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Monitoring of agricultural drought in Poland using data derived from environmental satellite images

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Abstract. In Poland one can observe a lack of sufficient amount of rainfall during plant growth season. This results in the occurrence of agricultural drought and the consequent drop in crop yields. For the early detection of drought, satellite images taken by environmental and meteorological satellites have been used. On the basis of these images various plant indices like NDVI, VCI and TCI have been determined. Analysis of changes in these indices allows preparation of maps showing the emergence and extent of drought. These vegetation indices were also used in the model of cereal yield forecast. Comparison of the results provided by the model show a high conformity with the results published by the Polish Central Statistical Office. Elaborated model estimating crop yield reduction due to drought, based on satellite-derived data allows venture of measures to mitigate results of drought and prevent the lowering yields by artificial irrigation.

Keywords: agricultural drought, satellite derived vegetation indices, vegetation growth, yield reduction

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1. Introduction

Poland is located in the region where normally precipitation had surpassed transpiration. For years the amount of rainfall was sufficient to cover the demand by the crops, which resulted in good yields. Since the end of sixties of the last century one can observe decrease of rainfall of about 70 mm, so much that some regions of the country started to suffer from insufficient amount of water. Droughts occurred in the country more and more frequently. Drought appears as so-called atmospheric drought, which is a significant reduction in rainfall compared to the average of several years. It is assumed that the reduction of rainfall to 80% of normal value in the region gives rise of the drought effect. The prolonged atmospheric drought causes soil drought which means the decline of water resources in the surface layer of soil. Continued lack of rain causes the appearance of hydrological drought, resulting in depletion of groundwater resources and reducing the amount of water in streams and rivers.

Shortage of precipitation especially during the growing season, as well as the influence of other climatic factors, like harsh winters, strong spring temperature fluctuation, lack of warm weather in the summer cause that the yield of many crops can vary from year to year. The average yield of main crops in Poland is much lower than in majority of West European countries but large areas under cultivation put Poland in third place in production of rye (20.8% of the world production in 2009), sixth in production of sugar beets (4.7% of the world production in 2009) and seventh in production of potatoes (2.9% of the world production in 2009).

Droughts are one of the major natural disasters affecting agriculture production in Poland. They occur almost each year, usually in different parts of the growing season, and in different locations. The yield reduction depends on the type of crop and its development stage when the drought occurs. In Poland the losses of agricultural production caused by weather anomalies can reach even 40% of cereals yield.

There are many definitions of drought phenomenon. One of them is a definition accepted by the Institute of Meteorology and Water Management. It defines the drought taking into account the amount of rainfall, the number of rainless days, the difference between the amount of rainfall and evapotranspiration in the period from 1 June to 1 September and the number of days at a specified temperature of the soil at a depth of 5 cm after 1 June. Another definition of drought based on a special index determined as the ratio of potential evapotranspiration to the average amount of rainfall during the growth of plants (April – October). It ranges from 1.6 in areas with high risk of drought to 1.0 in areas where rainfall is greater than the potential evapotranspiration. This index proved to be a better indicator of drought occurrence than rainfall data.

Drought, as a meteorological phenomenon, it is virtually impossible to predict. In Poland existing methods for the determination of agricultural drought occurrence are based on measurements of meteorological parameters, including the amount of precipitation, air temperature and the amount of evaporation. This information comes from relatively low-density network of meteorological stations and limited number of points of ground assessment of the status of the plants development and quite often is not available early enough in order to make accurate estimates of crop production. It should be noted that determination of the drought using above mentioned method is time and labour consuming.

At present remote sensing methods play a significant role in detecting drought, defining its scope and intensity. Specific indicators derived from data acquired by satellites allow the characterization of plants development, an assessment of water availability to plants and therefore a possible occurrence of drought. Studies on the use of remote sensing for drought monitoring and yields forecasting are conducted in many countries. It should be mentioned that the National Centre NOAA/NESDIS has developed several indicators used in many semi-arid areas for drought detection and monitoring of vegetation. They were also used successfully in the United States (Kogan and Sullivan, 1993; Kogan, 1995, 1997).

2. Satellite images applied to detect a drought

The Remote Sensing Department of the Institute of Geodesy and Cartography (IGIK) has also undertaken an attempt to use satellite data to detect drought and monitor its expansion in order to estimate its impact on crop production. In the investigations satellite images acquired by Terra/Modis, SPOT-4/Vegetation 1, SPOT-5/Vegetation 2 and NOAA/AVHRR 14, 16, 18, 19 have been used. The images taken by Terra satellite has been applied to determine the agricultural production area across the country, while images taken by NOAA and SPOT have been used do determine vegetation indices such as Normalised Vegetation Index (NDVI), Vegetation Condition Index (VCI) and also Temperature Condition Index (TCI) from NOAA/AVHRR. Terra and SPOT images were supplied by official providers, NOAA images were received at the station situated in the Institute of Geodesy and Cartography.

To determine the agricultural production area in Poland Terra/Modis images were interpreted using computer aided classification supported in some cases by visual analysis of aerial photographs. The result of the work was a map presenting distribution of agricultural area in the country. The map served as a mask in case of analysis of NOAA/AVHRR and SPOT/Vegetation images to compute vegetation indices only for agricultural area, excluding forest and artificial surfaces (Turlej, 2009).

3. Vegetation indices derived from satellite data

Vegetation indices (NDVI, VCI and TCI) have been derived from data collected by SPOT and NOAA satellites in visible and near as well as in far infrared radiation. Images taken by these satellites were subjected to the geometric correction. Transformation of the image from the sensor-based projection to an Earth based projection was done using information on a satellite position during image acquisition. In order to ensure the appropriate accuracy of the reprojection, an additional adjustment to selected control points and lines was performed by an operator. Moreover, the solar/satellite viewing angles, i.e. a satellite zenith angle and a Sun zenith angle, were computed during spatial rectification. These imaging geometry parameters were also useful in the atmospheric correction process and during the search for pixels contaminated by clouds.

NOAA/AVHRR satellite images were acquired every day, however, the cloudiness often caused it impossible to obtain pictures presenting the whole agricultural area of the country. It was assumed that within 10 days one could obtain clouds free images of all parts of the country. Therefore, from each image only a portion free of clouds was chosen for further analysis. On the basis of the 10 days composite the image of the whole country free from clouds was created. In order to enable the comparison of the decade mosaics they were resampled into a constant grid of 1 km pixels in Albers projection.

In a radiometric calibration procedure digital numbers registered in channels 1 and 2 were converted into reflectance values and digital numbers registered in channels 4 and 5 were converted into radiance at the satellite level. *NDVI* index at a satellite level was computed from calibrated values of partial albedo before the atmospheric correction of images.

The purpose of the next stage of processing was to obtain albedo and radiance at the ground level. The atmospheric correction of albedo in channels 1 and 2 was performed according to the algorithm designed by Teillet and Santer (1991) with the help of 6S software (Tanré et al., 1990) assuming a standard profile of the atmosphere for middle latitude regions during summer. In the next step, the corrected albedo values were used to determine *NDVI* at the ground level.

The preliminary processing gave at the output the set of digital maps. This product contained maps of the spatial distribution of the following quantities: albedo A_1 and A_2 at a ground level, $NDVI^{sat}$ at a satellite level, raw digital numbers DN_4, DN_5 registered in channels 4 and 5, satellite zenith angle Θ_{sat} and Sun zenith angle Θ_{sol}.

A decade mosaic was composed using the values of $NDVI^{sat}$ as a compositing criterion (Holben, 1986). Since the composition process only diminishes the number of cloud-contaminated pixels, but usually does not remove them completely, a threshold method was applied to detect clouds in the decade mosaics. Cloud detection was performed according to the algorithm in which the albedo in channel 1, *NDVI* and a difference of temperature measured in bands 4 and 5 were checked against the thresholds. This algorithm is partially based on the method of cloud detection developed by Kriebel et al. (1999).

Corrected *NDVI* and land surface temperature *TS* can be treated as the indices of vegetation condition and can be also used for the calculation of some other rational indices which are described below. The AVHRR-based reflectance in the visible (VIS) and near infrared (NIR) wave bands and the Normalized Difference Vegetation Index has been used. *NDVI* for each pixel of the agricultural production area has been calculated on the basis of decade mosaics.

It is well known that the *NDVI* fluctuates due to favourable or unfavourable weather and environmental conditions (Kogan, 1997; Dabrowska-Zielinska et al., 2002). These variability of *NDVI* were estimated relative to the maximum and minimum intervals of *NDVI*, named the Vegetation Condition Index (*VCI*), which was calculated according to the formula

$$VCI = 100\,(NDVI - NDVI_{min})/(NDVI_{max} - NDVI_{min}) \quad (1)$$

where *NDVI* is actual 10-days value, while $NDVI_{max}$ and $NDVI_{min}$ are absolute maximum and minimum values of *NDVI* in multi-year period.

Following the assumption that $NDVI_{min}$ represents poor crop growth conditions and $NDVI_{max}$ represents good crop growth conditions, the high values of *VCI* represented good conditions while low *VCI* values represented poor, dry conditions.

On the basis of temperature the Temperature Condition Index (*TCI*) has been calculated from *BT* values (Kogan, 1997) for each decade in the period 1997–2010 according to the formula

$$TCI = 100\,(BT_{max} - BT)/(BT_{max} - BT_{min}) \quad (2)$$

where *BT* is actual 10-days value, while BT_{max} and BT_{min} are absolute maximum and minimum values of *BT* in multiyear period respectively derived from NOAA.

The high *TCI* values indicate low temperature and favourable crop growing conditions especially in the second part of the season, while low *TCI* values indicate dry conditions, unfavourable for development of crops during summer. The research has proved that the low values of *TCI* in spring represent favourable conditions for vegetation as the brightness temperature of vegetation is close to maximum, which is optimal for this period. Low *TCI* values during the maximum growth of vegetation indicate stress in crop development expressed by high values of brightness temperature close to maximum for this period (Dabrowska-Zielinska et al., 1998).

The third index was calculated as cumulated values of *NDVI*.

$$CNDVI_n = \sum_{i=10}^{n} NDVI_i \quad (3)$$

Accumulation starts at the beginning of April, when vegetation starts to grow.

It has to be noted that the beginning of the vegetation season fluctuates. Also the length of the vegetation growing season vary from year to year. These changes are shown in the graph presenting the values of *NDVI* in time (Fig. 1).

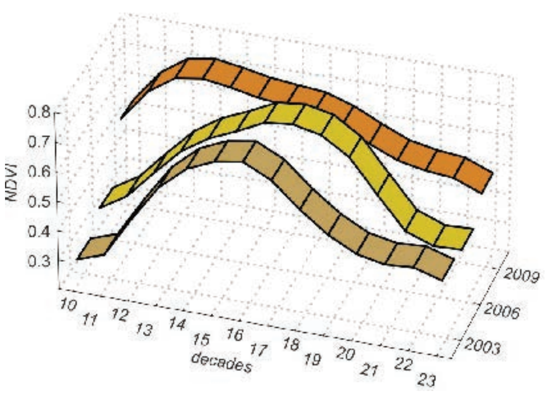

Fig. 1. *NDVI* curves in dry years (2003, 2006) and humid year (2009)

The start of the vegetation in 2009 was when *NDVI* reached value of 0.40 (Fig. 2) while the start in 2010 was when *NDVI* was close to 0.35. The rate of increase *NDVI* was rapid in 2009 comparing to 2010, the maximum value of *NDVI* was 0.75 while maximum value of *NDVI* in 2010 was less than 0.75.

It is very important to monitor the phenology of vegetation growth. The most important factor driving the crop development is weather. The analysis of phenology stages is indispensable for climate change studies. Remote sensing techniques could give information about the phenology stages of crop. Therefore it was considered to examine the *NDVI* time series, taking into account the start of the season and the peak of greenness (maximum of *NDVI* value which respond to the heading stage and calculate the length of the growing season (Rouse et al., 1974; Tucker, 1979; Holben et al., 1986). The TIMESAT programme was used for extracting seasonal parameters for Wielkopolska Region (Fig. 2, and Fig. 3) to present how *NDVI* series differ in various years (Curnel and Oger, 2008; Klish et al., 2008).

Figure 4 shows the values of cumulated *NDVI* at each ten day period of the year. Cumulating starts from the beginning of April, when vegetation starts to grow. The highest values of cumulated *NDVI* (*CNDVI*) occurred in 2007 and 2009 (high crop yield), while the lowest values occurred in 2003, 2006 and 2000 (low crop yield). The *CNDVI* curve for the year 1998 is rather low, however the crop yield in this year was pretty high. Therefore taking into account the information about *CNDVI* only, is not sufficient for crop yield modelling. Every year the crop develops differently, as the start of vegetation season occurs at the various time.

It was noticed that when crop started to grow the *CNDVI* index reaches value of 0.5. It usually happened in the 11 decade of the year, but in the years 2005, 2007, and 2009 vegetation started to grow earlier, i.e. at the 10 decade in these years, than *CNDVI* index reaches value of 0.5 (Fig. 5). From this it follows, that the *CNDVI* index represents the phenological stage of vegetation growth, crop stage development and conditions of crop growth.

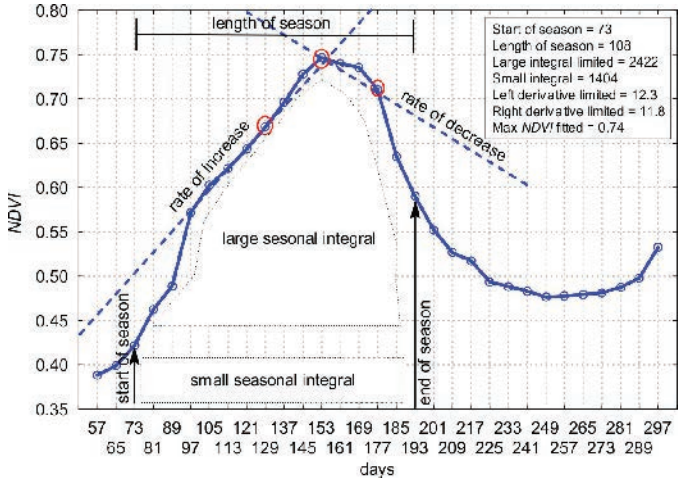

Fig. 2. Start and length of the season, rate of increase of *NDVI* values in Wielkopolska Region 2009

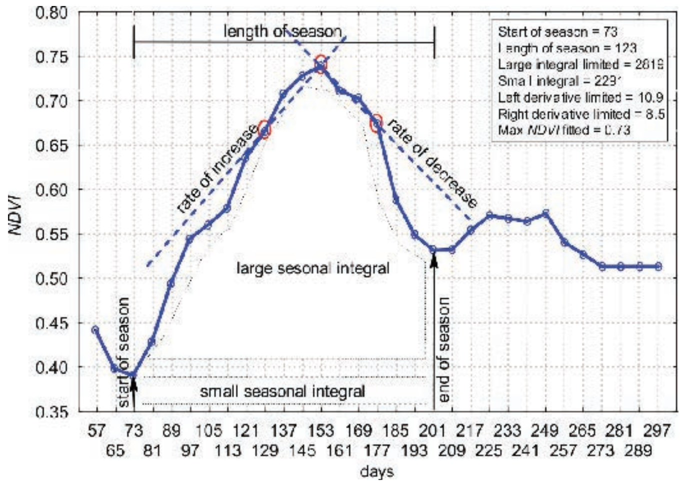

Fig. 3. Start and length of the season, rate of increase of *NDVI* values in Wielkopolska Region 2010

4. Model of yield prediction

Having this hypothesis it was necessary to consider the crop growth conditions at particular phenological stage instead of taking the vegetation index (*VCI* or *TCI*) at the specific decade of the year.

Through modeling it was proved that crucial time for yield forecast of cereals occurred twice, first is when *CNDVI* reached value of 0.5 (start of vegetation growth) and then when it reached value of 4. It was noted (Fig. 5) that the time when *CNDVI* reached value of 4 was in 2009 at the decade 15, in 2000 at 16th and in 2003 at 17th.

The model for yield prediction contains indices *VCI* and *TCI* from various decade (n) of the year. The hypothesis is as follows:

If *CNDVI* is equal to 0.5 then *VCI* is taken from this decade, if *CNDVI* is equal to 4.0 then *TCI* is taken from this decade as an input to the model.

At the beginning of the crop development, when *CNDVI* equals to 0.5, *VCI* well characterizes the vegetation growth. Later, when *CNDVI* equals to 4,

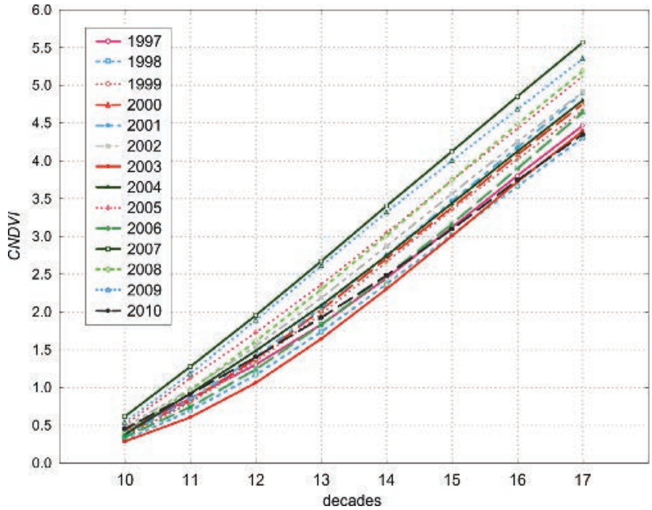

Fig. 4. Cumulated *NDVI* values for the decades 10 to 17 for Wielkopolska Region in the years 1997–2010

TCI characterizes well crop-soil conditions. *TCI* seems to characterize better water stress of vegetation at the important time of cereals phenology.

The Model for Crop Yield prognosis using above described approach is as follows:

$$Y = 23.16 + 0.09\ VCI\ (\text{when } CNDVI = 0.5) + 0.13\ TCI\ (\text{when } CNDVI = 4) \quad (4)$$

Figure 6 presents distribution of *VCI* values in particular NUTS3 regions when *CNDVI* was 0.5 in the years 2003 and 2009. In the year 2009 *VCI* values were the highest in all NUTS3 regions in the time when *CNDVI* was 0.5. In the year 2003 *VCI* values were the lowest at the time when *CNDVI* was 0.5.

Figure 7 presents distribution of *TCI* values in particular NUTS3 regions when *CNDVI* was 4 in the years 2003 and 2009. In 2003, the *TCI* values in the time when *CNDVI* equals to 4 was low (<50) what was reached in decade 17 in most of the regions in the country. In 2009 *TCI* values were high and reached values of 50–80, mostly in decade

CNDVI	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
0.5	11	11	11	11	11	11	11	11	10	11	10	11	10	11
1.0	12	12	12	12	12	12	12	12	11	12	11	12	11	12
1.5	13	13	13	13	13	12	13	12	12	13	12	12	12	12
2.0	14	14	14	13	13	13	14	13	13	14	13	13	13	13
2.5	15	15	14	14	14	14	15	14	14	15	13	14	13	14
3.0	15	15	15	15	15	15	15	15	14	15	14	14	14	15
3.5	16	16	16	15	16	15	16	16	15	16	15	15	15	16
4.0	17	17	17	16	16	16	17	16	16	17	15	16	15	17
4.5	18	18	18	17	17	17	18	17	17	17	16	17	16	18
5.0	18	19	19	18	18	18	19	18	17	18	17	17	17	19
5.5	19	20	20	19	18	19	19	19	18	19	17	18	18	19
6.0	20	21	21	20	19	19	21	19	19	19	18	19	19	20
6.5	21	22	22	21	20	21	22	20	20	20	19	20	19	22
7.0	23	23	23	22	21	22	23	21	21	21	20	21	20	23

Fig 5. Cumulated *NDVI* values (0.5 – 7.0) for the period 1997–2009 at the particular decades

Table 1. Regression results

$N = 13$	Summary of regression; dependent variable: CEREALS $R = 0.76601131$; $R^2 = 0.58677332$; region: wielkopolskie $p < 0.01205$; Std. estim. error 2.9751					
	b^*	St. error from b^*	b	St. error from b	$t(10)$	p
Intercept	–	–	23.165	3.024	7.660	0.000
$VCI_n.5$	0.562	0.204	0.091	0.033	2.754	0.020
$TCI_n.4$	0.471	0.204	0.127	0.055	2.307	0.044

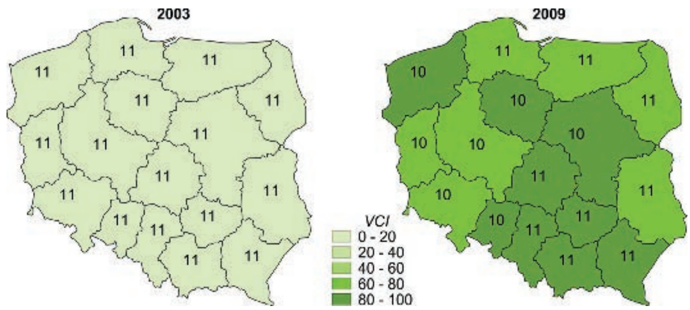

Fig. 6. Different values of *VCI* at a decade when *NDVI* reaches cumulative value of 0.5 in 2003 and 2009

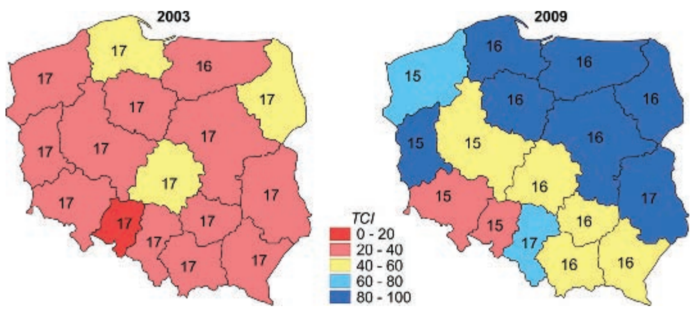

Fig. 7. Different values of *TCI* at a decade when *NDVI* reaches cumulative value of 4.0 in 2003 and 2009

16 (earlier than in 2003) when *CNDVI* equals 4. Among considered years of investigation, the year 2003 was the driest. *TCI* values were low, below 50, what indicated the drought. The vegetation growth conditions in 2009 were good with sufficient amount of precipitations.

Reduction of the crop yield was calculated from actual crop prognosis (*Y*) in relation to maximum yield for the given region during time of satellite NOAA observation 1997–2010 (Eq. 4).

Figures 8–10 show the reduction of cereals yield in the years 2003, 2009 and 2010 due to drought calculated by IGIK on the basis of data provided by NOAA satellites and calculated by Central Statistical Office (CSO).

5. Conclusions

Taking into account in modeling of crop yield only the values of vegetation indices from the par-

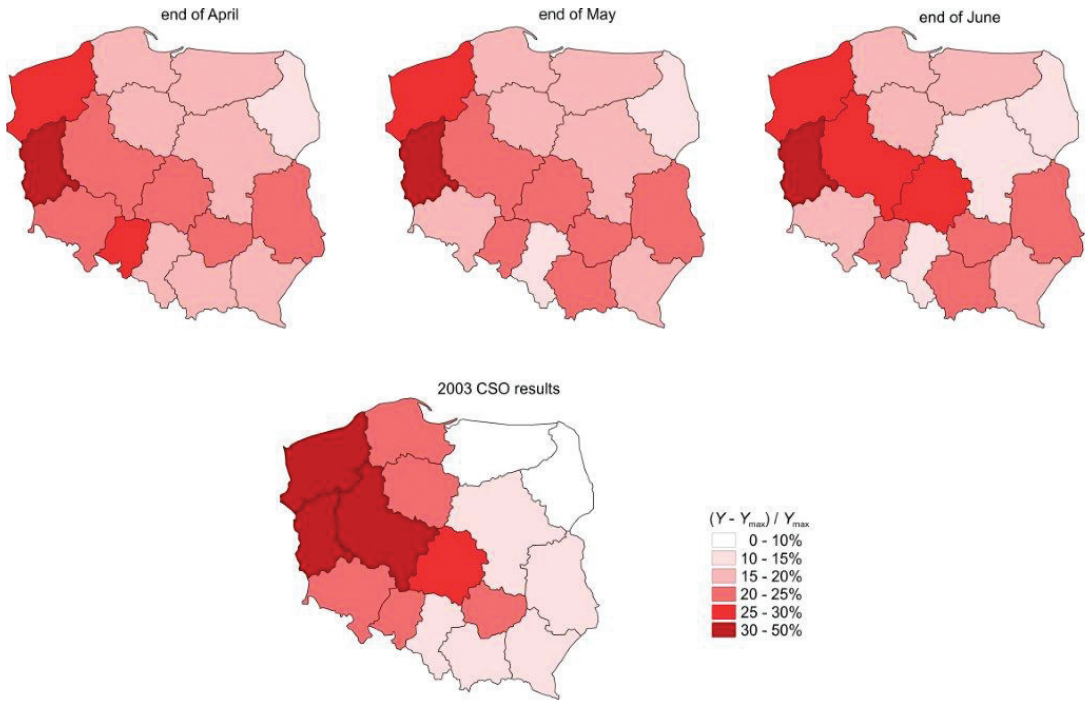

Fig. 8. Cereals yield reduction in 2003

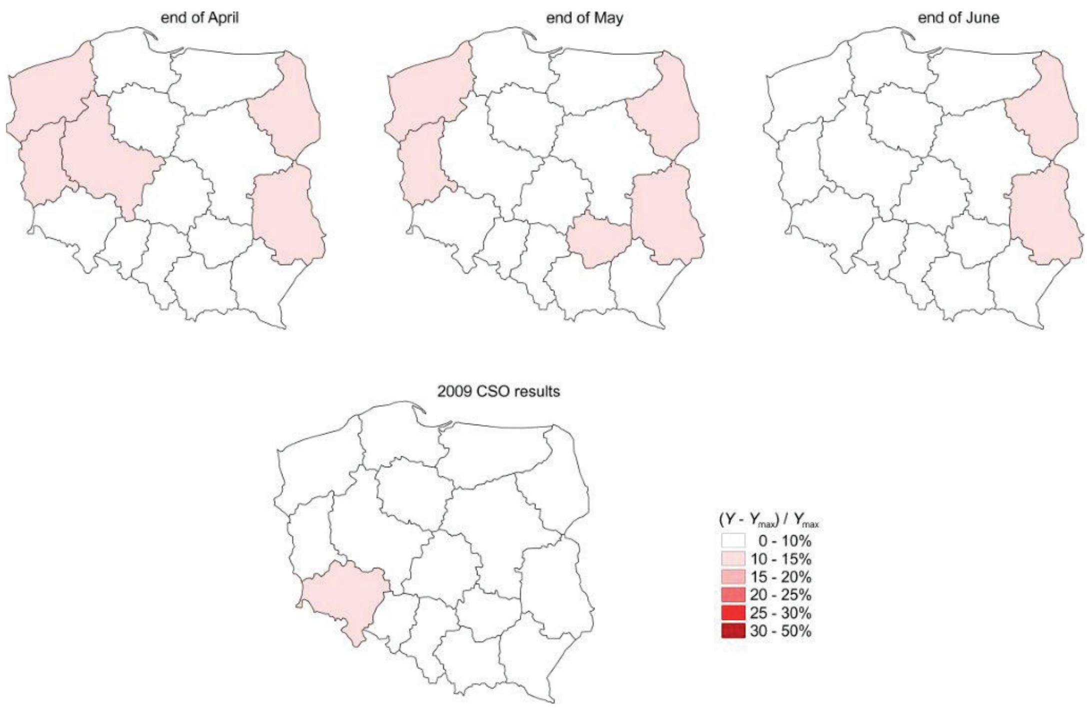

Fig. 9. Cereals yield reduction in 2009

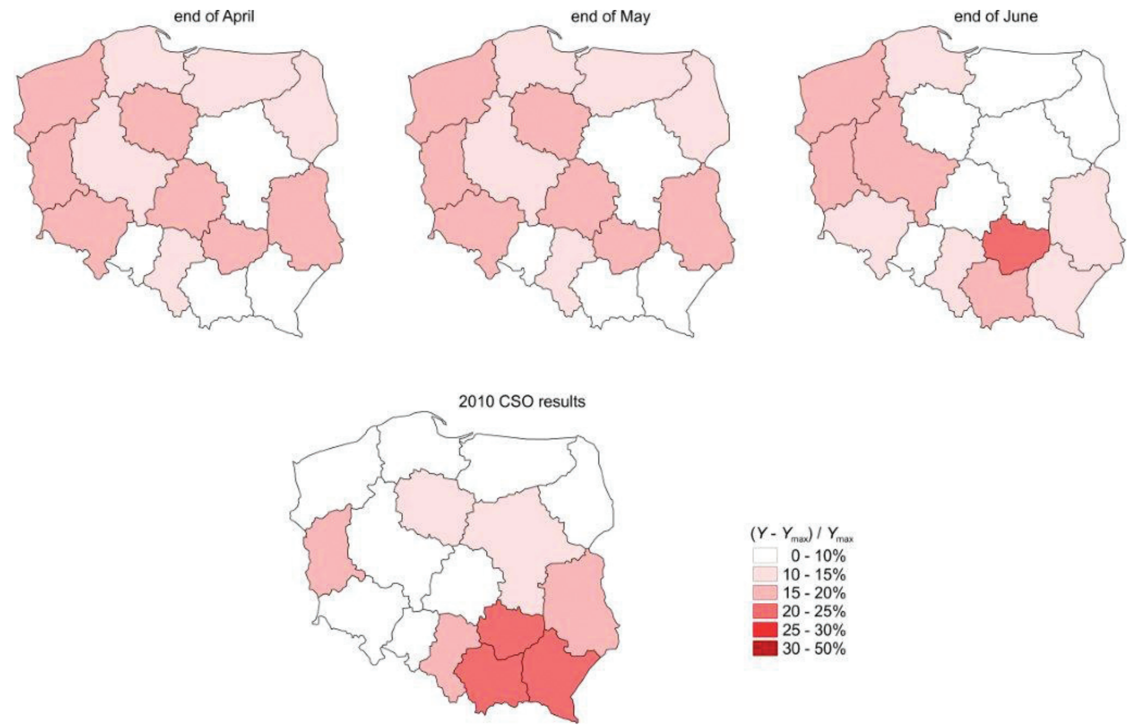

Fig. 10. Cereals yield reduction in 2010 was much lower than in 2003

ticular decades of the growing season could be erroneous, as the crop growing conditions may vary each year. It was presented that the *NDVI* course differs in various years. Therefore in modeling the crop development the phenology has to be considered. In the presented method the phenology of the crop was represented by the accumulated values of *NDVI*. The important stage of crop development coincides with the periods when accumulated *NDVI* index reaches the first value of 0.5 and then 4. In these phenology stages the crop yield forecast are the most accurate.

It was also shown that the crop yield prognosis may indicate the crop yield reduction due to drought. The study shows that the crop yield reduction occurs when the *TCI* values drops below 50. In the considered period it has happened in 2003. The prognosis of crop yield reduction may be assessed already in 15–17 decade of the year. The information may be sent to the farmers early enough to mitigate result of drought by proper management including watering of crop.

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Monitoring suszy rolniczej w Polsce na podstawie danych pozyskiwanych za pomocą satelitów środowiskowych

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Streszczenie. W Polsce obserwuje się brak dostatecznej ilości opadów w okresie wzrostu roślin. Prowadzi to do wystąpienia suszy rolniczej i w konsekwencji spadku plonów. Do wczesnego wykrywania suszy zostały wykorzystane zdjęcia satelitarne wykonane przez satelity środowiskowe i meteorologiczne. Na podstawie tych zdjęć określono różne wskaźniki roślinne, takie jak NDVI, VCI i TCI, charakteryzujące kondycję i wigor roślin. Analiza zmian tych wskaźników pozwala na wnioskowanie o wystąpieniu zjawiska suszy, jej zasięgu oraz natężenia. Wskaźniki wegetacyjne zostały również wykorzystane w modelu prognozy plonów zbóż. Wyniki modelowania wykazują dużą zgodność z wynikami opublikowanymi przez GUS. Opracowany model szacowania redukcji plonów upraw z powodu suszy dostarcza informacji umożliwiających przedsięwzięcie działań na rzecz łagodzenia skutków suszy i zapobieżeniu redukcji plonów poprzez np. sztuczne nawadnianie.

Słowa kluczowe. Susza rolnicza**,** wskaźniki roślinne wyprowadzane z danych satelitarnych, wzrost roślin, redukcja plonów.