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A 200-year climate record in Central Europe: implications for agriculture

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Abstract The close links of climate, soil conditions, and agricultural productivity have been used in Central Europe for taxation purposes since the eighteenth century. Since agroclimatic conditions are variable, their fluctuations in the past centuries can provide a valuable context for analyzing changes expected in the coming decades. Here, historical agroclimatic conditions and future projections were constructed for key agricultural regions in Central Europe. The agroclimatic zoning method used in this study incorporates (1) the sum of temperatures for days with a mean temperature above 10°C during the frost-free period,

(2) the water deficit during the summer period from June to August, defined as the difference between precipitation and reference evapotranspiration, and (3) information regarding the suitability of soil and terrain for agriculture production based on twentieth century soil surveys. Changes in selected agroclimatological indices were also analyzed. To produce a weather series representing climate conditions between 1803 and 2008 over the study area, we used a stochastic weather generator trained on high-quality daily observations from 52 representative meteorological stations during the baseline period from 1961 to 1990. To estimate the extent of agroclimatic zones and the values of selected agroclimatic indices, the parameters of the weather generator were perturbed by the deviations of the temperature and precipitation means from the baseline using a long-term climate series from 1803 to 2008, from Brno. To generate a weather series representing the climate in 2050, we used an approach known as “pattern-scaling” in combination with outputs of three general circulation models. To our knowledge, this is the first study analyzing both continuous fluctuations in agroclimatic conditions over the past 200 years and expected shifts in the coming decades over Central Europe.

In the study region, our results demonstrate that changes in climate factors since the second half of the twentieth century have favored the expansion of warmer and drier agroclimatic conditions in the most fertile areas, progressively endangering the sustainability of rain-fed agriculture. Conversely, the agroclimatic conditions of regions at higher elevations have improved over the past six decades, as witnessed by increases in maize production areas but also an influx of previously absent pests, e.g., the European corn borer. The length of the vegetation summer has been increasing and shows daily average temperature exceeding 15°C. The mean number of days with snow cover has decreased by up to 30 days since a peak in the late

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nineteenth century. In lowland areas, the date of the last frost, with a 20-year return period, has moved closer to beginning of the season. Our results show that the predicted rate of change is unprecedented in available agroclimatic records; thus, adaptation cannot rely on past. Consequently, agricultural producers in the region will be forced to significantly bolster their adaptive capacity and develop flexible procedures that reflect the rapidly changing agroclimatic conditions.

Keywords Agroclimatic zoning · Climate reconstruction · Climate variability · Drought stress · Growing season

1 Introduction

The overall climatic conditions provide a general context for agriculture production and determine, to a large extent, the type of agricultural systems and growing conditions, including direct and indirect impacts on crop yield potentials, in a given region. Plant growth and development are related to environmental conditions through a combination of linear and nonlinear responses. Even processes for which the general response is linear are susceptible to conditions that can influence the rate of the process, e.g., the decreased speed of leaf expansion or the decreased rate of growth in most C_3 crops when the air temperature is above a certain threshold (Porter and Gawith 1999). The influence of climatic factors extends beyond the conditions in a given year or season because the climate tends to exert a major influence on other indirect drivers related to crop yield potentials at the regional scale (e.g., weed and pest pressure, soil evolution and fertility, soil erosion, prevailing type of land-use or field size). However, because this

influence occurs over decades, centuries or millennia (Klijn and de Haes 1994) and does not fit the standard time frame of traditional agricultural studies, it is typically neglected in analyses.

The close links among climate, soil conditions, and agricultural productivity have been used in Central Europe for taxation purposes since the eighteenth century (Kořistka 1860; Němec 2001). Kořistka (1860) based his zoning on various agroclimatic indicators, including the length of the growing season, water availability, and the occurrence of late or early frosts, and his analysis was subjective and adhered to administrative borders. During this time period, farmers grouped fields into four major classes (16 total) based on the main cereals, wheat, barley, oat, and rye, for which a given field was the most suitable (Červený 1871). In the 1920s, more general zoning schemes covering a wider range of crops, including sugar beet and maize, were introduced; these delineations followed administrative rather than natural boundaries (Dokládál 1947). In the early 1970s, a new concept based on hydrothermal characteristics was applied in former Czechoslovakia (Petr 1991). The Czech Republic was divided into ten areas that provide similar climatic conditions for the production of field crops (Petr 1991; Němec 2001). In this scheme, five agroclimatic zones were defined and named after the most commonly grown crop in the region (Němec 2001). In the present study, the cereal- and potato-growing zones were merged into one category because of overlapping climate parameters (Table 1). The location of a region within a particular agroclimatic zone is a key indicator that determines the official land tax rate for farmers, characterizes the potential productivity of the land and determines the land's market value. A similar concept is used for taxation in Austria (Harlfinger and Knees 1999). While the number (four or

Table 1 Overview of thresholds used for agroclimatic zoning after Němec (2001)

Agroclimatic zone	TS10 (°C) ^a	K _{JJA} (mm) ^b	Annual mean air temperature (°C)	Annual precipitation total (mm)	Prevailing altitude (m a.s.l.)	Prevailing soils (under present climate)	Major crops grown in the zone	Potential productivity (%) ^c
Grain maize-growing	2800–3200	–90 to –180	9–10	450–600	<250	Chernozems, fluvisols	Grain maize, sugar beet, grapes, peaches, apricots, high-quality wheat, malting barley	>82
Sugar beet-growing	2550–2950	–50 to –120	8–9	500–650	250–350	Chernozems, cambisols	Sugar beet, grain maize, grapes, high-quality wheat, malting barley, hops	>84
Cereal- and potato-growing	2150–2700	–100 to +130	5–8.5	550–900	300–650	Cambisols	Cereals, rape, technical crops (growing sugar beet is not profitable)	>56
Forage and grassland	<2150	>–10	5–6	>700	>600	Poor cambisols, gleysols	Potatoes, rye, flax, hay, forage crops	>34

^a TS10 (°C): sum of temperatures in days with mean daily temperature above 10°C

^b K_{JJA}: the water deficit during the period from June to August

^c Productivity as defined by Němec (2001) with 100% being the largest economic return possible

five) and names of the agroclimatic zones are similar for the classification systems used in the study region, the represented spatial patterns are markedly different (e.g., Kořistka 1860; Dokládál 1947; Němec 2001). Some of these differences stem from different methodologies and initial datasets, but they may also be caused by long-term climate variability.

Changing climate conditions over the past few decades have made the basic assumption of agroclimatic zoning, that agroclimatic conditions remain stable in long-term, untenable (Perarnaud et al. 2005). When climate trends are not reflected in updates of agroclimatic zoning, farmers and the environment may suffer negative consequences from the application of potentially biased adaptation measures. Although the risks of using climatically inappropriate fertilization schemes, crop rotations, or cultivars are well known, subtle shifts in agroclimatic zones have rendered many practices obsolete or unsustainable in areas where the same approach would have constituted “good practice” only one generation ago.

One of the aims of the present study was to develop an objective methodology, with scientific merit and policy relevance, that would enable regionalization of a given

study area based on the agroclimatic conditions under past, present and future climate conditions. The proposed methodology was used to assess the degree of variability of agroclimatic conditions in the study region over the past two centuries using nine 25-year periods. The method enabled the reconstruction of past agroclimatic conditions by combining data from a dense network of recently installed climatological stations with global climate data. In addition, the same method can be used to project the extent of agroclimatic zones and thereby compare past changes with those expected during the next few decades.

2 Methods

2.1 Description of the study area

The study area is located in eastern Central Europe in southeast Czech Republic and northeast Austria between 46°34′–50°10′ N and 11°18′–20°13′ E (Fig. 1). It covers 69,163 km² of land, 37,205 and 23,115 km² of which are agricultural and arable lands, respectively. The area includes a wide range of agroclimatic conditions, from the

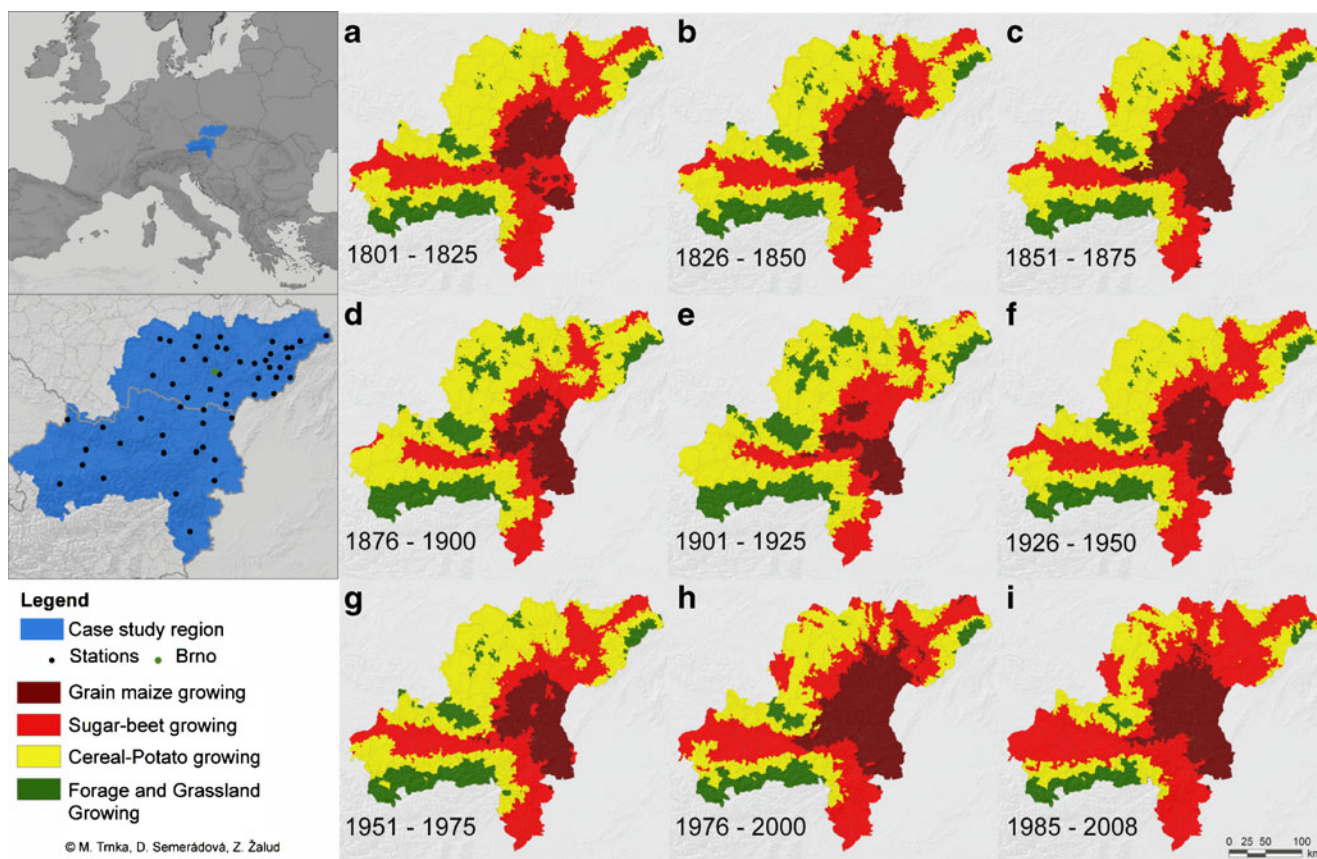


Fig. 1 Study area, climatological stations (*left*) and reconstructed agroclimatic zones for nine periods between 1803 and 2008 (**a–i**), using the thresholds listed in Table 1 and with regionalization of

cadastre units. Grain maize- and sugar beet-growing zones tended to expand at the expense of forage and grassland zone

relatively dry Pannonian Lowland to the comparatively wet highland and mountain regions including the northern-most fringe of Alps. Winter wheat, spring barley, and winter rape dominated production in the Czech Republic, and durum wheat, grain maize, soybeans, and sunflowers were dominant in the warmest parts of Austria. Grasslands prevailed in the highland and mountainous regions in both countries and were found, in particular, at the fringes of the study area. The baseline (1961–1990) climate conditions of the area were obtained from 52 climatological stations, and these data passed quality and homogeneity tests using ProClimDB and AnClim software (Štěpánek et al. 2009). The soil conditions were based on a 1:1,000,000 FAO map of soil types (BMLFW 2007) and complemented by a 1:500,000 soil map of the Czech Republic (Tomášek 2000) and a 1:25,000 soil map of Austria (Murer et al. 2004). The terrain was represented by a digital elevation model derived from the Shuttle Radar Topography Mission (Farr et al. 2007). Study results were interpolated to a 0.5×0.5 km grid and aggregated into cadastre units.

2.2 Reconstruction of regional climates for the period from 1803 to 2008

For most of the twentieth century, observed weather data could be potentially used. However, the density of available data rapidly decreased prior to 1890. To produce a weather series representing past climate conditions for the study area, we applied an approach routinely used in climate change studies (e. g., Trnka et al. 2004). This method is based on the use of the

Met&Roll stochastic weather generator (Dubrovský et al. 2004), which was trained on daily observations from 52 meteorological stations during a baseline period from 1961 to 1990. During this procedure, statistical parameters of the weather generator that captured the properties of observed weather series were obtained for each site. The trained weather generator was then used to produce time series of weather data of an arbitrary length that climatologically resembled the observed series. When the statistical parameters are altered, for example, by modifying monthly temperature means or precipitation totals, series representing different climate conditions are produced. In this study, the weather generator was first perturbed by the deviations of the temperature and precipitation means representing predefined 25-year time periods from the past 200 years (Table 2). To determine the range of values by which the weather generator parameters were perturbed, continuous observations from Brno were used. Temperature measurements, beginning in May 1799, were provided by a pensioned captain, Ferdinand Knittelmayer (Brázdil et al. 2006). Continuous precipitation records, beginning in January 1803, were available from a land accountant, Zachariáš Melzer (Brázdil et al. 2005). These observations, available for more than two centuries in different parts of Brno without significant interruption, facilitated the compilation of qualitatively checked long-term monthly temperature and precipitation series. These series were homogenized in the framework of the HISTALP database to the recent position of the Brno airport station ($49^{\circ}09' \text{ N}$, $16^{\circ}42' \text{ E}$, 241 m a.s.l.), where measurements were available starting in 1958 (Auer et al. 2005). The Brno temperature

Table 2 CO₂ concentration and changes in mean monthly temperatures and precipitation totals as key inputs for the development of daily data series using the pattern-scaling technique

Period	Mean temperature April–September (°C) ^a	Mean precipitation total June–August (mm) ^a	TS10 (°C) ^b	K _{JJA} (mm) ^c	Mean CO ₂ concentration (ppmv) ^d	Area within the given agroclimatic zone (%)			
						Grain and maize-growing	Sugar beet-growing	Cereal- and potato-growing	Forage and grassland
1803–1825	15.1	223	2774	−4	283	15.2	43.1	39.9	1.8
1826–1850	14.9	200	2722	−32	285	24.3	32.2	40.4	3.1
1851–1875	14.8	186	2721	−49	289	26.4	31.1	40.0	2.5
1876–1900	14.8	227	2635	−2	292	16.4	28.2	49.1	6.3
1901–1925	14.5	225	2593	7	300	11.8	27.8	52.0	8.4
1926–1950	15.2	221	2746	−6	307	17.9	38.2	41.5	2.4
1951–1975	15.0	222	2733	−5	320	17.9	37.4	41.6	3.1
1976–2000	15.5	184	2854	−64	346	29.3	42.1	27.3	1.3
1985–2008	16.2	196	3011	−47	365	24.0	56.5	18.9	0.6

The temperature and precipitation changes were with respect to 1975

^a Mean temperatures from April to September and mean precipitation totals from June to August were derived from observations made at the Brno station (1803–2008)

^b Sum of temperatures during days with mean daily temperature above 10°C averaged over all 52 stations included in the study (Fig. 1)

^c K_{JJA}: the water deficit during the period from June to August

^d Carbon dioxide levels for historical periods were based on data provided in MAGICC v. 4.1 model

series was representative of the entire studied region based on the spatially consistent temperature patterns in Central Europe (Dobrovolný et al. 2010). Although spatial precipitation correlations were slightly weaker than those for temperature, Brno was the only representative series available over an extended period in the study area.

2.3 Regional climate change scenarios

One approach used in this study to downscale the low-resolution output from General Circulation Model (GCM) into the spatial and temporal scales required for agroclimatic analysis involves the use of a stochastic weather generator, the parameters of which are calibrated using site-specific weather observations and modified according to GCM-based climate change scenarios. This approach is widely used because of the flexibility of weather generators and the assumption that GCMs reproduce shifts in climatic characteristics more accurately than they reproduce absolute values of individual weather variables.

To produce weather series representing climate change, we used an approach known as “pattern-scaling” (Santer et al. 1990), in which the climate change scenario is defined by the product of a standardized scenario and the change in global mean temperature (Table 3). First, a set of three standardized scenarios that relate responses of climatic characteristics to a 1°C rise in global mean temperature (ΔT_G) were determined using a regression method and three GCMs. These GCMs included ECHAM5/MPI-OM, HadCM3, and NCAR-PCM, denoted as ECHAM, HadCM,

and NCAR, respectively, in this article. Changes in ΔT_G for the year 2050 were calculated with a simple climate model, MAGICC (Hulme et al. 2000), assuming the SRES-A2 emission scenario and high climate sensitivity (i.e., an equilibrium change in the global mean surface temperature of 4.5°C following a doubling of the atmospheric equivalent CO₂ concentration, $\Delta T_{G,2 \times CO_2}$). Then, daily weather series were prepared with a stochastic weather generator and the perturbations listed in Table 3. This approach is virtually the same as the procedure described in section 2.2 for the 1803–2008 period (the difference is that the GCM-based climate change scenarios are now used instead of the climate shifts based on historical observations). Ninety-nine-year simulation runs were performed for all GCMs.

2.4 Agroclimatic zoning and selected agroclimatic indicators

The agroclimatic zoning method used in this study included the following main agroclimatic indicators: (1) temperature sums of all days with a mean temperature above 10°C during the frost-free period of the given year (TS10); (2) the water deficit during the period from June to August (K_{JJA}), calculated as a difference between precipitation and reference evapotranspiration; and (3) information regarding the soil type and slope of the agricultural land. TS10 is a good proxy of growing season duration, and K_{JJA} provides an integrated overview of precipitation and reference evapotranspiration during the summer, the season with the highest water demand. Reference evapotranspiration was

Table 3 Assumed change (Δ) in mean monthly temperature (T_{avg}), precipitation total and global radiation, under the SRES-A2 emission scenario and high climate sensitivity (increase of global mean temperature by 4.5°C following a doubling of the CO₂ concentration) in 2050

Month	ΔT_{avg} (°C)			Δ Precipitation (%)			Δ Global radiation (%)		
	HadCM	ECHAM	NCAR	HadCM	ECHAM	NCAR	HadCM	ECHAM	NCAR
Jan	2.5	3.3	2.3	16.0	30.8	20.1	-8.2	-3.3	-9.8
Feb	2.7	2.7	2.7	8.0	9.4	14.8	-6.8	-1.6	-7.8
Mar	2.3	2.5	1.4	3.1	-9.8	25.8	0.4	1.2	-6.8
Apr	2.5	2.1	1.2	10.7	-8.8	10.9	3.1	5.5	0.2
May	2.7	1.4	1.4	5.5	17.0	-3.3	4.7	-2.5	-0.4
June	2.9	1.8	1.6	-13.7	-13.9	-4.5	7.4	3.7	1.8
July	3.9	2.7	2.9	-28.7	-24.8	-9.6	7.0	5.9	8.6
Aug	4.7	3.3	3.1	-35.7	-27.3	-5.3	12.3	8.0	5.9
Sep	4.3	2.7	2.5	-20.3	-23.2	-18.5	13.5	5.1	8.2
Oct	2.9	2.9	3.1	2.9	3.1	-42.6	4.1	3.5	14.6
Nov	2.3	2.5	2.9	-5.7	13.5	-8.6	-1.0	-1.4	2.7
Dec	2.9	2.9	2.3	12.7	14.8	14.1	-7.8	-1.6	-7.8
Year	3.1	2.5	2.3	-5.3	-1.6	-2.1	5.1	3.3	2.7

The CO₂ concentration in the target year was set to 535.9 ppm, and the corresponding change in global mean temperature was 2.05°C. The values were based on the MAGICC v.4.1 model, and the temperature changes were with respect to 1975. HadCM, ECHAM, and NCAR were the General Circulation Models used in this study

calculated at a daily time step using the Penman–Monteith equation (Allen et al. 2005), with adjustments (Table 2) for changing CO₂ concentrations (Kruijt et al. 2008).

Based on the daily inputs, seasonal values of TS₁₀ and K_{JJA} were determined for each year of the period. The median values of both indices were calculated at each site and then interpolated using a geographically weighted regression method that accounted for the influence of altitude (Fotheringham et al. 2002). The interpolation errors of both parameters were similar for all periods and should not influence the overall results of the study. However, a substantial improvement in the resolution of climatic data is needed to ensure interpolation accuracy at the local level.

To verify the performance of the method described in section 2.2, all calculations for the 1985–2008 period were performed with observed data as well. The values of TS₁₀ and K_{JJA} at 52 climatological stations and those interpolated to individual cadastre units were not significantly different, and they agreed in more than 96% of cases. Similarly, the maps of agroclimatic conditions were nearly identical, with less than 3% of cadastre units classified differently in the two datasets.

Because climate alone does not guarantee profitable growing conditions in a region, additional abiotic factors must be considered. Therefore, soils, based on national soil survey data from 1961 to 1970, were divided into the following three subclasses: (1) excellent and good soils that were extensively used for agriculture without serious limitations caused by soil properties (in Central Europe, these soils included chernozems, gray soils and fluvisols, with a water-holding capacity in the rooting zone that varied between soil polygons and was generally greater than 200 mm); (2) fair quality soils with typical retention capacities between 140 and 220 mm and medium production capacities with some limitations, which, in many cases, were partly ameliorated by additional measures, such as

drainage (in Central Europe, these soils included vertisols, eutric cambisols, and cambisols, with a pH > 5.5); and (3) soils of inferior quality. The accessibility of agricultural land to machinery was the final parameter used in the classification scheme. In this study, the domain was divided between areas with slopes of less and/or greater than 7°.

To provide additional information for the agroclimatological analysis of the past two centuries, the following four agroclimatological indices were considered: (1) the mean duration of the vegetation summer (i.e., the period with a mean daily air temperature continuously above 15°C); (2) the number of days in the fifth percentile, with water stress between April and June (i.e., a 20-year drought); (3) the mean number of days with snow cover, calculated using the SnowMAUS model (Trnka et al. 2010); and (4) the date of the last spring frost, with a 20-year return period. The values were listed for the following three locations: Schwechat (48°6' N, 16°30' E, 184 m a.s.l.), Kroměříž (49°17' N, 17°24' E, 235 m a.s.l.), and Bystřice nad Pernštejnem (49°31' N, 16°15' E, 573 m a.s.l.). These locations were representative of conditions for the three most prevalent agroclimatic zones (grain maize-growing, sugar beet-growing, and cereal and potato-growing).

3 Results and discussion

Compared to all analyzed periods, the first quarter of the twentieth century was the coldest and wettest. For the period from April to September, the mean temperature was 0.6°C below the mean temperature of the 1803–1825 period and 1.7°C below the mean of the 1985–2008 period (Table 2). Regarding summer precipitation or TS₁₀ (Table 2), the temporal patterns were less pronounced, and the highest summer water deficits K_{JJA} were calculated for the 1851–1875, 1976–2000, and 1985–2008 periods.

Table 4 Proportion of arable land in the study area (%) in individual agroclimatic zones and subgroups in the nine periods listed in Fig. 1

Agroclimatic zone	Subgroup	Period								
		1803–1825	1826–1850	1851–1875	1876–1900	1901–1925	1926–1950	1951–1975	1976–2000	1985–2008
Grain maize	1	12.3	19.8	21.1	14.8	10.8	15.5	15.7	23.5	19.3
	2	3.0	4.7	5.1	2.5	1.7	3.1	3.0	5.9	5.5
Sugar beet	1	19.4	12.1	11.0	14.1	15.9	15.9	15.5	9.7	14.1
	2	11.3	9.5	9.6	7.1	6.4	10.7	10.6	14.7	18.5
Cereal and potato	1	1.8	1.6	1.3	4.6	6.7	2.0	2.2	0.2	0.0
	2	18.6	18.1	17.9	20.9	21.3	18.9	18.7	12.6	9.4
Forage and grassland	2	0.5	1.2	0.8	2.9	4.0	0.8	1.2	0.3	0.1

Subgroup 1 included the most fertile soils, which are primarily used for agricultural production; subgroup 2 included soils that are, in general, less fertile but that can be used for crop production, typically with some type of amelioration; in all cases, only areas with slopes less than 7° were considered. In the case of the forage and grassland zone, subgroup 1 was not present in the study area

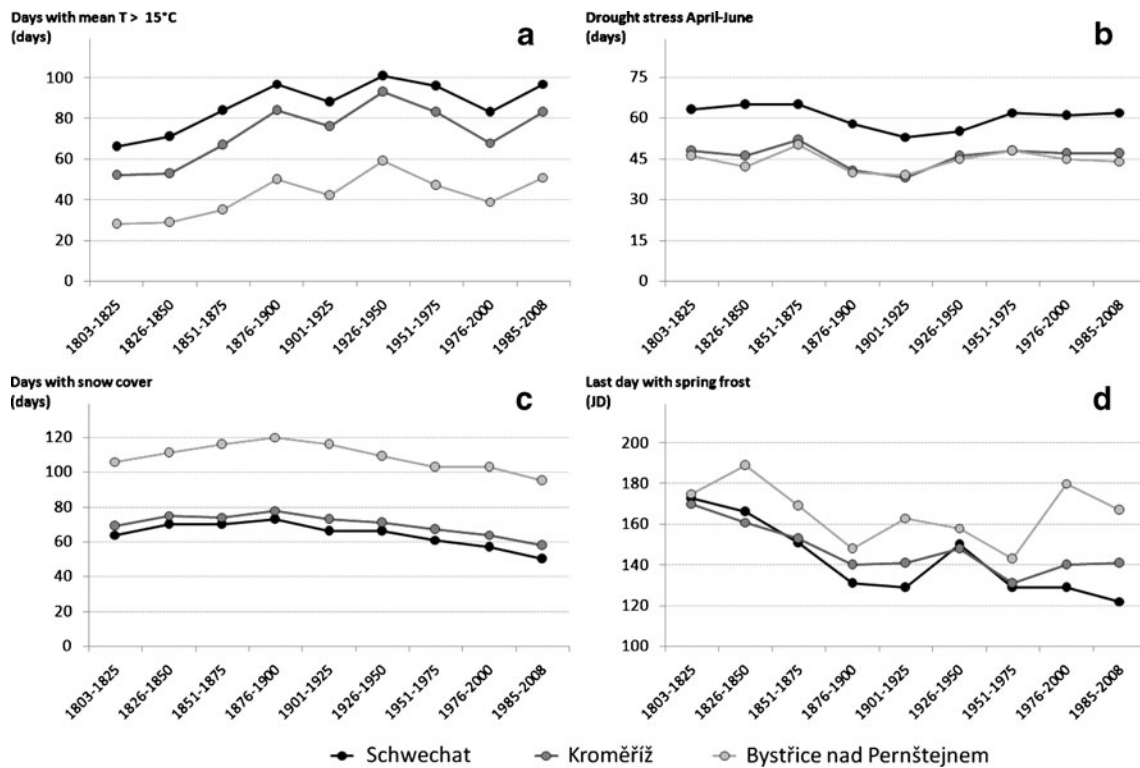


Fig. 2 Values of agroclimatic indicators for Schwechat, Kroměříž and Bystřice nad Pernštejnem: **a** mean duration of the vegetation summer; **b** number of days with water stress between April and June during dry

years, with 20-year return probability; **c** mean number of days with snow cover; and **d** the date of the last spring frost, with 20-year return probability (*JD* Julian days)

For the 1975–2000 period, the agroclimatic zone with the highest productivity (sugar beet-growing zone on most fertile soils) represented 9.7% of the study area in Austria and the Czech Republic, while the grain maize-growing zone on fertile soils (Table 4) represented 23.5% of the area and tended to be less productive. The temporal dynamics of

individual zones showing pronounced fluctuations are presented in Fig. 1. The total area of the grain maize-growing zone was the greatest between 1826 and 1875 and after 1976. In the 1901–1925 period, the area of the maize-growing and sugar beet-growing zones was reduced, and the area of the two remaining zones was the greatest. After

Fig. 3 Temporal stability of the given cadastre unit, expressed as the percentage of time between 1803 and 2008 in which the cadastre unit belonged to the same zone as in the 1975–2000 period. The *areas without shading* are areas in which the agroclimatic zone was stable for the entire 200-year period

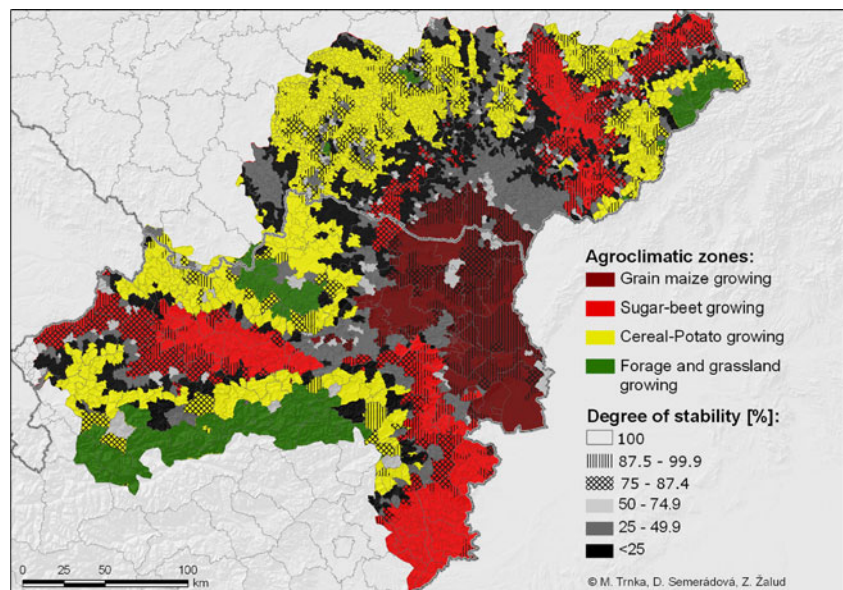
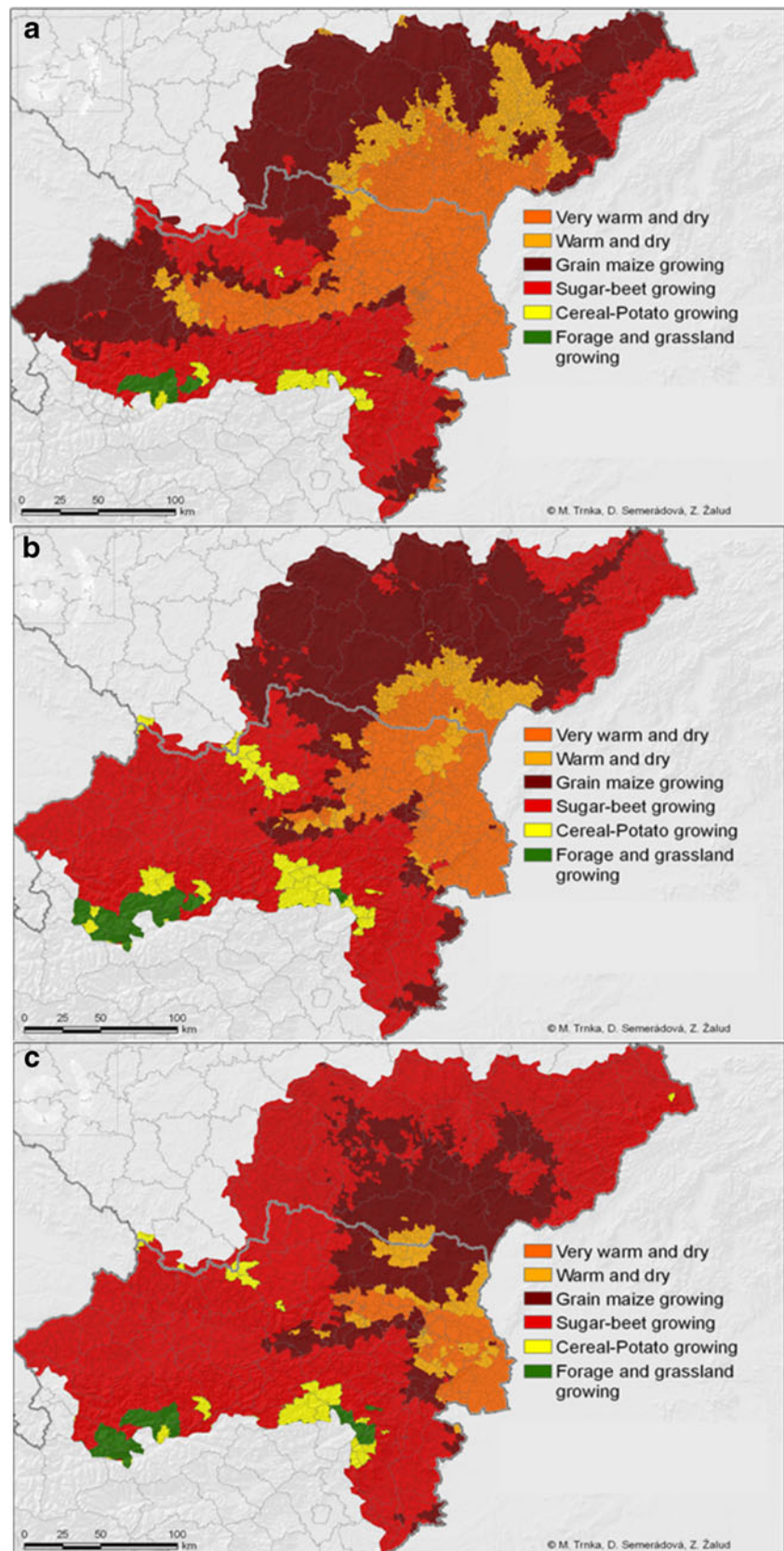


Fig. 4 The estimated extent of agroclimatic zones by 2050, assuming high climate sensitivity and a CO₂ concentration of 535.9 ppm, for three General Circulation Models: **a** HadCM, **b** ECHAM, and **c** NCAR. Compare to the changes estimated for the past 200 years (Fig. 1). A more detailed description of the agroclimatic zone classification is presented in Tables 1 and 5



1925, the continuous expansion of grain maize-growing and, particularly, sugar beet-growing zones, with significantly reduced forage and grassland areas, was estimated (Fig. 1 and Table 2). The situation after 1975 (Fig. 1h and i) was qualitatively different from that of the nineteenth century (Fig. 1c) due to unprecedented intrusions of sugar beet-growing zones into higher elevations, which reached 56.5% of the total area, and a northward expansion of the grain maize-growing region. In the same period, the forage and grassland zone was reduced to approximately 1% of the study area.

The shifts of agroclimatic zones shown in Fig. 1 were supported by changes in other indicators (Fig. 2). There was a clear trend toward longer vegetation summers at low and high elevations and in the north and south areas of the region (Fig. 2a). For all 52 sites, there was no significant trend in days with drought stress during the peak of the growing season (April–June). The mean number of days with snow cover decreased by up to 30 days since the peak in the late nineteenth century (Fig. 2c), and this was consistent for all sites. The date of the last frost (with a 20-year return period) shifted significantly closer to the beginning of the season (Fig. 2d) for lowland sites, while this date was mostly unchanged at higher elevations.

Figure 3 summarizes shifts in individual agroclimatic zones and shows the most and least stable regions in terms of agroclimatic zoning. While the core grain maize-growing zone was found near the Neusiedler See area in Austria on the Czech–Austrian border, the most stable area of the sugar beet-growing zone was found in the north of the study region around the Danube valley and in the southern tip of the region, which is one of the key breadbaskets of the Czech Republic. Although these regions were classified as stable, the agroclimatic conditions in the core regions changed, but the changes did not pass predefined thresholds. The area north of the Austrian border was, in general, the least stable region, as the conditions typical for a sugar beet-growing zone were frequently replaced by conditions for grain maize- or cereal- and potato-growing

zones (Fig. 1). The forage and grassland zone showed the highest temporal instability, particularly in the Czech Republic. The most stable area was located in the Alps. However, cultivation in these areas was complicated by the complex terrain, which in many cases required special machinery. At the same time, the poor soil quality in these areas and the topographically complex terrain hampered the adaptation of alternative production systems to the currently dominant and permanent grassland-based dairy farming or forestry.

The combination of increased air temperature and changes in the total and annual cycle of precipitation predicted for the next decades (Table 3) will lead to significant shifts in the area and location of individual agroclimatic zones (Fig. 4). In all cases, the area of the cereal- and potato- and forage and grassland zones will be reduced greatly by 2050 and substituted by sugar beet- and grain maize-growing zones. Similar claims were made by Olesen et al. (2007, 2011), who analyzed the expansion of the area suitable for maize production in Central and Northern Europe under climate change projections. However, the most striking difference with the present study was the appearance of two completely new agroclimatic zones, provisionally named the “warm and dry zone” and the “very warm and dry zone.” More detailed parameters are described in Table 5. Farmers currently located in the two most productive regions, the sugar beet-growing zone, where the climate is nearly optimal for rain-fed agriculture, and the grain maize-growing zone, would be the most severely impacted. Agricultural land within these zones is characterized by very fertile and deep soils and relatively flat terrain. The negative impact of the projected changes will likely be more severe in the Czech Republic because there are relatively limited possibilities for irrigation, overall water resources are likely to decrease (Dvořák et al. 1997; Kalvová et al. 2002) and larger average field sizes are an important factor for wind and water erosion during periods of drought. While the growing season in the warm

Table 5 Overview of thresholds used for “newly” emerging agroclimatic zones

Agroclimatic zone	TS10 (°C) ^a	K _{JJA} (mm) ^b	Annual mean air temperature (°C)	Annual precipitation total (mm)	Mean altitude (m a.s.l.)	Prevailing soils (under present climate)	Major crops grown in the zone	Potential productivity (%) ^c
Very warm and dry zone	>3400	<−250	>11.5°C	NA ¹	NA	NA	NA	NA
Warm and dry zone ²	3100–3500	−180 to −250	10–11.5°C	<600	<140	Solonetz, chernozems	Grain maize, soybean, grape wine, irrigated agriculture	NA

NA not available or not known

^a TS10 (°C): sum of temperatures in days with mean daily temperature above 10°C

^b K_{JJA}: the water deficit during the period from June to August

^c Conditions resembling the “warm and dry” zone could be identified in few cadastre units in low-lying regions of northeastern Austria during the analyzed period from 1995 to 2008

and dry production regions is much longer, pervasive drought during the summer months will limit rain-fed farming outside of the June–August period.

4 Conclusions

This study showed that agroclimatic conditions have varied substantially across most of the study area and, most likely, across the entire Central European region over the past 200 years. Changes of climate factors since the second half of the twentieth century favored the expansion of the maize agroclimatic zone. The length of the vegetation summer increased over the past two centuries, and the mean number of days with snow cover dropped by up to 30 days since the peak in the late nineteenth century. The date of the last frost became significantly closer to the season beginning in lowland sites but remained unchanged at higher elevations.

When analyzing upcoming decades, the time scale of the predicted changes is important. Farmers in Central Europe have never been forced, in past seven generations, to deal with such changes in agroclimatic conditions. They present great challenges for appropriate and sustainable farming strategies, such as change of crops, crop rotation schemes, cultivation timing and practices, and the abandonment of some forms of agricultural production. Based on the dynamics of the studied changes, the concept of stable agroclimatic zones used in the study region should, in general, be changed to a more flexible and continuous adaptive system that could be updated on the scale of decades or shorter timeframes. Finally, the results from this study are based on three GCMs, a rather small subset of all GCMs available. Hypothetically, if climate change scenarios based on all available GCM simulations were used in this analysis, then the GCM uncertainties in the results would likely be larger than those based on the three GCMs used in this study; however, the main trends would be preserved.

The methodology presented in this article can be easily applied to any region with available input data and a combination of long-term datasets and projections of future development to provide insight into the challenges that agriculture could face in the near future.

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