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PARAMETERIZATION OF DROUGHT VULNERABILITY ASSESSMENT IN AGRICULTURE

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Abstract

The aim of the present study has been an attempt at the assessment of agricultural drought vulnerability. The paper presents the proposal of the methodology and the preliminary results. The assessment is performed for the voivodships and the regions in Poland and takes into account two factors: the crop water deficit in the growing season and the share of light and very light soil area in the overall arable soil area. The vulnerability is evaluated for five crops with the largest area of cultivation in Poland. A differentiation of vulnerability to drought between crops and a spatial differentiation for each crop are determined. A spatial differentiation is similar for all crops. The most vulnerable region is the central and central-western part of Poland. The results indicate that late potato is the most vulnerable crop to be damaged by drought among all studied crops, whereas winter rape is the least vulnerable crop.

Key words: drought, agriculture, vulnerability, crop water deficit, soils.

INTRODUCTION

Vulnerability shows the degree of susceptibility of society to a hazard, which could vary either as a result of variable exposure to the hazard, or because of coping abilities, which include protection and mitigation. The purpose of assessing vulnerability is to identify appropriate actions that can be taken to reduce vulnerability before the potential for damage is realized (Wilhelmi and Wilhite 2002).

Vulnerability of agriculture to drought is generally referred to as the degree to which agricultural systems (crops) are likely to experience harm due to drought stress. When drought occurs, vulnerability of crops depends on several parameters, the most important ones being the ability of the particular type of crops to adapt to drought stress and the environment of its growth (soil, climate, available soil water). Because of the complexity of the issue of vulnerability, assessments are commonly subjective and vary between regions and hazards. Downing and Bakker (2000) state that vulnerability is a relative measure and the analyst must define its critical levels. Factors influencing drought vulnerability are numerous, and their inclusion may depend on data availability. The identification of key vulnerability factors are usually based on their significance for agricultural sector. Analysis of drought literature suggests that climate, soils, land use, cultivated crops, access to irrigation are the most significant factors of agricultural drought vulnerability that should be taken into account.

The goal of this study was to develop a method for assessing vulnerability to agricultural drought. The tasks were to identify key factors that define agricultural drought vulnerability, to evaluate the weight of the factors that contribute to drought vulnerability and to assess the vulnerability of chosen agricultural crops to drought using the developed numerical weighting scheme.

METHODS

For the purpose of the present study, at the present stage of analysis, an assumption is formed that two factors are taken for the assessment of agriculture vulnerability to drought:

1. an agroclimatological factor of vulnerability (hazard factor) defined by synthesizing climate, crop and soil data in the form of water deficit in the growing period for a particular crop on a particular soil
2. a soil factor defined by the area of very light and light soils in a region as a share in total arable soil area.

The assessment of agricultural drought vulnerability is made for crops with the largest area of cultivation in Poland: cereals (winter wheat, spring barley), maize, winter rape, sugar beet, late potato, in six regions of Poland. The country was divided into the regions on the basis of diversity of climate and agro-climatic conditions:

- north-eastern covering the voivodships: podlaskie, warmińsko-mazurskie;
- north-western covering the voivodships: pomorskie, zachodnio-pomorskie;

- central-western covering the voivodships: lubuskie, wielkopolskie, kujawsko-pomorskie,
- łódzkie;
- central-eastern covering the voivodships: mazowieckie, świętokrzyskie, lubelskie;
- south-western covering the voivodships: dolnośląskie, opolskie, śląskie;
- south-eastern covering the voivodships: małopolskie, podkarpackie.

Crop water deficits

In the study the assessment of vulnerability is made with reference to different crops and to the probability of water deficit of crops. It is assumed that the probability characterizes the agrometeorological conditions of crop production. The sum of water deficit in a growing season at the probability of exceedence 0.2 is assumed as a hazard index. Such deficit can occur once in five years. For this study water deficits of a particular crop were taken from the „Atlas of water deficit of cultivated plants and grasslands in Poland" (Ostrowski et al. 2008).

Crop water deficits arise when water demand is not fully covered by rainfall and the available soil water in the root zone. Deficiencies may indicate a need for net irrigation to be applied to achieve high yields. The demand of crop water (water needs) is the amount of water needed to achieve a certain production level (of a specified final yield). A measure of water demand by a particular crop, is the potential evapotranspiration of the plant (ET_p). Potential evapotranspiration is the actual evapotranspiration expected under conditions of sufficient water supply to the plant. This is the amount of water consumed by the plant to produce certain yields in a particular state of development, fertilized at a certain level, under the circumstances of climate, soil and habitat. It is assumed that the conditions of plant development and nutrient supply are good.

Crop water deficit is the amount of water that is needed to meet crop water demand (ET_p) after deduction of precipitation and current water readily available soil water for plants. Crop water deficits were calculated using an available soil water balance computation for the root zone, according to the methodology presented by Allen et al. (1998), for soils recommended for growing a given crop, using the model CROPBALANCE (Łabędzki 2006; Łabędzki et al. 2008) with the application of the equations:

when $ET_p^t \leq P^t$

$$N^t = 0 \tag{1}$$

when $ET_p^t > P$ and $ASW_p^t > (1-p)TASW$

$$N^t = ET_p^t - P^t - [ASW_p^t - (1-p)TASW] \tag{2}$$

when $ET_p^t > P$ and $ASW_p^t \leq (1 - p)TASW$

$$N^t = ET_p^t - P^t \tag{3}$$

where:

N^t – crop water deficit in the decade (10-day period) t,
ET_p^t – potential evapotranspiration in the decade t,
P^t – precipitation total in the decade t,
ASW_p^t – available soil water in the root zone at the beginning of the decade t,
$TASW$ – total available soil water in the root zone,
p – soil water depletion fraction, fraction of $TASW$ that a crop can extract from the root zone without suffering water stress (dimensionless), according to Allen et al. (1998).
All variables, except p, are expressed in millimetres.

Total available soil water *TASW* was estimated for the 10 cm layers of the 100 cm soil profile on the basis of data given by Walczak *et al*. (2002).

According to this procedure, water deficits were calculated with a time step of a 10-day period for 35-year time series (1971–2004) using the meteorological data coming from 40 stations in Poland. The growing season sum of water deficits at a given probability was estimated using the gamma probability distribution.

Connecting the maps of water deficits with the map of the actual distribution of soil cover in Poland, the maps of the spatial distribution of water deficits on real soil in each point of the country were created. Then, taking into account the area of crop cultivation in voivodships from the official statistical data for 2015 (Użytkowanie… 2016), the soil area-weighted mean water deficit of crops in every voivodship and region was estimated.

Soils

The geographic pattern of soil water-holding capacity is important for studying water stress for plants. Plant-available water-holding capacity of soil is estimated as the difference in water content between field capacity and permanent wilting point. Field capacity is the amount of water retained by a wetted soil after it has been freely drained by gravity for some period of time. The water-holding capacity of the soil is mostly dependent on soil porosity, which, in turn, depends on soil texture and structure. In Poland, soils vary from clay soils, with generally fine texture and high water-holding capacity, to sandy soils with coarse texture and low water-holding capacity. Sandy soils are most common. The soil root zone water-holding capacity, as a significant agricultural drought vulnerability factor, was used in this study to group soils with similar abilities to buffer crops during periods of water deficits.

Spatial differentiation of soil cover in Poland according to a susceptibility of different categories of soil to the drought comprises the categories: a very light soil (with very low soil water-holding capacity, very susceptible to drought), light soil (with low soil water-holding capacity, susceptible to drought), medium-heavy soil (with medium soil water-holding capacity, medium susceptible to drought), heavy soil (with high soil water-holding capacity, less susceptible to drought). Evaluation of the share of very light and light soils in the voivodships and the regions was made on the basis of the map showing the soil spatial distribution, used in the development of the „Atlas of water deficit of cultivated plants and grasslands in Poland" (Ostrowski et al. 2008).

Vulnerability assessment

The following numerical weighting scheme was used to assess drought vulnerability. Each class of two vulnerability factors has been assigned a rank between 1 and 6, with 1 being considered least significant in regard to drought vulnerability and 6 being considered most significant (Table 1). Besides each factor was assigned a relative weight based on an informed assumption on relative contribution of each factor to overall agricultural drought vulnerability. It is recommended that the sum of weights is equal 1. It was hypothesized that a hazard factor (water deficit at a given probability) is important two times more than a soil factor (area of very light and light soils). The assumption was based on the rather obvious fact that smaller area of light soils with low water capacity and smaller water deficits lessen vulnerability to agricultural drought in a region.

Table 1. Weighting scheme for assessing agricultural drought vulnerability

Agricultural drought vulnerability factor class j	Agricultural drought vulnerability factor i		Rank r_{ij}
	1	2	
	N (mm)	S (%)	
1	0-40	0-10	1
2	41-80	11-20	2
3	81-120	21-40	3
4	121-160	41-60	4
5	161-200	61-80	5
6	> 200	81-100	6
Weight w_i	0.667	0.333	

N – drought hazard: water deficit (mm), sum in the growing period
S – share (%) of very light and light soils in arable soil area
Source: own study

The final result of the combination of *n* factors is a numeric value, which is calculated using the equation:

$$V = \sum_{i=1}^{n} w_i r_{ij} \tag{4}$$

where:
V – vulnerability,
n – number of factors,
w_i – weight of factor i,
r_{ij} – rank j of factor i,
i – the number of a factor,
j – the number of a factor class.

Similar approach was presented by Wilhelmi and Wilhite (2002) for Nebrasca in USA and Slejko *et al.* (2011) for Slovenia in the framework of Drought Management Centre for Southeastern Europe.

According to this formula and the data from Table 1, the maximum value of vulnerability index is 6 and the minimum is 1. A high numeric value is assumed to be indicative of a geographic area that is likely to be more vulnerable to agricultural drought. Vulnerability was classified into five classes, identifying geographic areas with: no vulnerability, low, moderate, high and very high vulnerability (Table 2). The derived classes were based on the numerical weights, informed judgment and the analysis of the combined input variables.

Finally the number value of vulnerability V was calculated using data from Table 1 and Eq. 4, taking into account the weighted water deficit and the area of very light and light soils in each region as a ratio to the total arable soil area (in %). On the base of the assumed classification (Table 2) the verbal assessment was assigned.

Table 2. Agricultural drought vulnerability classification

Agricultural drought vulnerability	
V value	assessment
1.0-2.0	no
2.1-3.0	low
3.1-4.0	moderate
4.1-5.0	high
5.1-6.0	very high

Source: own study

RESULTS

The results are presented in Table 3 and the maps of vulnerability assessment in the regions in Figure 1.

Table 3. Assessment of vulnerability of different crops to drought

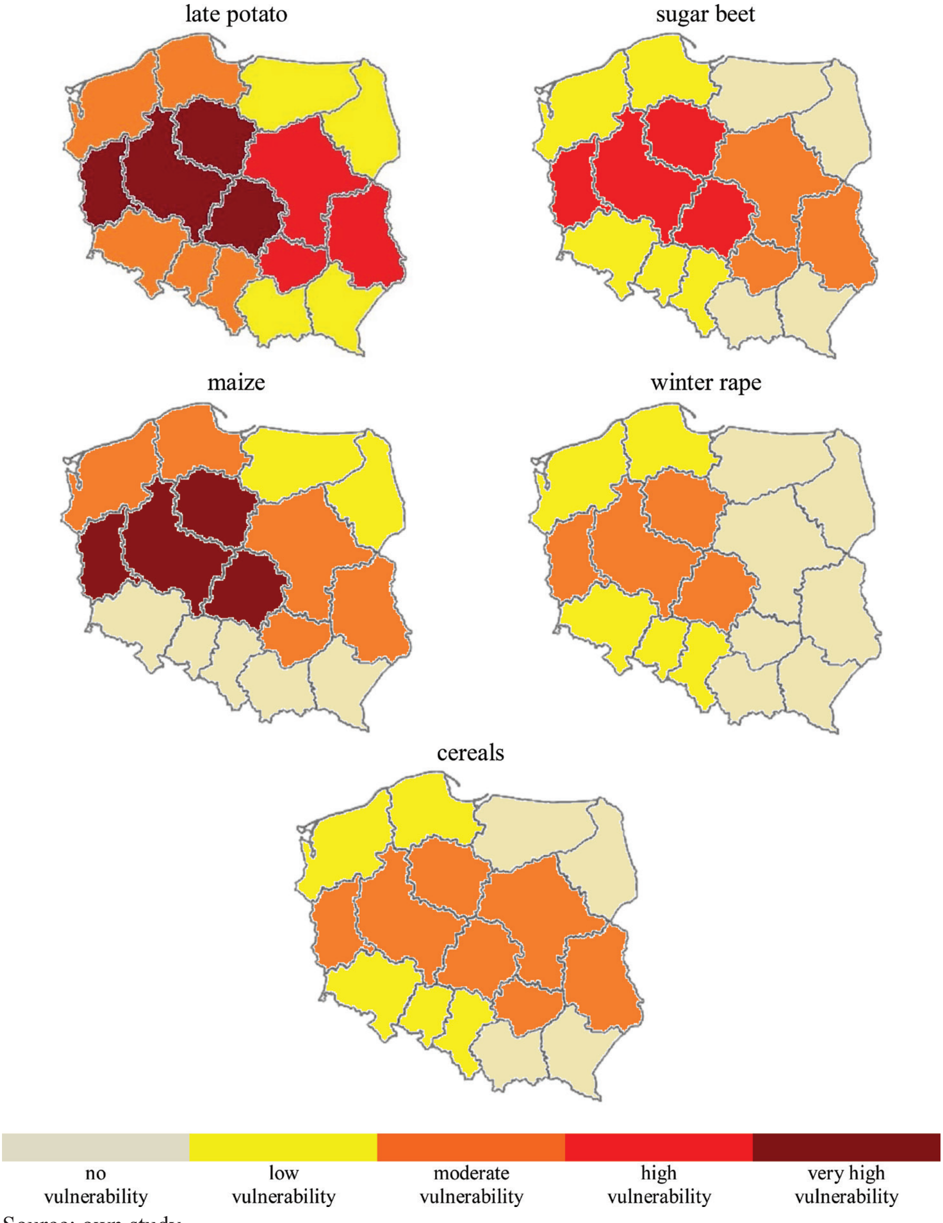
Region	Late potato	Sugar beet	Maize	Winter rape	Cereals
north-eastern	+	-	+	-	-
north-western	++	+	++	+	+
central-western	++++	+++	++++	++	++
central-eastern	+++	++	++	-	++
south-western	++	+	-	+	+
south-eastern	+	-	-	-	-

-	no vulnerability
+	low vulnerability
++	moderate vulnerability
+++	high vulnerability
++++	very high vulnerability

Source: own study

Agricultural crop vulnerability in the analyzed regions and voivodships is a combined effect of crop water deficit *N* determined on different soils recommended for crop growing and the share of light and very light soils *S* occurring in a voivodship. Crop water deficit is the recommended soil area-weighted mean water deficit of crops in every voivodship. The combination of these two factors (*N* and *S*) recognizes the relationship that the greater crop water deficit and the greater share of light and very light soils the greater vulnerability. The proportion of these two factors depends on the assumed weights what is rather subjective. Other weights could give different assessment of vulnerability and its spatial distribution. In this study it was assumed that water deficit was two times more important than the share of light and very light soils.

A differentiation of vulnerability to drought between crops and a spatial differentiation for each crop depending on the hazard of water deficit were found. A spatial differentiation is similar for all crops. Taking into account all analyzed crops the most vulnerable region is the central and central-western part of Poland. These regions are most threatened by agricultural droughts causing the greatest crop yield losses. The next are the central-eastern, north-western, south-western, south-eastern parts and the least vulnerable region is north-eastern.



Source: own study

Figure 1. Maps of agriculture vulnerability of different crops to drought in Poland

Late potato is the most vulnerable crop to be damaged by drought among all studied crops. It is very highly vulnerable in the lubuskie, wielkopolskie, kujawsko-pomorskie and łódzkie voivodships (central-western Poland). The low vulnerability is found in the north-eastern and south-eastern regions. The least vulnerable crop is winter rape. In central-western Poland this crop is moderately vulnerable. The whole eastern part of the country is characterized as low vulnerable in terms of the hazard of rape water deficit.

CONCLUSIONS

The paper presents the proposal of the methodology of agricultural drought vulnerability assessment and the preliminary results. The assessment is performed for the voivodships and the regions in Poland and takes into account two factors: the crop water deficit in the growing season and the share of light and very light soil area in the overall arable soil area. The vulnerability is evaluated for five crops with the largest area of cultivation in Poland.

A differentiation of vulnerability to drought between crops and a spatial differentiation for each crop are determined. A spatial differentiation is similar for all crops. The most vulnerable region is the central and central-western part of Poland. The results indicate that late potato is the most vulnerable crop to be damaged by drought among all studied crops. The least vulnerable crop is winter rape.

Further studies are required to improve the used methods directed at other factors e.g. access to irrigation, land use. More research needs to be done in developing weighting schemes of vulnerability factors. Nevertheless, the method presented in this paper can be a step forward in developing techniques for drought vulnerability assessment.

The identification of drought vulnerability is an essential step in addressing the issue of drought risk evaluation and can lead to mitigation-oriented drought risk management.

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