https://doi.org/10.17221/327/2020-PSE

Observed changes in the agroclimatic zones in the Czech Republic between 1961 and 2019

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Citation: Trnka M., Balek J., Brázdil R., Dubrovský M., Eitzinger J., Hlavinka P., Chuchma F., Možný M., Prášil I., Růžek P., Semerádová D., Štěpánek P., Zahradníček P., Žalud Z. (2021): Observed changes in the agroclimatic zones in the Czech Republic between 1961 and 2019. Plant Soil Environ., 67: 154–163.

Abstract: The paper shows a large-scale shift in agroclimatic zones in the territory of the Czech Republic (CR) between 1961 and 2019. The method used for agroclimatic zoning took advantage of high-resolution (0.5 km × 0.5 km) daily climate data collected from 268 climatological and 787 rain-gauge stations. The climate information was combined with soil and terrain data at the same resolution. The set of seven agroclimatic indicators allowed us to estimate rates of changes in agroclimatic conditions over the 1961–2019 period, including changes in the air temperature regime, global radiation, drought, frost risks and snow cover occurrence. These indicators are relevant for all main crops and agroclimatic zoning and account for local soil and slope conditions. The study clearly highlights major shifts in the type and extent of agroclimatic zones between 1961–2000 and 2000–2019, which led to the occurrence of entirely new combinations of agroclimatic indicators.

Keywords: climate change; production region; water deficit; growing season; Central Europe

One of the earliest attempts to classify what would be called "bio-climate" conditions were developed by the ancient Greeks (Sanderson 1999) but has received growing attention since the late 19th and first half of the 20th centuries when scientists sought to explain the diversity in vegetation and soils they encountered (e.g., Köppen 1900, Thornthwaite 1948). The classification scheme, originally developed by Wladimir Köppen, is used most commonly and is based on long-term averages of monthly values of temperature

Supported by the Ministry of Education, Youth and Sports of the Czech Republic for the project SustES – Adaptation Strategies for the Sustainability of Ecosystem Services and Food Security in Adverse Natural Conditions, Project No. CZ.02.1.01/0.0/0.0/16_019/0000797, and by the National Agency for Agricultural Research, Ministry of Agriculture of the Czech Republic, Project No. QK 1910338.

https://doi.org/10.17221/327/2020-PSE

and precipitation. While the Thornthwaite system in use since 1948 incorporates evapotranspiration along with temperature and precipitation information. As Altera (2011) review points out in a global and continental context, the climate is the main determinant of the ecosystem. Environmental and climatically similar areas can be interpreted as having similar potentials to support ecosystems and agricultural production (e.g., Metzger et al. 2005). Within the European Union, efforts that link climatic information to other environmental data have been used to introduce coherent policies dealing with climate change, nitrate pollution or biodiversity decline (e.g., Mooney et al. 2009, Metzger et al. 2010, Pereira et al. 2010). In case of the crop cultivation, the bio-climate zoning allows to determine an agronomically possible upper limit for the production of individual crops under given agroclimatic, soil and terrain conditions for a specific level of agricultural inputs and management conditions (Fischer et al. 2012). And systems for evaluating such potential exist on the global level, such as the agro-ecological zones approach (e.g., Fischer et al. 2001). However, global classifications provide limited regional detail by distinguishing only 10–30 classes globally, and with generally coarse spatial resolutions, and thus more regionalised approaches are needed (e.g., Petr 1991). Proper agroclimatic zoning might be very beneficial for long-term agricultural production planning and risk assessment in developing countries and in developed countries under ongoing climate change (Fischer et al. 2001, 2012); additionally, this method can be used to develop recommendations of short- to mid-term adaptation options, such as the breeding and selection of suitable cultivars (e.g., State Institute for Agriculture Supervision and Testing 2019) or investments in agricultural water management options (e.g., investment in irrigation systems). For a long time, such zoning has been essential for the objective and socially acceptable division of the tax burden on farmers based on the potential revenue from their farms. Over the territory of the Czech Republic (CR), several types of agrometeorological zoning have been used. One of the first attempts was introduced by Kořistka (1860) in the northwestern parts of the Austrian Empire (including the current CR). Although Kořistka's zoning was based on various agroclimatic indicators (e.g., length of the growing season, water availability), it was subjective and adhered strictly to administrative borders. As a consequence, it was replaced in the 1920s by more general zoning schemes that covered a range of crops and followed natural rather than administrative boundaries. In the early 1970s, a new concept based on hydrothermal characteristics was applied for the former Czechoslovakia region (Kurpelová et al. 1975) and was later reviewed by Petr (1991). The CR was divided into ten agro-climatic zones that provided similar climatic patterns for the production of field crops (see Petr (1991) for more details). Based on these climatic parameters, four agro-climatic zones are usually defined (Němec 2001) and are named after the most typical crop grown in the corresponding region (Table 1), indicating the zone's highest productivity under the defined conditions. The position of a given area within a particular climate region is a key indicator in determining the official tax rate of the land for farmers, characterising the potential productivity of agricultural land and determining the market value of that land (e.g., Novotný et al. 2013). In Austria, a similar concept of the same historical base is used for taxation (Harlfinger and Knees 1999). However, the basic assumption of agroclimatic zoning, i.e., that agroclimatic conditions remain more or less stable over a long-term period has been shattered by ongoing climate change (e.g., Zahradníček et al. 2020). When the ongoing changes in local climates are not considered, the zoning bias will increase over time, potentially leading to misinterpretations or even maladaptation. While the risks of using inappropriate fertilisation schemes, crop rotations or cultivars are well known (e.g., Kopáček et al. 2013, Martínková et al. 2018), less widely acknowledged is the fact that creeping shifts in agroclimatic conditions can make many practices obsolete or even unsustainable in areas where the same approach would have constituted "good practice" just twenty years ago. The main aim of the present study is to test the hypothesis that changes in the agroclimatic conditions that have occurred over the past six decades can sufficiently alter the extent and location of traditional crop cultivation regions. If such changes have occurred, then the study aims to find which regions have been affected the most and whether the reported changes can inform us about the developments in the near future or not.

MATERIAL AND METHODS

Study area. The complex orography and various altitudes are geographic factors influencing the pattern of agroclimatic conditions over the territory of

https://doi.org/10.17221/327/2020-PSE

the CR, in which the climate continentality tends to increase eastwards. Based on 2019 data of the Czech Statistical Office (https://www.czso.cz/csu/czso/13-zemedelstvi-mrtn8qi7tz), the four dominant annual crops covering 75% of arable land include wheat (mostly winter wheat with 33%), barley (mostly spring barely 13%), winter rape (17%) together with maize (both silage and grain maize being at 12%). None from the remaining crops, e.g., other cereals, forage crops (alfa-alfa, clover), sugar beet, potatoes, sunflowers, soybean poppy seed or flax, represent more than 3% of the arable land. Soybean and sunflowers are grown together with perennials (e.g., grapes and hops) in the sunniest and warmest parts of the CR. Grasslands are dominant in the highlands and mountainous regions. In total, 268 climatological and 787 rain-gauge stations representing observed daily weather data from 1961 till 2019, which went through data quality control and were homogenised by means of the software ProClimDB (Štěpánek et al. 2013). The missing station daily weather data were then interpolated using locally weighted regression that included the influence of altitude (more details can be found in Štěpánek et al. 2011). In the final step, the station daily weather data were then interpolated by means of regression krigging (using various terrain characteristics as predictors) into maps in 500 m spatial resolution, in daily scale, the information on the soil type was derived from the 1:500 000 soil map of the CR (Tomášek 2000). The grided estimate of soil available water capacity in 500 m resolution was based on data provided by the Research Institute for Soil and Water Conservation (Vopravil et al. 2018) and study of topsoil physical properties for Europe (Ballabio et al. 2016). The terrain was represented by the digital elevation model derived from the Shuttle Radar Topography Mission (Farr et al. 2007). The study results are presented using 0.5 km × 0.5 km grids aggregated to cadaster units, which represent the smallest administrative area in the Czech Republic.

Agroclimatic zoning. The agroclimatic zoning scheme, according to Němec (2001) and as simplified by Trnka et al. (2009), was applied in this study. This adjusted scheme takes into account several agroclimatic indicators: the sum of daily mean temperatures above 10 °C during the frost-free period of the year (TS10), the soil water deficit during the months June–August (K_{JJA}), and information about the soil type and slope of agricultural land. While TS10 is a rather good proxy of the growing season duration, K_{JJA} provides an integrated overview of precipitation and potential evapotranspiration during the summer months, which have the highest water demand. The calculation of potential evapotranspiration was done primarily on a daily time step based on the Penman-Monteith method (Allen et al. 2005) using the SoilClim model (Hlavinka et al. 2011). Based on the daily inputs, the values of TS10 and K_{JJA} were determined for each year during the evaluated period. In the next step, the median values of both indices were calculated at each 0.5 km × 0.5 km grid and then interpolated using locally weighted regression that included the influence of altitude. The thresholds used to determine the classified types of production region of the given cadastre unit to a particular agroclimatic zone were based on the previously used values, compiled, e.g., by Němec (2001) and Trnka et al. (2009), with adjustment for interpolation errors for both TS10 and K_{JJA} parameters. The adjustments were designed to prevent "wet" and "warm" biases in classification schemes, including approximately 5% higher values of TS10 and about 5% lower water deficits compared to Trnka et al. (2009). Trnka et al. (2009) concluded that the set of original agroclimatic zones derived for the climate of 1931–1960 and used, for example, by Němec (2001), would not cover the conditions expected during the 21st century. Therefore, one additional "grapevine production region" was added to account for the warmer and drier part of the classification scheme based on Trnka et al. (2009), as presented in Table 1.

To test the study hypothesis, the production region classification was performed using 1961–2000 as the reference period and 2000–2019 as the period representative of the most recent climate.

Climatic conditions alone do not represent the only requirements for crop production in a given region because the region may have highly diverse soil conditions. One of the key aspects affecting climate-plant interaction is the available soil water-holding capacity. This parameter, the soils in each 500 m grid have been classified according to their available water capacity in 0–100 cm depth into three classes:

(*i*) subclass 1 represents soils with high available water-holding (water retention) capacity in the rooting zone higher than 200 mm;

(*ii*) subclass 2 represents soil with good to fair soils available water capacity between 140 and 200 mm;

(*iii*) subclass 3 includes soils of low available water capacity set for this study below 140 mm.

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Table 1. Overview of thresholds used for agroclimatic zoning

Name of the zone	TS10 (°C)	K_{JJA} (mm)	Mean annual temperature (°C)	Annual precipitation total (mm)	Altitude (m a.s.l.)	Major crops grown	Potential productivity (Němec et al. 2001)
Grapevine production region	2 950–3 250	–210 to –140	> 10	< 600	< 140	grain maize, sunflower, soybean, grape wine, irrigated agriculture, vegetable, peaches, apricots	NA
Grain maize production region	2 800–3 100	–180 to –100	9–10	450–600	< 250	grain maize, sugar beet, grape wine, apples, peaches, apricots, high-quality wheat, malting barley	> 82
Sugar beet production region	2 550–2 950	–140 to –40	8–9	500–650	250–350	sugar beet, grain maize, grape, high-quality wheat, malting barley, hops	> 84
Cereal and potato production region	2 100–2 700	–90 to 120	5–8.5	550–900	300–650	cereals, rape, technical crops (growing sugar beet is not profitable)	> 56
Forage and grassland production region	< 2 150	> –30	5–6	> 700	> 600	potatoes, rye, flax, hay, forage crops	> 34

K_{JJA} – soil water deficit during the months June–August; NA – data not available

The mean slope of agricultural land was the final parameter used in this classification scheme. In total, four classes for arable land are distinguished, including:

(*i*) flat or nearly flat areas with (slopes of 0–2°);

(*ii*) areas with mild slope and thus the medium risk of soil erosion (slopes of 2–6°);

(*iii*) areas in which medium slope and considerable soil erosion risk (slopes of 6–12°);

(*iv*) areas where large-scale mechanisation is very difficult and with a very high risk of soil erosion (slopes >12°).

Dynamics of agroclimatic conditions. To analyse the rate of the temporal change in key agrometeorological indicators, the annual means of TS10 and K_{JJA} for the 1961–2019 period were evaluated together with the significance of the eventual change over the time period. In addition to the dynamics of the two already described indicators, five additional parameters were analysed:

(*i*) number of frost days (minimum daily temperature below 0 °C);

(*ii*) number of days with snow cover (snow depth at least 3 cm);

(*iii*) number of days with limited soil water availability (soil water content in the top 40 cm of the soil below 50% of maximum water holding capacity);

(*iv*) number of tropical days (maximum daily temperature above 30 °C);

(*v*) the annual sum of incident global radiation (MJ/m^2/season).

All indicators were calculated over all 0.5 km × 0.5 km grids that are mostly composed of agricultural land (Corine, CLC2018), and then the median value for each year were analysed. Linear trends of indicators were calculated, and their statistical significance was evaluated (P = 0.05).

RESULTS AND DISCUSSION

Under the baseline 1961–2000 climate, the agroclimatic zones with the highest productivity (i.e., sugar beet PR (production region) and grain maize PR on soils with high soil available water capacity) represented 13% and 6% of the agricultural land in the CR, respectively. Another 19% of the zones were zones of cereal and potato PR with soils with high available water capacity and sugar beet PR fair

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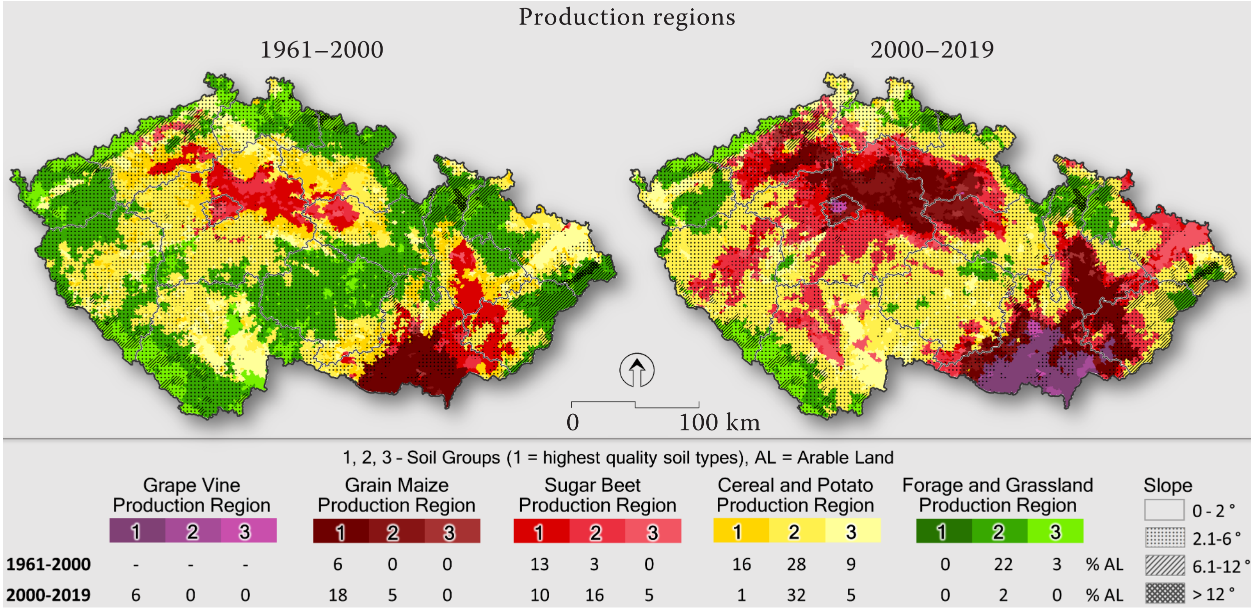

Figure 1. Agroclimatic zoning of the Czech Republic for the baseline 1961–2000 and the recent 2000–2019 period based on the classification in Table 1. Each cadaster unit fits into one agrometeorological indicator (color) with prevailing soil quality (depicted by the color and numbers 1–3). The accessibility of arable land is represented by the dominating slope of agricultural land units with three shading tones

soils (Figure 1). However, one-third of agricultural land during the 1961–2000 period was situated either on soils that with low available water capacity and/or within forage and grassland PR where the agricultural land is used predominantly as meadows or pastures (Figure 1). Cultivation in these areas is further affected by complex terrain (Figure 1), which in many cases requires special machinery. Under the 1961–2000 climatic conditions, the warm and dry regional conditions of grapevine PR have not dominated any region of the CR. However, Figure 2 indicates that in individual years, such conditions have occurred both in the southeastern part of the CR and in the River Elbe basin (northern part of the CR). The conditions of cereal and potato PR together with forage and grassland PR were most frequent throughout the landscape during the 1961–2000 period.

Figure 1 illustrates the massive and evident shift in the agro-climatic zones across the entire CR. Grapevine PR is becoming dominant in the southeast but also in central Bohemia and accounts for 6% of the country's arable land. Massive shifts in other regions are also obvious at the expense of the forage and grassland PR. The area of grain maize PR, with its suboptimal soil moisture regime, increased threefold to 18% in the 2000–2019 period, while the area of sugar beet PR on soils with high available water capacity decreased. The changes captured in Figure 1 appear clearer in Figure 2. The extent of grapevine PR, at least in some seasons, is considerable, as is the massive increase in the likelihood of grain maize PR. The emergence of this grapevine PR indicates the need to look for new crops, such as from the Mediterranean area or subtropics (e.g., sorghum, millets), that can adapt to the regional conditions but that have different day lengths and growing season characteristics from the current crops.

The combination of increased air temperature and changes in the annual cycle and totals of precipitation obviously leads to considerable shifts in the area and location of individual agroclimatic regions (Figure 1). The proportion of grassland and forage PR has diminished and was valued at 2% in the 2000–2019 period compared to 25% during the 1961–2000 reference period. This particular change was driven by an increase in evapotranspiration combined with insufficient precipitation totals during the peak of the vegetation period from June to August. This change consequently led to water deficits and could result in yield depressions for productive grasslands, which were indeed observed, e.g., during the 2015 summer drought (Žalud et al. 2017). The relatively low available soil water capacity and the

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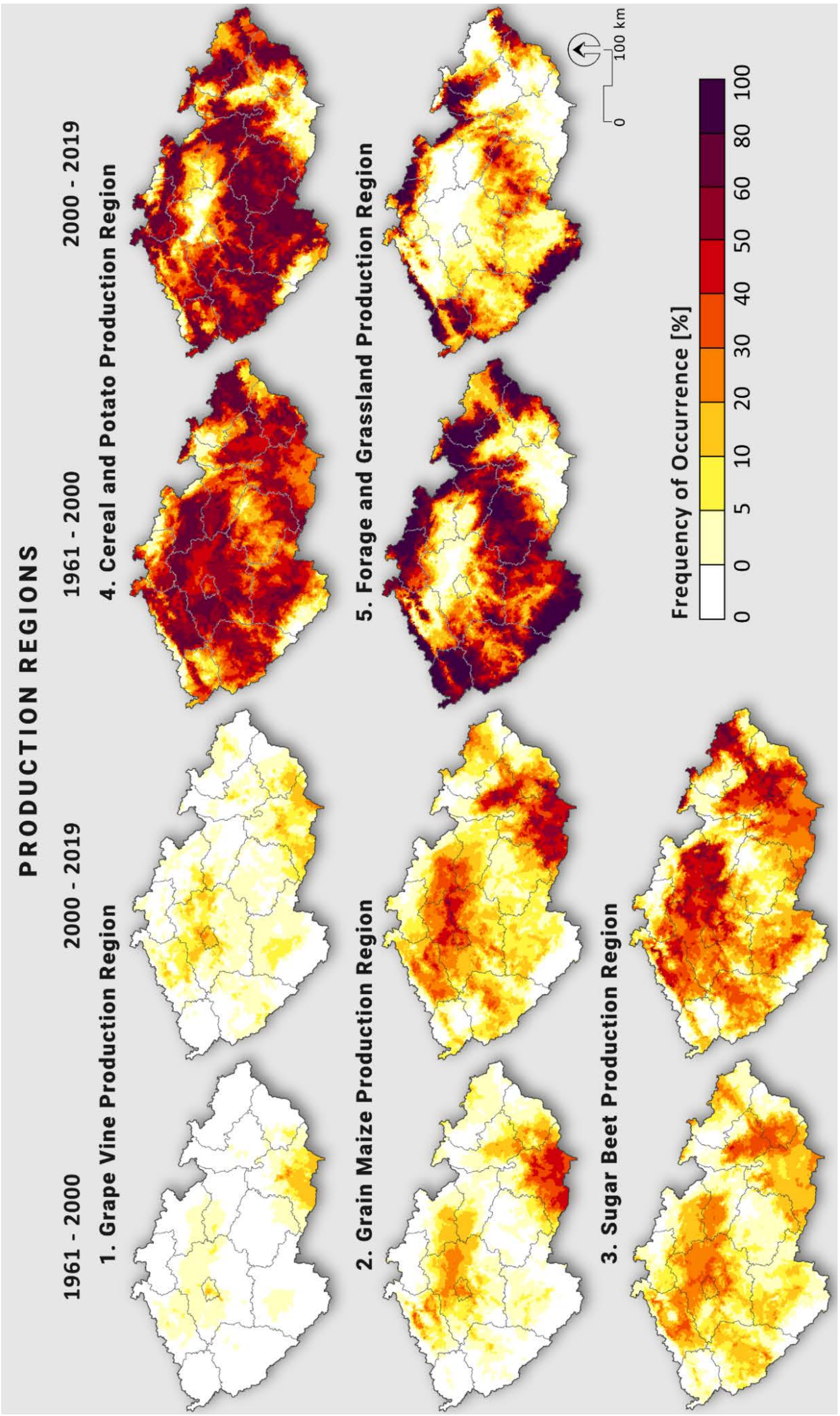

Figure 2. The frequency of seasonal agroclimatic conditions fitting to a particular production region (as defined in Table 1). The probability of occurrence has been depicted for individual seasons during the 1961–2000 and 2000–2019 periods. The classification covers all 0.5 km × 0.5 km grids

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complex topography in these areas make it difficult to adapt alternative production systems to the currently dominant permanent grassland-based dairy farming. The shifts in the agroclimatic conditions of areas formerly belonging to the cereal and potato PR and forage and grassland PR have meant a general improvement of the agroclimatic conditions, which use will be hampered both by more complex terrain and in general shallower and lighter soils. In the same time, the areas that belonged to the zone with the best agroclimatic conditions (sugar beet PR with high available soil water capacity) in 1961–2000 have seen the biggest decline and were from over 90% replaced grain maize and to smaller extend grape vine PRs. The drop in the sugar beet PR on soils with high available water capacity is seemingly only 3% (Figure 1); however, this masks the fact that the sugar beet PR is shifting away from Chernozems and from alluvial flatlands to the rolling hills areas and to higher elevation. The sharp increase in days with limited water availability and tropical days has been most apparent in these areas in this study and also documented recently by Zahradníček et al. (2020) drought and heat stress.

In particular, the time scale of the predicted changes must be underlined. Never in the recent history of agriculture in Central Europe have farmers been faced with such strong changes in agroclimatic conditions within just one generation or a few decades (e.g., Trnka et al. 2011). This change has posed and will continue to pose great challenges in terms of appropriate farming strategies (changes in crops, crop rotation schemes, cultivation timing and practices, or even abandoning some forms of agricultural production and/or change to different types of production). Figure 3 shows that less than 10% of cadasters at the grain maize PR and sugar beet PR remained within the same production region conditions in both periods that were analysed. Over 77% of agricultural land have seen a shift by at least one category between 1961–2000 and 2000–2019, while shifts by more than two categories have also been relatively common (7% of agricultural land). The most widespread shift by two categories was noted in the case of cereal and potato PR (almost 14%).

As the analysis shown at Figure 4 indicates, both K_{JJA} and TS10 have undergone marked changes in the past 59 years. While TS10 has been growing by almost 100 °C per decade, K_{JJA} decreased by approximately 8 mm per 10 years. While the change in K_{JJA} has not been statistically significant, the dip in annual values after 2010 is clearly visible, and a significant decrease can be found when the period from March to May is considered. The number of days with snow cover has been decreasing by almost six days per decade, while the decrease in the number of frost days has been significant, with a decline of approximately four days per decade (Figure 4). After 2000 the rates of change in both indicators have increased several times compared to the pre-2000 period (Figure 4). The number of tropical days has been increasing by almost two days per decade, while the number of days with soil moisture limiting growth has significantly increased by approximately seven days per 10 years over the 1961–2019 period. The rate of the change in both indicators doubled after 2000. This result means that over 40 days of less-than-optimum soil moisture content and 10 tropical days have been added since the 1960s. While total incident global radiation increased over the evaluated period, the

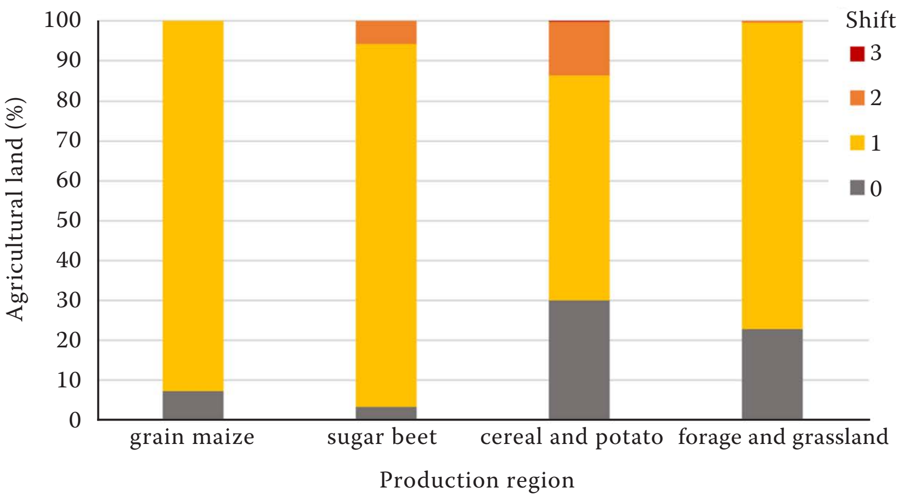

Figure 3. The proportion of grids belonging to the particular production region category based on 1961–2000 data that remained stable (0 – no change) or have shifted (color) by 1, 2 and 3 categories during the 2000–2019 period

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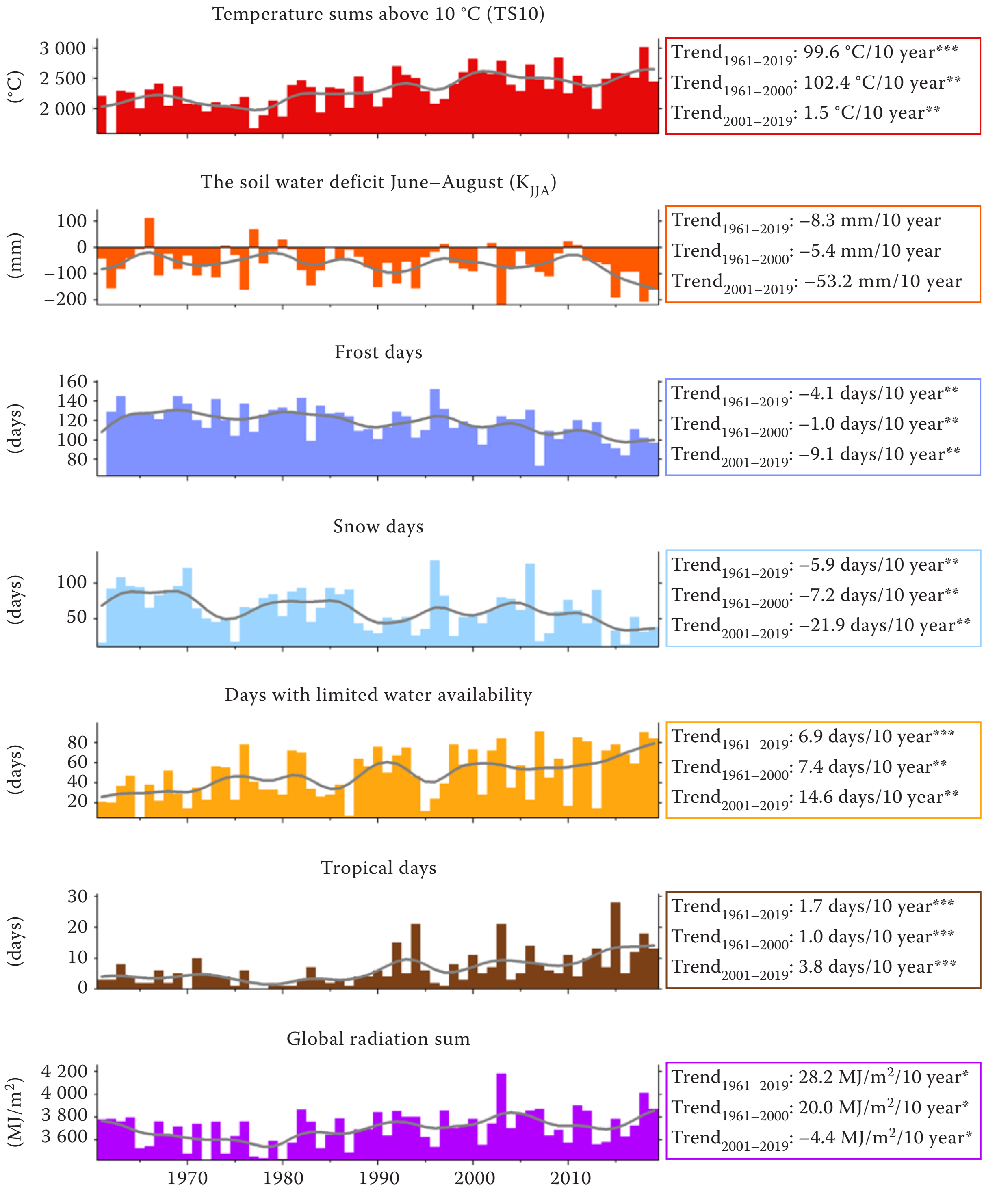

Figure 4. Median values of selected climatological characteristics across agricultural land grids during the 1961–2019 period. The line is smoothed by a 10-year Gaussian filter. Values of linear trends are added for each characteristic for three time periods. $^*P \leq 0.05$; $^{**}P \leq 0.01$

changes have been negligible both in annual (Figure 4) and seasonal totals. The findings also lead us to the conclusion that the concept of static agroclimatic zones as used until now must, in general, be changed to a more flexible and continuously adaptive system that would allow for updates on the scale of decades or even shorter time frames. While a similar assertion was made by Trnka et al. (2009) based on the

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climate change scenarios for the 2020s and 2050s, the present study clearly comes to similar conclusions but is based on observed data and a more robust methodology. The new concept of agroclimatic zones presents challenges that farmers will face in finding new species, cultivars, and management techniques (agronomic practices) to ensure sustainable agriculture in times of climate change.

The presented results indicate that the combination of increased air temperature and decreased plant-available soil water during the summer (June–August) caused significant and widespread shifts in the agro-climatic zones in 2000–2019 compared to 1961–2000. As a result, the most productive rain-fed crop cultivation areas (i.e., sugar beet PR) have shifted to having warmer and drier conditions, resulting in a decreasing production potential for rain-fed farming. On the other hand, the higher elevations with below-optimum temperatures in the past have experienced an improvement in their temperature profiles. However, judging on the rate of change over the 2000–2019 period, this improvement is likely to be only temporary. It is likely that with the current rate of change, even the areas at higher altitudes will experience drier and warmer-than-optimum conditions by the 2030s and 2040s.

REFERENCES

Allen G.A., Walter I.A., Elliot R.L., Howell T.A. (2005): ASCE Standardized Reference Evapotranspiration Equation. Reston, American Society of Civil Engineers. ISBN: 9780784408056

Altera (2011): Recommendations for establishing Action Programmes under Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. Final report. Part A. Available at: https://op.europa.eu/en/publication-detail/-/publication/057e5f2e-904a-4507-815e-cdf5c616a750/language-en/format-PDF/source-search

Ballabio C., Panagos P., Montanarella L. (2016): Mapping topsoil physical properties at European scale using the LUCAS database. Geoderma, 261: 110–123.

Corine CLC2018: Available at: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download

Farr T.G., Rosen P.A., Caro E., Crippen R., Duren R., Hensley S., Kobrick M., Paller M., Rodriguez E., Roth L., Seal D., Shaffer S., Shimda J., Umland J., Werner M., Oskin M., Burbank D., Alsdorf D. (2007): The shuttle radar topography mission. Review of Geophysics, 45: RG2004.

Fischer G., Nachtergaele F.O., Prieler S., Teixeira E., Toth G., van Velthuizen H., Verelst L. (2012): Global Agro-ecological Zones (GAEZ v3.0) – Model Documentation. Laxenburg and Rome, International Institute for Applied Systems Analysis and Food and Agriculture Organisation.

Fischer G., Shah M.M., van Velthuizen H.T., Nachtergaele F.O. (2001): Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results. IIASA Research Report. Laxenburg, IIASA, RR-02-02.

Harlfinger O., Knees G. (1999): Climate Handbook of the Austrian Soil Assessment. Wien, Communication from the Austrian Soil Science Society. ISBN 3703003413 (In German)

Hlavinka P., Trnka M., Balek J., Semerádová D., Hayes M., Svoboda M., Eitzinger J., Možný M., Fischer M., Hunt E., Žalud Z. (2011): Development and evaluation of the SoilClim model for water balance and soil climate estimates. Agricultural Water Management, 98: 1249–1261.

Kopáček J., Hejzlar J., Posch M. (2013): Factors controlling the export of nitrogen from agricultural land in a large central European catchment during 1900–2010. Environmental Science and Technology, 47: 6400–6407.

Köppen W. (1900): Versuch einer Klassification der Klimat, Vorsuchsweize nach ihren Beziehungen zur Pflanzenwelt. Geographische Zeitschrift, 6: 593–611. (In German)

Kořistka K. (1860): Die Markgrafschaft Mähren und das Herzogthum Schlesien in ihren geographischen Verhältnissen. Wien and Olmüz, Eduard Hölzel's Verlags-Expedition.

Kurpelová M., Coufal L., Čulík J. (1975): Agroclimatological Conditions of the Czechoslovakia. Bratislava, Hydrometeorological Institute. (In Slovak)

Martínková M., Hejduk T., Fučík P., Vymazal J., Hanel M. (2018): Assessment of runoff nitrogen load reduction measures for agricultural catchments. Open Geosciences, 10: 403–412.

Metzger M.J., Bunce R.G.H., Jongman R.H.G., Mücher C.A., Watkins J.W. (2005): A climatic stratification of the environment of Europe. Global Ecology and Biogeography, 14: 549–563.

Metzger M.J., Bunce R.G.H., Van Eupen M., Mirtl M. (2010): An assessment of long term ecosystem research activities across European socio-ecological gradients. Journal of Environmental Management, 91: 1357–1365.

Mooney H., Larigauderie A., Cesario M., Elmquist T., Hoegh-Guldberg O., Lavorel S., Mace G.M., Palmer M., Scholes R., Yahara T. (2009): Biodiversity, climate change, and ecosystem services. Current Opinion in Environmental Sustainability, 1: 46–54.

Němec J. (2001): Assessment and Evaluation of Farm Land in the Czech Republic. Prague, Research Institute of Agriculture Economics. ISBN 808589890X (In Czech)

Novotný I., Vopravil J., Kohoutová L. (eds.) (2013): Methodology of Mapping and Updating of Soil Ecological Units. 4th Edition. Prague, Research Institute for Soil and Water Conservation. ISBN 978-80-87361-21-4 (In Czech)

Pereira H.M., Belnap J., Brummitt N., Collen B., Ding H., Gonzalez-Espinosa M., Gregory R.D., Honrado J.O., Jongman R.H., Julliard R., Mcrae L., Proenã§a V.N., Rodrigues P.C., Opige M., Rodri-

https://doi.org/10.17221/327/2020-PSE

guez J.P., Schmeller D.S., Van Swaay C., Vieira C. (2010): Global biodiversity monitoring. Frontiers in Ecology and the Environment, 8: 459–460.

Petr J. (ed.) (1991): Weather and Yield. Developments in Crop Science 20. Amsterdam and New York, Elsevier. ISBN 044441617X

Sanderson M. (1999): The classification of climates from Pythagoras to Koeppen. Bulletin of the American Meteorological Society, 80: 669–673.

State Institute for Agriculture Supervision and Testing (2019): Available at: http://eagri.cz/public/web/file/625530/obilniny_2019.pdf (accessed June 20, 2020)

Štěpánek P., Zahradníček P., Farda A. (2013): Experiences with data quality control and homogenization of daily records of various meteorological elements in the Czech Republic in the period 1961–2010. Időjárás, 117: 123–141.

Thornthwaite C.W. (1948): An approach toward a rational classification of climate. Geographical Review, 38: 55–94.

Tomášek M. (2000): Soils of the Czech Republic. Prague, Czech Geological Service. ISBN 8070756888 (In Czech)

Trnka M., Brázdil B., Dubrovský M., Semerádová D., Štěpánek P., Dobrovolný P., Možný M., Eitzinger J., Málek J., Formayer H., Balek J., Žalud Z. (2011): A 200-year climate record in Central Europe: implications for agriculture. Agronomy for Sustainable Development, 31: 631–641.

Trnka M., Eitzinger J., Hlavinka P., Dubrovský M., Semerádová D., Štěpánek P., Thaler S., Žalud Z., Možný M., Formayer H. (2009): Climate-driven changes of production regions in central Europe. Plant, Soil and Environment, 55: 257–266.

Vopravil J., Khel T., Heřmanovská D., Holubík O., Huislová (2018): The map definiton of water retention capacity characteristics in agricultural and non-agricultural soils with territorial categorization within the Czech Republic. Prague, Research Institute for Soil and Water Conservation, Certificate No. 8/14130-MZe-2018.

Zahradníček P., Brázdil R., Štěpánek P., Trnka M. (2020): Reflection of global warming in trends of temperature characteristics in the Czech Republic, 1961–2019. International Journal of Climatology, 41: 1211–1229.

Žalud Z., Hlavinka P., Prokeš K., Semerádová D., Balek J., Trnka M. (2017): Impacts of water availability and drought on maize yield – a comparison of 16 indicators. Agricultural Water Management, 188: 126–135.

Received: July 1, 2020
Accepted: February 2, 2021
Published online: February 24, 2021