POTENTIAL IMPACTS OF CLIMATE CHANGE ON DAMAGING FROST DURING GROWING SEASON OF VEGETABLES*

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This study has, for the first time, analyzed the potential impacts of climate change on damaging frost during growing season of vegetable crops at a high horizontal resolution of 10 × 10 km in the Bohemian Plateau. The main objective of this study was to assess the potential changes in the timing of the last spring frost, the first autumn frost for three frost severities (mild, moderate, and severe), and the length of the frost-free period during growing season of vegetables based on the regional climate model ALADIN-Climate/CZ simulated data. The daily minimum air temperature from 116 grid points throughout the studied area for the current (1961–2000) and two future climates under A1B SRES scenario (2021–2050 and 2071–2100) was used. The projections suggest that during the mid-21st century, the dates of the last spring frost will end on an earlier date (by ≥ 12 days) and the first frost date in the autumn will be delayed to a later date (by ≥ 18 days) across the Bohemian Plateau. Under the A1B scenario the frost-free period will be extended by ≥ 35 days compared with the current climate. Projected future climate conditions could result in significant shifts in the median of the last spring frost and the first autumn frost to earlier and later dates, respectively, relative to the current climate.

spring frost; autumn frost; Elbe River lowland; ALADIN-Climate/CZ

INTRODUCTION

Future climate change is projected to increase the lenght of the growing season.. Numerous studies have revealed that the already significant impact on the agricultural system is associated with the 20th century warming (Hughes, 2000; Chmielewski, Rotzer, 2002; Solomon et al., 2007; Lobell, Burke, 2008; Olesena et al., 2011). The global temperature increase by 1.4–5.8°C in the next century will most certainly have large consequences, when some crops will benefit from a warmer and longer growing season, while others will disappear (Rosenzweig et al., 2007). A study in Germany (Menzel et al., 2003) has revealed that between 1951 and 2004 the advance for field agricultural crops (2.1 days/decade) was significantly less marked than for fruit trees (4.4–7.1 days/decade). All the reported studies concern Europe, where recent warming has clearly advanced a significant part of the agricultural calendar. Increased temperatures, associated with earlier last spring frost and delayed autumn frost dates, are clearly apparent in temperate regions of Europe (Chmielewski, Rotzer, 2002; Menzel et al., 2003; Rosenzweig et al., 2007; Scheifinger et al., 2003).

The accelerated rates of change observed in the past three decades indicate that 'in a near future we will see large changes in ecosystems; latitudinal/altitudinal extension of species' range boundaries by establishment of new local populations and, consequently, extinction of low latitude/altitude populations; increasing invasion of opportunistic, weedy and/or highly mobile species; progressive decoupling of species interaction (e.g. plants and pollinators) because of out-of-phase phenology' (Hughes, 2000). The consequences of climate changes for the modern agriculture will depend on three main factors. The first is the nature of the climate change itself. The second key factor is the response of cropping systems to changes in climate and atmospheric constituents such as carbon dioxide (CO_2) and ozone (O_3). The third factor will be the response of agriculture to changes in cropping

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systems throughout the world (Lobell, Burke; 2008). As a result of climate change, breeding new and improved vegetable crop varieties can lead to extending border areas suitable for profitable cultivation of vegetables. Intensive farming systems in Central Europe are generally less sensitive to climate change than those in south-eastern Europe. For example, Romania and Moldova lie in a transition region for the changing of precipitation pattern; projected changes of seasonal temperature and precipitation show warmer and wetter winters and hotter and drier summers and autumns which would likely induce extreme humidity deficit in the growing season (Potop et al., 2012c).

The two important field vegetable regions in the Czech Republic are South Moravia and the Elbe River lowlands, in which partially different assortments of vegetables are grown. The Elbe River lowland has traditionally been a region of cultivation of brassica vegetables, while South Moravia is a profitable region for thermophilic vegetables. These differences in the assortments of cultivated vegetables grown in the two regions are mainly due to differences in the temperature conditions of these regions. In the warmest parts of the Elbe River lowland, growing thermophilic vegetables such as tomatoes (*Solanum lycopersicum* L.) and cucumbers (*Cucumis sativus* L.) is profitable only in warmer years (Potop et al., 2012 a). The combination of changes in European agricultural commodities and ongoing climate changes (increases in temperatures) can lead to higher costs for vegetable imports and stricter requirements for the maturity and quality of yields. In addition, favourable national agricultural policies could extend the areas suitable for growing thermophilic field vegetables from the hottest regions of South Moravia to the Elbe region. In addition to the current assortment of vegetables grown, non-traditional vegetables such as melons (*Cucumis melo* L.) and eggplants (*Solanum melongena* L.) could also be grown.

There were two objectives in this study: (*i*) to assess the potential changes in the date of the last spring frost (LSF), the first autumn frost (FAF) for three frost severities (mild, moderate, and severe), and the length of the frost-free period (FFP) during the growing season of vegetable crops in the Bohemian Plateau based on the regional climate model ALADIN-Climate/CZ simulated data; and (*ii*) to identify the optimum areas for growing thermophilic vegetables based on climate projections of regional climate model in the Elbe River basin.

MATERIAL AND METHODS

The Elbe River lowland is a traditional designation of the lowlands region located in the Bohemian Plateau. The analysis was performed throughout the Bohemian Plateau with regard to a possible extension of vegetables growing outside the traditional area of the Elbe River lowland. The Bohemian Plateau is constituted by tablelands, valleys, and hills. Vegetable growing areas are found in all of these landforms with regard to the climatic requirements of particular vegetables (thermophilic, cold-resistant, and frost-resistant). As an example can be mentioned areas with a widespread cultivation of cabbage (*Brassica oleracea* L.) on the border of the Jičín Upland and the East Bohemian Plateau. In the Bohemian Plateau, the mean long-term annual precipitation total (1961–2000) was 591.6 mm compared with the 674 mm average for the entire territory of the Czech Republic. In the growing season, the mean precipitation totals are 365 mm. The annual mean temperature in the region of the Bohemian Plateau is 8.4°C while the whole-country annual mean is 7.5°C (Potop et al., 2013a). Mean temperature during the growing season is 14.5°C.

The station network in the Bohemian Plateau has significantly fewer units located primarily in non-agricultural areas, and their data series are not complete. Thereby, a regular gridded network (CZGRIDS, ALADIN-Climate/CZ) established by the Czech Hydrometeorological Institute (CHMI) was applied. High-density gridded datasets allow very precise and detailed delimitation of the area in which frosts occur in comparison with the station network datasets. The study was based on gridded daily series of minimum air temperature data at a 10-km horizontal resolution for observed (1961–2000) and future (2021–2050 and 2071–2100) climate conditions.

Frost-free period indicators were determined using the inclusive threshold of 0°C for daily minimum temperature from 116 grid points throughout the studied area for the current (1961–2000) and two future (2021–2050 and 2071–2100) climates under A1B SRES scenario. These indicators include the frost-free period length, the first autumn occurrence of frost, and the last spring occurrence of frost. The LSF day is defined as the last date in a year on or before July 15th on which the daily minimum temperature $T_{min} \leq 0°C$. The FAF day is defined as the first date in a year on or after July 16th on which $T_{min} \leq 0°C$. The FFP is the number of days between the LSF and the FAF. The daily values of minimum air temperature ranges of 0°C to −1.1°C, −1.2°C to −2.2°C, and below −2.2°C were considered to constitute mild, moderate, and severe frost intensities, respectively (Potop et al., 2014b). Using these definitions, the last three spring and first three autumn frosts were specified for the spring and autumn of each year.

In the present study, the regional climate model (RCM) ALADIN-Climate/CZ was adopted to assess and project risk level of the last spring frost (first autumn frost) and the length of the frost-free period during growing season of vegetable crops under future climates (2021–2050 and 2071–2100) in the Bohemian Plateau. High resolution climate model simulations

Table 1. Observed dates[1] of the last spring frosts and the first autumn frosts for three frost severities and the length of frost-free period for current climate (1961–2000)

	Last mild spring frost	Last moderate spring frost	Last severe spring frost	First mild autumn frost	First moderate autumn frost	First severe frost	Frost-free period (days)
Median	113	104	99	292	301	306	178
STDev	10	10	11	10	11	14	16
Earliest	91	87	76	269	280	282	143
Latest	133	128	121	310	333	334	217

[1]corresponding serial numbers of the calendar days

STDev = standard deviation

are thus needed to provide accurate climate change scenarios accounting for this complex spatial and temporal modulation of the climate change signal. This Czech regional climate model has been shown to compare well with other RCMs in impact studies (F a r d a et al., 2007). However, it should be always kept in mind that model simulations of future climate are affected by many uncertainties, and it is necessary to apply some type of post-processing of model outputs from the RCM simulation before using the results in other applications.

First, the observed data of air minimum temperature was transferred into a regular grid of ALADIN-Climate/CZ model. The ALADIN-Climate/CZ simulations forced with the ARPEGE global circulation model (GCM) have been corrected against the systematic errors induced by the GCM. The bias correction was applied on the scenario runs. The bias correction method is based on variable correction using individual percentiles whose relationship is derived from observations and the control RCM simulation (D e q u é, 2007; Š t ě p á n e k et al., 2008). After the correction, the model outputs (2021–2050 and 2071–2100) are fully compatible with gridded observation dataset (1961–2000). The gridding and all data processing including the presented analysis were done using the ProClimDB (Version 8.6, 2010) database software for processing of climatological datasets (http://www.climahom.eu/ProcData.html). More details on quality control and homogenization procedures are provided in Š t ě p á n e k et al. (2011).

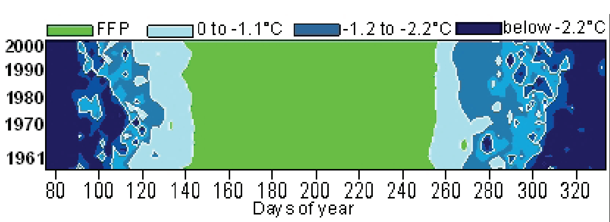

Fig. 1. Hovmoller-type diagram of the spatiotemporal evolution of date of the last spring and the first autumn frosts for various severities and the length of the frost-free period (FFP) derived from minimum temperature at 116 grid-points x 40 years x 365 days of year in Bohemian plateau (1961–2000)

RESULTS

Observed changes in dates of occurrence of the last spring frosts, the first autumn frosts, and the length of the frost-free period under current climate (1961–2000)

The observed median, standard deviation, latest and earliest occurrence of the LSF and the FAF, and length of the FFP for current climate (1961–2000) are given in Table 1. The mean date of occurrence of the last mild spring frosts in the region of the Bohemian Plateau is on day 113 (23^{rd} April). The mean dates of the last spring frost with moderate and severe intensity were April 14^{th} and April 9^{th}, respectively. The earliest last mild, moderate, and severe spring frosts occurred on day 91(April 1^{st}), 87 (March 28^{th}), and 76 (March 17^{th}), respectively. The latest mild frosts occurred on day 133 (May 13^{th}). According to these results, the highest risk for field vegetables is the late spring frost. The mean dates of occurrence of the first mild, moderate, and severe autumn frosts were days 292 (October 19^{th}), 301 (October 28^{th}), and 306 (November 2^{nd}), respectively. The earliest first mild autumn frosts occurred on September 26^{th} and their latest onset was registered on November 6^{th}. Frosts with a higher intensity occurred later, and the earliest onsets of moderate and severe frosts were on October 7^{th} and 9^{th}, respectively, whereas the latest onsets of moderate and severe frosts appeared by the end of the autumn season – on November 29^{th} and 30^{th}, respectively. In the studied region, there were years with a possible extension of the growing season for frost-resistant vegetables, allowing distribution of the harvest. According to Table 1, the average length of the FFP in the studied area ranged from 143 to 217 days. The average length of the frost-free period was 178 days, i.e. almost a half of the year.

The Hovmoller-type diagram provides a visualization of the spatiotemporal evolution of dates of the last spring and the first autumn frosts for various severities and the length of the frost-free period over the entire region in 1961–2000 (Fig. 1). The severe spring frosts in the period of 1981–2000 ended earlier than in the

Table 2. Projections of the dates[1] of the last spring frosts and the first autumn frosts for three frost severities and the length of frost-free period for two future climates over the Bohemian Plateau

	Last mild spring frost	Last moderate spring frost	Last severe spring frost	First mild autumn frost	First moderate autumn frost	First severe autumn frost	Frost-free period (days)
2021–2050 (A1B scenario run)							
Median	99	90	87	313	322	324	213
STDev	7	7	9	11	13	14	13
Earliest	82	76	72	283	290	293	173
Latest	111	103	100	332	347	354	239
2071–2100 (A1B scenario run)							
Median	88	76	73	317	326	327	228
STDev	11	13	17	12	11	13	16
Earliest	65	48	31	300	308	309	201
Latest	106	102	99	344	352	353	271

[1]corresponding serial numbers of the calendar days

STDev = standard deviation

period of 1961–1980; consequently, the end of the 20th and the beginning of the 21st century is a suitable period for the growth extension of vegetable species and varieties with longer growing seasons and higher demands on temperature. Lengthening of the frost-free period could result in earlier planting of vegetables, ensuring maturation and allowing the possibility of multiple cropping. The extension of the FFP mainly in the Elbe River lowland region may also greatly reduce the frost risks to vegetable crops and bring economic benefits to Czech agricultural producers. However, our regional average frost date series suggests that the frost-free period exhibits a large amount of inter-annual variability, and it is also apparent that on the region's average the frost-free period has lengthened over the preceding two decades.

Temporal variability of the projection of the LSF, FAF, and FFP

The projected dates of the last spring and the first autumn frosts for three frost severities (mild, moderate, and severe) and the length of frost-free period for two future climates (2021–2050 and 2071–2100) over the Bohemian Plateau are presented in Table 2. Under future climates, for the entire study region dates of LSF are projected to advance significantly (i.e. occur earlier) than under the current climate conditions. Under the A1B scenario, in the mid-21st-century period the median of the last mild spring frost is projected to advance to day 99. At the end of the 21st century, the median of the last mild spring frost is projected to advance significantly to day 88. The latest mild frosts are projected to occur on day 111 during 2021–2050 and on day 106 during the period 2071–2100.

In general, the FAF is projected to be significantly delayed (i.e. occur later) under the climate change scenario compared with the current climate. Under the A1B scenario for the period 2021–2050, the earliest date of the first mild autumn frost onset is projected to day 283. Our regional projections for the end of the 21st century indicate that the earliest date of the first mild autumn frosts could be significantly delayed. It is worth noting that the earlier end of spring, together with the late onset of autumn frosts provides suitable conditions for sowing/planting field vegetables, as well as their ripening and harvesting. The late onset of autumn frosts extends the growing season of field vegetables. ALADIN-Climate/CZ simulation projected increases of the length of the frost-free period (Table 2). Under A1B scenario, the shortest and the longest frost-free period varies between 173 and 239 days for the period 2021–2050 and between 201 and 271 days for the period 2071–2100.

Table 3 displays the predicted changes in dates of spring and autumn frosts for three frost severities (mild, moderate, and severe) and the length of frost-free period for two future (2021–2050 and 2071–2100) climates over the Bohemian Plateau. The projections suggest that during the mid-21st century, the last spring frost will end on an earlier date (by ≥ 12 days) and the onset of the first frost date in the autumn will be delayed (by ≥ 18 days) across the Bohemian Plateau (Table 3). Consequently, under the A1B scenario the FFP will be increased by ≥ 35 days compared with the current climate. The advance of the last mild, moderate, and severe spring frosts will be greater at the end of the 21st century (by ≥ 25 days). The ALADIN-Climate/CZ simulation for the period 2070–2100 also projects delays in the first mild, moderate, and severe autumn frosts (by ≥ 21 days). The last mild spring frost will be advanced by 25 days and the first mild autumn frost will be delayed by 25 days in the period 2071–2100. Therefore, the A1B scenario results in a

Table 3. Changes in dates of spring and autumn frosts for three frost severities (mild, moderate, and severe) and the length of frost-free period for two future climates over the Bohemian Plateau (in days)

Climate period	Last mild spring frost	Last moderate spring frost	Last severe spring frost	First mild autumn frost	First moderate autumn frost	First severe autumn frost	Frost-free period
2021–2050	advance 14	advance 14	advance 12	delay 21	delay 21	delay 18	increase 35
2071–2100	advance 25	advance 28	advance 26	delay 25	delay 25	delay 21	increase 50

projected lenghtening of the FFP by 50 days on average compared with the current climate.Our results show that under the A1B scenario the increased FFP was foremost due to the significantly delayed first autumn frost during the period 2021 to 2050. In contrast, for the 2071 to 2100 period, the increase of FFP was due to almost equal changes in spring and autumn frosts. These results agree with other studies conducted at a European scale (e.g. Rosenzweig et al., 2007).

Risk level of the last spring frost (first autumn frost) that occurs after (before) the average date of the last spring frost (first autumn frost) under current and future climates

The aim here is to identify the risk level of LSF (FAF) after (before) the average date of LSF (FAF) during the growing season of vegetables under current (1961–2000) and two future climates (2021–2050 and 2071–2100) in the Bohemian Plateau. The LSF can dictate sowing/planting dates whereas the FAF determines the length of the harvest period and quality of vegetable yields. These dates are also utilized to guide farmers in determining when certain vegetables can be planted directly in fields. A wide assortment of vegetables grown in the studied region has been divided into three basic vegetable types according to their sensitivity to low temperatures: thermophilic (heavy damage to plants at all development stages), cold-resistant (plants can tolerate a short period of temperature decreasing slightly below 0°C), and frost-resistant (plants can tolerate frost exceeding –2.2°C depending on the development stage) (CAgM Report No. 75, 1997; Petříková, Malý, 2003). Table 4 shows the level of risk of the frost damage to vegetables for various severity under current (1961–2000) and two future (2021–2050 and 2071–2100) climates. The level of risk is related to the percentage of LSF (FAF) that occurs after (before) the average date of LSF (FAF). According to the per cent values for frost occurrences, four types of frost risk sowing/planting (harvesting) dates were defined: low (2%), moderate (20%), high (30%), and critical (40%). This information can be also used for risk analyses by decision markers.

From an agronomic point of view, thermophilic vegetables (e.g. tomato, pepper, pumpkins, and cucumber) should be planted before May 15th, considering the risk. The critical temperature after May

Table 4. Projected level risk of the last spring frost (first autumn frost) that occurs after (before) the average date of the last spring frost (first autumn frost) under current and future climates

Risk level	Last mild spring frost	Last moderate spring frost	Last severe spring frost	First mild autumn frost	First moderate autumn frost	First severe autumn frost
1961–2000 (current climate)						
Low	May 15	May 8	May 6	September 25	October 2	October 20
Moderate	May 4	April 23	April 19	October 10	October 19	October 23
High	April 29	April 18	April 15	October 14	October 23	October 28
Critical	April 26	April 17	April 12	October 16	October 26	October 31
2021–2050 (A1B scenario run)						
Low	April 24	April 15	April 14	October 15	October 19	October 25
Moderate	April 15	April 6	April 5	October 31	November 7	November 9
High	April 13	April 4	April 3	4 Nov	November 11	November 13
Critical	April 11	April 2	April 1	7 Nov	November 14	November 16
2071–2100 (A1B scenario run)						
Low	April 20	April 12	April 10	October 17	October 24	October 26
Moderate	April 7	March 28	March 26	November 4	November 12	November 14
High	April 4	March 23	March 21	November 7	November 16	November 18
Critical	April 1	March 19	March 17	November 10	November 19	November 22

15th for thermophilic vegetables is $T_{min} \leq -0.1$°C (Petříková, Malý, 2003). In the current climate, mild frost damages after May 15th are low (only 2%). The moderate and severe frost in spring corresponds to the low risk on or later date than May 5th and May 2nd, respectively (Table 4). Under the projected future climates, date of the low risk of the last frosts will be significantly shifted to an earlier date (to the second half of April). The earlier ending of spring frosts allows earlier planting mainly of thermophilic vegetables. Moderate frost risk in the spring corresponds to 20% of damaged plantings of field vegetables. In the current climate, there is a planting date with moderate risk on May 4th or later for thermophilic vegetables, on April 23rd for cold-resistant vegetables (e.g. early kohlrabi, summer savoy cabbage, late cauliflower, late cabbage, late carrots, and celeriac), and on April 19th for frost-resistant vegetables (e.g. onion, root parsley). At the end of the 21st century, these dates will advance on April 7th, March 28th, and March 26th, respectively. The high and critical frost risks are already the limit factor for farmers due to mainly re-cultivated planting, which threatens high economic losses. The high risk of frost damage for planting of thermophilic field vegetables can be after April 29th in the current climate, and under the A1B scenario after April 13th (2021–2050) and April 4th (2071–2100). The end of the harvest season of thermophilic vegetables is given by the occurrences of the first mild autumn frosts. Over the period 1961–2000, the risk level of the first mild autumn frost before September 25th and October 10th was low to moderate, respectively (Table 4).

Observed and projected changes in spatial variability of LSF, FAF, and FFP

The aim here is to determine the optimum areas for growing thermophilic vegetables based on climate projections of regional climate model in the Elbe River basin. Combining the outputs of RCM with GIS-interpolation tools was used to create maps of spatial distribution of frost events during growing season of vegetable crops at the regional level. The patterns of spatial distribution of observed and projected dates of the last spring frosts and the first autumn frosts and the length of frost-free period for current climate (1961–2000) and two future climates (2021–2050 and 2071–2100) over the Bohemian Plateau are presented in Fig. 2. Under 1961–2000 climate condition, the sequence of these maps shows three basic regions of the length of the frost-free period (top panel of Fig. 2). The first region, with the longest FFP duration (over 184 days), is located on the north-eastern Prague plateau and is connected to the warmest areas of the middle Elbe River valley. Furthermore, this area shifts towards the middle Ohře River region in the western part of the Bohemian Plateau. The second region, with a moderate length of the frost-free period (170–184 days), is a contiguous area in the central part of the Elbe River basin stretching from Mladá Boleslav through the Orlická plateau to the Svitavy Upland. The third region, with the shortest FFP, is the transition area between the frost hollows of Kokořín and the Ralské hory hills, where the lowland relief of the Elbe River basin passes into the northern elevations of the Bohemian Plateau. This area, in conjunction with the Svitavy Upland (eastern part), has the shortest growing season.

Under projected future climates, for the period 2021–2050, the frost-free period will get significantly longer. A climate warming scenario suggests lengthening of the FFP in the coldest areas of the study region to the level of the warmest areas under the current climate (map of top panel of Fig. 2). Most of the territory of the Bohemian Plateau will have the frost-free period longer than 208 days, which meets the requirement of the most perspective thermophilic vegetables on the length of the growing season. At the end of 21st century, the area with suitable condition for growing vegetables (low frost risk) will be shifted from lowlands of the Elbe River valley to higher elevations of the Bohemian Plateau (top panel of Fig. 2). However, profitable cultivation of vegetables in these areas is complicated by the complex sloping terrain. Therefore, the shift of areas with longer FFP from lowlands to higher elevations could lead to higher potential agroclimatic productivity, which will, however, be difficult to utilize due to the lack of water resources for irrigation and the inaccessibility of these areas to machinery.

The ending of the last spring frost in the current climate, evaluated as an areal average for the period 1961–2000, varies between April 12th and May 10th in the Elbe River basin (map of mid panel of Fig. 2). In the warmest areas of the middle Elbe River lowland, middle Poohří region, and north-east of the Prague platform, the mean date of ending of the last spring frost occurred by April 21st. Conversely, in the hilly lands of northern and eastern part of the Bohemian Plateau, the ending of the last spring frosts shifted to the first third of May. In the future climate, for period 2021–2050, the last spring frost can occur by April 15th over an area of 80% of the Bohemian Plateau, while in the coldest areas by April 20th. The May frosts will likely be sporadic. By the end of the 21st century, the end of the last spring frost in the hottest areas will be shifted to the second half of March. North-east of the Prague platform through the middle Elbe River lowland towards the southern Jičín Upland an area of early termination of spring frosts (up to March 24th) will appear. Nowadays, this area serves for growing of the most important field vegetables in the Elbe River lowland. The last spring frost will be over till the end of March, which corresponds to the currently peripheral areas of vegetable farmland (Nymburk, Pardubice, and Hradec Králové).

According to the ALADIN-Climate/CZ simulation, the significant magnitude of changes in the first autumn frosts onset will be recorded mostly in hilly areas. A similar tendency, but less pronounced changes of the onset of FAF in the lowland areas, is evident from the map of middle panel (Fig. 2). At the end of the 21st century two main areas with different onset of early autumn frosts will be profiled. The late onset of FAF in the second half of November will traditionally occur in the middle Elbe River lowland and also in a newly formed region around Hradec Králové, whereas in the NW and SE of the Bohemian Plateau the first autumn frosts will start in the first half of November.

The sequence of the maps given in Fig. 2 shows shift areas with early termination of the last spring frost, delayed onset of the first autumn frosts, and the lengthening of the frost-free period east of the Prague plateau toward the middle Elbe River lowland. The terrain of the Východolabská and the Orlická plateaus is mostly flat and the projections suggest a possible expansion of potential agricultural lands for growing vegetable crops. This area can be climatically close to optimum for vegetables production. On the contrary, the rugged topography of the north of the Bohemian Plateau (Severočeská plateau) does not indicate, despite optimal temperature conditions, a suitable area for the production of vegetables, mainly with regard to the non-availability of water resources for irrigation systems. As apparent from Fig. 2, profitable area for vegetables cultivation will be significantly extended from the middle Elbe River lowland towards the eastern part of the Bohemian Plateau. Damaging frosts are an important constraint to vegetables production in this region and the rising temperatures are predicted to have significant effects on LSF, FAF, and FFP. LSF is expected to occur earlier while FAF is expected to start later over the entire region. As a result, FFP is anticipated to become longer.

DISCUSSION

There has been little research on the impacts of climate variability on the assortment of field vegetables grown in the Elbe River lowland. This subject continues to be of interest to climatologists, although the

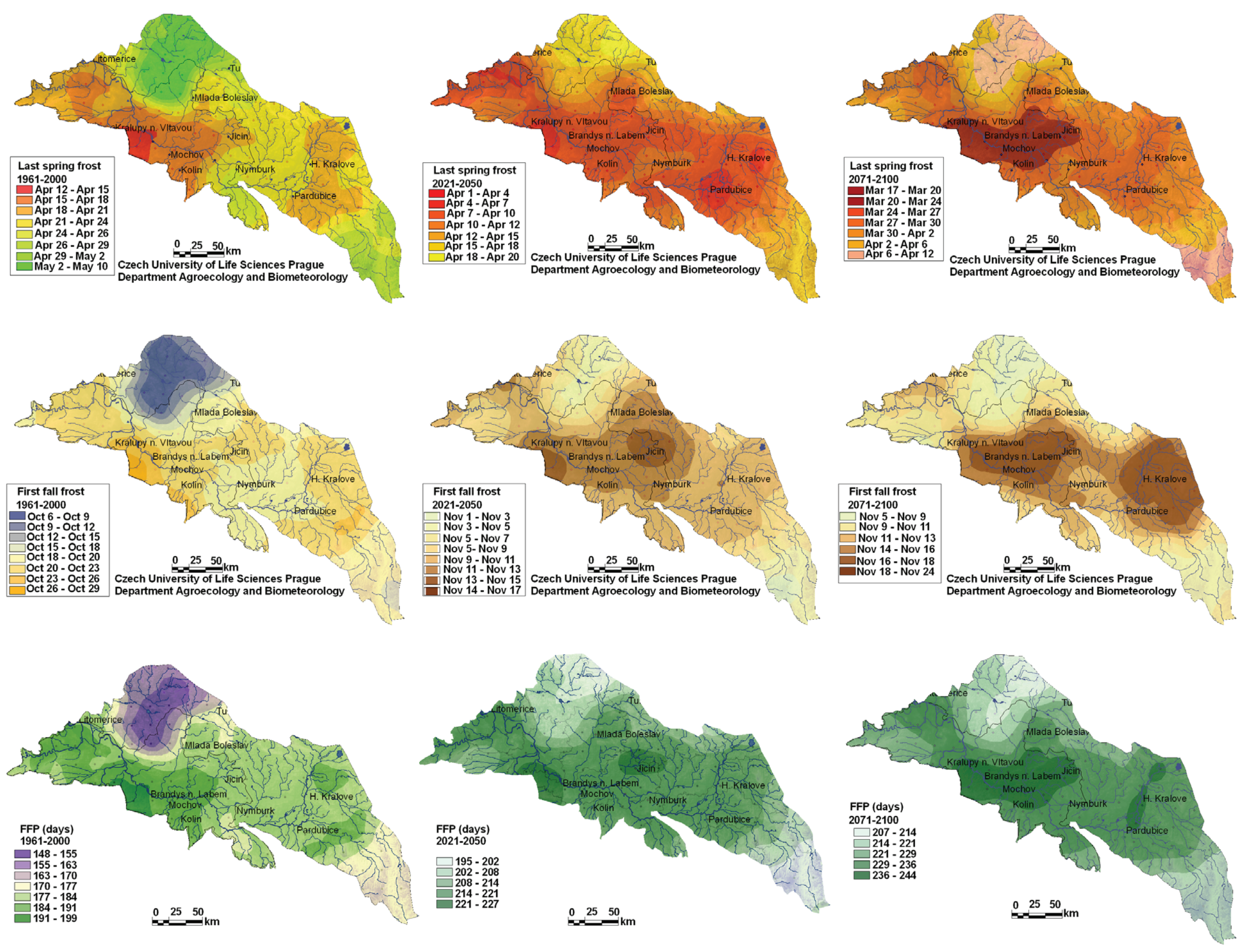

Fig. 2. Observed and projected changes in spatial distribution of the dates of the last spring frost and the first autumn frosts, and the length of frost-free period for current climate (1961–2000) and two future climate projections (2021–2050 and 2071–2100) over Bohemian plateau

range and yield of vegetable crops grown in the Czech Republic are primarily determined by temperature (Potop et al., 2014a-b). New detailed results on the temporal evolution of the meteorological extreme events in the Elbe River basin were discussed (Potop 2010; Potop et al., 2011, 2012a, b; Potop, 2013; Potop et al., 2013 a–c). However, more in-depth analysis is required to explore the vulnerability to frost events in the context of climate change based on a denser gridded network to better represent various climate conditions across the Elbe River basin. The main objective of this study is to evaluate the effect of climate change on the risk for spring and autumn frosts damage during growing season of vegetables using both gridded observed data and RCM projections. We try to assess potential changes in timing of the LSF, FAF, and FFP in the Bohemian Plateau as simulated using the regional climate model ALADIN-Climate/CZ under the A1B SRES scenario (for the periods 2021–2050 and 2071–2100). The model was developed at the CHMI and has become the standard RCM for climate impact studies in the Czech Republic. The A1B SRES scenario is a baseline scenario referred to in Solomon et al. (2007). The A1B emission scenario describes a world of rapid economic growth, global population that peaks in mid-century, and more efficient technologies based on balanced energy mix. The regional climate model ALADIN-Climate/CZ is able to capture the main features of the present climate of the Czech Republic (Farda et al., 2007) and works well over smaller areas with rather complex orography (tablelands, valleys, and hills), such as the Elbe River basin. In our future work, we plan to compare the ALADIN-Climate/CZ simulation of the LSF, FAF, and FFP to simulations conducted using other RCMs. This will lead to improved quality in projections of regional frost events.

The future projections of this study support the hypothesis that climatic warming can decrease the risk of frost damage during the growing season. Changes in the timing of frost events and in the minimum temperatures are important measures for characterizing the overall risk of damage. The positive effects of increased warmth and frost-free period length can lead to increased vegetable production, however, adaptation to current vegetable management regimes is likely to be required to reduce the risk of damage caused by extreme weather events (Potop et al., 2012). Many kinds of thermophilic vegetable are susceptible to later spring frost. A climatic warming will advance the date of the last spring frosts and the risk of damage to vegetables caused by later spring frosts is likely to decrease. However, problems with pests and diseases may arise very easily. Notable changes towards earlier sowing dates are expected in order to avoid hot and dry periods during the summer and to use as much of winter precipitation as possible. The anticipation of large shifts in timing of cultivation is probably enhanced by a pronounced prolongation of the growing season that will allow introduction of longer duration cultivars (Olesena et al., 2011).

Overall, the Bohemian Plateau has experienced a decrease in the number of frost days, while the frost-free period between the last spring frost and the first autumn frost has lengthened (Potop et al., 2013b, c). Our previous regional results (Potop et al., 2013e) have demonstrated the last spring frosts have shifted to an earlier date, the first frost date in the autumn has been delayed to a later date, and the frost-free period has been prolonged. These results corroborate other research, indicating that spring frost is a critical period for detecting recent climatic changes and their impacts (Menzel et al., 2003; Scheifinger et al., 2003). Moreover, earlier spring events and a longer growing season in Europe are most apparent for time-series ending in the mid-1980s or later (Chmielewski, Rotzer, 2002). We may conclude that the general warming trend of the past several decades in the Elbe River region resulted in an advance in spring planting date of vegetables. This affirmation was also confirmed by our experimental results on the vegetable-field scale (Potop, Možný, 2011; Potop et al., 2012a).

According to Trnka et al. (2009) the combination of increased air temperature and changes in the amount and annual cycle of precipitation will obviously lead to further shifts as concerns the area and location of the individual agro-climatic zones in Central Europe. In agreement with observed and projected regional datasets, the last spring frosts were of earlier dates, especially in the middle Elbe River valley, and the first autumn frosts started later (especially in the region between Kolín and Kralupy nad Vltavou), which resulted in the prolongation of the frost-free period.

CONCLUSION

This study has, for the first time, analyzed in detail the potential impacts of climate change on damaging frosts during the growing season of vegetable crops at a high horizontal resolution of 10 × 10 km in the Bohemian Plateau. According to the regional frost-maps for current climate, the risk level of frost after May 10th in the traditional vegetable growing areas (up to 250 m a.s.l.) is low. At higher altitudes (251–300 m a.s.l.), areas with zero incidences of negative temperatures were found, which may allow for the possible expansion of thermophilic vegetable growing. The high risks after May 10th are related to high altitudes in the region (Svitavy, Doksy, Jičín Uplands) and frost hollows (Mělník basin).

For the observed period (1961–2000), the lengthening of the FFP is attributed mainly to the advance of the LSF rather than to delay in the FAF. Under the A1B scenario, during the mid-21st century, the prolongation of the FFP is attributable mainly to the delay of the first frost in autumn rather than to the advance of the last frost in spring. Conversely, for the period 2071–2100, changes in spring and autumn frosts will be almost equal. The FFP is projected to lengthen considerably by the end of the 21st century compared with the mid-21st century and the current climate (1961–2000). Projected future climate conditions could result in significant shifts in the median of LSF and FAF to earlier and later dates, respectively, relative to the current climate.

According to ALADIN-Climate/CZ simulation, the most significant shifts in the date of beginning of the first autumn frosts in the hilly areas are projected. The prolongation of the frost-free period and the flat topography of the Východolabská and Orlická plateaus will create favourable conditions for the extension of vegetables areas, mainly towards the eastern part of the Elbe River basin. The results also suggest a potential for the northerly expansion of vegetables cultivation, although most of the lands to the north of the current frontier will remain due to their complex terrain only marginally suitable for growing field vegetables. We may conclude, in agreement with recent and current studies, that the Bohemian Plateau may become a major producer of a large assortment of vegetables in the Czech Republic and significantly increase its competitiveness in the production of market vegetables.

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