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VAPOUR PRESSURE DEFICIT AND VARIABILITY OF YIELD OF ONION (*Allium cepa* L.) IN POLAND

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Abstract. Vapour pressure deficit, in addition to light and temperature, is the main meteorological element that influences the degree of transpiration rate, which in turn determines the impact of drought stress on the yield of onions. In this study we attempt to assess the effect of vapour pressure deficit on onion cultivation in Poland and present a temporal and spatial distribution of vapour pressure deficit for the years 1966–2005. During the period "end of emergence–harvest" (Ee–H), vapour pressure deficit had the greatest impact on onion yield in central western Poland and in the Sandomierz Basin (south east). In these regions the average total yield of onion was 15% lower than the long-term average for the entire country, and yields lower than the long-term average occurred every 1–2 years. A statistically significant year-to-year increase in vapour pressure deficit during the Ee-H period indicates the possibility of a further increases in the risk to onion cultivation.

Key words: climate change, air moisture conditions, arable farming, vegetable plants

INTRODUCTION

Due to a shallow and poorly developed root system, the onion is very sensitive to water deficit in agrobiocenose [Al-Jamal et al. 2000, Pelter et al. 2004, Karczmarczyk and Nowak 2006, Enciso et al. 2007]. Most roots are located in the top soil, within a radius of 30 cm and depth of 15–20 cm [Tendaj 2000, Babik 2004]. Under favorable conditions, in good soil, some of the roots extend to 30 cm, and individual roots to 50 cm. Formation of a good root system is facilitated by an early cold and relatively wet spring [Kalbarczyk 2010]. The suction force of onion roots is moderate, greater than the cucumber and almost the same as cabbage [Kaniszewski 2005].

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Onion foliage is prepared for economical water management. Tubular leaves have a relatively low surface transpiration and a waxy coating additionally protects them from evaporation. As a result, water losses occur mainly due to evaporation in the soil in inter-rows that until the time of leaf-bending are almost entirely exposed to sunlight [Karczmarczyk and Nowak 2006]. Water deficiency in each stage of growth, particularly in emergence and during formation and intensive growth of bulbs, decreases yield and often deteriorates the quality of onions [Tendaj 2000, Kalbarczyk et al. 2011]. Drought during germination and emergence reduces the number of plants per unit area, and is also a cause of late, weak and uneven emergence [Kaniszewski and Perłowska 1988, Shock et al. 2000, Pelter et al. 2004, Kaniszewski 2005]. During the formation of bulbs, vapour pressure deficit in an arable field reduces their individual weight and increases the number of bulbs with two apical meristems [Karczmarczyk and Nowak 2006].

Various methods are used to evaluate moisture conditions during the growth and development of vegetables. In Poland, soil moisture in the main root area is often evaluated by the determination of water content in the soil, as well the proportion of soil water content to field capacity and water potential [Knaflewski 1987, Kaniszewski 2005, Rumasz-Rudnicka et al. 2008]. Methods based on trends in weather conditions and measurements of potential evapotranspiration are used more frequently outside Poland [Meranzova and Babrikov 2002, Piccinni et al. 2009].

Vapour pressure deficit (VPD) is one of the few weather indicators that have a major impact on cloud cover and the incidence of precipitation, and in conjunction with air temperature plays an important role in the process of evaporation [Bryś and Bryś 2005, Wypych 2008, Baranowski 2010, Kajewska and Rojek 2011]. VPD, next to light and air temperature, is the main determinant of transpiration, which in turn decides the impact of drought stress on the yield of onions. However, VPD is rarely the subject of detailed analysis, especially with regard to the cultivation of vegetables in arable farmland. Therefore, this study attempts to assess its effect on the cultivation of onions in Poland caused by vapour pressure deficit and its temporal and spatial distribution.

MATERIAL AND METHODS

This study analyzed the size of total yield and agronomic and phenological dates for medium-late varieties of onions over the years 1966–2005. These data included the results of experiments conducted in 17 experimental stations of the Research Center for Cultivar Testing in Słupia Wielka (COBORU) (fig. 1). Agrophenological dates in the study included: sowing (Sg), the end of emergence (Ee), the beginning of leaf bending (Blb), and harvest (H). The size of yield and the dates of agrophases were presented in a collective pattern for the most widely cultivated medium-late cultivars of onion. The use of a collective pattern was based on the assumption that intraspecies differences do not obscure the overall regularities. Onions were grown in wheat soil complexes – very good and good, and a very good rye soil complex [Domański 1998]. Mineral and organic fertilization was used according to COBORU methodology. Manure or sometimes compost were usually used in the second year of onion cultivation at a dosage of 30 do

50 t·ha^{-1}, while mineral fertilizers were applied at an average rate of 370 kg per hectare. Cereals and legumes were usually used as a forecrop.

Fig. 1. Arrangement of experimental stations (■) and meteorological stations (●) in Poland that are included in the study

The study also used daily and ten-day average data regarding vapour pressure deficit (VPD) in all agrophenological periods for onions: sowing–end of emergence (Sg–Ee), end of emergence–beginning of leaf bending (Ee–Blb), and beginning of leaf bending–harvest (Blb–H), and also all the other possible periods between the stages (i.e. also Sg–Blb, Sg–H, Ee–H). The data were collected from all the weather stations operating at the COBORU experimental sites and, in the absence of such stations, from the closest stations of the Institute of Meteorology and Water Management (IMGW). The analysis of spatial dynamics of VPD Poland used data from 51 IMGW stations. The study did not take into account regions located in south-western or south-eastern Poland, because of the very high diversity of physiographic conditions and altitudes often above 500 m above mean sea level, considerably limiting the possibility of arable farming [Kalbarczyk 2011].

The effect of VPD on the yield of onion was determined by multiple curvilinear regression analysis.

$$y_p = - a + bx_1 - cx_2 + dx_2^2$$

where:

x_1 – linear trend, consecutive years of the period 1966–2005,

x_2 – vapour pressure deficit (hPa).

The fit of the regression function to empirical data was measured by the correlation coefficient (r), coefficient of determination (R^2, %) and an indicator describing the difference between the standard deviation of the dependent variable and the standard error of estimation for the SD-Sy equation (SD-Sy, $t \cdot ha^{-1}$). The relevance of quantitative forecasts determined for the equation were determined by two ex-post indicators: the relative forecast error (RFE) and the average relative forecast error (ARFE) [Kalbarczyk 2011]. ARFE was determined for all analyzed COBORU stations and all years in the 1966–2005 period. We also identified the number of times the relative forecast error for 1966–2005 was $|RFE| \leq 5$ (very good forecast) and $5 < |RFE| \leq 10$ (good forecast).

Based on the regression equation we determined the decrease in total onion yield in Poland induced by an unfavorable VPD. The equation was also used to determine the threshold value of VPD, i.e. the VPD which would result in at least the 5% reduction in the total yield of onion below the long-term average for the period 1966–2005. Then the equation describing the effect of VPD during the period Ee-H on the size of the total yield of onion was supplemented with the average VPD level, but only for the years in which the VPD exceeded the designated threshold. The yield induced by the incidence of adverse VPD levels was calculated for each IMGW and COBORU station separately. The differences between the long-term real yield of onion determined for the whole country and the yields calculated according to the procedure described above allowed determination of the reduction in the total yield of onion caused by unfavorable VPD.

The incidence (P_1, %) of a too high VPD (above the determined threshold) during Ee-H in the period from 1966 to 2005 was calculated by the formula:

$$P_1 = \frac{n_1}{N} \cdot 100\%$$

where:

n_1 – number of periods with an excessive vapour pressure deficit,
N – the total number of periods under consideration.

The spatial distribution of the vapour pressure deficit, as well as the distribution of yield reduction and incidence of VPD, are shown graphically as isorithms, allowing for the physiographic diversity of the Polish territory.

RESULTS

The closest relationship between the overall yield of onion and vapour pressure deficit was shown in the period “end of emergence–harvest” (Ee–H). As shown in table 1, the analyzed weather-yield relationship could be described by a multiple regression equation, which, in addition to VPD, also included a linear trend for consecutive years of the period 1966–2005. All the regression coefficients and the intercept of the equation were significant at $P \leq 0.01$, and the Student's t-test levels ranged from -2.835 for the intercept to 4.633 for the regression coefficient, describing the contribution of the linear trend in the prediction of the equation. The coefficient of determination determined for the equation $R^2 = 56.4\%$, and the difference between the standard deviation of the dependent variable and the standard error of estimate of the equation was 3.6 t·ha^{-1}. Average relative forecast error for the equation ARFE = 10.1%. Very good forecasts, $|RFE| \leq 5$, were observed in 45.3% of cases, and good $5 < |RFE| \leq 10$ – in 43.8%.

Table 1. Correlation between the total yield of onion and vapour pressure deficit during the period "end of emergence–harvest" (1966–2005)

Equation				Characteristics				Frequency of the occurrence of |RFE| in range	
symbol	value	t	*P*	r	R^2 (%)	SD-Sy (t·ha^{-1})	ARFE (%)	0–5 (%)	5–10 (%)
β_o	-267.643	-2.835	0.01	0.771	56.4	3.6	10.1	45.3	43.8
$\beta_1 x_1$	0.212	4.633	0.01						
$\beta_2 x_2$	-35.255	-4.668	0.01						
$\beta_3 x_2^2$	2.369	3.351	0.01						

x_1 – linear trend, which is further analyzed across the multi-year period 1966–2005, x_2 – vapour pressure deficit in the period „end of emergence–harvest" (hPa), β_o – intercept of the equation, β_1, β_2, β_3 – regression coefficients, t – Student's *t*-test, *P* – level of significant, r – correlation coefficient, R^2 – determination coefficient (%), SD-Sy – difference between a standard deviation of a dependent variable and a standard error of equation estimation (t·ha^{-1}), ARFE – average relative forecast error (%), RFE – relative forecast error (%)

Table 2. Indicators characterizing variables that were included in the multiple regression equation describing the relationship between total yield of onion and vapour pressure deficit in the period "end of emergence – harvest" (1966-2005)

Variable	Characteristics				
	$\bar{x}$ ±SD	min	max	Q_1	Q_3
y_o, t·ha^{-1}	32.0 ±11.3	10.8	67.2	23.2	38.8
x_2, hPa	5.5 ±0.7	3.6	7.1	5.1	5.9

y_o – total yield of onion (t·ha^{-1}), x_2 – vapour pressure deficit in the period „end of emergence–harvest" (hPa), $\bar{x}$ – average, SD – standard deviation, min – minimum value, max – maximum value, Q_1 – lower quartile, Q_3 – upper quartile

The average yield of onion in Poland, calculated for 17 COBORU stations in the years 1966–2005, was 32.0 ±11.3 t·ha^{-1} and ranged from 10.8 to 67.2 t·ha^{-1}, with other statistical indicators describing the variability of yield amounting to Q_1 = 23.2 t·ha^{-1} and Q_3 = 38.8 t·ha^{-1} (tab. 2). VPD during the Ee-H, included in the multiple regression equation as an independent variable, averaged 5.5 ±0.7 hPa, and the extreme values were 3.6 and 7.1 hPa.

Multiple regression analysis indicates (tab. 1, fig. 2), that the higher the VPD during Ee-H, in the range of 5.5 to 7.0 hPa, the greater the loss in total yield of onion. Usually high and above average levels of VPD were accompanied by above-average lighting and thermal conditions and lower than average rainfall resulting, for example, in the intensification of evapotranspiration and thus insufficient soil moisture. At least a 5% reduction in the total yield of onions across the country caused by VPD (x_2) was found at 5.7 hPa. For example, when $x_2 \geq 6.0$ hPa the reduction in yield may reach almost 15% below the long-term average level, while at $x_2 \geq 6.5$ hPa – by about 23%, and at $x_2 \geq 7.0$ hPa – by about 26%.

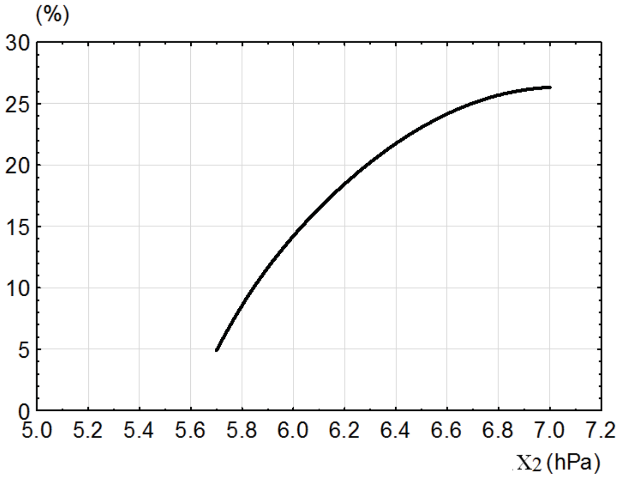

Fig. 2. The national average reduction in the total yield of onion during the period Ee–H (%) induced by excessive vapour pressure deficit ($x_2 \geq 5.7$ hPa), calculated by regression equation (tab. 1)

A decrease in the total yield of onion caused by VPD during Ee-H was not uniform across all regions in Poland (fig. 3). The largest, a more than 15% reduction in yield related to VPD occurring in central western Poland and the Sandomierz Basin. The smallest, a less than a 9% decrease in yield, was in the south-west, south-east and the Lublin Upland. In northern and central eastern Poland the yield of onion was lower than the long-term average by 9% to 12% , while in central, north-western and southern Poland – by 12% to 15%.

Vapour pressure deficits in Ee-H which resulted in at least a 5% reduction in the total yield of onion, occurred in Poland at a rate of about 43%, on average every two or three years (fig. 4). VPD at 6.0 hPa, a level that caused a decrease in the yield of onion by about 15% below the long-term average level in the years 1966–2005, occurred at a frequency of about 14%, or on average every seven years. In Poland the spatial distribution of VPD ≥ 5.7 hPa during Ee-H varied considerably and between 10% to 70% (fig. 5). Vapour pressure deficits $x_2 \geq 5.7$ hPa were the least common (below 30%) during Ee-H in northern, eastern and southern Poland, especially the south-west and south-east, where the VPD was recorded only every 10 years. In central and central western Poland, and also in the Sandomierz Basin, $x_2 \geq 5.7$ hPa during Ee-H was noted every two years, and in the Wielkopolskie Lakeland, Lubuskie and around Warsaw – every 1–2 years.

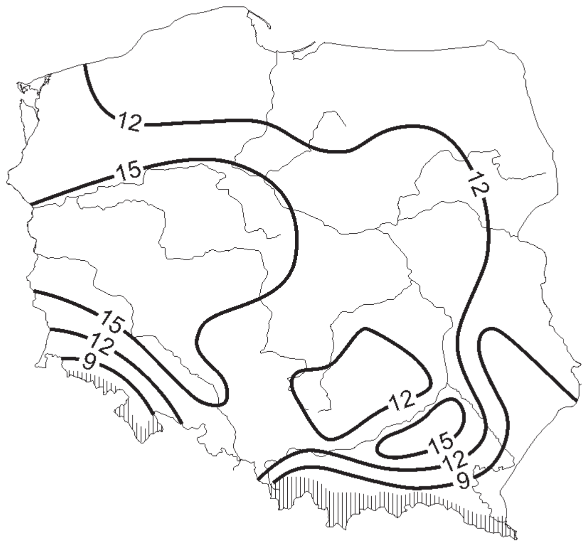

Fig. 3. Reduction of the total yield of onion during the period Ee–H (%) caused by excessive vapour pressure deficit ($x_2 \geq 5.7$ hPa), calculated by regression equation (tab. 1)

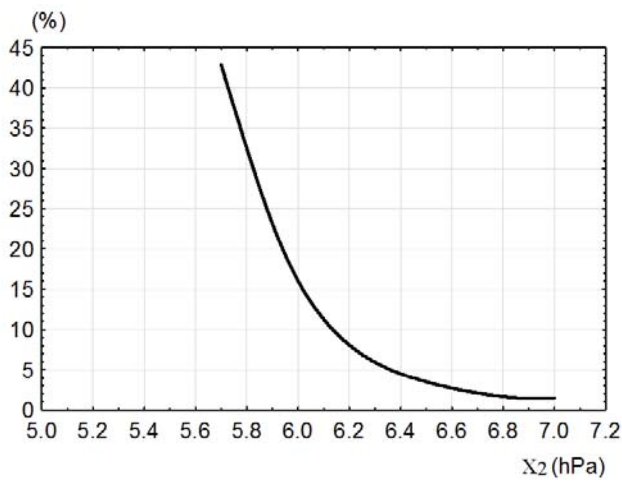

Fig. 4. Average national incidence of vapour pressure deficit ≥ 5.7 hPa in the period Ee–H (%)

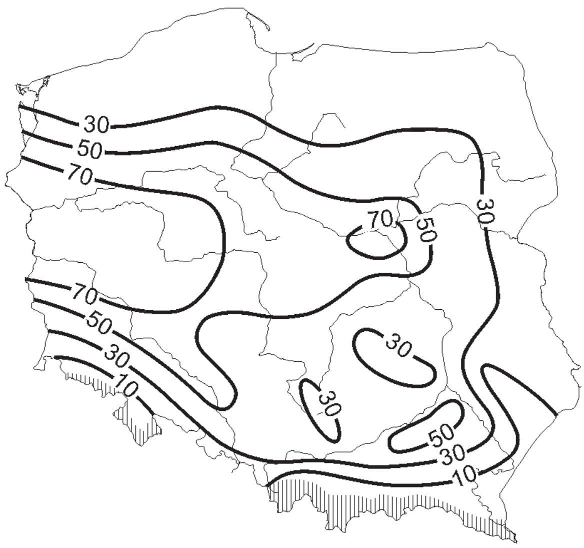

Fig. 5. Incidence of vapour pressure deficit ≥ 5.7 hPa (%) in the period Ee–H (%)

Vapour pressure deficit during Ee-H in Poland demonstrated a significant linear trend over the years 1966–2005 (fig. 6). In the first two decades (1966–1985), in 13 years the average annual VPD was lower than the long-term average in the years 1966 to 2005, and in the two following decades (1986–2005) – in only seven years. The largest extreme deviation of x_2 from the long-term average was recorded in 1974 (-0.42) and 1992 (+0.71). Spatial variation of VPD in each year under consideration was quite different (fig. 7). The year 1992 was warm and dry [Kalbarczyk 2011], and x_2 during Ee-H in most parts of the country ranged from < 5.5 hPa to > 7.0 hPa, with the worst conditions for onion cultivation in the Wielkopolskie Lakeland.

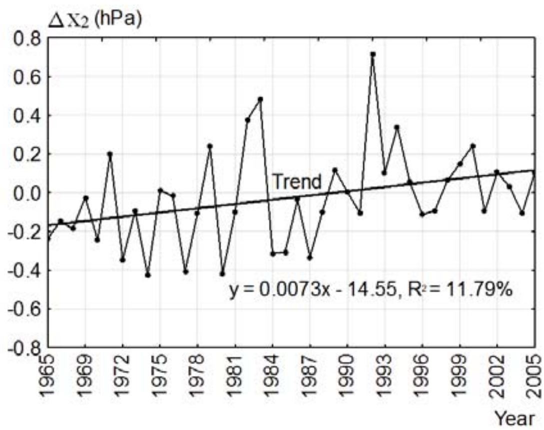

Fig. 6. Deviation from the national average vapour pressure deficit in the period Ee–H (1966–2005)

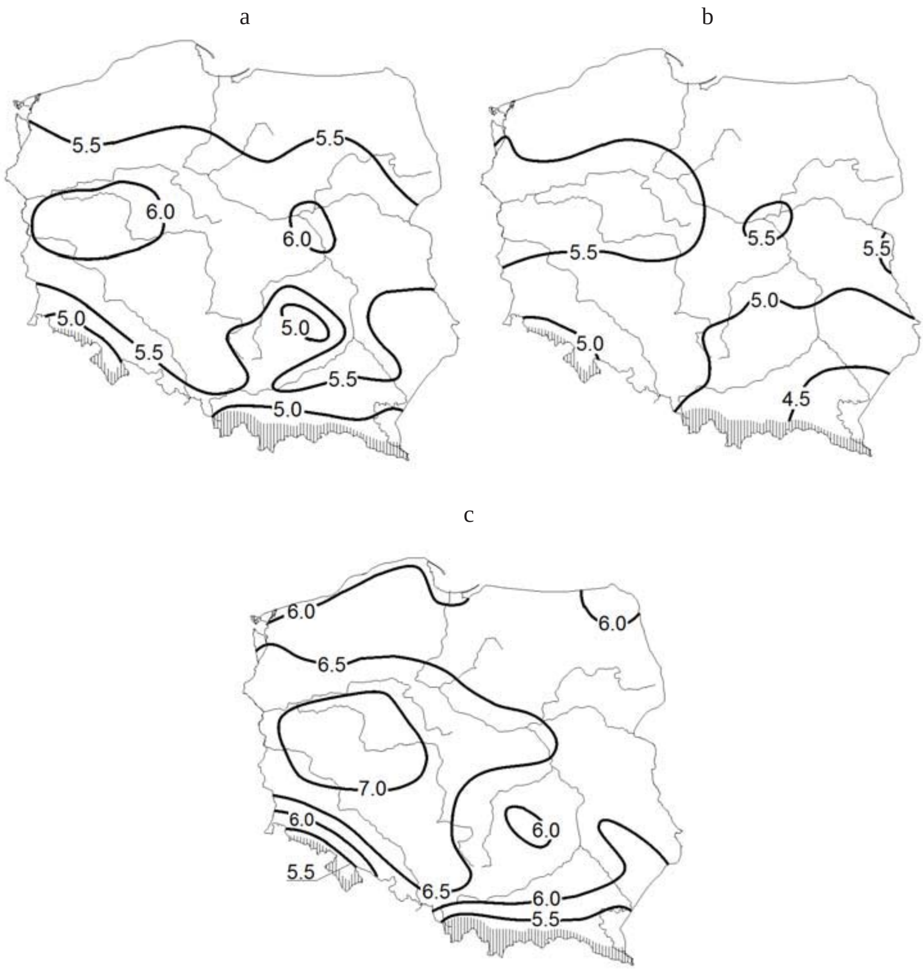

Fig. 7. Spatial distribution of the vapour pressure deficit (hPa) in the period Ee–H: a – average for the period 1966–2005, b – in 1974, c – in 1992

In the cool and moist year 1974, VPD ranged mainly from 4.5 to 5.5 hPa. The highest VPD was recorded in central western Poland and in the vicinity of Warsaw and Włodawa. Over the years 1966–2005 the spatial distribution of x_2 during Ee-H had a close to latitudinal distribution; in northern and southern regions as well as the Małopolskie and Lublin Uplands it was lower than 5.5 hPa, while in south-western and south-eastern Poland, as well as the Kielce Upland, it was lower than 5.0 hPa. On average, vapour pressure deficits least favorable for growing onions prevailed in the central belt of the country, especially in the Wielkopolskie Lakeland and in the central part of Mazovia Lowland, where x_2 was more than 6.0 hPa.

DISCUSSION

In literature, there are few reports on the assessment of the risk to onion cultivation resulting from unfavorable weather conditions which describe not only the potential reduction in yield but also the incidence [Kalbarczyk et al. 2011]. There is also a low number of papers on the relationship between yield, rate of onion growth and development and meteorological conditions, including air humidity in the region, let alone the entire country [Pelter et al. 2004, Ibrahim 2010, Kalbarczyk 2009, Kalbarczyk 2010]. The results of this work partially confirm previous reports on the strongest negative influence of atmospheric moisture conditions on the yield of onion in the period from emergence to leaf bending or even until harvest. A deficiency of moisture in the field contributes significantly to the reduction of yield of onion and deterioration of its quality [Kaniszewski and Perłowska 1988, Karczmarczyk and Nowak 2006]. However, losses in yield are not evenly distributed throughout Poland, and may range from about 10% to as much as 45% below the average long-term yield [Dzieżyc and Dzieżycowa 1986, Kalbarczyk et al. 2011]. The highest losses in the yield of onion caused by a deficiency of precipitation, similar to those caused by an excessive VPD, occurred predominantly in central Poland. Dzieżyc and Dzieżycowa [1986] found a decrease in the yield of onions on a national scale, even where total rainfall exceeded the optimal level by about 10% – on medium quality soils and by about 20–30% on heavy soils. In years when precipitation was less than 200 mm, the yield of onion, compared to the optimum precipitation, was even 24% lower on heavy soils and 43% lower on medium quality soils. Excessive rainfall in the final stage of growth may delay the ripening of onions and worsen its quality and storage stability [Tendaj 2000]. Studies carried out in different climatic conditions in the world show that the response of onion, the shortage of moisture in arable farmland, manifested in changes in growth, development and yield, depends not only on meteorological conditions but also on the stage of development, the terrain, type and richness of the soil and plant protection measures [Rumpel et al. 2003, Rumasz-Rudnicka et al. 2008].

Application of well-matched irrigation methods provides considerable possibilities of humidity deficit unfavourable results soothing. According to research carried out by Enciso et al. [2007], the total yield of onion has been increased by 12–14 kg per 1 m^{-3} of used water due to the sub-surface drip irrigation (SDI). Rumasz-Rudnicka et al. [2008] proved the minisprinklers overhead irrigation influence on the total yield of onion growth by about 10% in comparison with non-irrigated plants. A favourable influence of fertigation on the total yield of onion under conditions of mildly dry climate in India has been confirmed by Kumar at al. [2007].

The incidence of VPD determined for the period "end of emergence–harvest" is consistent with the results of earlier papers analyzing vapour pressure deficit on a monthly basis at selected meteorological stations [Wypych 2008, Baranowski 2010, Wypych 2010].

Publications on the variability of vapour pressure deficit usually refer to its spatial and temporal distribution on a monthly basis over different multi-year periods [Bryś and Bryś 2005, Wypych 2008, Baranowski 2010, Wypych 2010, Kajewska and Rojek 2011], and not according to developmental stages. These studies confirm the high diversity of moisture conditions not only between Polish regions, but also from year to year. A significant increase in VPD shown for the period 1966–2005 is confirmed by Baranowski [2010], Bryś and Bryś [2005] and Wypych [2010]. Considering the results obtained in this study in the context of projected climate change for Europe, we can expect a further increase in climate risk to onion cultivation in arable farmlands in Poland [Bárek et al. 2009, Lippert et al. 2009, Kundzewicz and Kędziora 2010, Mitovski et al. 2010, Szwed et al. 2010].

CONCLUSIONS

The strongest adverse effect of vapour pressure deficit on the overall yield of onion in Poland was found during the period "end of emergence–harvest". In Poland, a VPD ≥ 5.7 hPa during this period resulted in a decrease in the total yield by less than 9% to over 15% compared to the long-term average. The greatest decrease was recorded in the mid-west and in the Sandomierz Basin. In most parts of Poland, adverse air moisture conditions in the period of their strongest impact on the yield of onion occurred at a rate of less than 10% in the south-west and south-east of the country, and at a rate of 70% in the central western and in the vicinity of Warsaw.

The significant year-on-year increase in VPD during the period "end of emergence–harvest" can indicate a further increase in the coming years and an even greater risk to onion cultivation. Due to the changing climatic conditions, the impact of the meteorological variability of vapour pressure deficit on growth, development and yield of onion in Poland should be assessed on the basis of constructed scenarios of climate change in Central Europe.

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NIEDOSYT WILGOTNOŚCI POWIETRZA A ZMIENNOŚĆ PLONU CEBULI (*Allium cepa* L.) W POLSCE

Streszczenie. Niedosyt wilgotności powietrza jest, oprócz światła i temperatury, głównym elementem meteorologicznym wpływającym na wielkość współczynnika transpiracji, od którego zależy oddziaływanie stresu suszy na plon cebuli. W pracy podjęto próbę oceny ryzyka polowej uprawy cebuli w Polsce powodowanego przez niekorzystne warunki wilgotnościowe atmosfery. Poza tym w pracy scharakteryzowano rozkład czasowy i przestrzenny analizowanego elementu meteorologicznego w latach 1966–2005. Największe ryzyko polowej uprawy cebuli powodowane zbyt wysokim niedosytem wilgotności powietrza w okresie koniec wschodów–zbiór (Ee–H) występowało w Polsce środkowozachodniej i południowo-wschodniej – w Kotlinie Sandomierskiej. W regionach największego zagrożenia uprawy przeciętne potencjalne zmniejszenie plonu ogólnego analizowanego warzywa było o ponad 15% niższe od średniego wieloletniego poziomu plonów i występowało z częstością co 1–2 lata. Potwierdzony statystycznie wzrost wartości niedosytu wilgotności powietrza z roku na rok w okresie Ee–H może świadczyć w najbliższych latach o wzroście ryzyka polowej uprawy cebuli powodowanego przez rozpatrywany element meteorologiczny.

Słowa kluczowe: zmiana klimatu, warunki wilgotnościowe powietrza, uprawa polowa, rośliny warzywne

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