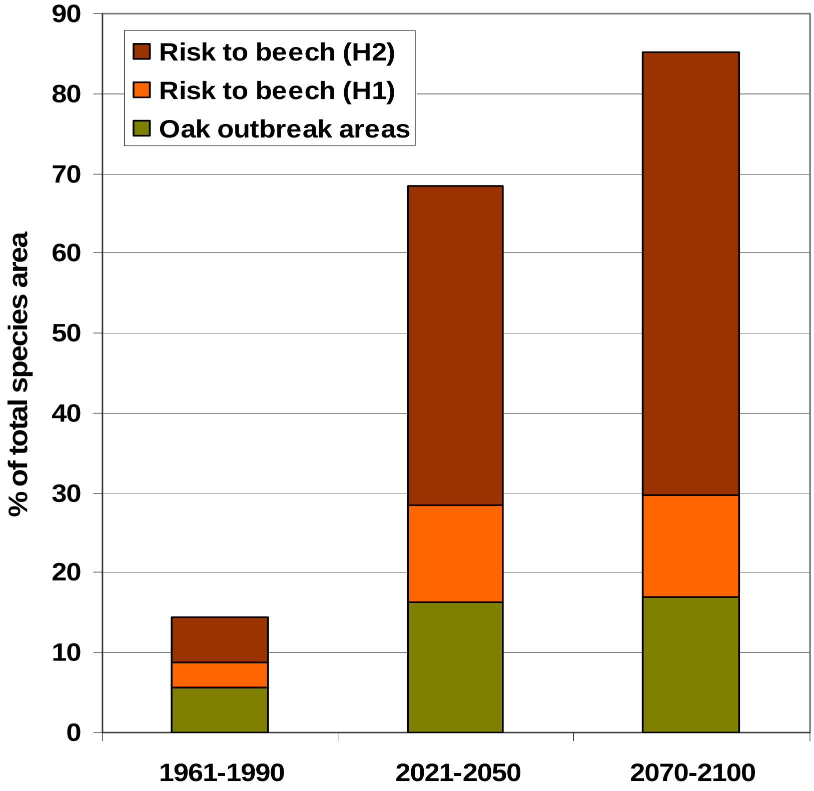

Fig. 2.11 *Proportion of projected oak outbreak areas (OOA) and areas with risk of defoliation to beech stands of the total area of respective species under ALADIN Climate-CZ climate change scenario. In case of assessment of risk to beech Hypothesis 1 and Hypothesis 2 are considered.*

In case of assessment of defoliation risk to beech according to Hypothesis 1 (presumption of the neighboring oak outbreak spots) the pattern on increase of risk areas is similar to that projected for the oak outbreaks. The extent of potentially endangered beech stands significantly increases between the reference and NFC, while it remains constant between NFC and FFC. Totally, 13% of beech stands in the country is supposed to be endangered by gypsy moth defoliations both in NFC and FFC.

The "pessimistic" Hypothesis 2 supposes that the shift of gypsy moth to higher elevations will be limited only by pest`s upper temperature limit of 8°C (mean annual air temperature) (Fig. 2.13). After relaxing from the need of presence of oak outbreak spot, the species spreads in NFC over 40% and in FFC over 50% of beech stands in the country. However, such scenario has lower probability, mainly because of lower quality of beech as food tree and thus lower reproduction success of gypsy moth. On the other hand, mixed oak-beech forests (not necessarily in the vicinity of outbreak spots in oak stands) may provide suitable conditions for gypsy moth, as oak is an optimal food for young larvae, while older instars are widely polyphagous and may also feed on beech.

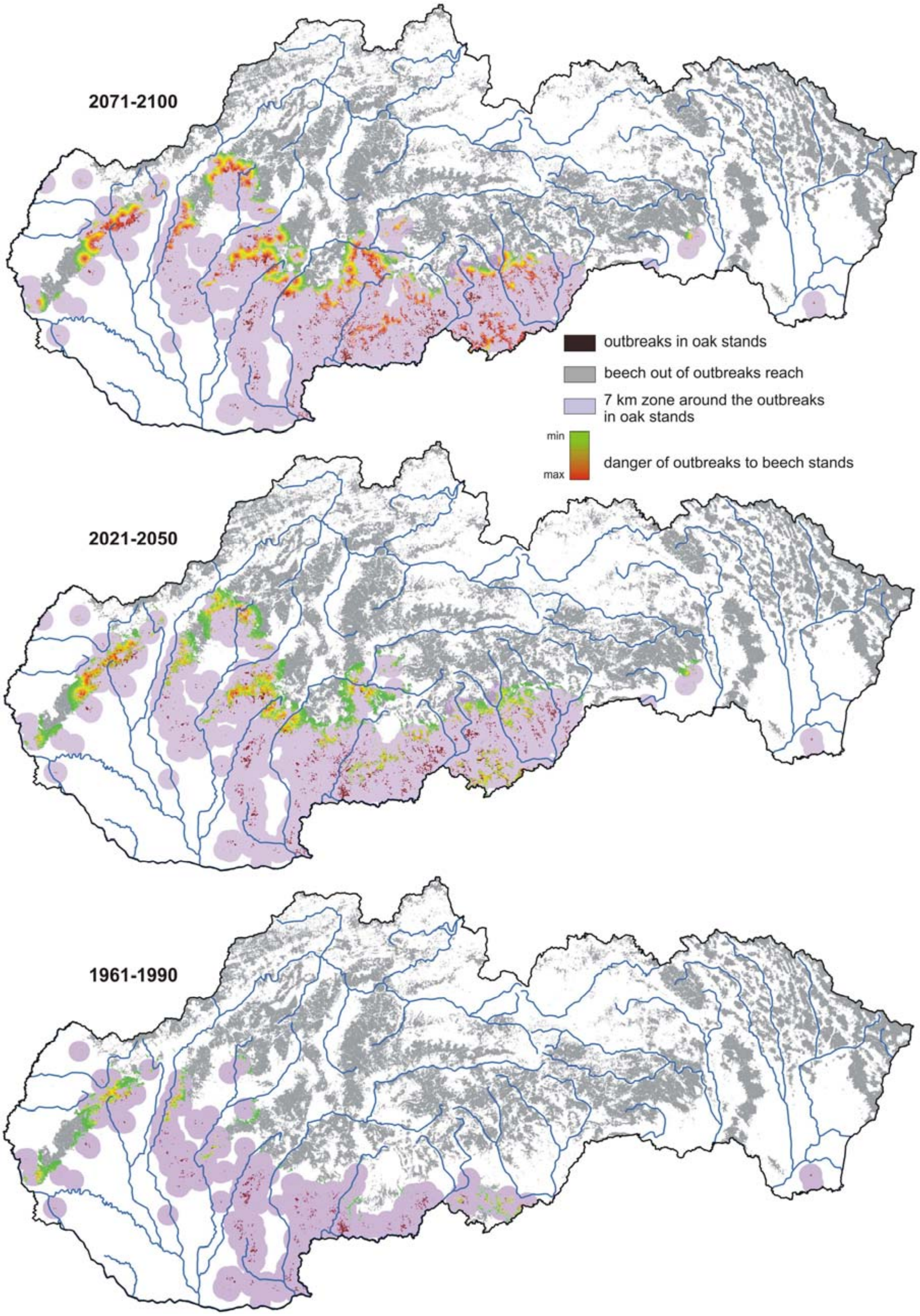

Fig. 2.12 *Projected development of oak outbreak areas and risk of defoliation to beech stands under ALADIN Climate-CZ climate change scenario (Hypothesis 1).*

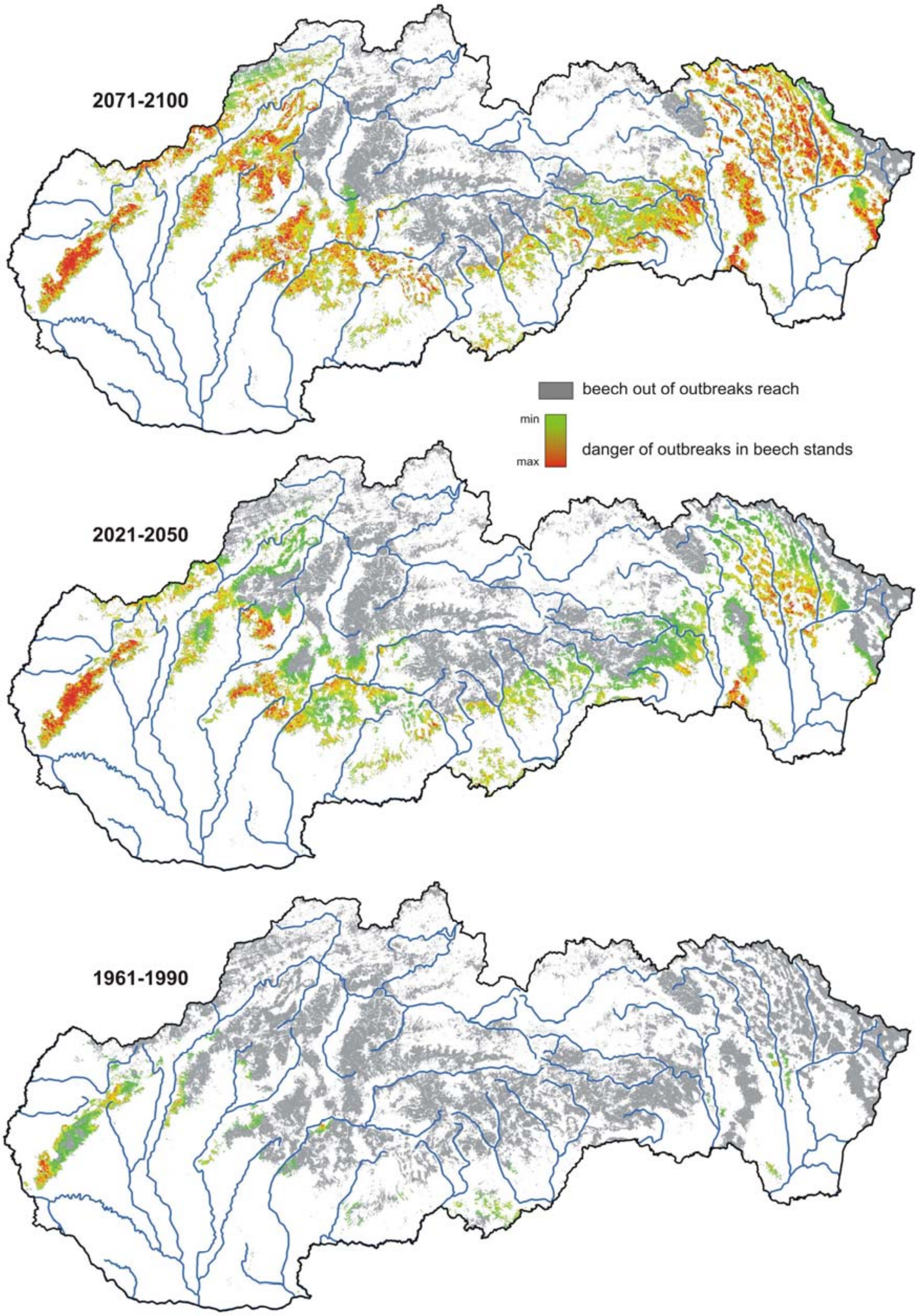

Fig. 2.13 *Projected development of defoliation risk to beech stands under ALADIN Climate-CZ climate change scenario (Hypothesis 2).*

2.5. Conclusions and discussion

In this study we analyzed how climate change can alter insect pest related forest disturbances in Central Europe. The two species we focused on – *Lymantria dispar* and *Ips typographus* – are generally agreed to be sensitive to temperature, thus changes in their distributional ranges and population dynamics can be expected. Indications of this have already been observed in recent years worldwide. Studies on climate change impacts suggest that the observed trends will accelerate. In this study we found that:

1. The area providing climatic conditions suitable for the full development of the second generation of *Ips typographus* within the current distribution range of spruce will increase by 30% in 2021-2050 in comparison to 1961-1990. Significant areas (7% of the current range of spruce distribution) with potential for the full development of the third generation are expected to appear in this period. This will continue up to 53% in 2071-2100. The fourth generation is not expected to occur in the current distributional range of spruce at all. The spring emergence of bark beetle will be accelerated by 5 days in 2021-2050 and 12 days in 2071-2100 (the average shift over the all country).
2. Further, we investigate the emergence of areas, where the number of bark beetle generations is expected to increase, thereby altering the bark beetle related forest disturbance regime. We found that in the 2021-2050 most of spruce stands (58%) remains in the regions with two-generation regime. 42% of spruce stands will be faced to the one-generation increase of bark beetle pressure. In 2071-2100, almost all regions within the actual distribution of spruce will be faced to one-generation increase of bark beetle.
3. *Lymantria dispar* outbreak areas are expected to enlarge significantly in the near future (from 111 km^2 in 1961-1990 to 313-325 km^2 in the NFC/FFC), while further it remains stable, because of reaching the upper distributional range of Turkey oak.
4. There are strong indications that pests will feed on beech as an alternative host, mainly in the vicinity of Turkey oak outbreak spots. Under the assumptions described above, the area of endangered beech stands will be almost four times bigger, compared to the 1961-1990 period. Subsequently, the restricted growth of oak outbreak spots will keep this rate stable. Provided, the pest will spread regardless of the positions of Turkey oak outbreak spots, increasing temperature may enable it to grow unrestrictedly up to the upper distributional limit of other oak species (*Q. petraea* s. l.) and beech. Under this assumption, in the period 2021-2050 the pest can potentially spread over 40% and in the period 2100 over 50% of beech stands in the country.

We focused on three temporal time scales: 1961–1990, 2021-2050 and 2071-2100. Thus we can provide the fundamental data for the development of short-term, medium-term, and long-term adaptation and mitigation strategies. Apart from increasing temperature, the main distinct feature of these time scales is the potential distribution of target tree species. While in near future climate this remains similar to the status quo, in 2071-2100 time scale it moves beyond this. In general, forest management practices tend to adapt to forthcoming changes, therefore the impact may be expected to be less pronounced than indicated by our projections. However, it is difficult to currently assess the efficiency of applied measures.

In the case of bark beetle, the most endangered areas are those where the second and third generations appear, thereby dramatically altering the disturbance regime. Moreover, these are expected to occur in regions currently dominated by spruce. Trees in such regions are not adapted to more bark beetle generations per year, thus it may result in further extensive mortality of spruce stands.

Apart from temperature, moisture conditions play important role in *Ips typographus* population dynamics, as physiological condition of a potential host tree are crucial for the success of a bark beetle attack. Vital trees have higher resistance to prevent attacking bark beetles from successfully establishing broods. Expected increase in the frequency and duration of drought periods probably influences the speed and success of attack.

Ips typographus shows variation in their reaction towards synthetic pheromone (Lieutier et al. 2004) what indicates their genetic variability. Probably, the gene pool in the current populations in central Europe still has a potential to adapt their voltinism to changing environment. These topics were not discussed, however they are expected to play an important rule in analysis of expected changes of *Ips typographus* population dynamics.

In the case of gypsy moth, outbreaks repeat every 10 to 11 years in the Central Europe. Thus, a temperature increase between cycles may cause an unprecedented growth of outbreak areas and the intensity of defoliation. The last gradation occurred in 2004-2006 (Kunca et al. 2007). The defoliated area reached 48 000 hectares. Compared to the previous outbreaks in 1992-1995, the defoliated area was 1.5 times larger (increasing from 32 000 to 45 000 hectares). The growing trend in the extent of outbreak areas is evident: for example, the total defoliated area during the 1983-1987 outbreak was only 8 400 ha.

Changes in gypsy moth outbreaks were evaluated only in relation to selected environmental parameters. Other factors, which are difficult to assess, are ecosystem relationships such as host trees/gypsy moth, parasitoids/gypsy moth, and predator/gypsy moth interactions. Further research will also aim at shifts of host distributional ranges. Another aspect, which has yet to be analyzed, are expected changes in the intensity of defoliation that is also forecast to occur. In contrast, outbreak cycles should remain stable. Johnson et al. (2006) reported similar cycles as those observed in Slovakia also in southern countries with warmer climates – Hungary and northern Croatia. The south of Croatia is the first region where outbreaks are occurring in shorter cycles (the main period lasts 7-10 years and inter-outbreaks 2-3 years).

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