Climate-driven changes of production regions in Central Europe

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ABSTRACT

The presented work complements studies on agroclimatic zoning that were performed during 19th and 20th century in the Czech Republic and Austria and allows estimating the effect of climate change on the spatial distribution of agroclimatic conditions within both countries. The main conclusions of the study are: (1) The combination of increased air temperature and changes in the amount and distribution of precipitation will lead to significant shifts in the agroclimatic zones by the 2020's. The current most productive areas will be reduced and replaced by warmer but drier conditions, which are considered less suitable for rainfed farming. (2) While trends in the changes expected in lowlands are mostly negative (especially for non-irrigated crops), higher elevations might experience improvement in their agroclimatic production potential. However, the production potential of these regions is usually limited by other factors such as the soil quality and terrain accessibility. Additionally, these positive effects might be short-lived, as by the 2050's, even the areas in higher altitudes might experience much drier conditions than nowadays. (3) Dairy-oriented agriculture (based on permanent grassland production) at higher altitudes could suffer through an increased evapotranspiration demand combined with a decrease in precipitation, leading to higher water deficits and yield variations. (4) All above listed changes will most likely occur within less than four decades. The rate of change might be so high that the concept of agroclimatic zoning itself might lose its relevance due to the perpetual change.

Keywords: climate change; agroclimatic zoning; water deficit; growing season; AgriClim

One of the basic axioms of agroclimatology postulated by a number of authors (e.g. Petr 1991 or Fisher et al. 2000) is the notion that specific crops grow well in specific climate regions and that the success of a crop can be related to climate factors (e.g. frequency of frost damage, length of growing season, total rainfall), physical factors (e.g. soil, slope, aspect) and economic factors (e.g. farm size, intensity of the crop production) as shown by Reidsma (2007), among others. Understanding the complex interactions between crops, soil conditions and regional climate allows for better management decisions. In many respects, proper agroclimatic zoning might be very beneficial for agricultural

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production planning and risk assessment in developing countries and in developed countries under the climate change (Fisher et al. 2000). Several types of agrometeorological zoning have been used within the study area over the last 150 years. One of the first attempts was introduced by Kořistka (1860) in the western parts of what was then the Austrian-Hungarian Empire. Although Kořistka's zoning was based on various agroclimatic indicators (e.g. length of 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 the hydrothermal characteristics of an area was applied in what was formerly Czechoslovakia (Kurpelová et al. 1975) and reviewed by Petr (1991). The Czech Republic was divided into ten agroclimatic zones that provide similar climate conditions for the production of field crops (for more details, refer to Petr 1991). Based on these climate parameters, four agroclimatic zones were defined (Němec 2001) and named after the most typical crop grown in that region (Table 1). The position of a given region within a particular agroclimatic zone is a key indicator in determining the official tax rate of the land for farmers, characterizing the potential productivity of agricultural land and determining the market value of that land. In Austria, a similar concept is used for taxation (Harlfinger and Knees 1999). It is, however, rarely realized that during past few decades the basic assumption of agroclimatic zoning (i.e. that agroclimatic conditions remain stable long-term), has been shattered by ongoing climate change (e.g. Perarnaud et al. 2008). When these changes are not reflected in updates of agroclimatic zoning, there might be negative consequences for farmers as well as the environment due to application of potentially biased adaptation measures. While the risks of using climatically inappropriate fertilization schemes, crop rotations or cultivars are well-known, less widely acknowledged is the fact that creeping shifts in agroclimatic zones make many practices obsolete or even unsustainable in areas where the same approach would have constituted 'good practice' just one generation ago. The main aim of the present study was to develop an objective methodology that would enable regionalization of the study area based on the agroclimatic conditions under present and expected climate conditions that would have not only a scientific merit

Table 1. Overview of thresholds used for agroclimatic zoning based on the 1961–1990 climate conditions adjusted according to Němec (2001)

Symbol used	Brief description of the region (common name[1])	TS10 (°C)	Kvi-viii (mm)	Annual mean temperature (°C)	Annual sum of precipitation (mm)	Altitude (m)	Prevailing soils (under present climate)	Major crops grown in the zone	Potential productivity	Area under baseline climate (%)
A	very warm and dry zone	> 3400	< –250	NA[2]	NA	NA	NA	NA	NA	0.0
B	warm and dry zone	3100–3500	–180 to –250	> 10°C	< 600	< 140	solonetz, chernozems	grain maize, soybean, grape wine, irrigated agriculture	NA	0.5
C	grain maize-growing zone	2800–3200	–90 to –180	9–10°C	450–600	< 250	chernozems, fluvisols	grain maize, sugar beet, grape wine, peaches, apricots, high-quality wheat, malting barley	> 82	13.6
D	sugar beet-growing zone	2550–2950	–50 to –120	8–9°C	500–650	250–350	chernozems, cambisols	sugar beet, grain maize, grape, high-quality wheat, malting barley, hops	> 84	25.5
E	cereal- and potato-growing zone	2150–2700	–100 to + 130	5–8.5°C	550–900	300–650	cambisols	cereals, rape, technical crops (growing sugar beet is not profitable)	> 56	48.6
F	forage and grassland zone	< 2150	> –10	5–6°C	> 700	> 600	poor cambisols, gleysols	potatoes, rye, flax, hay, forage crops	> 34	11.8

The zones of C–F to large degree correspond with the crop growing regions that are used commonly in the Czech Republic; NA – not available or not known but would be also understandable to farmers and policy makers.

MATERIAL AND METHODS

Description of the study area

The study area is located in Central Europe between 48°50'–51°04'N and 12°05'–18°52'E (Figure 1) and covers over 114.438 km^2, including 63.627 km^2 used for some kind of agricultural production. It includes a wide range of agroclimatic conditions and a complex orography. The altitude and geographical relief influence the climate, especially in Austria, where the orographical impact of the Alps must be taken into account. The prevailing annual crops include winter wheat, spring barley and winter rape in most of the Czech Republic, and durum wheat, grain maize, soybean and sunflowers in the warmest parts of Austria and the southeast Czech Republic. Grasslands are dominant in the highlands and mountainous regions in both countries. The territory of the Czech Republic and the four Austrian federal states Upper and Lower Austria, Vienna as well as Burgenland was represented by 129 weather stations; data went through quality control, and when possible homogenized by means of the programs ProClimDB (Štěpánek 2007) and AnClim (Štěpánek 2006). The soil conditions were derived based on a 1:1 000 000 FAO map of soil types (BMLFW 2007) 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 the digital elevation model derived from the Shuttle Radar Topography Mission (Farr et al. 2007). Study results are presented using 0.5 × 0.5 km grid cells aggregated to cadastre units.

Regional climate change scenarios for Central Europe

There are number of ways to construct climate scenario data to guide agroclimatic tools at a suit-

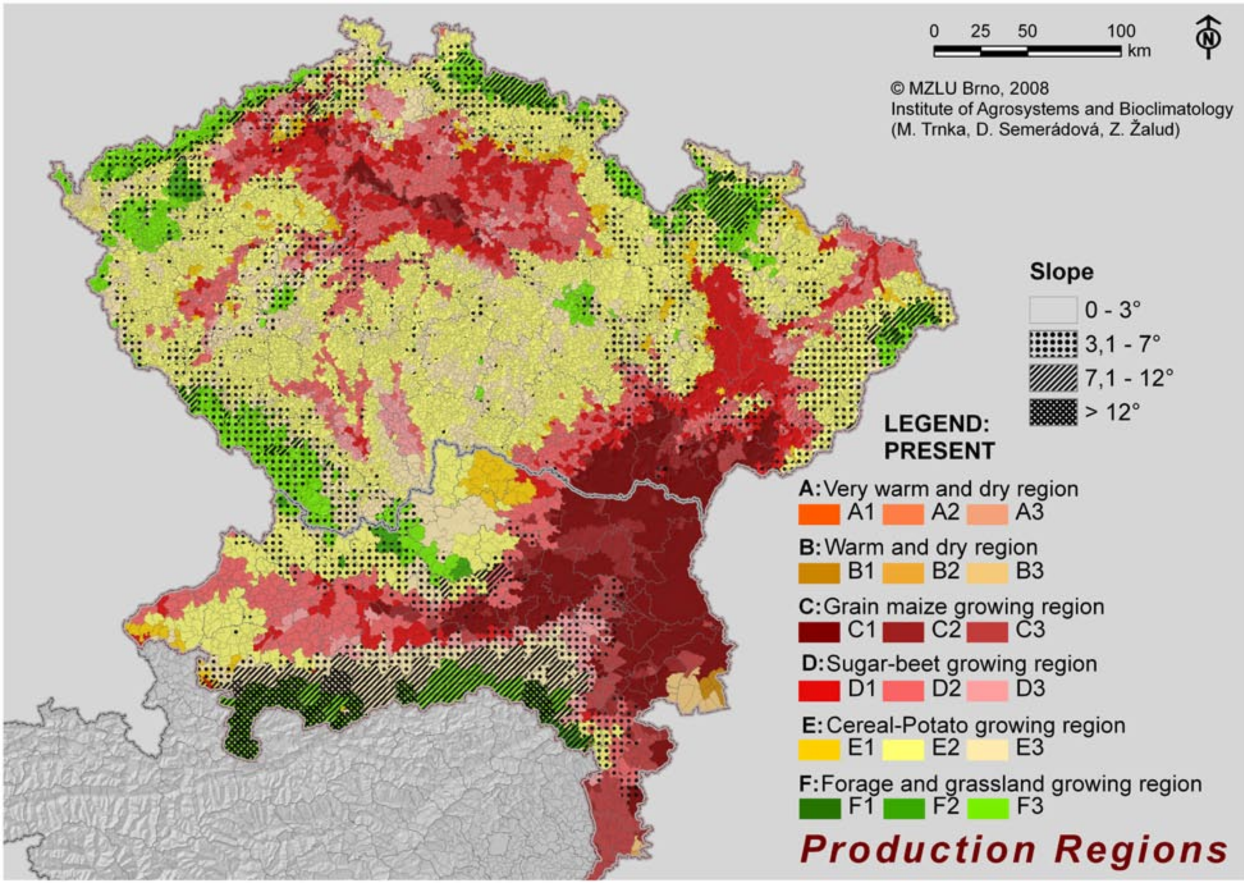


Figure 1. Agroclimatic zoning of the region for the baseline period 1961–1990, using thresholds according to Table 2, with regionalization at the level of cadastre units. The regionalization takes into account the combination of agrometeorological indicators (color and letters A–F), soil quality (tones and numbers 1–3) and accessibility expressed in terms of slope (shading)

able resolution. To produce weather series representing the changed climate for the present study, we used an approach validated and employed in our earlier studies (e.g. Zalud and Dubrovský 2002, Trnka et al. 2004a, b). This methodology consists in using the stochastic weather generator Met & Roll (Dubrovský 1997, Dubrovský et al. 2004) whose parameters were modified according to the climate change scenarios developed from the output of Global Climate Models (GCMs). The present scenarios were derived by means of a 'pattern-scaling' technique (Santer et al. 1990), in which the climate change scenario is defined by the product of the standardized scenario (Table 2b) and the change in global mean temperature (Table 2a). The standardized scenarios, which relate responses of climatic characteristics to a 1°K rise in global mean temperature (ΔT_G), were determined using regression method (Dubrovský et al. 2005). The three GCMs include ECHAM5/MPI-OM, HadCM3 and NCAR-PCM and will be denoted as ECHAM, HadCM and NCAR in the following text. Changes in ΔT_G for two periods (2020 and 2050) were calculated by a simple climate model MAGICC (Harvey et al. 1997, Hulme et al. 2000) assuming two combinations of emission scenario and climate sensitivity (equilibrium change in global mean surface temperature following a doubling of the atmospheric equivalent CO_2 concentration, $\Delta T_{G,\, 2 \times CO_2}$); here, these two changes represent the lower and upper estimates of the global mean temperature rise (Table 2a). The two emission scenarios will henceforth be referred to as B1-low and A2-high, and the two versions of scenarios (for each of the three GCMs) related to the two values of ΔT_G will be referred to as low and high

Table 2a. CO_2 concentration and change in mean global temperature as the key inputs for construction of climate change scenarios using the pattern-scaling technique. The values are based on the MAGICC v.4.1 model, and the temperature changes are with respect to 1975

Scenario	2020		2050	
	climate sensitivity (emission scenario)			
	CO_2 (ppm)	temperature change (°C)	CO_2 (ppm)	temperature change (°C)
High (SRES-A2)	418.0	0.90	535.9	2.05
Low (SRES-B1)	413.6	0.50	490.4	0.90

Table 2b. Assumed change in mean monthly temperature, precipitation sum and global radiation per 1°C in the global temperature increase

	ΔT_{avg} (°C)			ΔPrecipitation (%)			ΔGlobal radiation (%)		
	HadCM	ECHAM	NCAR	HadCM	ECHAM	NCAR	HadCM	ECHAM	NCAR
Jan	1.2	1.6	1.1	7.8	15.0	9.8	–4.0	–1.6	–4.8
Feb	1.3	1.3	1.3	3.9	4.6	7.2	–3.3	–0.8	–3.8
Mar	1.1	1.2	0.7	1.5	–4.8	12.6	0.2	0.6	–3.3
Apr	1.2	1.0	0.6	5.2	–4.3	5.3	1.5	2.7	0.1
May	1.3	0.7	0.7	2.7	8.3	–1.6	2.3	–1.2	–0.2
Jun	1.4	0.9	0.8	–6.7	–6.8	–2.2	3.6	1.8	0.9
Jul	1.9	1.3	1.4	–14.0	–12.1	–4.7	3.4	2.9	4.2
Aug	2.3	1.6	1.5	–17.4	–13.3	–2.6	6.0	3.9	2.9
Sep	2.1	1.3	1.2	–9.9	–11.3	–9.0	6.6	2.5	4.0
Oct	1.4	1.4	1.5	1.4	1.5	–20.8	2.0	1.7	7.1
Nov	1.1	1.2	1.4	–2.8	6.6	–4.2	–0.5	–0.7	1.3
Dec	1.4	1.4	1.1	6.2	7.2	6.9	–3.8	–0.8	–3.8
Year	1.5	1.2	1.1	–2.6	–0.8	–1.0	2.5	1.6	1.3

scenarios. In the final step, daily weather series of meteorological data were prepared with the use of a stochastic weather generator (Dubrovský 1997) that has been "trained" on the 1961–1990 observed weather series and then perturbed with the climate change scenario (Table 2b). Ninety-nine-year simulation runs were performed for all GCM and scenario combinations.

Agroclimatic zoning

The agroclimatic zoning is based on daily meteorological data in combination with experimentally validated water balance model. It takes into account several agroclimatic indicators; in particular, temperature sums or growing degree days above 10°C during the frost-free period of the year (TS10), the water deficit during the period from June to August (Kvi-viii), and information about soil type and slope of the agricultural land. While TS10 is a rather good proxy of growing season duration, Kvi-viii provides an integrated overview of precipitation and potential evapotranspiration during the three months of year with the highest water demand. Calculation of potential evapotranspiration was done primarily in a daily time step using the Penman-Monteith method presented by Allen et al. (2005). Based on the daily inputs the seasonal values of TS10 and Kvi-viii were determined for each year during the evaluated period. In the next step the median values of both indices were calculated at each site and then interpolated using locally weighted regression that included influence altitude. The thresholds used to determine the classified types of production region of the given cadastre unit to particular agroclimatic zone was based on the previously used values and compiled e.g. by Němec (2001) with adjustment for interpolation errors of both TS10 and Kvi-viii parameters. The adjustments were designed to prevent 'dry' and 'warm' biases in classification schemes and thus slightly higher values of TS10 and of water deficits were set up (Table 1). It became also apparent that the set of original agroclimatic zones derived for the climate of 1931–1960 would not cover the conditions expected during the 21st century. Therefore, two additional zones, marked by the letters A–B, were added at the warmer, drier end of the classification scheme (Table 2). Despite interpolation errors of individual parameters being rather small, the final product is ultimately composite of all deficiencies that are inherent to individual steps and thus should be used with care. We are confident that the main agroclimatic features under the present and expected climate are depicted well but for regionally accurate agroclimatic zoning higher resolution of climate data (especially in case of precipitation) would be required in order to consider local climatic effects.

Climate conditions alone do not guarantee profitable crop production in a given region, and soil conditions have to be taken into account. In order to do so, the soils were divided into three sub-classes marked with numbers from 1 to 3, in which: (1) represents excellent to very good soils that are extensively used for agriculture without serious limitations caused by soil properties (in Central Europe, these include chernozems of all kinds, grey soils and fluvisols with a water-holding capacity in the rooting zone generally higher than 200 mm); (2) good to fair quality soils with retention capacity typically between 140 and 220 mm and medium production capacity, usually with some limitations that in many cases can be partly ameliorated by additional measures such as drainage (in Central Europe, these soils include vertisols, eutrofic cambisols and cambisols with a pH > 5.5); and (3) soils of inferior quality that usually suffer from severe limitations (usually shallow soils with a water-holding capacity below 140 mm). The accessibility of agricultural land by machinery is the final parameter used in this classification scheme. In total, four classes are distinguished, including (i) areas with very good terrain for machinery (slopes of 0–3°); (ii) areas where most machinery can be used with medium risk of soil erosion (slopes of 3–7°); (iii) areas in which some machinery is applicable, albeit with limitations, and there is high soil erosion vulnerability (slopes of 7–12°) and (iv) areas where large-scale mechanization is impossible and there is a very high risk of soil erosion (slopes > 12°) on arable land.

RESULTS AND DISCUSSION

Under the baseline climate conditions (i.e. 1961–1990), the agroclimatic zones with the highest productivity (i.e. D1 and C1) represent 8.1% and 9.0% of the considered region of Austria and Czech Republic; another 18.7% belong among the slightly less productive zones of C2, D2 and E1 (Table 3 and Figure 1). On the other hand, almost one-third of agricultural land is situated on soils that are unsuitable as arable land and used as meadows or pastures (i.e. B3–F3 subtypes). Cultivation in

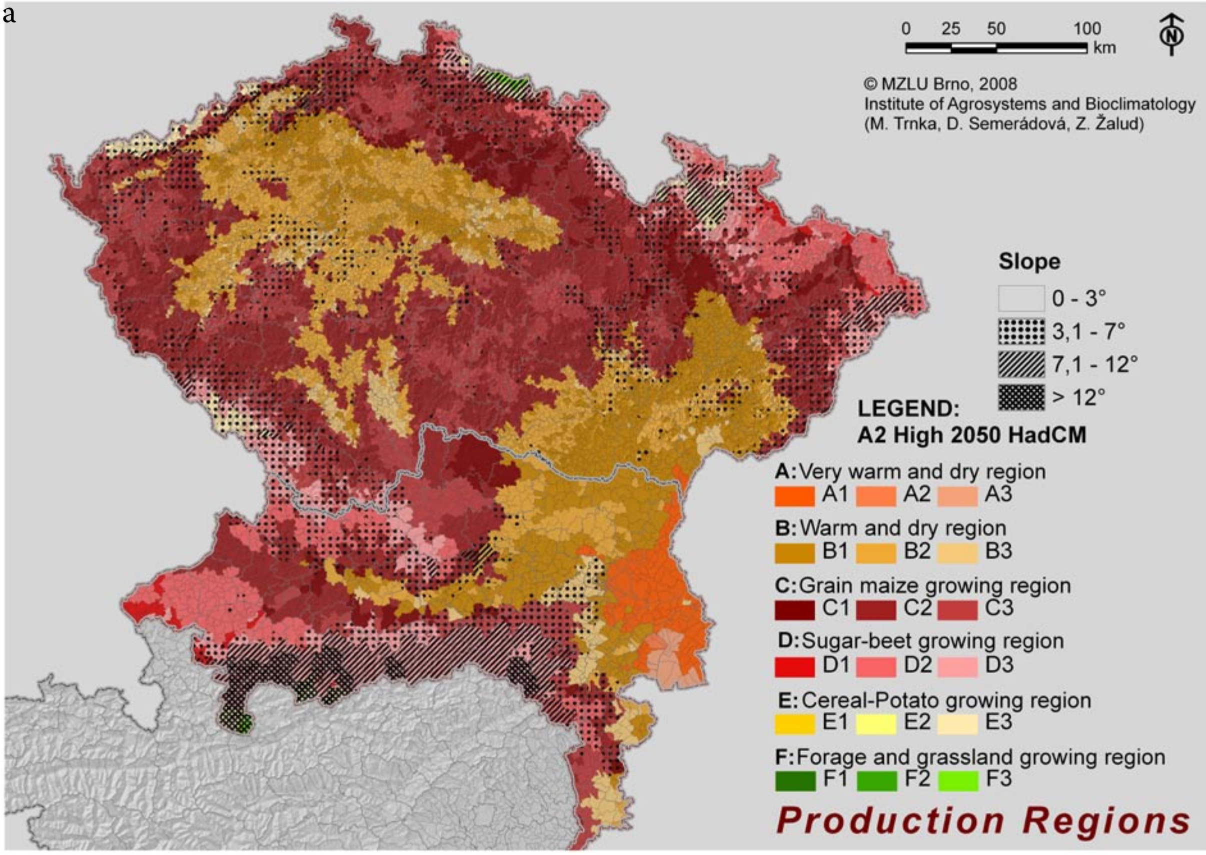
Table 3. Proportion of arable land in the study area belonging to individual production regions and subregions. The values are given for the baseline (1961–1990) and two future periods (centered around 2020 and 2050) for low and high versions of three GCM-based scenarios (HadCM, ECHAM and NCAR)

Region symbol common name	Subgroup based on soil type	Baseline climate 1961–1990	HadCM				ECHAM				NCAR			
			B1-low		A2-high		B1-low		A2-high		B1-low		A2-high	
			2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050
A very warm and dry	A1					2.5				0.8				
	A2					0.1				0.2				
	A3					0.5				1.1				
B warm and dry	B1	0.1		1.4	4.9	12.7		0.1	2.0	8.4	2.8		0.2	4.1
	B2	0.0			0.2	14.3				2.7	0.3			0.2
	B3	0.4		0.5	0.6	3.7		0.1	0.5	2.2	1.6		0.3	0.5
C grain maize-growing	C1	9.0	14.7	13.8	12.0	3.8	13.4	13.6	13.9	9.4	10.0	11.8	12.0	12.8
	C2	2.3	11.1	17.3	27.8	29.2	7.3	11.2	20.4	38.9	7.1	7.0	11.6	21.8
	C3	2.3	2.9	3.6	6.7	13.9	1.9	2.7	4.4	14.5	2.8	1.6	2.1	5.2
D sugar beet-growing	D1	8.1	4.8	4.5	2.8	0.8	6.0	5.8	3.8	1.0	6.7	7.6	7.5	2.7
	D2	14.0	27.4	28.1	21.4	7.6	27.7	29.8	26.3	9.4	27.7	30.8	32.8	24.1
	D3	3.4	7.5	10.2	11.4	9.3	7.9	8.7	10.3	7.7	8.3	9.1	10.9	9.2
E cereal/potato-growing	E1	2.4	0.1	0.0			0.2	0.1	0.0		0.2	0.2	0.0	0.0
	E2	33.5	12.5	5.8	1.7	0.0	16.0	10.0	4.3	0.0	15.9	13.3	6.7	5.0
	E3	12.6	13.9	12.4	9.4	1.8	14.1	14.3	11.6	3.5	12.8	15.0	13.2	11.8
F Forage and grassland growing	F1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	F2	1.3	0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.0	0.0
	F3	10.5	5.0	2.5	1.2	0.2	5.4	3.5	2.4	0.3	3.8	3.6	2.6	2.6

Subgroup 1 includes the most fertile soils, which are primarily used for agricultural production; subgroup 2 includes soils that can be used for crop production, but some sort of amelioration is usually needed and the soils are, in general, less fertile; and subgroup 3 is not in general suitable for crop production these areas is further complicated by complex terrain (Figure 1), which in many cases requires special machinery. Under 1961–1990 climatic conditions, zone B is limited to the very southeast corner of the studied region (in Austria), with only 0.5% of total arable land area (Table 3 and Figure 1). Compared to the work of Němec (2001) based on 1931–1960 climate conditions, we can see a relatively pronounced decrease in the extent of cool and wet zones (E, F) and an expansion of warmer but also drier zones C and D.

The combination of increased air temperature and changes in the amount and annual cycle of precipitation will obviously lead to further shifts in the area (Table 3) and location (Figure 2) of individual agroclimatic zones. Table 3 and Figure 2 indicate that the magnitude of changes depends, to a large extent, on the combination of the SRES scenario, climate sensitivity and GCM used. However, there are some tendencies that are common for all 6 scenarios (B1-low and A2-high versions of scenarios based on three GCMs) tested. In all cases, the area of the agroclimatic zone E 1–3 will be reduced greatly by 2050 (Table 3) and substituted by D, C and, in some cases, by the very dry and warm B zone. According to B1-low scenario, we will experience a relatively slow transition of areas from E to D agroclimatic zones; the change would be much faster according to the A2-high scenario (especially according to HadCM or ECHAM). The proportion of zone F in the studied region will be reduced by half by 2020 and almost entirely gone by 2050 due to large water deficits during the summer (Table 3). This particular change is driven by an increase in evapotranspiration combined with inadequate precipitation during peak of the vegetation period from June to August. This would consequently lead to water deficits and related yield depressions in productive grasslands (Table 3 and Figure 2) during the summer period. At the same time, the mostly poor soil quality in these areas and the topographically complex terrain makes it difficult to adapt alternative production systems to the currently dominant permanent grassland-based dairy farming or forests. Therefore the shifts in the agroclimatic conditions of areas presently belonging to the E and F production zones could lead to higher potential 'climatic' productivity, which will be however difficult to utilize due to unfavorable soil conditions (especially low soil water holding capacity) and accessibility by machinery. At the same time the areas presently belonging among the most fertile zones will decrease their 'climatic' production potential due to increasing drought and heat stress. As to the most productive sub-region, D1, which is climatically close to optimum for rainfed sugar beet production (and suitable for almost any other crop), and which is, besides favorable climate, characterized by good soils and relatively flat terrain, it will be the most significantly influenced by the changes. According to all scenarios the extent of D1 sub-region will be reduced; the reduction from present 8.1% to 0.8–2.7% at 2050 is estimated by A2-high scenario. In parallel with the retreat of the cooler and wetter agroclimatic zones E and F and their replacement by zone D, the rapid expansion of the region C will take place (Table 3). The expansion of the area suitable for maize production in central and northern Europe has been reported also by other studies (e.g. Olesen et al. 2007). As is apparent from Figure 2, zone C will become the dominant zone across the studied region over next few decades. We expect that the shift to the warmer and drier climate of the C region will also lead to lower rainfed potential productivity of summer crops due to higher risk of drought, especially during summer months and especially in the drier regions. This can, depending on soil texture, in many cases combine with restricted soil workability (caused by the lower soil water content) during the summer and increase the risk of soil erosion by heavy precipitation and wind on bare and dry soils. The negative impact of these changes will more likely occur in the Czech Republic, as there are relatively limited possibilities for irrigation, overall water resources are likely to dwindle (Dvořák et al. 1997, Kalvová et al. 2002), and because larger average field sizes are an important factor for soil erosion potential. According to some scenarios (A2-high in combination with ECHAM or HadCM), the migration of agroclimatic zones will continue further with a tendency toward a progressively drier and warmer climate. While the growing season in the warm and dry production regions (A and B) is much longer, the pervasive drought during the summer months will limit rainfed crop farming during the June–August period.

In particular, the time scale of the predicted changes must be underlined. Probably never in the history of agriculture in Central Europe have farmers been faced with such changes of agroclimatic conditions within one generation. This will pose great challenges in terms of appropriate farming strategies (change of crops, crop rotation schemes, cultivation timing and practices or even abandoning some forms of agricultural production). The presented dynamics of the change (when taking a



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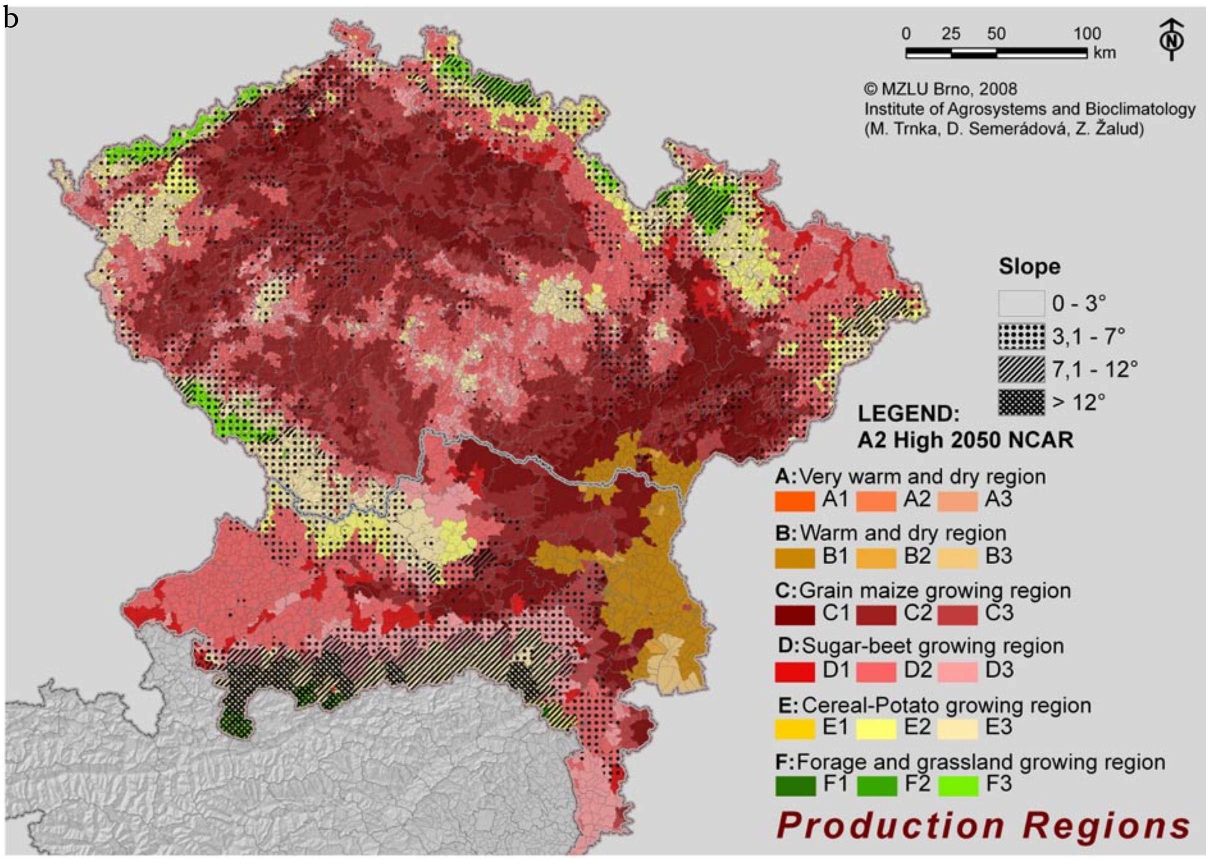

Figure 2. Estimated distribution of production regions for the time slice centered around 2050. Both Figures represent likely distribution of production regions when A2-high scenario is realized. The Figure (a) is based on the HadCM global circulation model while (b) on the NCAR

into account A2-high scenario) also lead us to the conclusion that the concept of static agroclimatic zones as used until now should, in general, be changed to a more flexible and continuous adaptive system that would allow for updates on the scale of decades or even shorter time frames. Finally, we should emphasize that the present results are based on three GCMs, which may seem rather small subset of all GCMs presently available. Hypothetically, if climate change scenarios based on all available GCM simulations would be used in this analysis, it is likely that the between-GCM uncertainties in obtained results would be somewhat larger than those based on the three GCMs used here; however, the main trends would be preserved.

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