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Impact of meteorological drought on crop water deficit and crop yield reduction in Polish agriculture

Leszek ŁABĘDZKI ABCDEF ✉, **Bogdan BĄK** CDF

Institute of Technology and Life Sciences, Kujawsko-Pomorski Research Centre, ul. Glinki 60, 85-174 Bydgoszcz, Poland;
e-mail: l.labedzki@itp.edu.pl, b.bak@itp.edu.pl

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Abstract

The study presents the quantification of the effect of meteorological drought on crop water deficit and crop yield reduction in different agro-climatic regions of Poland. The regression equations describing the relationship between the standardized precipitation index *SPI* (meteorological drought) and the crop drought index *CDI* (evapotranspiration reduction) were used in a first step. Then the FAO equation describing the relationship between *CDI* and yield reduction was used. Crop water deficit measured by *CDI* is spatially differentiated and depends on the intensity of meteorological drought and soil water availability. The greatest evapotranspiration reduction is found for late potato growing in the central-west Poland (30–60%). The smallest reduction of evapotranspiration was stated for winter rape (12–16%) in the same region on soils with small water retention and no reduction can be on soils with large water retention. A good correlation between estimated and observed yield reduction was found. Potential yield reduction of late potato can reach more than 50% in central Poland. Least yield reduction is for winter wheat and winter rape. The main advantage of the method used in the study is the combination of meteorological drought, soil water retention capacity, evapotranspiration, soil water balance and crop yield, and so help provide more accurate assessments.

Key words: *crop drought index CDI, crop water deficit, drought, soil water balance, standardized precipitation index SPI, yield reduction*

INTRODUCTION

Risk is an important aspect of the farming business. The uncertainties inherent in weather, yields, prices, government policies, global markets and other factors that impact farming can cause wide swings in farm income [ERS 2017]. The agricultural sector as the largest water users becomes the most severely affected when catastrophic drought occurs. Climate change impacts more susceptible agricultural products, lowering crop production [MIODUSZEWSKI 2009]. For example, detailed calculations made by BARANOWSKI *et al.* [2012] for the Kujawsko-Pomorskie Voivodeship (Poland) and the period 1999–2011 showed that losses caused by natural disasters, mainly by droughts, amounted about 3.4 billion PLN (over 800 million €).

Information on agricultural drought vulnerability levels is extremely useful for the implementation of long term drought management measures. Different areas are differentially exposed to drought and have various levels of vulnerability mainly due to natural conditions, socio-economic factors, infrastructure etc. Assessment of agricultural drought vulnerability is important from multiple perspectives – drought risk management, crop insurance, climate change etc. [MURTHYA *et al.* 2014]. Research made by TRNKA *et al.* [2013] shows that climatic conditions across Central Europe and USA, with a special focus on temperature, hydrologic regime, drought hazard and potential agricultural productivity, will change in the time horizons of 2025, 2050 and 2100 dramatically in both regions, with significant consequences for agricultural plant growth.

Relationship between meteorological and agricultural drought is complex and dependent on many factors and determinants. The factors influencing drought vulnerability are numerous. Their inclusion in the assessment of the impact of meteorological drought on agricultural drought 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 and cultivated crop types are the most significant factors that should be taken into account.

Effect of meteorological drought on agriculture is a combined effect of drought hazard (likelihood) and drought consequence (vulnerability) [WILHELMI, WILHITE 2002; WILHITE 2000]. Drought hazard is determined by frequency and severity of droughts. Vulnerability of agriculture to drought is generally referred to as the degree to which agricultural systems (crops) are likely to suffer damages due to drought stress. When drought occurs, vulnerability of crops depends on several parameters, the most important ones being the drought tolerance of different crops, the ability of the particular type of crops to adapt to drought stress, the difference in growing periods (e.g. winter cereals and summer crops), agro-techniques (e.g. irrigation/partial irrigation, fertilization level, crop density etc.) as well as soil type and available soil water.

The most obvious effects of drought on cultivated plants are evapotranspiration reduction and its consequence in the form of the final crop yield reduction.

Relationships between crop yield and meteorological conditions, water and soil are complex. To describe and quantify them understanding and quantitative description of many climatic, biological, physiological, physical, chemical and agronomic processes and factors are required. In terms of soil water scarcity, they should be limited to the most important and it must be assumed that – apart from the water factor – they are optimal. Then water is the main factor determining crop yield. The reduction of the final yield is the negative effect of water shortage in the soil, caused mainly by insufficient rainfall. The direct cause of the reduction of yield is associated with a reduction in evapotranspiration.

Many research and work were devoted to the relationship between evapotranspiration and yield and its reduction as a result of meteorological drought. Among Polish studies should be mentioned first of all the synthetic issues by DOROSZEWSKI *et al.* [2012; 2014], DZIEŻYC (ed.) [1989; 1993], KARCZMARCZYK and NOWAK (eds.) [2006], KOWALIK [1989; 1995; 2010]. KOZYRA and GÓRSKI [2005] have determined the occurrence of meteorological droughts in Poland, assuming that the decline in yield below 90% of the average of the multi-year marks the boundary of moderate drought and below 75% – severe drought. KOŹMINSKI *et al.* [1990] and KOŹMINSKI and MICHALSKA [2001] have identified the periods and areas of greatest negative impact of rainfall shortage on crop yields in Poland. They calculated the potential reduction in yield as a result of rainfall shortage and determined the probability of rainfall shortage causing a reduction in the yield of 5%. They identified the risk of growing 10 main crops, associated with a potential reduction in yield due to insufficient soil moisture. ŁABĘDZKI and BĄK [2006] analyzed the impact of meteorological drought on sugar beet yield reduction, using the standardized precipitation index *SPI* as a meteorological drought index and the FAO method [DOORENBOS, KASSAM 1979] for yield reduction assessment in the period of intensive water demand. KOPACZ and TWARDY [2016] evaluated the potential risk of agricultural drought in selected, administrative areas of Lesser Poland Voivodeship. The analysis shows that the risk is not significant and is more dependent on the soil factor than the structure of cultivation. In the regions where drought occurred, the importance of agricultural production was relatively small.

In the world literature, you can find a range of methods and assessments of yield losses caused by drought. These methods are mainly of an indicator character, allowing to estimate the yield on the basis of water deficits. The most popular method is the FAO method [DOORENBOS, KASSAM 1979; ŁABĘDZKI 2006], which describes the relationship between the reduction in yield and reduction in evapotranspiration. However, it has some limitations. First, it is effective for the reduction of evapotranspiration in the range of 0–50%, wherein the relationship between the relative yield and relative evapotranspiration is linear. Secondly, it was assumed that the impact of water scarcity on the yield in the subsequent periods (phenological phases) is independent. This means that using this dependence the reduction of yield reduction may be estimated when water stress occurs only in one phase and does not occur in others. To express complex (cumulative) impact of water scarcity in several growth periods on final yield, the multiplicative or additive procedures are used. One such proposal is the Jensen method (model) [HANKS 1974; JENSEN 1968; KIPKORIR, RAES 2002], describing the relationship between the relative yield and relative evapotranspiration in successive phases. This method is very important in assessing the impact of water deficits on final yield when shortages occur in different periods of crop development and the reduction of final yield is the cumulative effect of these deficits. Another multiplicative method is the method proposed by Rao [RAO *et al.* 1988; STEWART, NIELSEN 1990]. RAES [2004] and RAES *et al.* [2006] modified this method, allowing the estimation of the reduction of the yield based on the reduction of evapotranspiration in shorter periods than a phenological phase.

Among the agrometeorologists the regressions models of the “weather-yield” type were very popular [KUCHAR 1987; ROJEK 1987]. Other approach relies on developing the relationships between meteorological or agricultural drought index and crop yield reduction. An example of this approach may be the study by WOLI *et al.* [2014]. They used Agricultural Reference Index for Drought (*ARID*), to quantify water stress for use in predicting crop yield loss from drought for several locations and years in the south-eastern USA. For this purpose they performed regression analyses of crop yields vs. monthly *ARID* values during the crop growing season.

It is also necessary to mention the mapping of climatic water balance and crop water supply conditions as well as forecast yields, made operationally every month for Europe (primarily for the EU countries) by the Joint Research Centre, Ispra (Italy) within the MARS project (Monitoring Agriculture with Remote Sensing) [NIEUWENHUIS *et al.* 2015]. This system is based on a simple soil water balance model and the crop growth model WOFOST (WOrld FOod STudies), which are used to assess the impact of weather conditions on crop growth. In the literature attention is also paid to the economic aspects of crop yield losses due to drought, e.g. the study by BOUBACAR [2012] and POWELL and REINHARD [2016].

The aim of the presented study is to quantify the effect of meteorological drought on crop water deficit and crop yield reduction in different agro-climatic regions of Poland, by using the relationship between the standardized precipitation index *SPI* and the crop drought index *CDI*.

METHODS AND MATERIALS

For the purpose of the present study of the relationship between meteorological and agricultural droughts three factors are taken:

1) a climatic factor (hazard factor) defined as meteorological drought and measured by the standardized precipitation index *SPI*;
2) two vulnerability factors:
   - crop water deficit defined as the reduction of evapotranspiration caused by soil water deficit due to meteorological drought,
   - potential crop yield reduction caused by crop water deficit.

These factors can be combined in the form of the relationship showing the dependence of vulnerability factors on a hazard factor.

SPI values describe meteorological drought at the end of a period (a month, a half-year, the growing season, a year) caused by a deviation of precipitation during this period in relation to the median value (values with the 50% probability) [MCKEE *et al.* 1993; 1995]. *SPI* is an index based on the probability distribution of precipitation. It depends on the fitted density probability function, the length of the series used to estimate the parameters of the probability function and the method of estimation. In the study a gamma probability density function was fitted to the monthly series for the selected timescale, checking goodness of fit by using the χ^2-Pearson test. The parameters were estimated by the maximum likelihood method. Then the cumulative probability of an observed precipitation amount was computed. An equiprobability transformation (an inverse normal function) was applied from the fitted distribution to the standard normal one, so that the mean *SPI* is zero and the standard deviation is one. The values of the standard normal variable are actually the *SPI* values [GUTTMAN 1999]. Technically, the *SPI* is the number of standard deviations that the observed value deviates from the long-term mean, for a normally distributed random variable or a standardized deviation of precipitation in a given period from the median long-term value of this period.

Crop water deficit is described by the crop drought index *CDI* which is used to quantify agricultural drought intensity [BRUNINI *et al.* 2005; ŁABĘDZKI 2006; NARASIMHAN, SRINIVASAN 2005; TIAN, BOKEN 2005]. It indicates the reduction of evapotranspiration in relation to potential evapotranspiration due to soil water deficit and is calculated as:

$$CDI = 1 - \frac{ET}{ET_p} \tag{1}$$

where: ET = actual evapotranspiration under soil water deficit (mm), ET_p = potential evapotranspiration under sufficient soil moisture content (mm).

CDI assumes the values within the range $\langle 0,1 \rangle$:
$CDI = 0$ when $ET = ET_p$
$CDI < 1$ when $ET < ET_p$
$CDI = 1$ when $ET = 0$

The actual evapotranspiration was calculated in decades (ten-day periods), months and the whole growing seasons, using the crop and water stress coefficient approach and the methodology described by ALLEN *et al.* [1998]. Evapotranspiration ET^t in a decade t is calculated as:

$$ET^t = k_s^t k_c^t ET_0^t \tag{2}$$

where: ET_0^t = reference evapotranspiration in a decade t, according to the Penman-Monteith equation [ALLEN *et al.* 1998] (mm·decade^{-1}), k_c^t = crop coefficient (dimensionless), k_s^t = water stress coefficient (dimensionless).

Under excellent soil water conditions $k_s^t = 1$ and

$$ET^t = ET_p^t = k_c^t ET_0^t \tag{3}$$

where ET_p^t = potential evapotranspiration in a decade t (mm·decade^{-1}).

Reference evapotranspiration ET_0^t incorporates the effect of weather conditions on evapotranspiration. Crop coefficient k_c^t predicts evapotranspiration under standard conditions, i.e. under excellent agronomic and soil water conditions. It depends on the growth phase of the plant and on the yield. Values of this coefficient were estimated for selected crop plants in lysimetric studies [ŁABĘDZKI 2006] and/or based on literature data [ALLEN *et al.* 1998].

The effect of soil water stress on crop evapotranspiration is described by reducing the value of the crop coefficient, multiplying it by the water stress coefficient k_s^t. The water stress coefficient is calculated as [ALLEN *et al.* 1998]:

when $ASW_p^t < (1 - p)\ TSW_r$

$$k_s^t = \frac{ASW_p^t}{(1-p)TASW_r} \tag{4}$$

when $ASW_p^t \geq (1 - p)\ TSW_r$

$$k_s^t = 1 \tag{5}$$

where: ASW_p^t = available soil water in the root zone at the beginning of a decade t (mm), TSW_r = total available soil water in the root zone (mm), p = soil water depletion fraction, fraction of $TASW_r$ that a crop can extract from the root zone without suffering water stress (dimensionless), according to ALLEN *et al.* 1998].

Total available soil water *TASW* is calculated in the 10-cm layers as the difference between the water content at field capacity (pF = 2.0) and wilting point (pF = 4.2).

The estimation of water stress coefficient k_s^t requires a water balance computation for the root zone. It is calculated as:

$$ASW_p^t = ASW_k^{t-1} = ASW_p^{t-1} + P^{t-1} - ET^{t-1} \tag{6}$$

where: ASW_k^{t-1}, ASW_p^{t-1} = available soil water in the root zone at the end and at the beginning of a decade t–1 (mm), P^{t-1} = precipitation in a decade t–1 (mm), ET^{t-1} = evapotranspiration in a decade t–1 (mm). The limits imposed on ASW_k^{t-1} are:

$$0 \leq ASW_k^{t-1} \leq TASW_r \tag{7}$$

The effect of meteorological drought on agricultural drought is quantified using the relationships between *CDI* and *SPI*. The relationships as the linear regression equations

$$CDI = a + b\ SPI \tag{8}$$

were determined by BĄK [2006], ŁABĘDZKI and BĄK [2006] and ŁABĘDZKI *et al.* [2008] for 40 meteorological stations in Poland, using the meteorological data series from the multi-year period 1970–2004. The data included the 10-day (decade) mean values of air temperature and humidity, sunshine hours, wind velocity and the 10-day (decade) sums of precipitation. The equation (8) for different crops was derived for the whole growing period, i.e. *CDI* was calculated for the sum of evapotranspiration in this period and *SPI* was the 6-month *SPI* at the end of September.

The reduction of evapotranspiration *CDI* was calculated for the values of *SPI* equal to –1.0, –1.5 and –2.0. They are the threshold values of the class of moderate, severe and extreme meteorological drought, respectively, according to the classification reported by PAULO and PEREIRA [2006] and VERMES [1998].

Finally a linear crop-water production function is used to predict the reduction in crop yield *YR* [DOORENBOS, KASSAM 1979; MLADENOVA, VARLEV 2007]:

$$YR = \left(1 - \frac{Y_{re}}{Y_p}\right) = k_y\left(1 - \frac{ET}{ET_p}\right) \tag{9}$$

where: Y_{re} = actual crop yield reduced due to water stress, Y_p = maximum (potential) yield that can be expected under the given growing conditions for non-limiting water conditions, k_y = yield response factor after DOORENBOS and KASSAM [1979], ET = actual evapotranspiration under soil water deficit, ET_p = potential evapotranspiration under non-limiting water conditions. Equation (9) can be written then as:

$$YR = k_y\ CDI \tag{10}$$

which combines agricultural drought measured by *CDI* and its effect as crop yield reduction.

Assessment of potential crop yield losses on the basis of *CDI* is made for the following chosen field crops: late potato, sugar beet, winter wheat, winter rape and grain maize on two mineral soils: one with total available soil water *TASW* = 120 mm and the other with *TASW* = 200 mm in the soil profile 0–100 cm and for permanent grasslands (meadows) on two mineral-organic soils with *TASW* = 50 mm and *TASW* = 80 mm in the soil profile 0–30 cm. Yield reduction is predicted for the whole growing period of a specified crop. An assumption is formed that drought is distributed evenly throughout the growing period. The consequence of this assumption is that the *SPI* values qualified the whole growing period as moderately, severely and extremely dry (starting respectively at *SPI* = –1.0, –1.5, –2.0) and yield response factors k_y are seasonal yield response functions.

The evaluation of crop yield reduction was made in seven regions differing with regard to agro-climatic conditions (Fig. 1), with the representative meteorological stations:

A – Podlasie (north-east, meteorological station Białystok),
B – Kujawy (central-north, meteorological station Bydgoszcz),
C – Wielkopolska (central-west, meteorological station Poznań),
D – Dolnośląskie (south-west, meteorological station Wrocław),
E – Łódzkie (central, meteorological station Łódź),
F – Lubelskie (central-east, meteorological station Lublin),
G – Małopolska (south, meteorological station Kraków).

To evaluate the yield reduction calculation the comparison between estimated and actual crop yield reduction is made in seven provinces (Podlaskie,

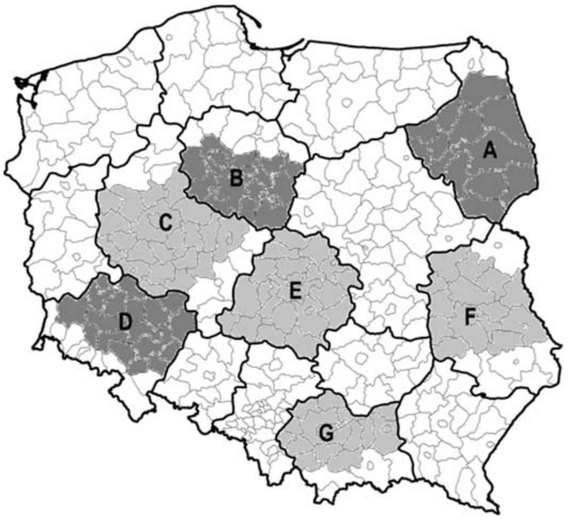

Fig. 1. Agro-climatic regions in Poland separated for the study; source: own elaboration

Kujawsko-Pomorskie, Wielkopolskie, Dolnośląskie, Łódzkie, Lubelskie and Małopolskie voivodeships) and for crops (sugar beet, late potato, grain maize and meadow) in 1999–2015. Yields as mean in the voivodeship were taken from the official statistic data published by Central Statistics Office [GUS 2017]. Actual yield reduction was calculated as the ratio of the yield in each year to the maximum yield obtained in 1999–2015.

RESULTS AND DISCUSSION

According to DOORENBOS and KASSAM [1979] the reduction of evapotranspiration defined as crop drought index *CDI* and yield reduction are linked by the yield response factor k_y. This factor indicates the drought sensitivity of the different crops. It shows how many times the reduction in the yield is greater ($k_y > 1$) or smaller ($k_y < 1$) than the reduction in evapotranspiration or they are equal. The following values of k_y was used: 1.0 for sugar beet, 1.1 for late potato and meadow, 1.05 for winter wheat and winter rape, 1.25 for grain maize.

Crop water deficit measured as the reduction of the growing season evapotranspiration sum, due to soil water deficit, is spatially differentiated and depends on the intensity of meteorological drought and soil water availability (Tab. 1).

Table 1. Crop drought index *CDI* at the standardized precipitation index *SPI* values in the growing season on two soils with different total available soil water *TASW*

Region	*TASW* = 120 mm			*TASW* = 200 mm		
	SPI			*SPI*		
	–1.0	–1.5	–2.0	–1.0	–1.5	–2.0
Sugar beet						
A – north-east	0.23	0.28	0.33	0.05	0.07	0.08
B – central-north	0.40	0.47	0.53	0.16	0,20	0,24
C – central-west	0.41	0.48	0.55	0.20	0.25	0.29
D – south-west	0.33	0.39	0.45	0.12	0.15	0.18
E – central	0.36	0.43	0.49	0,14	0,18	0,21
F – central-east	0.25	0.29	0.32	0.06	0.07	0.08
G – south	0.20	0.24	0.28	0.03	0.04	0.05
Late potato						
A – north-east	0.30	0.36	0.41	0.12	0.15	0.18
B – central-north	0.44	0.50	0.56	0.25	0.30	0.35
C – central-west	0.46	0.53	0.60	0.28	0.34	0.39
D – south-west	0.35	0.41	0.46	0.17	0.21	0.24
E – central	0.39	0.45	0.51	0.22	0.27	0.32
F – central-east	0.31	0.35	0.39	0.14	0.17	0.19
G – south	0.26	0.30	0.34	0.09	0.11	0.13
Winter wheat						
A – north-east	0.13	0.16	0.18	0.02	0.03	0.03
B – central-north	0.25	0.29	0.33	0.05	0.06	0.07
C – central-west	0.23	0.27	0.30	0.05	0.06	0.07
D – south-west	0.18	0.21	0.24	0.02	0.03	0.03
E – central	0.20	0.23	0.26	0.03	0.04	0.04
F – central-east	0.11	0.12	0.12	0.02	0.02	0.02
G – south	0.08	0.10	0.12	0.00	0.00	0.00
Winter rape						
A – north-east	0.05	0.07	0.08	0.00	0.00	0.00
B – central-north	0.14	0.17	0.20	0.00	0.00	0.00
C – central-west	0.12	0.14	0.16	0.00	0.00	0.00
D – south-west	0.08	0.10	0.11	0.00	0.00	0.00
E – central	0.08	0.10	0.11	0.00	0.00	0.00
F – central-east	0.05	0.06	0.06	0.00	0.00	0.00
G – south	0.02	0.03	0.03	0.00	0.00	0.00
Grain maize						
A – north-east	0.15	0.19	0.22	0.01	0.01	0.01
B – central-north	0.25	0.30	0.35	0.04	0.05	0.06
C – central-west	0.31	0.37	0.43	0.05	0.07	0.08
D – south-west	0.18	0.22	0.26	0.03	0.04	0.05
E – central	0.23	0.28	0.33	0.05	0.07	0.08
F – central-east	0.12	0.14	0.16	0.01	0.01	0.02
G – south	0.11	0.14	0.17	0.01	0.02	0.02
Meadow (*TASW* = 50 and 80 mm)						
A – north-east	0.18	0.23	0.27	0.11	0.13	1.15
B – central-north	0.37	0.43	0.49	0.22	0.26	0.29
C – central-west	0.39	0.46	0.53	0.33	0.39	0.45
D – south-west	0.31	0.37	0.42	0.22	0.24	0.26
E – central	0.35	0.42	0.48	0.29	0.35	0.40
F – central-east	0.18	0.22	0.25	0.12	0.14	0.15
G – south	0.14	0.18	0.21	0.06	0.08	0.09

Source: own study.

The impact of meteorological drought and soil on the magnitude of crop water deficit is different for the analysed crops. The greatest evapotranspiration reduction is found for late potato growing in the central-west region represented by the meteorological station in Poznań. It amounts from 46% when moderate meteorological drought starts (*SPI* = –1.0), through 53% at severe drought (*SPI* = –1.5) up to 60% at extreme drought (*SPI* = –2.0), on the light soil with total available soil water equal to 120 mm. In the case of soil water of 200 mm the evapotranspiration reduction is 28, 34 and 39%, respectively. The smaller reduction of evapotranspiration was stated for winter rape – 12–16% in central west Poland on light soils and no reduction can be encountered on soils with 200 mm of stored soil water.

Potential crop yield losses in the selected regions of Poland caused by meteorological drought of different intensity are shown in Table 2. The range of potential crop yield reduction is presented as the effect of moderate meteorological drought ($-1.0 \ge SPI > -1.5$), severe meteorological drought ($-1.5 \ge SPI > -2.0$) and extreme meteorological drought ($SPI \le -2.0$). Crop yield reduction is a mean value of reductions on two soils with different total available soil water ($TASW = 120$ mm and 200 mm in the soil profile 0–100 cm for field crops and $TASW = 50$ mm and 80 mm in the soil profile 0–30 cm for meadows), estimated by Equation (10).

Table 2. Yield reduction (%) caused by meteorological drought in a growing period

Region	Meteorological drought			
	no drought	moderate	severe	extreme
Sugar beet				
A – north-east	2–14	15–17	18–21	>21
B – central-north	7–28	29–33	34–39	>39
C – central-west	8–31	32–36	37–42	>42
D – south-west	5–23	24–27	28–32	>32
E – central	5–25	26–30	31–35	>35
F – central-east	7–16	17–18	19–20	>20
G – south	2–12	13–14	15–17	>17
Late potato				
A – north-east	4–23	24–28	29–32	>32
B – central-north	14–38	39–44	45–50	>50
C – central-west	13–41	42–48	49–54	>54
D – south-west	9–29	30–34	35–39	>39
E – central	9–34	35–40	41–46	>46
F – central-east	10–25	26–28	29–32	>32
G – south	6–19	20–23	24–26	>26
Winter wheat				
A – north-east	2–8	8–9	10–11	>11
B – central-north	5–16	17–18	19–21	>21
C – central-west	5–15	16–17	18–19	>19
D – south-west	3–11	11–12	13–14	>14
E – central	5–12	13–14	15–16	>16
F – central-east	5–6	6–7	6–7	>7
G – south	0–4	4–5	6–7	>7
Winter rape				
A – north-east	0–3	3–4	3–4	>4
B – central-north	1–8	8–9	9–11	>11
C – central-west	2–7	7–8	8–9	>9
D – south-west	1–4	4–5	5–6	>6
E – central	1–4	4–5	5–6	>6
F – central-east	1–2	2–3	2–3	>3
G – south	0–1	1–2	1–2	>2
Grain maize				
A – north-east	1–10	11–12	13–15	>15
B – central-north	3–18	19–22	23–26	>26
C – central-west	4–23	24–27	28–32	>32
D – south-west	1–13	14–16	17–19	>19
E – central	2–18	19–22	23–26	>26
F – central-east	3–8	9–10	10–11	>11
G – south	0–8	9–10	11–12	>12
Meadow				
A – north-east	2–16	17–20	21–23	>23
B – central-north	12–32	33–38	39–43	>43
C – central-west	11–40	41–47	48–54	>54
D – south-west	13–29	30–33	34–37	>37
E – central	9–35	36–42	43–48	>48
F – central-east	6–17	18–19	20–22	>22
G – south	0–11	12–14	15–17	>17

Source: own study.

A spatial differentiation of crop yield reduction depending on meteorological drought category is determined. The effect of meteorological drought on crop water deficit and yield reduction is different for different crops. Crop water deficit caused mostly by precipitation deficit does not affect crops having short growing period, small water needs, deep root zone (winter wheat, winter rape). Deep rooting enables crops to take water from deeper layers of the soil profile [Aroca (ed.) 2012]. Late potato, characterized by shallow root system and long-lasting growing season, is the most vulnerable crop to be damaged by drought. Its potential yield reduction can be more than 50% in Kujawy and Wielkopolska regions during extreme meteorological drought. Least yield reduction is for winter wheat and winter rape. In most regions there is no negative effect of meteorological drought on yield of winter rape. For winter wheat yield reduction does not exceed 20% in all regions when meteorological drought is weaker than the extreme.

It is noteworthy that reduction in yield may also occur under precipitation conditions qualified as no meteorological drought according to *SPI*. It means that precipitation described as average does not provide for obtaining potential yields in many regions of Poland. It is obvious in light of the fact that, for example, water demand (potential evapotranspiration) of sugar beet is 500–600 mm in central Poland while precipitation sum in the growing period is about 300 mm as a multi-year average. Detailed research in this area and proving that fact in Kujawy region showed Bąk [2006].

The spatial distribution of yield reduction of all crops shows the central, central–north, central–west and south–west part of Poland where agriculture drought risk is the greatest. These regions of Poland are most threatened by agricultural droughts causing the greatest crop yield losses.

The important question to answer in the next stage of the study was whether estimated crop yield reduction coincides with actual crop yield reduction under conditions of actual meteorological drought. Table 3 presents the data for Dolnośląskie voivodeship as an example.

The ability of Equations (1)–(10) to predict yield loss from drought was evaluated using the root mean square error (*RMSE*). The used *SPI-CDI*-based yield model predicted relative yields with the *RMSE* values for all seven voivodeships of 0.22, 0.15, 0.14 and 0.11 $kg \cdot ha^{-1}$ of actual yield per $kg \cdot ha^{-1}$ of potential yield or 22, 15, 14 and 11% yield reduction for sugar beet, late potato, grain maize and meadow, respectively. Total for all provinces and crops *RMSE* is 0.26. These values indicate that the used procedure can predict the yield loss from drought for these crops with reasonable accuracy.

Table 3. Yield reduction (%) in Dolnośląskie voivodeship (region D, station Wrocław)

Year	Meteorological drought	Sugar beet		Late potato		Grain maize		Meadow	
		calculated	actual	calculated	actual	calculated	actual	calculated	actual
1999	moderate	24–27	52.7	30–34	37.5	–	–	13–29	34.9
2000	no drought	5–23	45.6	9–29	20.5	–	–	13–29	40.9
2001	no drought	5–23	47.1	9–29	38.2	–	–	13–29	36.0
2002	no drought	5–23	45.1	9–29	26.3	–	–	13–29	37.2
2003	moderate	24–27	51.3	30–34	38.6	–	–	30–33	52.8
2004	extreme	>32	43.5	>39	24.6	>19	17.4	>37	33.4
2005	no drought	5–23	32.3	9–29	26.3	1–13	14.1	13–29	40.4
2006	no drought	5–23	43.1	9–29	43.0	1–13	41.2	13–29	39.1
2007	no drought	5–23	28.9	9–29	20.1	1–13	8.6	13–29	19.6
2008	moderate	24–27	38.7	30–34	28.7	14–16	15.2	30–33	26.8
2009	no drought	5–23	28.6	9–29	30.4	1–13	11.6	13–29	23.4
2010	no drought	5–23	28.3	9–29	29.4	1–13	6.2	13–29	21.5
2011	no drought	5–23	15.6	9–29	11.6	1–13	0.1	13–29	19.2
2012	no drought	5–23	19.1	9–29	5.1	1–13	0.0	13–29	14.3
2013	no drought	5–23	26.7	9–29	16.4	1–13	11.0	13–29	15.5
2014	no drought	5–23	0.0	9–29	0.0	1–13	2.6	13–29	0.0
2015	extreme	>32	33.1	>39	28.7	>19	33.9	>37	18.9

Source: own study.

Comparing the obtained estimation of yield reduction and actual reduction in each year, it is worthy to notice a complex character of the used methods and the results. Actual yield reduction comes from statistical data concerning the whole voivodeship and is averaged in this area. A given crop could be cultivated on various soils other than those for which the calculation was carried out. Moreover, estimation of yield reduction was performed on the base of meteorological data coming from one station adopted as representative for the region. Actual meteorological conditions in the area of a voivodeship could also differ more or less from those observed at the station. It is known that yield reduction depends in which growth stage water deficit occurs. This impact is the greatest in the development crop stages. In the presented study the whole growing season is treated as influenced by water deficit evenly. The method would perform better when it was adapted to the most drought sensitive phenological periods of the crops [Eitzinger *et al.* 2006]. Then the assessment of yield reduction would be more reliable. The reason of the observed differences can also be the fact that some crop cultivation area could be irrigated in a voivodeship in a given year. This could cause that mean yield reduction in a voivodeship was less than the estimated in the study on the assumption of no irrigation. Also the inconsistency between calculated and actual yield reduction is caused by the errors of the linear regression Equation (8) which is not the functional but statistical relationship. Finally, what is the crucial point in this comparison study in our opinion, yield reduction in the voivodeships in a particular year from the period 1999–2015 is related to the maximum yield determined in these years. According to the FAO method presented by Equation (9), the actual yield in a given year should be related to the potential yield and it should be the potential yield in this year. Because final yield depends not only on water availability but also on temperature and radiation (among climatic parameters) as well as agricultural practices, determination of potential yield is much more difficult task and should be done by using more sophisticated simulation models (e.g. WOFOST, CEREAL, ELCROS, BACROS, EPIC). However, due to the lack of the estimation of the potential yield in a particular year, actual yield is most often related to the mean or maximum yield in the multi-year period.

Comparing the obtained results with the different other elaborations and publications in the similar subject, it can be stated good consistency. On the base of the study by Koźmiński and Michalska [2001] it can be found that mild drought can cause yield reduction of 5% for different crops in Poland. In extremely dry years (1992 and 2000) which occurred in Poland, up to 40% of the country area was affected by drought. Average decrease in crop yield is estimated at 10–40% in those years as compared to the normal year [Łabędzki 2007]. Summer drought in 2015 in Poland due to severe rainfall deficit (precipitation in August amounts 10–30% of mean from 1971–2000) and combined with over a dozen days with temperature above 25°C caused a significant decrease in hay yield of permanent grasslands, especially during the second cut, from 25% to 77% [Łabędzki, Bąk 2015]. Doroszewski *et al.* [2014] showed that meteorological droughts in 1961–2010 were a serious threat to crop yielding in Poland. They pointed out areas where drought caused a loss in yield at least 20%. The most vulnerable areas coincide with the regions appointed in this study.

It is worth comparing the method used in this study and the obtained results for Poland with the results in regions with similar climatic conditions. Dodd *et al.* [2011] estimated that 30% of the UK wheat acreage is planted on drought-prone land such that 10% of potential production is lost annually because the moisture available to the crop is insufficient. Van der Velde *et al.* [2012] reported that crop yields were greatly influenced by drought and heat stress in

2003 in France. Regional maize and wheat yields were historically low in this year. The yield of wheat in 2003 was lower by 18% compared to the median yield from 1998–2007 and of maize by 22%. Other publications confirm the suitability of the adopted methods and the reliability of the results. WOLI *et al.* [2014], using the Agricultural Reference Index for Drought (ARID) for predicting crop yield loss from drought, obtained the error of prediction (*RMSE*) of 0.087–0.144 ($\mathrm{kg{\cdot}ha^{-1}}$ yield per $\mathrm{kg{\cdot}ha^{-1}}$ potential yield) for cotton, maize, peanut and soybean for several locations and years in the south-eastern USA. These values are similar to those obtained in the study presented in this paper (0.11–0.22). EITZINGER *et al.* [2006] examined various drought estimation methods and their relation to crop yields (wheat, barley and maize) and permanent grassland in Austria. They stated that the relationships could be improved significantly when a simplified soil water balance model (FAO model) was used. The consideration of soil water has a better potential to explain the reasons of yield reductions. In our study the same model was used to determine the evapotranspiration reduction and crop drought index *CDI*.

This study contributes to the literature on climate and agriculture relations by assessing the impact of meteorological droughts on crop yields. Yields are examined in relation to the actual regional weather data and observed yields. These results provide convincing evidence that meteorological droughts occurring in Poland have visible and significant impact on productivity in agriculture.

CONCLUSIONS

1. The effect of meteorological drought on crop water deficit and crop yield reduction in different agro-climatic regions of Poland is examined, by using the relationships between the standardized precipitation index *SPI*, the crop drought index *CDI* and crop yield reduction.

2. The most obvious effects of drought on cultivated plants are evapotranspiration reduction and its consequence in the form of the final crop yield reduction. Therefore, the regression equations describing the relationship between SPI (meteorological drought) and *CDI* (evapotranspiration reduction) were used in a first step and then the FAO equation describing the relationship between *CDI* and yield reduction was used.

3. Crop water deficit measured by *CDI* is spatially differentiated and depends on the intensity of meteorological drought and soil water availability. The greatest evapotranspiration reduction is found for late potato growing in the central-west Poland (30–60%). The smallest reduction of evapotranspiration was stated for winter rape (12–16%) in the same region on light soils and no reduction can be on heavy soils.

4. Aware that crop yield depends on many factors, a good correlation between estimated and observed yield reduction was found. Greater yield reduction occurred in the years with more intensive meteorological droughts and high water deficit. Potential yield reduction of late potato can reach more than 50% in central Poland due to extreme meteorological drought. Least yield reduction is for winter wheat and winter rape. In most regions there is no negative effect of meteorological drought on yield of winter rape. Reduction in yield may also occur under precipitation conditions qualified as no meteorological drought according to *SPI*.

5. Performed studies enabled the quantitative parameterization of crop water deficits and their effect on potential crop yield in Poland. Aware that the assumption of the qualification of the whole growing period as dry can cause unreliable assessments, more detailed study is required to assess the impact of meteorological drought occurring in particular growth stages of a crop on final yield reduction.

6. The main advantage of the method used in the study is that meteorological drought, soil water retention capacity, actual evapotranspiration, actual soil water availability and crop yield are accounted for in combination, and so help provide more accurate assessments. This approach would also allow crop water use and yield to be modelled, to predict irrigation water requirements in an operational mode.

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Leszek ŁABĘDZKI, Bogdan BĄK

Wpływ suszy meteorologicznej na deficyt wody i zmniejszenie plonu roślin uprawnych w polskim rolnictwie

STRESZCZENIE

W pracy zaprezentowano ilościową ocenę wpływu suszy meteorologicznej na deficyt wody i zmniejszenie plonu roślin uprawnych w różnych regionach agroklimatycznych Polski. W pierwszym etapie zastosowano równania regresji opisujące zależność między wskaźnikiem standaryzowanego opadu *SPI* (susza meteorologiczna) i wskaźnikiem suszy rolniczej *CDI* (ograniczenie ewapotranspiracji). Następnie zastosowano równanie opisujące zależność między *CDI* i zmniejszeniem plonu. Deficyt wody roślin uprawnych, którego miarą jest *CDI*, jest przestrzennie zróżnicowany i zależy od intensywności suszy meteorologicznej i dostępności wody w glebie. Ewapotranspiracja zmniejszyła się najbardziej w przypadku ziemniaka późnego w środkowo-zachodniej Polsce (30–60%), a najmniej w przypadku rzepaku ozimego (12–16%) w tym samym regionie na glebach o małej retencji wodnej, natomiast na glebach o dużej retencji wodnej ewapotranspiracja się nie zmniejszyła. Stwierdzono dobrą korelację między obliczonym i rzeczywistym zmniejszeniem plonu. W centralnej Polsce zmniejszenie plonu ziemniaka późnego może przekroczyć 50%. Plony najmniej się zmniejszyły w przypadku pszenicy ozimej i rzepaku ozimego. Główną zaletą metody zastosowanej w pracy jest skojarzenie suszy meteorologicznej, zdolności retencjonowania wody w glebie, ewapotranspiracji, bilansu wody w glebie oraz plonów i umożliwienie dzięki temu bardziej dokładnych i wiarygodnych ocen.

Słowa kluczowe: *wskaźnik standaryzowanego opadu SPI, wskaźnik suszy rolniczej CDI, deficyt wody roślin uprawnych, susza, bilans wody w glebie, zmniejszenie plonu*