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## Estimation of the drought sensitivity of Hungarian soils based on corn yield responses

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### ABSTRACT

During our soil-specific drought sensitivity research, an aim of ours was to ascertain how drought, a stress factor caused by the lack of precipitation, affects soil fertility. We used the five-year-long (1985–1989) soil and corn yield data of the National Pedological and Crop Production Database (NPCPD). We assigned the annual Pálfi Drought Index (PaDI) to the annual corn yield data of the NPCPD in order to identify drought-free corn yields and production areas. We determined the drought sensitivity of soils by comparing drought-free and annual yields. Based on the results of our statistical analyses, we created a seven-point drought sensitivity scale of soil types, based on which we produced a national soil-specific drought sensitivity index map. Our results may provide a good starting point for constructing large-scale (1: 10,000) climate sensitivity soil maps of agricultural lands, which can assist with soil-specific crop production that also adapts to climate change.

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Soil-specific drought sensitivity index; annual effect of climate; soil varieties; corn yield; NPCPD ver3.0 database

## 1. Introduction

Potential soil fertility and the environmental impacts affecting it can be explained and predicted with different accuracy by employing a variety of methods (Van Diepen, Van Keulen, Wol, & Berkhout, 1991). Nowadays it is possible to estimate and model the fertility of an agricultural land by applying different geo-statistical and GIS methods. Research into this direction began in the 1970s, and, in modern land evaluation practice, especially the results of European researchers allowed classifying agricultural lands into categories on the basis of their real soil fertility (Beek, 1978; McRea & Burnham, 1981; Olson, 1974). In order to classify arable lands, fertility estimations based on quantifying significant soil properties and using IT applications were made by Bouma & Bregt first (1989), who were followed by Wagenet and Bouma (1993), then Hack-ten Broeke, Van Lanen, and Bouma (1993). Lots of authors aimed at quantifying the attribute information of digital soil maps as well as harmonizing pedological datasets on the basis of uniform scales (Agbu & Olson, 1990; Beckett & Webster, 1971; Boehm & Anderson, 1997; Gaston, Nkedi-Kizza, Sawka, & Rao, 1990; Mahmoudjafari, Kluitenberg, Havlin, Sisson, & Schwab, 1997; Thompson, Bell, & Butler, 1997; Webster, 1985; Schellentrager &

Doolittle, 1991). Warrick and Nielsen (1980) made spatial estimation for the soil properties of areas not having been studied before on the basis of small-scale soil map data. As a result of their research, they concluded that certain properties of the same soil types can exhibit great spatial heterogeneity. Inaccurate soil map data can be improved by different point estimation procedures. Over the past four decades, different interpolation and kriging methods were often used to spatially extend the point data of soil properties (Burgess & Webster, 1980; Journel & Huijbregts, 1978).

Soil mapping has had a long-standing tradition in Hungary (Stefanovits, 1992; Várallyay, 1989, 2012), and these works provide a great amount of pedological information. At the same time, these data have not been evaluated and analysed in relation to environmental protection (Sisák & Bámer, 2008), although digital soil mapping procedures would provide an opportunity to carry out complex analyses. The National Soil Strategy (Németh, Stefanovits, & Várallyay, 2005) as well as the INSPIRE directive of the EU (EC, 2007) also address and encourage their use.

Several authors have highlighted that in recent years there has been an increasing demand for soil-related information coming from other scientific areas besides

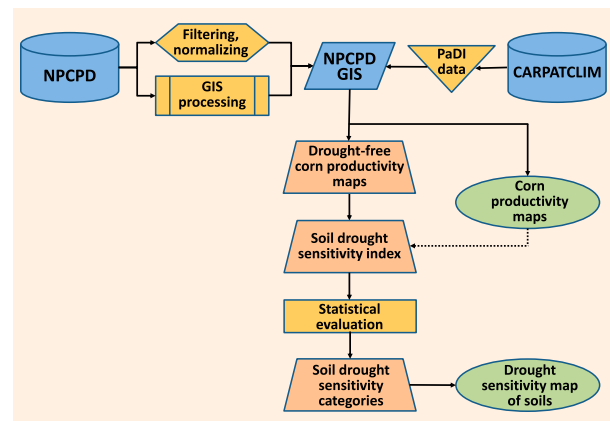
soil evaluation (Behrens & Scholten, 2006; McBratney, Mendonca Santos, & Minasny, 2003; Szabó, Pásztor, & Bakacsi, 2005). Digital soil mapping methods, the development of GIS, and increasing accuracy of spatial details allow a more accurate classification of soils (Tóth & Máté, 2006) and their highly detailed analysis. GIS tools and methods as well as the development of pedological information allow the integration of existing maps and other soil databases (Bakacsi, Laborczi, Szabó, & Takács, 2014; Behrens & Scholten, 2006). Digital soil mapping and its wide range of applications offered by the faster and faster progress is highly prevalent nowadays (Pásztor, Szabó, Bakacsi, & Laborczi, 2013; Pásztor, Szabó, Bakacsi, & Laborczi, 2014; Szatmári & Barta, 2013). The means, instruments, and the application possibilities of soil mapping is described in Pásztor and Takács's 'Remote sensing in soil mapping' article (2014) in detail.

Extreme weather events nowadays that occur as a result of climate change are causing unequal rainfall distributions, which can cause drought, among other things. The droughty periods appear more often and they take longer and longer in the last 40 years, moreover, their impact is also increasing, which is a growing problem for agriculture. It influences negatively the soil fertility through natural water supply. Different soils react differently to the stress effects evolved as a result of lack of precipitation, so their drought sensitivity will not be the same. The method prepared by us examined the drought sensitivity in a novel approach through the soil-specific yield reactions of different seasonal effects with the help of yield maps. Our investigations corn culture was chosen because in Hungary, together with winter wheat, corn has the biggest growing area among arable crops. Besides, corn is one of the most drought sensitive crops.

## 2. Materials and methods

### 2.1. National Pedological and Crop Production Database (NPCPD)

The NPCPD contains pedological information about different crop production sites of Hungary (arable land, meadows, pastures, vineyards, gardens, orchards, and afforested agricultural sites). The database includes data from about four million hectares of land and their complex crop production of five years (1985–1989) (Debreczeni et al., 2003; Makó, Tóth, Máté, & Hermann, 2007; Tóth, 2001; Tóth & Máté, 2006). In addition, it provides time-series data about fertilizer and manure use per field as well as the crop yields of 196 cultivated plant types and their forecrops (Kocsis, Tóth, Berényi Üveges, & Makó, 2014). The soil and corn yield data of the GIS-based NPCPD database were used for the determination of the microregional soil drought sensitivity values. The process of this task is shown on Figure 1.



**Figure 1.** Forming of soil drought sensitivity indices from the geocoding NPCPD database information. NPCPD: National Pedological and Crop Production Database; PaDI: Pálfi Drought Index; CARPATCLIM: Climate of the Carpathian Region Database.

### 2.2. Processing of the NPCPD database

Statistical analysis of the relationship between the soil/corn/seasonal effect was carried out on the basis of the filtered data of the NPCPD (NPCPD ver3.0). Inaccurate records resulting from erroneous data recording were excluded. For this reason, the filtered database used in our analyses currently consists of 321,915 data rows, and it provides information about 76,849 crop production units of 2,970,895 hectares of agricultural land on a mean annual basis. We also filtered the corn yield due to the elimination of the interfering effect of inappropriate and raised yield data. Then, we calculated the mean national corn yield and the standard deviation of the yields. We also assessed the double of the standard deviation of the yields both in the positive and negative directions. We excluded the yields that exceeded the double standard deviations in both directions.

Next, we normalized the corn yields due to the easier interpretability of the results and comparability to other crops to a scale ranging from 1 to 100 (equation 1):

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

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 ( $t\ ha^{-1}$ ). We carried out our analyses on the NPCPD (ver3.0) database consisting of 56,774 records of information about corn, which includes 11,349 fields and parcels on a five-year average as well as 613,156 hectares of arable land; all of which includes a total of 249,862 soil sampling locations.

### 2.3. GIS processing of the NPCPD

We converted the TIEDIT (Unified Digital Map of Hungarian Land Use Information) XY coordinates of the NPCPD soil-sampling sites into the HD 1972 Unified National Projection System (EOV in Hungary) in accordance with a method developed by us (Kocsis et al., 2014). The TIEDIT mapping system developed in the mid-1970s was also used for military purposes to a certain extent, furthermore, the mapping database called the Landcover System of Hungary was also based on this system (Domokos, 2004). The TIEDIT coordinates contain artificial distortions, as a result, their projections are dimensionally not stable concerning bigger areas. Their inaccuracy originating from artificially generated distortion may as well reach several kilometres (Kiss, Jordán, Detzky, & Vártesy, 2013). Based on our experiences, the TIEDIT coordinates shift 3–5 km to southeast in the western, and 3–5 km north-west in the eastern part of Hungary. Due to the distortions, we could not transfer the TIEDIT coordinates directly into the EOV projection system, so their conversion was carried out in two steps. Firstly, we used sampling sites with known EOV coordinates to perform an approximate inversion with linear regression fit, and, secondly, we performed the accurate geo-referencing of the soil-sampling sites. In order to do so, we used the 1: 100,000 scale CORINE Land Cover (CLC2000) database from 2000 (Büttner & Maucha, 2006; FÖMI, 2012), and the DTA-50 (Digital Mapping Database, scale: 1:50,000) database renewed in May 2000, which contains the data describing the hydrography of rivers and lakes as well as the administration (country, state, urban) boundaries.

### 2.4. Creating corn productivity maps

We created the yearly corn yield maps by ordinary kriging. The spatial extension of corn yields was carried out by estimating the crop produce of other 20 surrounding soil sampling points of each and every NPCPD soil sampling points. When kriging the maps based on the point estimations, we applied the highest spatial smoothing value of 0.5 (Map 1 (Main map)).

### 2.5. Construction of drought sensitivity map of soils for corn

In order to carry out annual climate effect analysis, we assigned the annual Pálfaí Drought Index (PaDI) to the corn yields. The PaDI is commonly used to quantify droughts in Hungary. It was developed in the 1980s, and it characterises the drought strength of an agricultural production year with a single numerical value (Equation 2). The PaDI is defined with only the monthly mean temperature and monthly precipitation data (Lakatos, Szentimrey, Bihari, & Szalai, 2013). We

modified the calculation of the drought index for practical applicability (Bihari et al., 2012). Based on this change, the base value of the Pálfaí Drought Index can be calculated by using the following formula:

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

where:  $PaDI_0$  – is the base value of the Pálfaí Drought Index ( $^{\circ}\text{C}/100 \text{ mm}$ );  $T_i$  – is the monthly mean temperature from April to August ( $^{\circ}\text{C}$ );  $P_i$  – is the monthly precipitation from October to September (mm);  $w_i$  – is a weighing factor;  $c$  – is a constant value (10 mm). The drought index data used in the present study were acquired from [www.carpatclim-eu.org](http://www.carpatclim-eu.org) website.

The Word Geodetic System 1984 (WGS84) projection vector files contain information on drought, where the values of Hungary, apart from the western frontier, are situated in a meteorological graticule containing 1,045 grids with a spatial resolution of  $10 \times 10 \text{ km}$ . The grid data were converted from the WGS84 coordinate system into the EOV projection.

We generated  $200 \times 200 \text{ m}$  resolution raster maps displaying the extent of drought in the country on the basis of the meteorological grid values per years. Then we assigned category variables to the PaDI values of the drought maps on the basis of Bihari et al. (2012), which we used to characterize the agricultural years of the NPCPD (1985–1989). Drought-free areas were also marked per year, and by merging these areas, we produced the drought-free area map of the 1985–1989-period (5 years). Where we could not mark any drought-free areas concerning the NPCPD years (eg. the Danube-Tisza Sand Ridge), we worked with the most moderate (mild) drought category.

The latter map helped us to determine the drought-free corn yields of the NPCPD years normalized for a 1–100 scale, which is independent from the annual effects of weather conditions. Then, for our statistical analyses, we assigned the values of the krigged corn yield maps as well as the raster values of the PaDI drought map to the GIS file of the NPCPD ver3.0.

When generating the soil drought sensitivity index, we calculated the difference between the ‘normal’ corn yield and the previously determined drought-free corn yield, then we divided the result with the Pálfaí drought-index value. We used the decision tree technique CHAID (Chi-square automatic interaction detection) to classify the results (Makó, Tóth, Kocsis, & Hernádi, 2013; Tóth, 2010; Tóth, Makó, Guadagnini, & Tóth, 2012) by taking into account certain soil parameters (sub-type, texture, pH, KCl value, humus and lime content). As a result, 133 groups (nodes) were determined. We formed equal-ranking category variables ranging from 1 to 10 from the mean values of the group estimated with the help of the CHAID method (SPSS/Transform/Visual binning).



Next, we applied an one-factor analysis of variance (Oneway) to see if the previously formed categories differ significantly from each other. Since the Levene's test of homogeneity showed that the standard deviations are different, we applied the Tamhane's  $T_2$  probe. Based on the results of the test, the groups of each category could not be separated from each other explicitly, so we merged them. In the end, we could characterize Hungarian soils with 7 different drought-sensitive groups (categories). The determined drought sensitivity values were extended to the 230 physical geography microregions (Dövényi et al., 2010; Csorba et al., 2018) with zone statistic.

Due to the lack of meteorological and drought index (PaDI) data, we could not compute soil drought sensitivity index for the soils located to the west of 17° E – the western frontier of Hungary. We determined drought sensitivity categories for this area by estimation, and in order to do so, we used the known soil-type parameters and corn yields from other parts of the country (Map 2 (Main map)).

### 3. Results and conclusions

According to the data provided by the geospatial NPCPD ver3.0 database (Kocsis et al., 2014), the crop maps of the agricultural years (1985–1989) show that the highest corn yields can be attributed to chernozem soils depending on the annual effect of climate (Pepó, 2005; Szász, 2005). On the basis of the calculated mean PaDI values, the years 1985 and 1989 were drought-free periods, while the interim three years were slightly dry. The corn yield maps of 1985 and 1988 represented in Map 1 shows the best corn-growing sites of Hungary, which are as follows: Kaloz-Igari Loess Ridges (1.4.32), Szigetköz (2.1.11.), Central Mezőföld (1.4.21), Southern Mezőföld (1.4.25), Tolnai-Sárköz (1.1.24), Békés Ridge (1.13.12), Csanád Ridge (1.13.11), Hajdúhát (1.11.11), Southern Hajdúság (1.11.12), and other subregions.

1989 was a drought-free year on average, since the Mohács Terraced Plain (1.1.26), Hatvan Plain (1.9.11) and the Tápíó Riverscape (1.9.12) had outstandingly high yields compared to the other years. High-yielding corn fields are situated on former or current alluvial fans, and on soils with loess parent material, soils with loam and clay-loam physical properties, and soils with appropriate water management. 1988 proved to be the driest of the slightly dry years (based on the mean national PaDI value of 5.28), since most of the ideal crop-producing areas had unusually low yields. High yields characterized only some subregions (Map 1), for example, Hajdúhát (1.11.11), Southern Hajdúság (1.11.12), Érmellék Loess Ridge (1.12.14), and Csanád Ridge (1.13.11). The other annual yield map also shows (Map 1) that yield differences between wet and dry years are significantly

greater (Kismányoky, 2005). In general, the lowest corn yields were found on sandy soil types (Dorozsma-Majsa Sand Ridge (1.2.15)), and on highly clayey soils (eg. Körösmenti Plain (1.12.23), Small Sárret (1.12.22)).

The map displaying the drought sensitivity of soils for corn (Map 2) also shows that the corn yields of the Central Great Plain are significantly affected by the limited amount of available water, which comes from precipitation and soil moisture (Csajbók, 2000; Jolánkai, Szentpétery, & Szöllősi, 2003). The past few decades are characterized by more and more serious drought, which affects the eastern and the south-eastern parts of the country with an absence of 200–300 mm of precipitation on average (Bocz, 1995; Jolánkai & Birkás, 2009; Márton, 2002; 2005; Molnár, 2006; Pepó, 2007; Sárvári, El-Hallof, & Molnár, 2006). It is reflected in greater crop yield deficit on the more drought-sensitive soils. Crop deficit can also be observed in south-west Hungary: in Kerka Riverscape (3.4.12), the left riverside of the Mura (3.4.31), Central Zala Hills (3.4.13) and Vas Ridge (3.1.32) (Map 2), which is the wettest region of the country with an average rainfall of around 800 mm (Varga-Haszonits & Varga, 2005). The Mediterranean climatic influence is increasing in this area, and, according to the 30-year long (1980–2010) time-series data of the National Weather Service (Bartholy et al., 2011), summer mean temperatures have increased by an average of 2 °C. The latter change is confirmed by Máté, Makó, Sisák, and Szász (2008, 2009), whose research on the climate sensitivity of soils found that Hungarian soil zones shift, and, in addition, the Mediterranean climatic influence becomes dominant at the expense of continental influence in some areas.

The drought-sensitivity of, highly acidic (clay illuviation and pseudogley) forest soils with low fertility found in south-western Hungary may be further strengthened by the fact, that the parent material of these soils is alluvial material (gravel) and they are often sandy and sandy loam type soils with poor water retention capability (Table 1). The drought sensitivity of clayey soils is proved by the research results of Csorba et al. (2012), who found that the croplands with mostly wet and highly clayey soil types located in the Great Plain (Map 2), for example, Southern Tisza Valley (1.8.12), Small Sárret (1.12.22) Körös Riverscape (1.12.23), are significantly affected by climate-change-induced drought.

The method we developed for corn, unfortunately, is not suitable for taking into account the cumulative effects of adverse weather factors, because we did not include the extent of the previous year's water shortage in our calculations. As for future research direction, we intend to make more precise drought sensitivity indicators on the basis of the strong relationship between the precipitation of the vegetation period and crop

**Table 1.** Distribution of soil specific drought sensitivity categories according to main soil types and soil texture for corn.

Distribution of drought sensitivity categories (%)		1	2	3	4	5	6	7
Soil parameters								
Main soil types according to the Hungarian Soil Classification	Skeletal soils	80.9	0.0	3.2	13.9	0.6	0.3	1.2
	Lithomorphous soils	10.9	2.7	0.0	64.3	6.2	0.0	15.9
	Brown forest soils	9.8	15.5	16.7	19.3	15.5	16.9	6.4
	Chernozem soils	6.4	14.6	11.5	39.8	11.1	6.9	9.8
	Salt-affected soils	45.2	0.0	16.1	8.3	1.4	25.3	3.7
	Meadow soils	12.4	4.6	13.7	48.7	9.2	2.7	8.7
	Bog soils	19.3	0.0	1.0	15.8	0.0	13.2	50.8
	Alluvial and sedimentary soils	10.3	0.9	2.6	43.4	1.2	8.5	33.2
Soil texture	Coarse sand	44.7	0.7	14.8	20.3	0.0	6.8	12.7
	Sand	41.4	3.6	23.5	20.8	4.1	3.4	3.2
	Sandy loam	7.6	0.2	23.9	35.7	7.9	20.6	4.2
	Loam	6.0	25.5	6.5	23.3	25.4	3.7	9.5
	Clayey loam	10.7	9.5	9.5	44.2	4.3	7.6	14.2
	Clay	21.1	2.5	7.4	53.9	0.2	3.0	11.9
	Heavy clay	10.5	8.8	4.3	50.5	0.4	4.0	21.5

yields as determined by Blaskó and Zsigrai (2000), then by Jolánkai et al. (2003), and the meteorological datasets for the vegetation period. We also plan to include some topographical factors (altitude above sea level, hillslope location, aspect, spatial position and other geomorphological attributes) to our drought sensitivity estimation model, as well as to determine the national-scale soil-specific drought sensitivity indicators of other arable crops, such as spring barley, rapeseed, alfalfa, etc.

The research results of different Hungarian long-term experiments concerning the climate sensitivity of soils are already available, but their synthesis, statistical analysis and nationwide extension have not been realized yet.

Our examination results prove the increasing of the drought sensitivity of forest soils situated in Southwestern part of Hungary. Moreover, the results also prove the large drought involvement of the areas where soils with high sand content or heavy soils with high clay content can be found. Not only the increasing extent of aridity can cause large problems but the increasing of mean temperature can also generate the increase of soil drought sensitivity. This can also be observed in case of forest soils situated in the Southwestern part of Hungary, where the precipitation amount is high. Our crop-specific drought sensitivity map, which is based on examinations of soil-climate-yield reactions and edited yield maps is a novelty on a European scale; till now, similar work has not yet been made.

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

### Software

We used the ESRI arcGIS 9.3 GIS software to carry out the vector operations, to convert the AIIR ver3.0

database into a map projection system (the Unified National Projection (EOV)), and to apply other spatial and statistical analyses. For further statistical tests, we used the IBM SPSS Statistics 18.0 software.

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### Disclosure statement

No potential conflict of interest was reported by the authors.

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