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Soil-specific drought sensitivity of Hungarian terroirs based on yield reactions of arable crops

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Abstract— The hypothetical climate change and the stress influences caused by the increasingly frequent found meteorological extremities affect the fertility of soils in even more degree. During our soil-climate sensitivity researches, the expression of the drought sensitivity as a stress influence, evolved as a result of lack of precipitation in soil fertility was studied. During our work, effects of increasing droughts of last decades were investigated through the yield results of the three most important crops, winter wheat (*Triticum aestivum L.*), corn (*Zea mays L.*), and sunflower (*Helianthus annuus L.*), based on the area rate in the Hungarian sowing structure, in relation to the natural geographical microregions and fertility of sites. For the examinations, yield data of the National Pedological and Crop Production Database (NPCPD) were used. The database contains complex plot-level crop production and soil information for 5 years (1985–1989). The examination results prove the considerable drought sensitivity of that lands, where soil types with high sand or clay content can be found. The mainly exposed microregions for the effects of drought are, e.g., the Dorozsma-Majsa Sand Ridge, Kerka Riverscape, Dévaványa Plain etc., while less sensitive sites are e.g. the Enying Ridge, Tolnai-Sárköz, Nógrád Basin etc.

Key-words: physical geograpy microregion, soil-specific drought sensitivity, soil variation, yield, NPCPD ver3.0 database

1. Introduction

The increasing climatic anomalies (extreme precipitation distributions, decreases in annual or seasonal precipitation, and increases in average temperature) resulted in the increase of fluctuation of yields (*Pepó*, 2005). The extreme meteorological situations (*Patrick*, 2002; *Szász*, 2005) can be considered as natural stress effects affected on soils. *Birkás et al*. (2007) considered the stress evolved in soils due to the climate change and the effect-specific replies given to this as the „climate sensitivity" of soils. According to *Nagy* (2005), the evaporation in the plant-soil water management system under semiarid climate circumstances is continuous throughout the growing season, but as a result of climate variability, the distribution of precipitation is not uniform in space and time. The biomass production of soil is highly depended on the water providing ability and water supply, so the water storage characteristics of soils play more and more significant role (*Rajkai*, 2004).

Máté et al. (2009) studied the shifting and changing of Hungarian soil zones occurred as a result of climate change with the help of 120-year-long (1881–2000) data queues of 16 meteorological stations disassembled to 30-year intervals. According to the results, the Atlantic and Mediterranean climatic effects were increased periodically but verifiably both by chernozem and brown forest soils, at the same time, the continental effect was dramatically decreased, especially by chernozem soils. The study concludes that climate, as an important soil-forming factor, is slowly changing the soil types and also the individual soil characteristics.

Csorba et al. (2012) developed 18 mesoregions with the merging of the Hungarian physical geography mesoregions, then investigated the potential future effects of climate change on different meteorological and environmental indicators (drought, inundation, inland water, water erosion, wind erosion, etc.) (*Pálfai* and *Herceg*, 2011; *Van Leeuwen et al.*, 2008; *Rakonczai*, 2011). According to the results it can be concluded, that the expectable change will certainly affects humid habitats (e.g., marsh forests, moss and peat bogs, saline lakes, wet meadows, floodplain forests). In crop production, the drought stress evolved as a result of more and more frequently occurred water deficit and heat-waves resulted in significant yield losses (*Ladányi et al.*, 2014).

The evolution of climatic relations was well supported by the results of *Rácz* (1999). According to his county-scale research, the amount of winter- (from the first half of the 1900s), spring- and autumn- (from the 1950s), and summer- (from the 1980s) precipitation was progressively decreased. From 1983, the seriously drought-damaging areas have been expanding from east and southeast directions towards north and west (*Bocz*, 1995). In the 1981–2000 period, the amount of drought seasons were doubled (increased by 52.6%) on the account of the average seasons (26.3%) (*Pepó*, 2007).

One of the most well-known consequences of extreme warm and low rainfall is the development of drought, which is a complex phenomenon and has many definitions. Meteorological drought is defined as periods of abnormally low rainfall (*Molnár* and *Gácser*, 2014). Lack of rainfall, mainly during the vegetation period, affects natural vegetation (forests, meadows) and crop yields. *Gyuricza* (2007) distinguishes three different forms of drought (atmospheric, physiological and soil droughts). The soil drought, as the most harmful form of droughts evolves when the moisture content of soils was limited to the unavailable water content only. In this case, there are not enough water in the soil for plants. The „soil drought sensitivity" is when certain functions of soils (e.g., water storage and water supplying ability) cannot provide their work as a result of drought periods or considerable lack of precipitation. In crop production it is resulted yield fluctuation (t/ha) (decreasing or, under extreme circumstances, total yield deficit) in different extent in different crops, which expresses in the decreasing of soil productivity.

For the quantification of soil-climatic interactions, the possibilities are limited. With indirect methods, it is possible to conclude to the soil component of the crop fluctuation caused by the climate using multiannual meteorological and yield data registered by different soil parameters. But, in fact, the crop fluctuation caused by the climate has other components also (e.g., phytopathological, physiological); and between the years, there are not only meteorological differences (e.g., differences between the varieties of plants, agricultural game damage, tillage failures, etc.) (*Jolánkai*, 2005; *Pepó*, 2005). *Kismányoky* (2005) estimated a 0.7/0.3 average soil/climate effect ratio determining the amount of yield.

Késmárki et al. (2005) studied the impacts of climate change on the yields of winter wheat, corn and alfalfa in the case of carbonated Danube Fluvisols, near Mosonmagyaróvár, Hungary. According to results, the length of vegetation period has a positive effect on the yield in case of different corn varieties, independently of the seasonal effects, and the soil drought-decreasing role of the subsoil water content. *Varga-Haszonits* and *Varga* (2005) investigated the relationship of the climate and yield of corn in Western Hungary. However, the analysis based on the data queues of meteorological stations and the data of Hungarian Central Statistical Office were not suitable to the accurate assessment of the climate impacts in case of different soil varieties, but they can be used as useful information on the climate sensitivity of the western-Hungarian forest soils. The authors concluded that in the examined area – which is the most humid area in Hungary –, primarily the moisture supply plays a significant role in formation of yield. A weak relationship was found between the length of the vegetation period and yield, which is – according to the authors – referring to the secondary role of the thermic factors in the formation of yield. The moisture conditions were described with a „precipitation-evaporation index” and the yield-decreasing impact of the excessive high and low water supply were presented by an optimum curve.

Harnos N. (2003) and *Harnos Zs.* (2005) investigated the effects of global climate change on the production of winter wheat using simulation models validated by almost 30 years meteorological and yield data of Győr-Moson-Sopron and Hajdú-Bihar counties. According to the results, it can be stated, that even 20% of yield decreasing can occur in the case of the investigated climate change scenarios. *Jolánkai et al.* (2003) investigated climatic and yield data of long-term winter wheat experiments (1996–2002) set on Chernozem soils. They did not found a significant relationship between the annual rate of precipitation and the yield of winter wheat, however, the rate of precipitation in the vegetation period and the average yield showed a close correlation. The extent and fluctuation of yields strongly depended on the applied agrotechnical treatments and the rate of (nitrogen) fertilization.

Pepó (2005) analyzed the seasonal effects on yields in long-time crop production experiments (1985–2003) set on Chernozem and Meadow soils. He established that the impact of climate factors (especially the lack of precipitation) appeared in an interactive and cumulative way in the case of winter wheat (e.g. the unfavorable effects of weather were buffered by the optimal fertilization, or the unfavorable forecrop effect was intensified in drought years). The author reported that the water supply of the crop is a key factor relating to the amount of yield in case of corn, and the favorable fertilization and forecrop effects were ascertainable only by the appropriate water supply. *Kismányoky* (2005) used and analyzed the yield results of decades-long field experiments set on Ramann-type brown forest soil (Keszthely) in terms of climate change. He found that the amount of yield did not decrease significantly in arid years in comparison with average years in case of winter wheat. However, in years, which were wetter than average, the amount of yield was significantly lower, probably due to phytopathological reasons. In case of corn, the yield differences between arid and humid years were substantially higher (the yield of corn in favorable humid years was almost double than the yield in arid years besides the same agrotechnical method). The differences between the two crops were explained by the length of vegetation periods and the precipitation distribution.

Ruzsányi (1996) summarized the crop production effects of drought based on literature data and introduced the drought susceptibility of the 9 Hungarian meteorological districts and the drought sensitivity of the major field crops (corn, winter wheat, sugar beet, sunflower). During the statistical analyzes, average yields concerned to regions and based on statistical data originated from districts, counties, or farms were compared to the amount of precipitation, with the simplification of 4 season types (average, droughty, arid, humid). The different drought sensitivity of the crops and regions were explained, among others, with water management (hydrophysical) properties of characteristic soil types of the regions.

During our research, the effects of natural plant water supplying depended on precipitation and evaporation circumstances on yield results were investigated in the frame of site-scale and physical geography microregion (*Dövényi et al.*, 2010) levels of soil climate sensitivity on the plot-level data of the vectoral National Pedological and Crop Production Database (NPCPD) (*Kocsis et al.*, 2014). The season effect was investigated by crops using the Pálfai Drought Index (PaDI) of meteorological grids ordered to NPCPD plots (*Szalai et al.,* 2014).

2. Materials and methods

The NPCPD contains pedological information about different crop production sites of Hungary (arable land, meadows, pastures, vineyards, gardens, orchards, and forests). The database includes data from about four million hectares of land and their complex crop production of seven years (1984-1990) (*Tóth*, 2001). In addition, it provides time series data about the fertilizer and manure use per field as well as the crop yields of 196 cultivated plant types and their forecrops (*Kocsis et al.,* 2014).

Statistical analysis of the relationship between the soil-crop-seasonal effects were carried out on the basis of the filtered data of the NPCPD (NPCPD ver3.0), so inaccurate records resulting from erraneous data recording were excluded. Moreover, the data queues containing incompatible basic analysis data within each soil subtypes were also excluded. The crop yields were also filtered. Next, the winter wheat, corn, and sunflower yields were normalized to a scale ranging from 1 to 100 (*Eq. 1*):

$$Crop_{100} = 1 + \left(\frac{Crop - Crop_{min}}{Crop_{max} - Crop_{min}}\right) \times 99 \qquad (1)$$

where $Crop_{100}$ is the yield of a certain crop normalized to a 1–100 scale; *Crop* is the yield of a certain crop (t ha^{-1}); $Crop_{min}$ is the minimum yield of a certain crop (t ha^{-1}); $Crop_{max}$ is the maximum yield of a certain crop (t ha^{-1}). The minimum and maximum yield was explained in national level, regarding 5 years (1985–89) of the NPCPD ver3.0.

The normalized yield maps for the three crops were made by seasons with ordinary kriging. In order to carry out annual climate effect analysis, the annual Pálfai Drought Index (PaDI) was assigned to the crop yields (*Eq. 2*). The PaDI is calculated with the monthly mean temperature and monthly precipitation data (*Bihari et al.*, 2012) only using the following formula:

$$PaDI_0 = \frac{\left[\sum_{i=apr}^{aug} T_i\right]/5 \times 100}{c + \sum_{i=oct}^{sept} (P_i \times w_i)} \tag{2}$$

where $PaDI_0$ is the base value of the Pálfai Drought Index (°C 100 mm^{-1}); T_i – is the monthly mean temperature from April to August (°C); P_i is the monthly precipitation from October to September (mm); w_i is a weighing factor; c is a constant value (10 mm). The data related to droughtness are in CARPATCLIM database, where the values of Hungary, apart from the western border, are situated in a meteorological graticule containing 1,045 grid with a spatial resolution of 10×10 km (*Szalai et al.*, 2014). The CARPATCLIM database is a long-term (1951–2010) series of climate data for the Carpathian region, derived from meteorological station measurement data using homogenization and interpolation processes. The dataset contains a number of measured weather parameters, such as meteorological variables, and climate and drought indices (*Lakatos et al.*, 2013). 200×200 m resolution raster maps were generated displaying the extent of drought in the country on the basis of the meteorological grid values per years. Then, the agricultural years of the NPCPD (1985–1989) were characterized by drought category variables assigned to the PaDI values of the drought maps (without drought=<4; light drought=4–6; moderate drought=6–8; medium drought=8–10; severe drought=10–15; very high drought=15–30; extreme heavy drought=>30), on the basis of *Bihari et al.* (2012). Drought-free areas were marked per year and drought-free crop yields were collected. In areas where none of the years under study was drought-free (e.g., the Danube-Tisza Sand Ridge), we considered the yield of the mildest drought year to be drought-free. By combining the drought-free crop yields per plant, we prepared a 5-year drought-free yield map for winter wheat, corn, and sunflower (normalized for a 1–100 scale). These maps can be considered as optimized crop maps, with crop results independent of drought effects.

When generating the soil drought sensitivity index, the difference between the "normal" (actual, not independent of drought) crop yields and the previously determined drought-free crop yields was calculated, then the result was divided with the Pálfai drought index value (*Table 1*).

Table 1. Measured and drought-free yields and their differencies by the investigated crops, in the years of NPCPD database

Years	Normalized 1–100 scale	Winter wheat				Corn				Sunflower			
		PADI categories											
		1.	2.	3.	4.	1.	2.	3.	4.	1.	2.	3.	4.
1985	Measured yields	48.6	59.4	0.0	0.0	57.2	57.2	2.1	0.0	46.4	52.8	0.0	0.0
	Drought-free yields	50.7	58.3	0.0	0.0	57.2	57.6	46.3	0.0	47.5	54.0	0.0	0.0
	Difference	2.1	1.1	0.0	0.0	0.0	0.4	44.2	0.0	1.0	1.2	0.0	0.0
	Number of cases	23647	24051	0	0	21530	22938	1	0	5166	6122	0	0
1986	Measured yields	42.6	50.2	47.9	0.0	57.8	53.7	36.9	0.0	52.1	57.8	61.8	0.0
	Drought-free yields	47.7	56.7	63.5	0.0	56.6	57.7	48.0	0.0	48.0	51.6	58.3	0.0
	Difference	5.1	6.6	15.6	0.0	1.2	4.0	11.0	0.0	4.1	6.2	3.5	0.0
	Number of cases	10935	25589	1083	0	14731	35427	1519	0	2894	9621	515	0
1987	Measured yields	50.2	47.3	49.4	0.0	59.3	47.6	33.8	0.0	47.6	61.0	56.9	0.0
	Drought-free yields	54.3	55.6	53.8	0.0	57.8	57.1	53.7	0.0	51.3	50.7	46.0	0.0
	Difference	4.1	8.3	4.4	0.0	1.5	9.5	19.8	0.0	3.7	10.4	11.0	0.0
	Number of cases	12029	13177	641	0	22703	25164	738	0	5227	6124	493	0
1988	Measured yields	55.6	65.9	70.4	13.2	53.9	47.3	34.8	36.1	47.7	49.9	47.0	46.5
	Drought-free yields	44.4	54.0	65.4	32.0	49.3	58.3	55.5	52.0	40.0	50.7	56.7	58.3
	Difference	11.1	11.8	5.0	18.9	4.6	11.0	20.6	15.8	7.7	0.8	9.7	11.8
	Number of cases	3331	12096	1460	9	1581	32633	6098	16	463	9149	1881	67
1989	Measured yields	60.2	59.3	59.4	0.0	55.7	49.4	54.0	0.0	49.7	49.8	0.0	0.0
	Drought-free yields	54.0	54.2	60.3	0.0	57.9	57.8	43.7	0.0	50.2	54.6	0.0	0.0
	Difference	6.1	5.1	0.9	0.0	2.3	8.3	10.3	0.0	0.5	4.9	0.0	0.0
	Number of cases	8143	4095	122	0	29272	5814	6	0	6906	2220	0	0

Pálfai Drought Index (PaDI) categories: 1. without drought category; 2. light drought category; 3. moderate drought category; 4. medium drought category.

The decision tree technique CHAID (Chi-square automatic interaction detection) was used to classify the results (*Tóth et al.*, 2012) by taking into account the most important soil parameters originated from the NPCPD database (sub-type, soil texture, pH_{KCl}, humus and lime content) from the point of view soil fertility. The NPCPD contains information regarding agricultural fields for 38 soil main types of the total 40, besides, 84 sub-types (*Jassó*, 1989) of the total 86 mentioned in the Hungarian Genetical Soil Classification System. Based on the taxonomic units and measured soil parameters, the database contains totally 8,530 soil varieties on the 76,849 agricultural plots and sub-plots. In case of the used soil-based investigations, the soil texture based on plasticity limit (liquid limit) was determined according to the Arany method (a Hungarian method to estimate soil texture), humus content was determined according to the Tyurin-method, pH_{KCl} was calculated potentiometrically, while $CaCO_3$ content was determined with the Scheibler-calcimeter (*Buzás et al.*, 1988, 1993). The soil investigation data used for estimation was decoded to the soil mapping category system included in the National Large-scale Soil Mapping Guide (*Jassó et al.*, 1989). In this code system, map categories and measuring ranges (e.g. loamy texture, low humus content etc.) are allocated to the soil examination results instead of exact values (*Farkas et al.*, 2009; *Makó et al.*, 2010). Equal-ranking category variables ranging from 1 to 10 were formed from the mean values of the groups estimated with the help of the CHAID method (SPSS/Transform/Visual binning) (*Fig. 1*).

Due to the lack of meteorological and drought index (PaDI) data, soil drought sensitivity index was not computed for the soils located to the west of 17°E – the western frontier of Hungary. The drought sensitivity categories for this area were determined by estimation, and in order to do so, the known soil-type parameters and crop yields from other parts of the country were used. Next, a one-factor analysis of variance (one-way ANOVA) was carried out to see if the previously formed categories differ significantly from each other.

The determined drought sensitivity values were extended to the 230 physical geography microregions with zone statistic. The mapping of the average drought sensitivity values were not performed where the sowing area of corn, winter wheat and sunflower based on the NPCPD in average of the 5 investigated years was under 500 hectares, separately. The numbers following the microregion names represent the microregion codes, which indicate the position of the microregions in the maps presented, based on the nomenclature of Inventory of Microregions in Hungary (*Dövényi et al.*, 2010).

For the vectoral map operations, other GIS applications and geostatistical analyses (i.e. ESRI ArcGIS 10.0 GIS software) were used. For further statistical tests, the IBM SPSS Statistics 18.0 software was used.

3. Results

According to the results, the year 1988 was the driest based on the PaDI index from the years of NPCPD database (*Table 2*). Depending on the crop, moderate drought was observed in the 8.3–17.2% of sowed area in that year. Medium drought was also observed, but the extent of these fields (0.5%) was not significant. Winter wheat was hit in the highest, while sunflower in the lowest extent by water scarcity in 1988.

Table 2. Distribution of Palfai Drought Index by the investigated crops to the years of the NPCPD database.

Plants	Years	PaDI categories (Total area, %)							Field units
		Without drought (<4)	Light drought (4–6)	Moderate drought (6–8)	Medium drought (8–10)	Severe drought (10–15)	Very high drought (15–30)	Extreme heavy drought (>30)	
Winter wheat	1985	45.94	54.06	0.00	0.00	0.00	0.00	0.00	12 963
	1986	28.83	68.06	3.11	0.00	0.00	0.00	0.00	11 115
	1987	44.70	52.99	2.31	0.00	0.00	0.00	0.00	8 801
	1988	22.39	69.28	8.30	0.04	0.00	0.00	0.00	6 706
	1989	59.60	38.99	1.41	0.00	0.00	0.00	0.00	5 276
Corn	1985	48.21	51.79	0.00	0.00	0.00	0.00	0.00	8 093
	1986	29.68	67.15	3.17	0.00	0.00	0.00	0.00	9 501
	1987	49.87	48.66	1.47	0.00	0.00	0.00	0.00	8 916
	1988	5.94	78.08	15.95	0.04	0.00	0.00	0.00	7 467
	1989	82.27	17.64	0.09	0.00	0.00	0.00	0.00	6 421
Sunflower	1985	42.73	57.27	0.00	0.00	0.00	0.00	0.00	2 976
	1986	21.61	73.97	4.42	0.00	0.00	0.00	0.00	3 465
	1987	44.49	51.66	3.84	0.00	0.00	0.00	0.00	3 042
	1988	2.82	79.60	17.15	0.43	0.00	0.00	0.00	2 853
	1989	75.41	24.59	0.00	0.00	0.00	0.00	0.00	2 246

For the adequate water supply of crop production, the most optimal conditions were in 1989, because more than a half (59.6–75.4%) of the fields were drought-free. It can also be stated by the distribution of PaDI-values by different categories, that in 1985 there were not areas affected by moderate drought, so this generated favorable conditions for crop production. In 1986 and 1987, the amount of areas affected by moderate drought by crops were between 2.3 and 4.4%. Considering the investigated 5 years (1985–1989) and the crops together, it can be observed that the amount of slightly drought fields were high; in 1988, which was the driest year, it was 69.3% in case of winter wheat, 78.1% in case of corn, and 79.6% in case of sunflower. The amount of slightly drought fields was between 17.6% and 39% in the least dry year of 1989.

During the formation of drought sensitivity indices, 133 groups (nodi) were separable by the CHAID method. Since the Levene's test of homogeneity showed that the standard deviations are different, the Tamhane's T2 probe was applied by one-way ANOVA. Based on the results of the test, the groups of each category could not be separated from each other explicitly, so certain groups were merged. At the end, Hungarian soils were characterized in 7 different drought-sensitive groups (categories). The determined groups were represented plant specifically in drought sensitivity maps, where the category 1 means the highest, the category 4 means medium while the category 7 means the lowest sensitivity or the non-sensitive soils (*Fig. 1*).

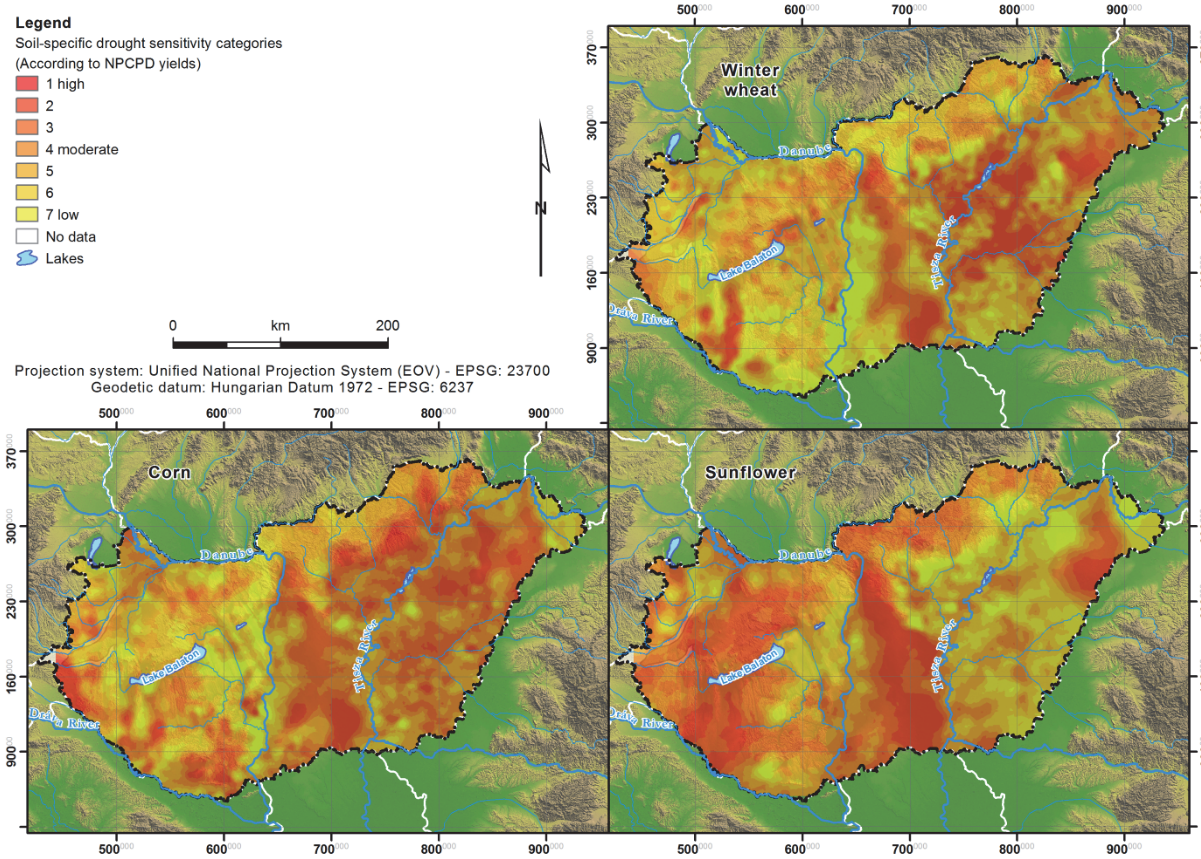

Fig. 1. Soil-specific drought sensitivity maps to the three crops produced in the largest area rate in Hungary.

For winter wheat, among the 230 micro regions, areas with predominantly clayey or sandy soils are the most prone to drought. The extreme drought sensitivity of clay and heavy clay textured soils can be explained with the high amount of plant unavailable water (below the permanent wilting point). Eastern Inside Somogy (4.2.12), Heves Plain (1.9.22) and Bihar Plain (1.12.21) proved to be medium drought sensitive areas. By winter wheat, Tolna Sárköz (1.1.24), Cserhátalja (6.3.24), Mohács Island (1.1.25) and Nyárád-Harkány Plain (1.5.13) microregions are the least drought sensitive areas (*Fig. 2*).

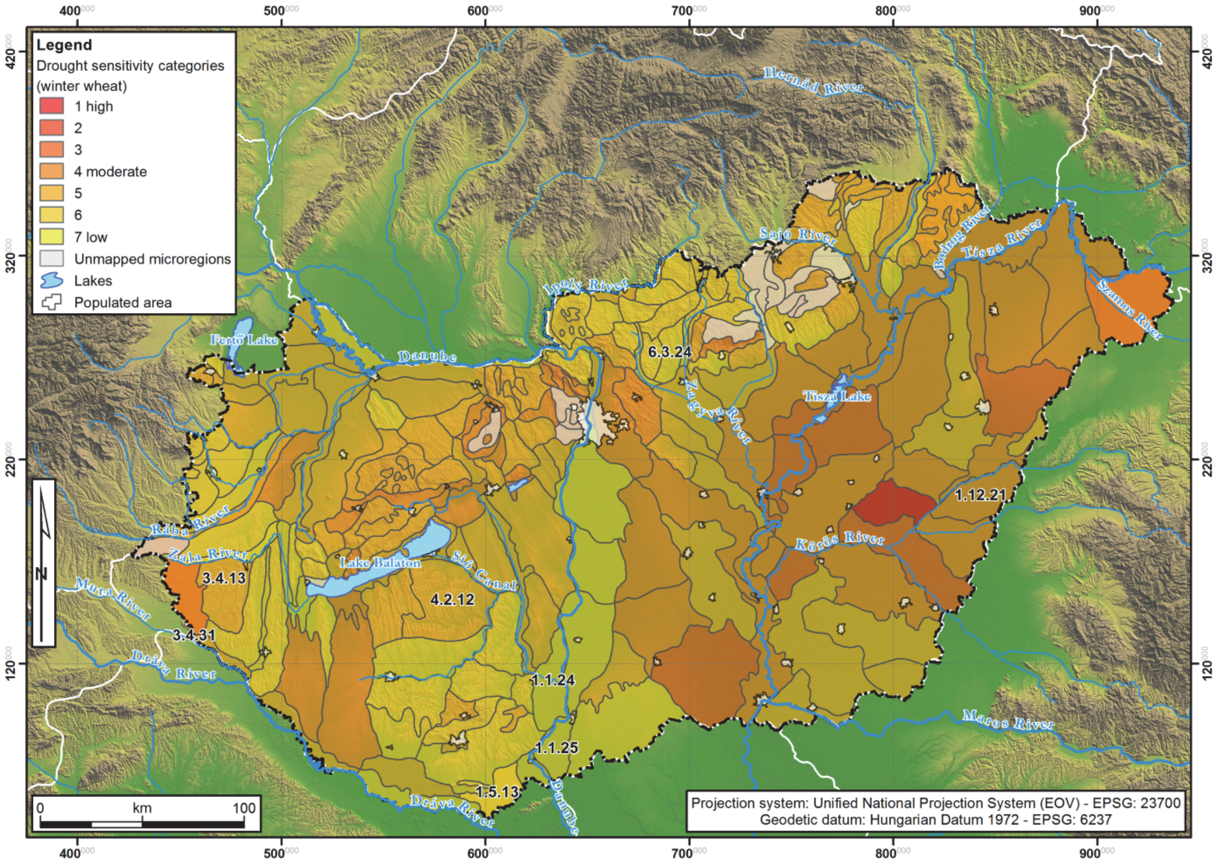

Fig. 2. Soil-specific drought sensitivity of the microregions of Hungary, according to the yield rates of winter wheat.

In case of corn, based on the average drought sensitivities, it can be concluded that the Kerka Riverscape (3.4.12), Westhern Mátraalja (6.4.22), Dorozsma-Majsa Sand Ridge (1.2.15) and Westhern or Loess Nyírség (1.10.21) are the most sensitive areas in term of drought sensitivity (Fig. 3). At less extent than the previous areas, but the Miskolc Bükkalja (6.5.23), Harangod (1.9.33), Dévaványa Plain (1.12.11), Bugac Sand Ridge (1.2.14), Érmellék Loess Ridge (1.12.14), Western Cserehát (6.8.54), Kiskunság Sand Ridge (1.2.13), Eastern Mátraalja (6.4.21), Southeashern Nyírség (1.10.13) microregions are also sensitive at high extent.

In case of corn, there are medium drought sensitive soils in the middle mountains and their basins, as well as in Bereg Plain (1.6.11), Szatmár Plain (1.6.12), Sárrét (1.4.23) and Baranya Mountridge (4.4.12) microregions. The non-drought sensitive areas can be found in the Soutern Mezőföld (1.4.25), Tolna Sárköz (1.1.24), Enying Ridge (1.4.31), Káloz-Igar Loees Ridge (1.4.32), and Litke-Etes Hills (6.3.42) microregions (*Fig. 3*).

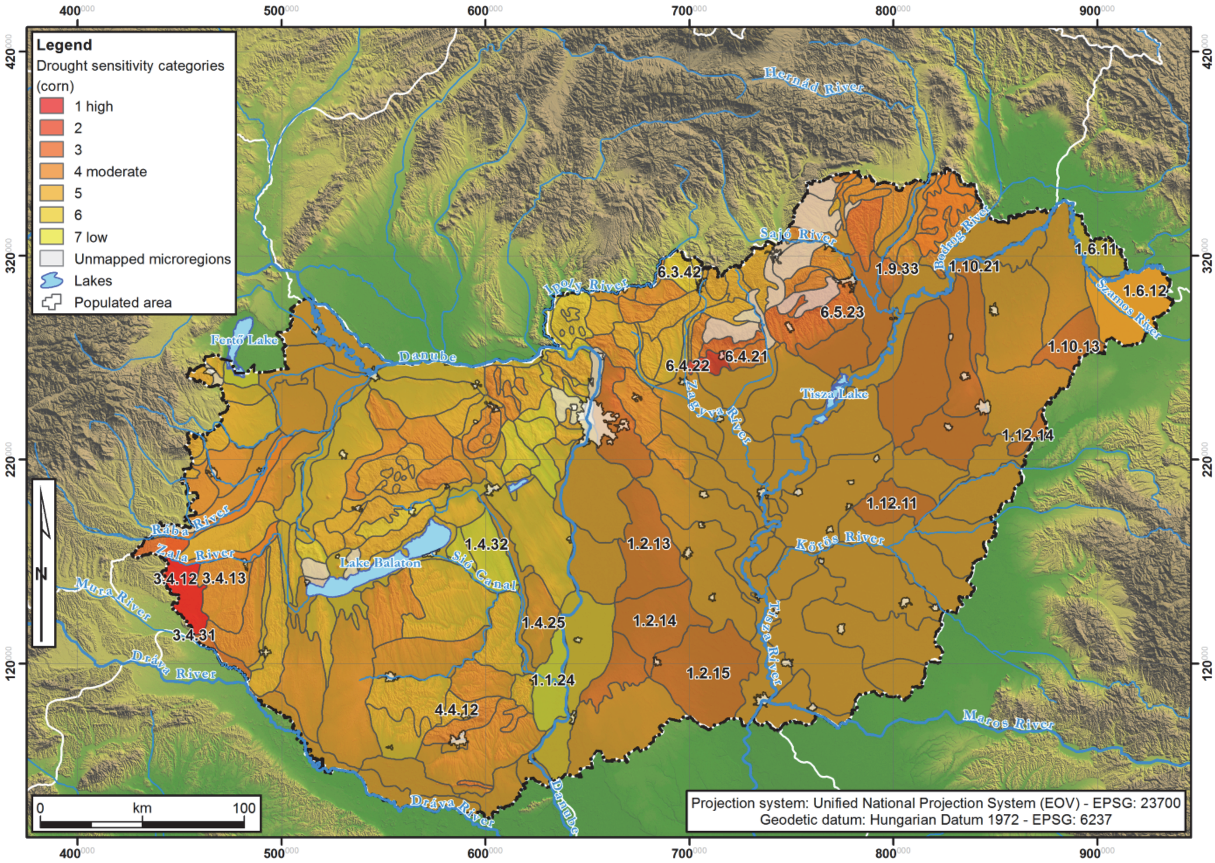

Fig. 3. Soil-specific drought sensitivity of the microregions of Hungary, according to the yield rates of corn.

In case of sunflower, signifcantly the sand fields are sensitive at the highest extent to the droughty meteorological periods. This sensitivity can be traced back to the disadvantageous characteristics of the soils formed there (good water conductivity, bad water holding characteristics). The great Hungarian sand areas, e.g. Marcali Ridge (4.3.11), Kemenesalja (2.2.12), Ikva Plain (3.2.11), Szigetköz (2.1.11) etc. have less sensitivity (Fig. 4). The results confirmed the conclusion of *Frank* (1999) for the terrain, whereas the cooler mountains and close basins are not suitable for sunflower production.

Related to the plant specificity, it can be stated that while in case of winter wheat the area of Mohács Island (1.1.25) was not drought-sensitive, simultaneously in case of sunflower, high drought sensitivity was observed. In case of sunflower there are medium drought sensitive areas, e.g. the Enying Ridge (1.4.31), Csanád Ridge (1.13.11), Sió Valley (1.4.33), Békési Ridge (1.13.12) and Jászság (1.7.15) microregions. According to the examinations, in case of sunflower the areas of Bereg Plain (1.6.11), Szatmár Plain (1.6.12), Harangod (1.9.33), Westhern or Loess Nyírség (1.10.21) microregions were not (or at very small extent) drought sensitive (*Fig. 4*).

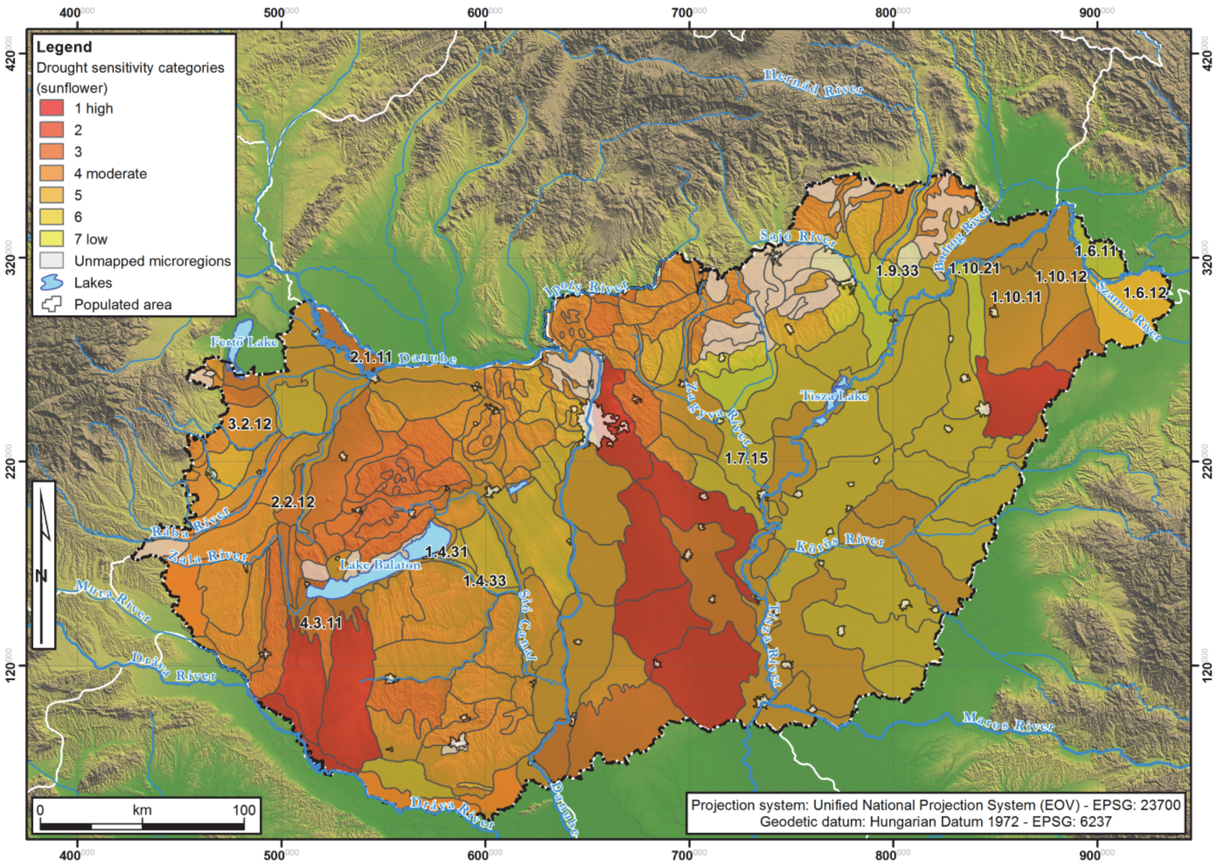

Fig. 4. Soil-specific drought sensitivity of the microregions of Hungary, according to the yield rates of sunflower.

For all three plants, it can be generally stated that among different soil types, Brown forest soils, Chernozem soils, Marsh soils, Alluvial and Slope deposit soils are the least sensitive for drought (*Fig. 5*). The highest drought sensitivity can be observed in soil types with high sand content and in saline soils which have extreme water properties. Sandy soils belonging to the Skeleton soils have very low humus content (e.g. Inside Somogy, Duna-Tisza Interfluve Sand Ridge, Nyírség), their fertility is also low. Increasing drought sensitivity of soils with high humus content can be explained with the combined effect of other soil properties (texture, pH, humus- and lime content etc.). As a result of high clay and unavailable water content, drought sensitivity of soils with high humus content can be higher. It is presumably formed as a result of the combination effect of the soil variety attributes. However, clay expresses the opposite effect, because it can protect the organic material from the rapid decomposition with surface bonding. In case of the given soil types, the relationship between humus- and clay content and effects evolving together was determined by the amounts and qualitative composition of these two materials. Due to the „double role" of clay, it is hard to determine how and to what extent can a certain soil attribute takes part in the combined effects forming together the response of soils to the stress effects caused by drought. Meadow soil types are medium sensitive for natural water supply.

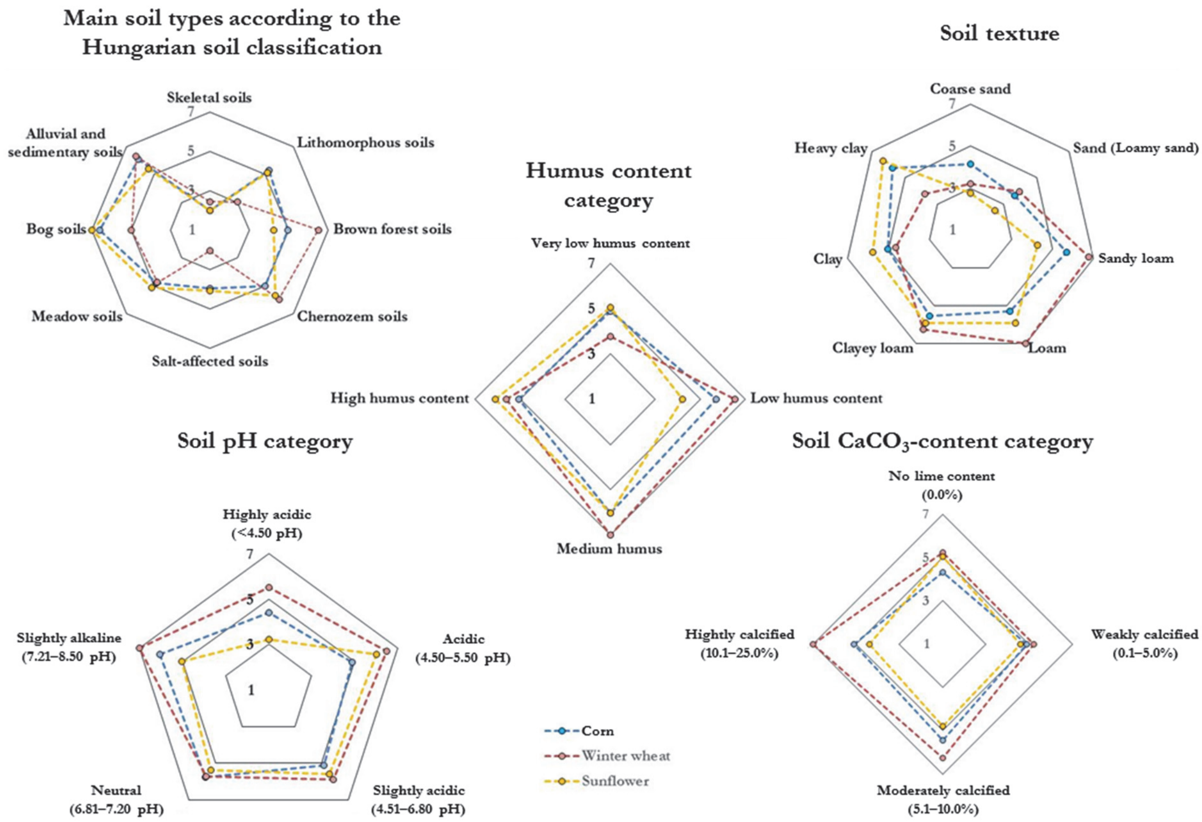

Fig. 5. Distribution of the drought sensitivity categories based on the examined soil parameters in case of the three most important crops. Cross-lines show the drought sensitivity categories: 1–extremely high drought sensitivity, 3–moderate drought sensitivity, 5–favorable drought sensitivity, 7–very low drought sensitivity.

The maps constructed to winter wheat and corn (*Figs. 2* and *3*) well demonstrate the statements of some authors (*Pepó*, 2007; *Jolánkai* and *Birkás*, 2009) that in the past decades the drought observed in Hajdúság, Nagykunság and Körös-Maros Interfluve became more and more severe because of the more and more serious (in average 200–300 mm) lack of precipitation. As a result, high yield deficit can be observed. Not only the increasing of drought periods and their seriousness can be problematic, but the increasing of the mean temperature can also cause the increase of drought. According to our estimations and based on the data of the investigated period (1985–1989), the latter can be observed in the southwestern part of Hungary, in the area of the Kerka Riverscape (3.4.12), the left riverside of the Mura (3.4.31) and in the Central Zala Hills (3.4.13) (where the most rainy places are situated in Hungary), where in average 800 mm precipitation is available (*Varga-Haszonits* and *Varga*, 2005).

In the regions, where the Mediterranean climate effects are intensified, according to the 30 years (1980–2010) data queue of the Hungarian Meteorological Service (*Bartholy et al.*, 2011), the mean summer temperatures has been increased with 2°C in average. The latter was verified by the climate sensitivity researches of *Máté et al.* (2009), whereas the Hungarian soil zones are shifting, and in certain areas, the Mediterranean climate effects become dominant on the account of continental effects. The drought sensitivity of low fertile, strongly acidic brown forest soils (with clay illuviation, pseudogley) situated in the southwestern part of Hungary can increase by the fact that these soil types were formed on fluvial alluvial gravel-sandy parent material and they are loamy textured, which types have bad water storage capacity. The yield fluctuations and depressions evolved to the joint effect of stress caused by the drought (longer and higher extent water deficit periods, increasing mean temperature) and the very extreme precipitation distribution may get worse in the next decades.

High drought sensitivity is clearly detectable in the microregions where strongly acidic soils can be found. Medium-acidic and pH-neutral soils can tolerate the stress effects caused by lack of water at medium extent (*Fig. 5*). The examination results of lime content are also confirmed this (*Késmárki et al.*, 2005): generally the pH-neutral soils and soils with medium lime content have the best drought-resistance ability. The appropriate carbonate content with neutral pH resulted in structure stabilization. The high amount of Ca-bridges evolved from carbonate can allow the formation of appropriate amount of organomineral complexes in soil, which can be favorable in terms of formation of ideal agronomical soil structure. Tendencies of forming crusts can decrease, and as a result of this, possibility of cultivation can be better, and the precipitation can pass into the surface and can settle there. These can favorably influence the water management of soils, high-quality organic matter can form, the nutrient turnover becomes optimal, and the efficiency of nutrient supply can increase. These positive effects can decrease or even neutralize the harmful effects of drought.

Assorting the microregions by the soil's texture, it can be observed that the sandy soils are the most drought sensitive, while the loam and clay loam soils are the least sensitive soils, which harmonizes with the scientific results of

Gyulai and *Nagy* (1995). The drought sensitivity is slightly increased in case of clay soils. Research results of *Csorba et al*. (2012) are proved the drought sensitivity of clay soils, whereas the drying caused by climate change can remarkably affect the wet and clayey sites situated in the Hungarian Great Plain.

4. Conclusions

Results of the investigation confirm that the drought sensitivity of the soils is different by plants, which can explain the different water demands and vegetation periods of corn, winter wheat and sunflower.

It is determinable that winter wheat is a shallow-rooted (20–30 cm) plant, so it can utilize only that water stock which is stored in the upper soil layer. Theoretically, it is sensitive to periods having insufficient amount of precipitation, but as a plant sowing in October, it can manage with the autunm-winter precipitation as well. Corn and sunflower are more sensitive to the spring arid periods than the cultures which are sown in autumn. The roots of corn and sunflower can reach to 2–3 meters deep in the soil, so across the capillary pores, they can easily obtain the moisture situated in the deeper soil layers.

During our fertility investigation, we subjectively selected some important soil properties only. The investigated soil parameters determine the drought sensitivity of soils through unascertained mode of action together with the other, uninvestigated attributes. The results are suited for demonstration of the main tendencies only.

As for future research direction, making more precise drought sensitivity indicators are planned on the basis of the strong relationship between the precipitation of the vegetation period and crop yields as determined by *Jolánkai et al*. (2003) and on the basis of meteorological datasets for the vegetation period. We would like to investigate the relation between the soil drought sensitivity indicators and the applied agrotechnical methods and the nutrient management – how the drought sensitivity depends on the applied agrotechnical methods, the effect of forecrop and the application of fertilizers.

The large scale (national) soil fertility research creates the possibility of preparing 1:10,000 scale climate sensitivity maps of crop production sites, which could contribute to the soil- and plant-specific crop production, that can adapt to climate change.

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