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Simulations of Colorado Potato Beetle Development in Poland Based on Four Climate Change Scenarios

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Additional information is available at the end of the chapter

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Abstract

The simulations were conducted using actual data and virtual data. The actual data were recorded in the period of 1986–2005 at 16 localities representing 16 regions of Poland. The virtual data were obtained after transformation of the recorded data to reflect a temperature changes under RCP2.6, RCP4.5, RCP6.0 and RCP8.5 scenarios according to giss_e2_r climate model. The model used in the study was based on scientific reports describing the influence of temperature on acceleration of the onset of egg laying and on successive stages of Colorado potato beetle as well as publications on the effects of photoperiod on the pest diapause. The study showed a growing threat to potato from Colorado potato beetles as a result of the temperature rise. The fastest development of the pest appeared in simulations under RCP8.5 scenario. Of 16 regions surveyed in the study, the south-western part of Poland was found to be most threatened by Colorado potato beetle as a result of anticipated climate change.

Keywords: Colorado potato beetle, number of generations, model, climate change, RCP scenarios

1. Introduction

The Colorado potato beetle, *Leptinotarsa decemlineata* (Say), is the most destructive pest of the potato in many countries all over the world [1]. The pest consumes about 40 cm² foliage at the larval stage and almost 10 cm² per day as an adult [2]. The distribution of the Colorado potato beetle covers about 8 million km² in North America [3] and about 6 million km² in Europe and Asia [4]. It has recently appeared in western China [1] and Iran [5]. According to Vlasova [6], Worner [7] and Jolivet [4], the expected climate change may promote the pest expansion into

Korea, Japan, certain areas of the Indian subcontinent, parts of North Africa and the temperate Southern Hemisphere. In Poland, the Colorado potato beetle appeared in 1944 [8]. In 1950, the first great invasion of this species was noticed [9]. Despite the systematic reduction of potato land, the Colorado potato beetle is still a major pest affecting potato crops in Poland [10–12]. Yield losses caused by the feeding of the pest, in the absence of chemical protection, are estimated at 35–40% [13], and in extreme cases, losses can reach 70% of yield [14]. Potato crop losses caused by the Colorado potato beetle are highly dependent on the growth rate of the pest population, which is heavily dependent on meteorological conditions, among which temperature plays a leading role. According to the data from a number of studies, temperature is also the main environmental factor which determines the number of pest generations. The close connection between these two factors indicates the opportunity of using mathematical models expressing relationships between temperature and the rate of Colorado potato beetle development for predicting the influence of climate change on the number of pest generations.

This has already been studied in Poland [15], but only for the Wielkopolska region and without considering new emission scenarios termed representative concentration pathways (RCPs) recommended by the international climate modeling community through the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) to be used in climate modeling and research [16].

RCP2.6, RCP4.5, RCP6 and RCP8.5 are four pathways named according to their 2100 radiative forcing level expressed in Watts per meter square. RCP2.6 is a “peak-and-decline” scenario. By mid-century, its radiative forcing level reaches a value of around 3.1 W/m² and then decreases to 2.6 W/m² by 2100 [17]. RCP4.5 [18–20] and RCP6.0 [21, 22] are stabilization scenarios in which total radiative forcing is stabilized shortly after 2100, following the reduction of greenhouse gas emissions. RCP8.5 is characterized by increasing greenhouse gas emissions over time. This is a representation of scenarios in the literature that lead to high greenhouse gas concentration levels [23].

The aim of this study was to determine the impact of climate change on the development of the Colorado potato beetle and to identify the region most at risk of increase in the number of pest generations.

2. Material and methods

2.1. Climate change model selection

In order to select the climate model, out of the 16 models presented on the Climate Change Knowledge Portal created by the World Bank (<http://sdwebx.worldbank.org/climateportal/>), we used the Taylor diagram technique. This diagram enables to assess how closely a pattern matches observations on the basis of three measures of model quality presented on one chart. These measures are: the correlation (R), the centered rootmean-square-error (RMSE) and the amplitude of the standard deviations (Std) [24]. We compared monthly temperature registered at 16 localities in the period 1986–2005 and the temperatures generated for this period and these locations by the climate models.

2.2. Meteorological data

Two kinds of meteorological data were used in the study: first, data were registered in the years 1986–2005 at 16 localities representing the 16 regions of Poland; and second, data obtained after transformation of the recorded data to reflect temperature changes under RCP2.6, RCP4.5, RCP6.0 and RCP8.5 scenarios according to the giss_e2_r climate model. Latitudes and longitudes of the analyzed localities are presented in **Table 1**.

2.3. Simulation of the impact of climate change on Colorado potato beetle development

The study was performed using the NumoGen 2 model, which was developed for the present study based on the earlier version called NumoGen 1 [15]. The main difference between these two models is that NumoGen 2 enables the calculation of differences in the dates of egg laying between regions and years, while NumoGen 1 was only able to consider the changes in temperature triggered by climate changes. But, for all these purposes, the same equation were used, presented by Wójtowicz et al. in [15], describing the relationship between the onset of the egg-laying period and temperature increase.

From experiments conducted in the Wielkopolska region at WinnaGóra in the years 2003–2005 when Colorado potato beetle egg laying was noticed in the first decade of June, it was decided to perform simulations of the pest development with the use of meteorological data collected in Poznan in 2005 starting from 27 May to 15 June. This covers the period from 5 days before the start to 5 days after the first decade of June. The start of simulations performed with the use of data collected in Poznań in 1986–2004, as well as those registered at the other 15 localities in the period 1986–2005 and virtual data generated by the giss_e2_r model were obtained with

Locality	longitude	latitude
Białystok	53°07'N	23°10'E
Gdańsk	54°22'N	18°38'E
Katowice	50°15'N	19°00'E
Kielce	50°53'N	20°37'E
Kraków	50°03'N	19°55'E
Lublin	51°15'N	22°34'E
Łódź	51°49'N	19°28'E
Olsztyn	53°47'N	20°30'E
Opole	50°40'N	17°56'E
Poznań	52°25'N	16°53'E
Rzeszów	50°02'N	22°00'E
Szczecin	53°25'N	14°32'E
Toruń	53°02'N	18°37'E
Warszawa	52°35'N	21°05'E
Wrocław	51°05'N	17°00'E
Zielona Góra	51°56'N	15°30'E

Table 1. Latitude and longitude of localities analyzed in the study.

the use of an equation describing the relationship between onset of the egg-laying period and temperature increase [15].

NumoGen 2 simulates the development of colorado Potato Beetle from the occurrence of egg clusters until meteorological conditions or photoperiods prevent further development of the pest. The model was developed from information presented in scientific reports. The development of the pest from egg to adult was based on information presented by Łarczenko [25]. The dates of egg laying by female beetles of succeeding generations were estimated according to data presented by Alyokhin and Ferro [26]. The beginning of the winter diapause was determined from data reported by Tauber et al. [27], who found that all females reared at a photoperiod between 10:14 and 14:10 (L:D) entered diapause. This information was used to determine the dates of diapause based on day length at the 16 localities analyzed in the study. Information about day length was found on the internet at: <http://www.timebie.com/sun/>.

For each locality, 20 simulations were performed. Each simulation generated information about CPB development based on meteorological data registered in the 20 years, 1986–2005, and data obtained after transformation of the recorded data to reflect temperature changes under four scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) and four periods (2020–2039, 2040–2059, 2060–2079 and 2080–2099) according to the giss_e2_r climate model.

Additionally for each locality, a model was developed to estimate the minimum temperature increase, in relation to 1986–2005, that ensured the emergence of the second generation of CPB.

The models were developed based on meteorological data (registered and obtained after transformation of the recorded data to reflect the temperature changes under four RCP scenarios) and simulation results describing the probability of the occurrence of CPB second generation. The models were developed with the use of the exponential function:

$$SGCPBP = a + \exp(b + c \times T) \quad (1)$$

where SGCPBP is the probability of the occurrence of CPB second generation; T the temperature increase for the temperature registered in 1986–2005; a, b and c are the equation coefficients.

3. Results

3.1. Climate change model selection

The results from the giss_e2_r model appeared on the Taylor diagram at the shortest distance from the observation point (**Figure 1**). On that basis, the giss_e2_r model was selected out of the 16 analyzed climate models for further analysis (**Figure 2**).

3.2. Simulation of climate change on Colorado potato beetle development

Simulations performed on data registered at 16 localities showed that the best meteorological conditions for the earliest egg laying in 2005 occurred in the west and south-west, while the

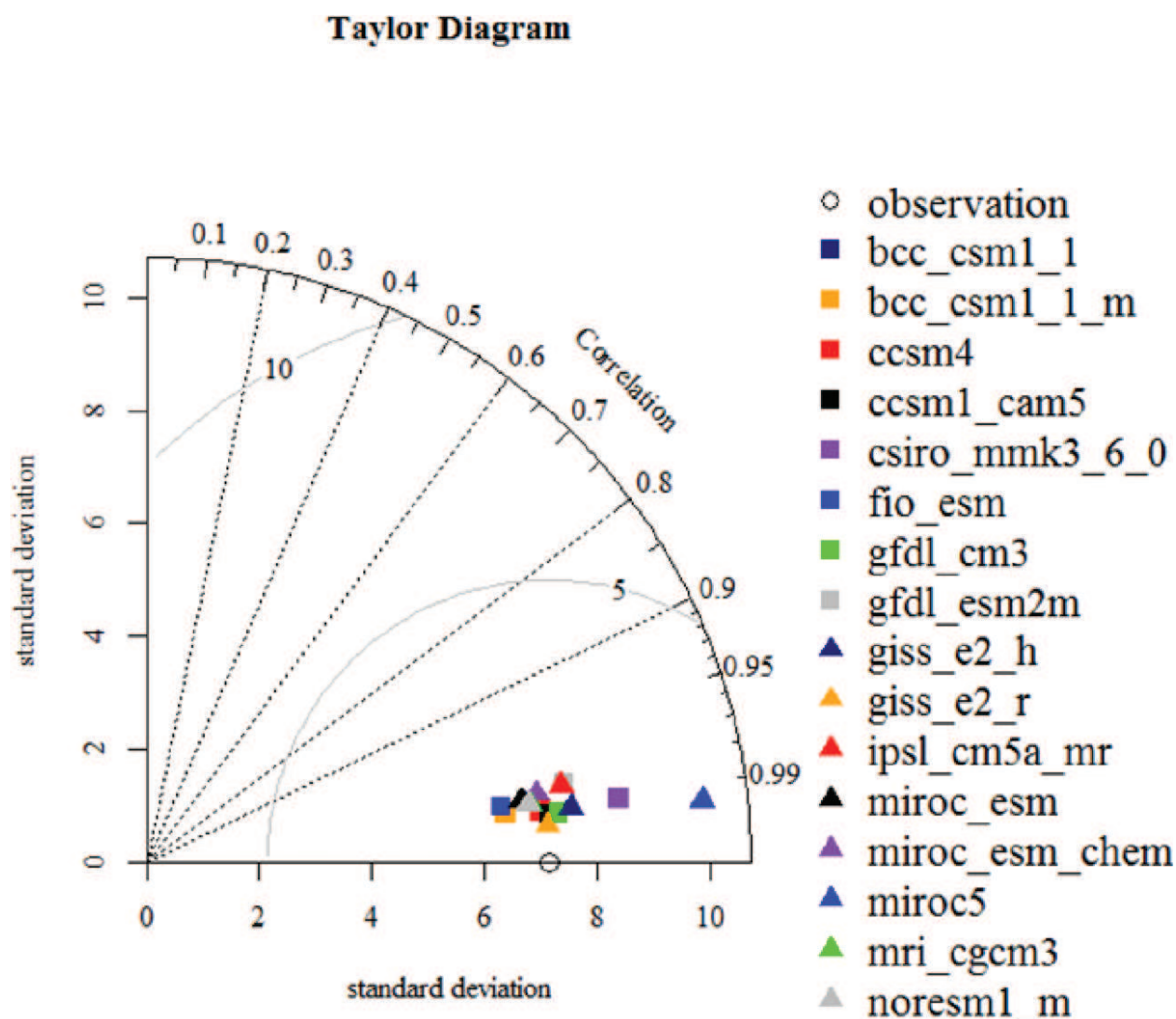


Figure 1. Taylor diagram illustrating the statistics of the comparison between observed and 16 model estimates of air temperature at 16 localities in 1986–2005. Bcc_csm1_1, bcc_csm1_1_m, ccsm4, cesm1_cam5, csiro_mk3_6_0, fio_esm, gfdl_cm3, gfdl_esm2m, giss_e2_h, giss_e2_r, ipsl_cm5a_mr, miroc_esm, miroc_esm_chem, miroc5, mri_cgcm3, noresm1_m: Model names used in the study.

worst conditions were noted in the northern and north-eastern parts of Poland (**Table 3**). Out of the four RCP scenarios, three (RCP4.5, RCP6.0 and RCP8.5) generated the greatest acceleration of egg laying in the period 2080–2099. But, according to the RCP2.6 scenario, the earliest egg laying is expected in the period 2020–2039 (**Table 2**). Comparison of meteorological data registered in 1986–2005 revealed that the differences between the earliest and the latest day of egg laying ranges from 12 at Białystok to 16 at Opole (**Table 3**).

Simulations performed on real data, except for Białystok (95.8%), Gdańsk (85%) and Olsztyn (99.3%), as well as on transformed data showed a 100% probability of the appearance of the first generation of CPB (**Figure 3**). Simulations performed on real data revealed that the average number of days needed for the development of the first generation of CPB was 56. Use of transformed data resulted in a shortening of the first generation development of the

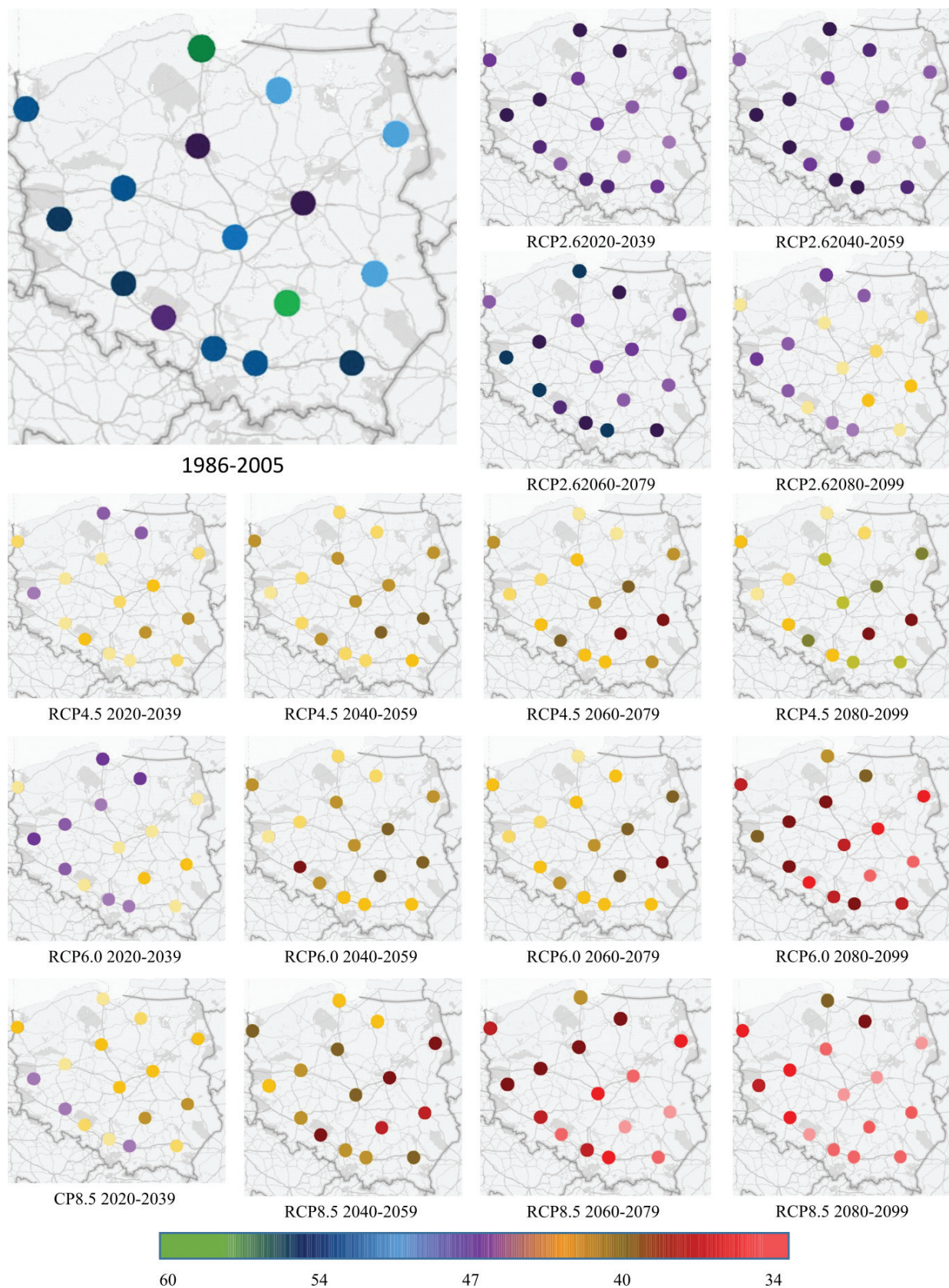


Figure 2. Effects of climate change on number of days needed to complete the first generation of CPB at 16 localities in Poland.

Locality	Registered temperature	RCP2.6				RCP4.5				RCP6.0				RCP8.5			
		20-39	40-59	60-79	80-99	20-39	40-59	60-79	80-99	20-39	40-59	60-79	80-99	20-39	40-59	60-79	80-99
Białystok	0	-2	-1	-2	1	-1	-1	-4	-3	-1	-2	-1	-5	0	-6	-7	-9
Gdańsk	0	-1	0	0	3	0	0	-2	-2	0	-1	0	-4	1	-5	-6	-8
Katowice	0	-2	-1	-1	2	0	-1	-3	-3	-1	-2	-1	-5	0	-4	-6	-10
Kielce	0	-4	-3	-3	-1	-2	-3	-5	-5	-3	-4	-3	-7	-2	-7	-8	-12
Kraków	0	-1	0	-1	2	0	0	-3	-2	-1	-1	0	-4	0	-4	-6	-9
Lublin	0	-3	-2	-3	0	-2	-2	-5	-4	-2	-3	-2	-6	-1	-7	-8	-11
Łódź	0	-1	0	-1	2	0	0	-3	-2	-1	-2	0	-4	0	-5	-6	-9
Olsztyn	0	1	2	2	5	2	2	0	0	2	1	2	-2	2	-3	-5	-6
Opole	0	0	1	0	3	1	1	-2	-2	0	-1	1	-4	1	-3	-5	-8
Poznań	0	-1	1	0	3	1	1	-2	-2	0	-1	1	-4	1	-4	-5	-8
Rzeszów	0	-1	-1	-1	1	-1	-1	-4	-3	-1	-2	0	-5	0	-5	-6	-10
Szczecin	0	-2	0	-1	2	0	0	-3	-3	-1	-2	0	-5	0	-5	-6	-8
Toruń	0	0	1	0	4	1	1	-2	-1	1	0	1	-3	2	-4	-5	-7
Warszawa	0	-1	0	0	3	1	0	-2	-2	0	-1	0	-4	1	-5	-5	-8
Wrocław	0	-1	0	0	2	0	0	-3	-2	-1	9	0	-4	1	-4	-6	-9
Zielona Góra	0	-1	1	0	3	1	1	-2	-2	0	-1	1	-4	1	-3	-5	-8
average	0	-1,3	-0,1	-0,7	2,2	0,1	-0,1	-2,8	-2,4	-0,6	-0,8	-0,1	-4,4	0,4	-4,6	-5,9	-8,8

Table 2. Effects of RCP scenario on the offset of the egg-laying period in relation to temperature registered in 1986–2005.

pest to 46–51 days for RCP2.6, 44 days for RCP4.5, 41–48 days for RCP4.5 and 39–46 days for RCP8.5. The greatest decreases were obtained for Gdańsk (9–14 days for RCP2.6, 15–16 days for RCP4.5, 11–19 days for RCP6.0 and 14–21 days for RCP8.5), Białystok (10–14 days for RCP2.6, 14–17 days for RCP4.5, 13–19 days for RCP6.0 and 16–22 days for RCP8.5), Kielce (9–15 days for RCP2.6, 16–17 days for RCP4.5, 13–19 days for RCP6.0 and 14–21 days for RCP8.5), Lublin (9–14 days for RCP2.6, 15–16 days for RCP4.5, 12–18 days for RCP6.0 and 14–20 days for RCP8.5) and Olsztyn (8–12 days for RCP2.6, 13–14 days for RCP4.5, 10–17 days for RCP6.0 and 14–20 days for RCP8.5). The smallest decreases were noted in simulations performed for Opole (1–6 days for RCP2.6, 7–8 days for RCP4.5, 4–11 days for RCP6.0 and 5–12 days for RCP8.5), Wrocław (0–6 days for RCP2.6, 8–9 days for RCP4.5, 4–11 days for RCP6.0 and 6–13 days for RCP8.5) and ZielonaGóra (1–6 days for RCP2.6, 8–9 days for RCP4.5, 4–12 days for RCP6.0 and 6–14 days for RCP8.5).

Simulations performed on meteorological data registered in the period 1986–2005 showed that the average probability of the appearance of the Colorado potato beetle second generation was 26% (**Figure 4**). The highest probabilities were obtained for Opole 62%, Wrocław 46% and ZielonaGóra 45%, whereas the smallest probabilities were achieved for Gdańsk 0%, Olsztyn 3.2% and Białystok 6%.

The use of data obtained after transformation of the recorded data to reflect temperature changes under four scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) and four periods (2020–2039, 2040–2059, 2060–2079 and 2080–2099), according to the giss_e2_r climate model, did not lead to much alteration in the list of the localities least threatened by the occurrence of CPB second generation. Out of 16 combinations of scenarios and periods, only four resulted in the replacement of Białystok by another locality in third position on the list. But, changes in the list

Year	Białystok	Gdańsk	Katowice	Kielce	Kraków	Lublin	Łódź	Olsztyn	Opole	Poznań	Rzeszów	Szczecin	Toruń	Warszawa	Wrocław	Zielona Góra
	5	8	2	3	-2	2	1	5	-1	0	0	4	3	1	-1	-1
Differences in the onset of the egg laying period between localities in 2005 in relation to Poznań																
2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2004	3	0	2	2	2	2	2	2	1	1	3	0	1	2	2	2
2003	-1	-1	-1	-1	-1	-1	0	0	0	-2	-1	-1	-2	-1	0	0
2002	-6	-6	-5	-4	-4	-4	-4	-7	-4	-4	-3	-3	-7	-5	-4	-2
2001	-2	0	-1	0	1	-1	2	0	1	0	0	-1	-1	0	1	1
2000	-8	-8	-8	-8	-6	-8	-9	-8	-6	-8	-6	-8	-10	-8	-7	-7
1999	1	0	-2	0	0	1	1	0	0	0	1	-1	-1	0	-1	0
1998	-3	-3	-4	-4	-2	-3	-2	-4	-4	-4	-2	-5	-4	-3	-2	-2
1997	4	5	3	4	5	4	5	5	4	5	5	3	3	5	5	6
1996	-2	0	0	-1	2	-2	0	-1	2	2	-1	1	-2	-1	3	4
1995	2	2	2	3	4	3	3	2	2	2	4	0	1	3	3	3
1994	1	1	0	1	2	1	1	2	2	2	1	-2	0	1	2	2
1993	-4	-6	-5	-3	-1	-3	-4	-6	-10	-6	-1	-9	-7	-4	-3	-5
1992	2	1	1	2	3	3	2	2	-4	1	3	-3	0	2	1	1
1991	4	4	5	5	7	5	5	5	6	5	7	3	4	5	6	7
1990	0	-1	0	1	3	1	0	-1	0	1	2	-3	-2	0	1	1
1989	-2	-1	-2	0	2	-1	0	-2	0	0	0	-2	-2	-1	1	1
1988	0	2	-1	1	4	1	0	0	0	0	2	-3	-1	0	1	1
1987	4	4	4	4	6	4	5	4	4	4	5	3	3	4	5	5
1986	-1	0	-5	-3	-1	-2	-1	-2	-3	0	-4	0	-1	-2	0	2
max	4	5	5	5	7	5	5	5	6	5	7	3	4	5	6	7
min	-8	-8	-8	-8	-6	-8	-9	-8	-10	-8	-6	-9	-10	-8	-7	-7

Table 3. Effects of locality and year on the offset of the egg-laying period.

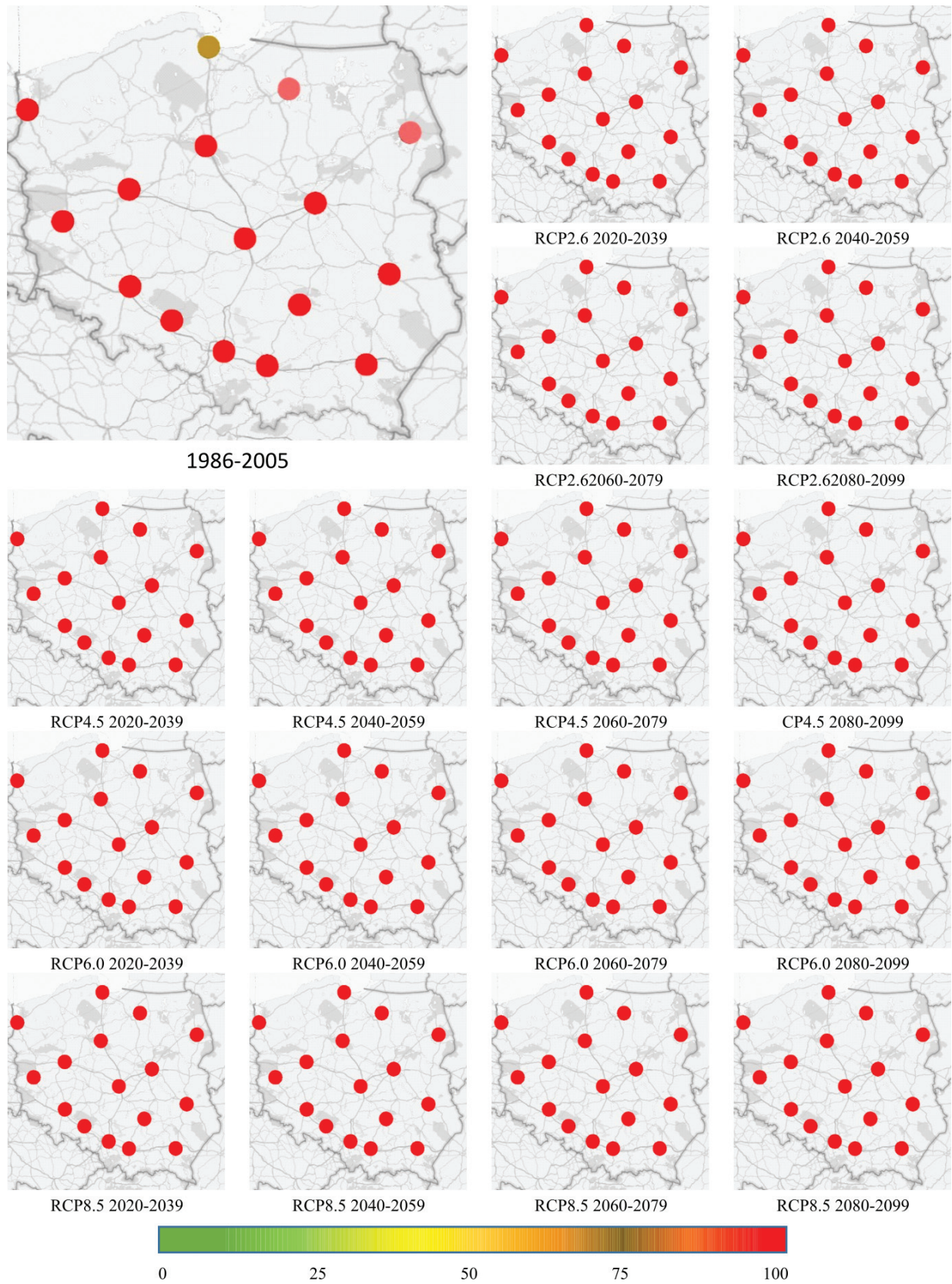


Figure 3. Effects of climate change on probability of the appearance of CPB first generation.

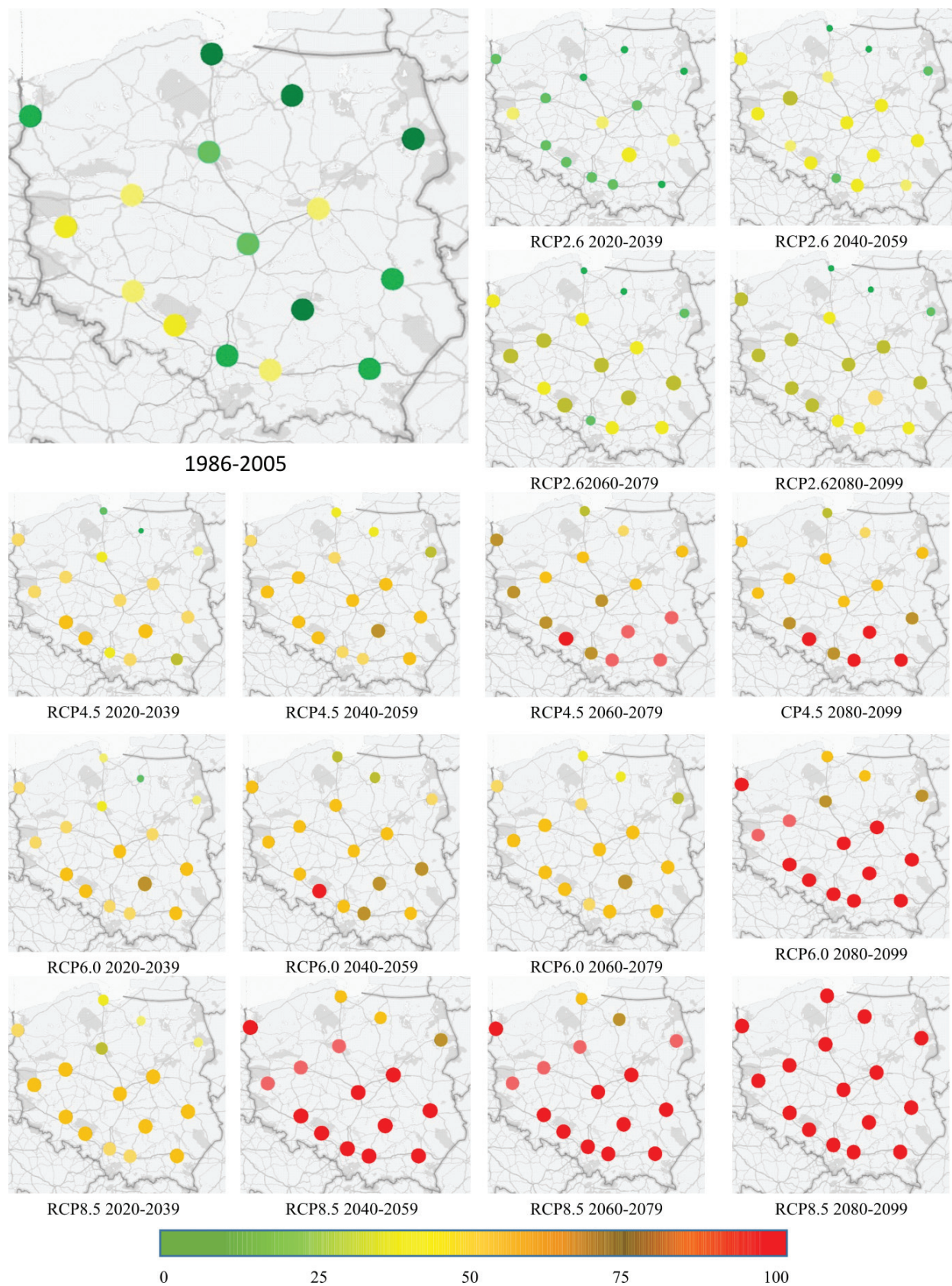


Figure 4. Effects of climate change on probability of the appearance of CPB second generation.

of the highest threatened localities were noticed. ZielonaGóra and Wrocław were replaced mostly by Lublin and Kielce.

Of the four scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5), three (RCP4.5, RCP6.0 and RCP8.5) generated a significant increase in the probability of CPB second generation appearance at the end of the century. But, in the periods 2020–2039, 2040–2059 and 2060–2079, increases in the probability of the second generation pest occurrence were generated under all four scenarios.

For the end of the century, the highest probability of the appearance of the second generation of CPB (99.5–100%) was obtained under scenario RCP8.5, whereas the smallest (5.5–50.3) was under RCP2.6. Scenarios RCP4.5 and RCP6.0 generated the following results, respectively: 60.3–97–3% and 79–100%.

Simulation under scenarios RCP2.6, RCP4.5 and RCP6.0 revealed that for the end of the century, the highest increase in probability (SGCPBP) were generated respectively for Kielce (42.3, 88.5, 92), Lublin (34, 84.8, 92) and Białystok (12.5, 70.3, 86.3), whereas under scenario RCP8.5, these were for Gdańsk (99.5) Olsztyn (96.8) and Białystok (94). The smallest increase in SGCPBP obtained in simulations under scenarios RCP4.5, RCP6.0 and RCP8.5 were, respectively, revealed for Opole (35.3, 37.3, 38), Wrocław (41.5, 52, 53.8) and ZielonaGóra (34.3, 52, 55.3). In simulations under scenario RCP2.6, besides an increase in SGCPBP, a decrease was also achieved. The highest decrease was generated for Opole (–27.5), Wrocław (–17.8) and ZielonaGóra (–12).

Simulations under scenario RCP2.6 produced 29 results with SGCPBP lower than 50%, 34 with SGCPBP ranging from 50 to 75% and one higher than 75%. The use of scenarios RCP4.5 and RCP6.0 resulted, respectively, in two and three results with SGCPBP lower than 50%, 18 and 17 results with SGCPBP ranged from 50 to 75% and 43 results higher than 75%. Simulations under RCP8.5 produced 10 results with SGCPBP ranging from 50 to 75% and 54 results higher than 75%.

Simulations also showed that the average number of days needed for completion of the second generation was 51–54 for RCP2.6, 47–52 for RCP4.5, 44–51 for RCP6.0 and 39–51 for RCP8.5.

Simulations on real data sets revealed no possibility of the third generation of CPB appearance at all analyzed localities, except for Opole (**Figure 5**). Introduction of transformed data did not change the results very much, except for scenarios RCP6.0 (period 2080–2099) and RCP8.5 (periods 2060–2079, 2080–2099).

The results of the simulations were also used to estimate the minimum temperature increase for 1986–2005 that ensure the emergence of the second generation of CPB. To achieve that aim, exponential models for 16 localities were developed (**Table 4**).

With a 95% probability, 1°C temperature rise at Opole guaranteed the appearance of CPB second generation (**Figure 6**). At Katowice, Rzeszów, Szczecin and Wrocław, temperatures ought to increase by 1.6°C. At Kraków and Toruń, 1.7 and 1.8°C temperature rises, respectively, led to the appearance of the pest second generation. At Łódź, Poznan, Warszawa and ZielonaGóra, temperatures ought to rise by 1.9°C. A temperature increase of 2.1 and 2.3°C

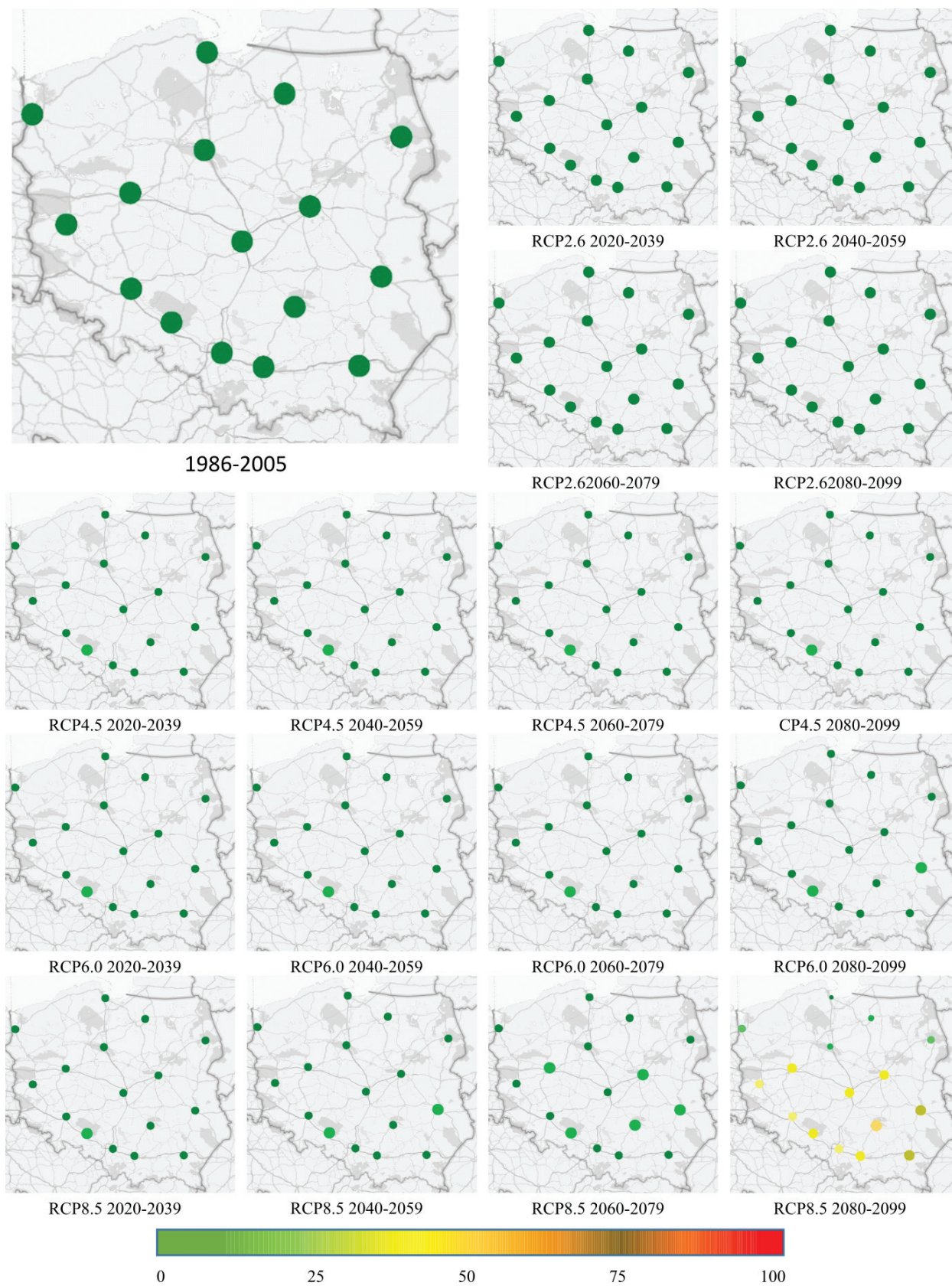


Figure 5. Effects of climate change on probability of the appearance of CPB third generation.

Locality	a	b	c	R ²
Białystok	1,014298	2,992209	1,923994	0,96
Gdańsk	0,928751	3,029688	2,179541	0,97
Katowice	1,015548	1,612499	2,540181	0,98
Kielce	1,029395	2,297799	1,934486	0,99
Kraków	1,033059	0,646070	1,892346	0,98
Lublin	1,028426	1,560441	1,933356	0,97
Łódź	1,051250	0,956814	1,696449	0,97
Olsztyn	0,968657	2,817530	2,298582	0,93
Opole	1,021316	-0,340691	2,289298	0,97
Poznań	1,043817	0,412160	1,468694	0,98
Rzeszów	1,033329	1,023897	2,295942	0,98
Szczecin	1,031734	0,880774	2,092321	0,95
Toruń	1,010716	0,341909	1,814728	0,96
Warszawa	0,997326	1,310552	2,273030	0,95
Wrocław	1,032427	0,079441	1,675169	0,89
Zielona Góra	1,058929	0,475526	1,437996	0,97

Table 4. Parameters of the exponential models [$SGCPBP = a + \exp.(b + c \times T)$] expressing the influence of temperature increase (T_i) on probability of the appearance of the second generation of CPB (SGCPBP).

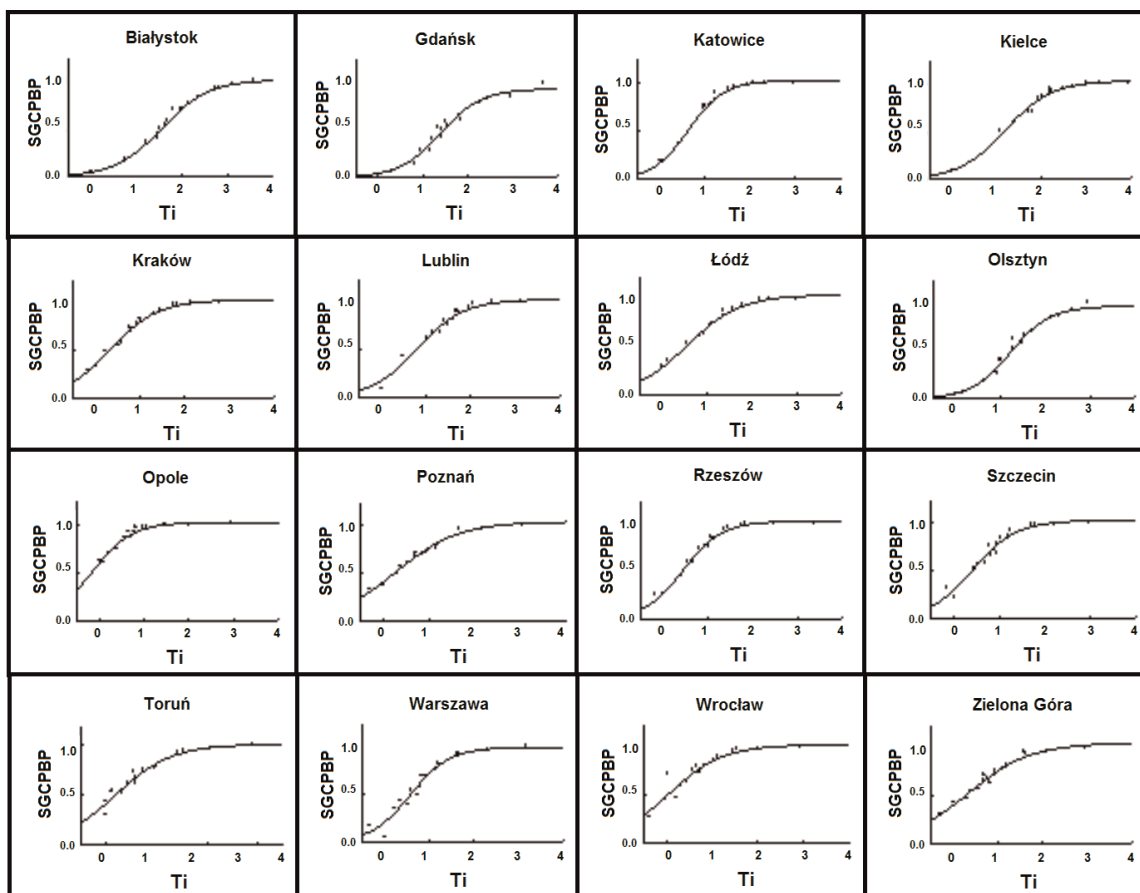


Figure 6. Effects of temperature increase on probability of the appearance of the second generation of CPB.

generated the appearance of the second pest generation at Lublin and Białystok, respectively. At Kielce and Olsztyn, temperature rises of 2.5 and 3°C were needed to trigger the appearance of the second generation, whereas at Gdańsk, the probability of the appearance of the second generation did not exceed 93%.

With a probability of 99%, a temperature rise of 1.4°C generated the second generation of CPB at Opole. At Katowice and Rzeszów, temperature had to increase by 1.9°C. At Kraków, Szczecin and Wrocław, a 2°C temperature rise triggered the appearance of the pest second generation. At ZielonaGóra and Łódź temperature had to rise by 2.2°C. A temperature increase of 2.3, 2.4 and 2.5°C generated the appearance of the second pest generation at Poznań, Toruń and Lublin. At Kielce and Białystok, temperature rises of 2.9 and 3.2°C were needed to trigger the appearance of the second generation, whereas for Gdańsk and Olsztyn, the models did not generate the appearance of the second generation with a probability of 99%.

4. Discussion

Results obtained in the present study are in line with our earlier prediction of CPB development under climate change in the Wielkopolska region, located in the western part of Poland [15]. In that study, two CPB generations were generated following a temperature increase of around 2°C for the Wielkopolska region by a model developed on simulation results obtained using meteorological data registered at WinnaGóra, located 60 km south of Poznań, and data obtained after transformation of the recorded data to reflect a temperature increase of 1–6°C. Similar results are presented in the present study for Poznań, where two generations of CPB are expected with a probability of 0.95 and 0.99 following a temperature increase of 1.9 and 2.3°C, respectively. Comparison of the results of 16 models describing the influence of temperature rises on SGCPBP indicated that thermal conditions in south-western Poland are most similar to those that guarantee the appearance of two generations. On the other hand, an increase in the number of CPB generations in north-eastern Poland required a much higher temperature rise. The main advantage of the current study over the study published in 2013 is not only the increase in the number of localities but also the inclusion of four RCP scenarios, which enable an assessment of regional variations in climate change.

Simulation results produced with the use of RCP scenarios in the present study show that an increase in the number of CPB generations is very likely to appear in Poland. Under three (RCP4.5, RCP6 and RCP8.5) out of the four analyzed scenarios, average SGCPBP calculated for 16 localities is going to exceed 75% after 2039. The only scenario which shows that, at the end of the century, the situation will not differ very much from that observed in 1986–2005 is RCP2.6. However, even under that scenario, simulations showed a shortening of the CPB first generation development time, especially in the northern (Gdańsk), north-eastern (Olsztyn, Białystok), eastern (Lublin) and southern parts of central Poland (Kielce). The same regions were indicated as being the most vulnerable to shortening of the CPB first generation development from simulation results under scenarios RCP4.5, RCP6 and RCP8.5. Moreover, analysis

of the pest development under scenarios RCP4.5, RCP6 and RCP8.5 showed that the second generation usually developed faster than the first generation. We decided not to compare the development time of the generations obtained in simulations on real data and under scenario RCP2.6 because of the excessive number of SGCPBP results lower than 50%.

As expected, the lowest values for SGCPBP were generated under scenario RCP2.6, whereas the highest were noted under RCP8.5. The SGCPBP values produced by the former are usually lower than 75%. That is why we did not use it to specify the regions to be threatened by CPB in the future. The values for SGCPBP produced by RCP8.5 are usually higher than 75%, but there are almost no differences in this analyzed parameter between localities, so this scenario was also not used for specification of the regions at most risk from CPB in the future. On the other hand, scenarios RCP4.5 and RCP6 can be helpful in identifying regions at risk from CPB in the future. Both produced quite differential results, usually higher than 75%. Comparison of simulation results obtained under scenario RCP4.5 enables identification of the south-western region (Opole, Wrocław), the south-eastern (Rzeszów), eastern (Lublin) and southern parts of central Poland (Kielce), as being the most threatened by CPB in the future. Simulations under scenario RCP6.0 additionally included the south of Poland (Katowice) as one of the region most at risk of CPB.

Comparison of SGCPBP obtained in simulations on real and transformed data also enables identification of the regions vulnerable to higher changes in SGCPBP. Based on scenarios RCP2.6, RCP4.5 and RCP6.0, the south of central Poland (Kielce) and the eastern part of Poland (Lublin) should be included into that category. The predicted increase in SGCPBP obtained in simulations under these scenarios for these two localities distinctly differs from the rest. According to simulation results from scenario RCP8.5, it appears that besides these two localities, another three (Białystok, Gdańsk and Olsztyn) are more vulnerable to increase in SGCPBP than other localities.

Considering the results of the study dealing with the risk of CPB third generation appearance, it seems that the south-western region (Opole), eastern region (Lublin) and southern part of central Poland (Kielce) may face the most problems caused by increased numbers of CPB generations.

Results obtained in the present study are also in line with predictions of CPB development under expected climate change in the Czech Republic presented by Kocmankowa et al. [28], who used a simulation performed with the use of the CLIMEX model to show a growing danger of an increase in the number of CPB generations. This is in line with the predictions by Menéndez [29], Das et al. [30] and Sangle et al. [31], who expected greater numbers of generation of so-called "stop and go" insects following climate change. Kocmankowa et al. [28] also predicted a widening of the area of CPB occurrence and a shifting of the pest to higher altitudes. The significant increase in SGCPBP in the Małopolska upland located in the southern part of central Poland (Kielce) showed in our study confirms the findings of Kocmankowa et al. [28]. Similar results were also presented by Pulatov et al. [32], who analyzed the effect of climate change on the potential spread of the Colorado potato beetle in Scandinavia. They showed a substantial increase in the frequency of years in which the temperature requirement for development of one generation was fulfilled. Additionally, they indicated regions where two generations per year may occur more often.

The results of the simulations performed by Žalud et al. [33] for middle Europe, including Poland, also show an increase in the number of CPB generations per year based on the temperature increase predicted by various scenarios. Possible increases in the number of CPB generations are also expected in some areas of Russia by Popova [34], who used cartographic modeling to show that this phenomenon is caused by an increase in the sum of effective air temperatures in those territories.

The differences in the effect of climate change on CPB development between regions shown in the present study are also in consistent with the findings of Wittchen and Freyer [35], who analyzed the impact of temperature increases at two localities in Germany (Potsdam and Ulm) on the appearance of subsequent developmental stages of CPB. Simulations performed under real temperatures generated faster development of CPB first generation at Potsdam (30 m a. s. l.) than at Ulm (470 m a. s. l.) (by 5 days). But, under increased temperatures, CPB developed faster at Ulm than at Potsdam (by 3 days). A similar situation was noticed while comparing the development of CPB in Poland at Toruń (46 m. a. s. l.) and Kielce (270 m. a. s. l.). Using real data, development of CPB first generation at Toruń was 5 days shorter than at Kielce, while under transformed data and depending on the RCP scenario at Toruń development was 2–3 days longer than at Kielce.

The results of this study clearly indicate not only increased rates of CPB development following expected climate change across Poland, but also the regions exposed to the most rapid changes in the number of pest generations. But, one has to be aware that the interaction among the environmental factors is very complex and changeable. Most insect pests can adapt to a wide range of environments through selection and evolution. Therefore, prediction based on factor-limited simulations produce results with limited accuracy. On the other hand, only simulations can aid a rapid investigation of the effects of a change in a real life situation that will take place in the future over several years. From simulation results, a problem expected in the future can be mitigated now. So, systematic monitoring of potato crops in the regions indicated in the present study as the most threatened by the appearance of additional generations of CPB should be our first priority. Knowledge about pest trends gained in simulations coupled with results of field monitoring allows the determination of the feasibility of using certain pest management strategies.

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