

THE RELATION BETWEEN ADVERSE THERMAL SOIL CONDITIONS AND VARIABILITY OF YIELD OF ONIONS (*ALLIUM CEPA* L.) IN ARABLE FARMLAND IN POLAND

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Abstract

KALBARCZYK R. and E. KALBARCZYK, 2014. The relation between adverse thermal soil conditions and variability of yield of onions (*Allium cepa* L.) in arable farmland in Poland. *Bulg. J. Agric. Sci.*, 20: 1211-1220

Edaphic conditions at the root zone are important not only for the growth and development of onions, but they also determine yield. Soil temperature, in contrast to other indicators used in agro-meteorological research, reflects an entire complex of meteorological conditions in combination with soil conditions. The aim of this study was to evaluate a decrease in yield of onion grown in arable farmland in Poland caused by adverse soil thermal conditions. To achieve this goal, we used data from 17 COBORU experimental sites and 47 meteorological stations concerning phenological and agronomic dates, the yield of onions, and soil temperature during the growing season over the period 1966–2005. In Poland, a decrease in the yield of onions of at least 5% occurs when the average soil temperature during the period “end of emergence–beginning of leaf bending” (Ee–Blb) exceeds 18.8°C. In 1992, the least favourable year for onion yield in the period 1966 to 2005, soil temperatures in most parts of the country ranged from 19.0°C to over 22.0°C; the highest being in central-western Poland. The greatest decrease in onion yield due to both excessive temperatures and a too frequent incidence of these temperatures, is observed in the central-western part of the country, the south-eastern area of Poland and around the area of Warsaw, where the average annual onion yield may be reduced by more than 15% compared to the long-term average.

Key words: arable farming, onion, soil temperature, yield reduction

Abbreviations: Sg – sowing, Ee – the end of emergence, Blb – beginning of leaf bending, H – harvest, Sg-H – the time from sowing to harvest, COBORU – Research Centre for Cultivar Testing, IMGW – Institute of Meteorology and Water Management, RFE – relative forecast error, ARFE – average relative forecast error

Introduction

Onion is very important in the international plant trade. In 2010, the annual harvest of onions in the world amounted to about 78.9 million tonnes, with 51.4 million tonnes harvested in Asia, followed by more than 8.7 million tonnes in Europe (FAO, 2011). The European leaders in onion production include Russia (1.5 million tonnes), the Netherlands (1.3 million tonnes) and Spain (1.1 million tonnes). Poland was fifth with 0.6 million tonnes, about 0.3 million tonnes less than Ukraine. In terms of onion export, Poland was third largest in Europe in 2010 with around 112 thousand tonnes, after

the Netherlands and Spain. Onions grown in Poland have for many years been known in the European market under the trade name of Polish Onions, valued for their attractive appearance and especially favourable gustatory properties.

Despite the large total yield of onion in Poland, the average yield rate is not satisfactory at about 21 t.ha⁻¹ (FAO, 2011). In addition, the yield is highly variable, ranging from 15 to 24 t.ha⁻¹. This variability depends not only on the selection of cultivar and the accurate and timely application of pesticides, but also on lack of irrigation and unfavourable agro-meteorological conditions, including soil temperature (Kalbarczyk, 2009; 2010; Kęsik and Błażewicz-Woźniak, 2010). Soil tem-

perature is an agro-meteorological indicator that describes not only thermal edaphic conditions at the root zone, but also indirectly its physical properties and moisture. The influence of soil temperature on the yield and morphological characteristics of plants, including onions, have been discussed by Diaz-Perez et al. (2004), Mallek et al. (2007), Choudhary et al. (2012) and Li et al. (2013). A distinct majority of studies have focused on improving agricultural technology of onion (Benkeblia and Varoquaux, 2003; Frąszczak et al., 2006; Kumar et al., 2007; Khokhar, 2009; Souza et al., 2013) and the evaluation of variability and trends in soil temperature, and the impact of vegetation, meteorological conditions and soil moisture on onion cultivation (Bednorz and Kolendowicz, 2010; Liu et al., 2012; Xue and Akae, 2012; Zhao et al., 2013).

In this work we evaluate how onion yield in Poland was affected by adverse soil thermal conditions across a 40 year period (1966–2005).

Materials and Methods

The data sourced for this paper provided the size of total yield and agronomic and phenological data for intermediate-late varieties of onion (*Allium cepa* L.) over the period 1966–2005 from 17 sites of the Research Centre for Cultivar Testing in Słupia Wielka (COBORU) (Figure 1).

The agro-phenological data included the following: sowing (Sg), the end of emergence (Ee), beginning of leaf bending (Blb) and harvest (H) and the time from sowing to harvest (Sg-H). We analyzed the collective pattern of plants, i.e. a collection of all the most commonly cultivated medium late

varieties of onion in the period under consideration, i.e. more than 40 varieties (each year on average four – six varieties), whose yield and agronomic and phenological dates was averaged and included at a later stage of the research. Application of the collective pattern was based on the assumption that intraspecific differences do not obscure overall regularities.

Onions were grown on wheat soil complexes (very good and good), and rye (very good). These soils were permeable, fertile, with humus, high water capacity, easily heated in the spring and not creating crust on the surface. Onions are generally grown two years after a manure application at a dose of 30 to 50 t.ha⁻¹ and plowed in autumn. Apart from the manure, fertilization was performed using compost at a rate of 20–30 t.ha⁻¹. Compost was distributed evenly over the frozen ground, and in spring it was mixed with the top layer of soil. Mineral fertilizers, depending on the nutrient content in the soil, were used at an average rate of 370 kg per 1 hectare, including N (120 kg), P₂O₅ (80 kg) and K₂O (170 kg). Phosphorus and potassium fertilization was applied in the autumn, while nitrogen fertilization was performed before sowing, at two thirds of the total predicted dose, and the rest during growth – by no later than 10 June. Cereals and legumes were usually used as a forecrop.

The study used daily and decade data regarding soil temperatures (°C) from a depth of 5 cm which were collected from all the weather stations operating at the COBORU experimental sites and 47 stations of the Institute of Meteorology and Water Management (IMGW) (Figure 1). Based on data collected from COBORU and IMGW stations, the mean soil temperature was calculated for times corresponding to

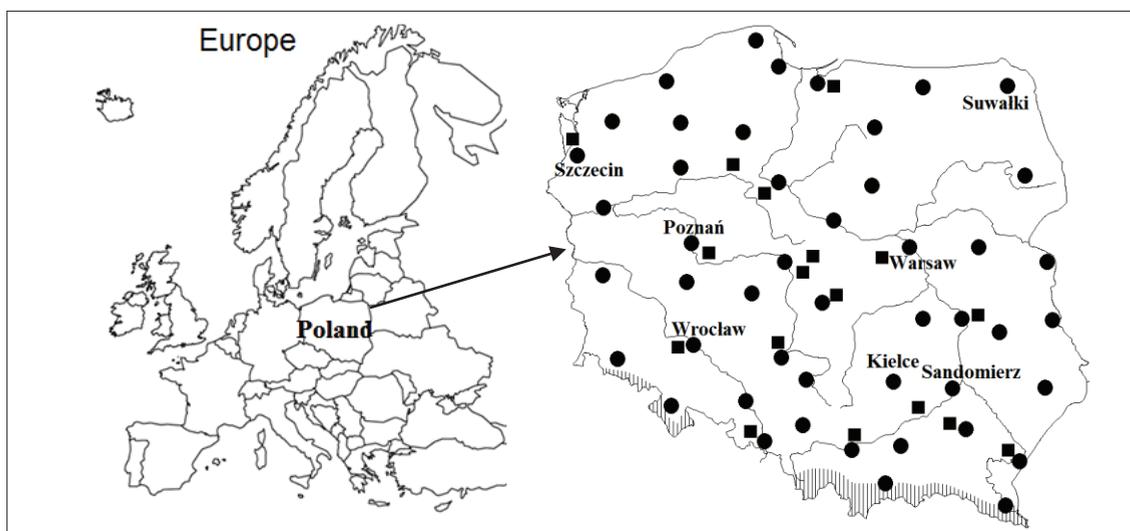


Fig. 1. Arrangement of experimental stations (■) and meteorological stations (●) in Poland that are included in the study

average Polish times of agrophenological periods for onions: sowing – end of emergence (April 9 – May 10), end of emergence–beginning of leaf bending (May 11 – August 4) and beginning of leaf bending – harvest (August 5 – September 2). In parentheses we present the average dates for the beginning and end of each agrophenological period for onions.

The study does not take into account regions located in the south-western and south-eastern Poland, because of the very high diversity of physiographic conditions and altitudes often above 500 m above mean sea level, so considerably limiting the possibility of arable farming (Kalbarczyk, 2011).

To assess the impact of soil temperature on the total onion yield (y_p , t.ha⁻¹) we applied multiple curvilinear regression analysis. We used the following equation:

$$y_p = -\beta_0 + \beta_1 x_1 - \beta_2 x_2 + \beta_3 x_2^2 \quad (1)$$

where x_1 – is linear trend, which further analyzed across the multi-year period 1966–2005, x_2 – soil temperature (°C), β_0 – intercept, $\beta_1, \beta_2, \beta_3$ – regression coefficients.

Regression function parameters were determined by the method of least squares. The significance of regression was evaluated by Snedecor *F*-test, while the significance of the regression coefficients by Student *t*-test. The fit of the regression function to empirical data was measured by the correlation coefficient (*r*), the coefficient of determination (R^2 , %) and the rate describing the difference between the standard deviation of the dependent variable and the standard error of equation estimation (SD-Sy, t.ha⁻¹).

The relevance of quantitative forecasts, set for equation (1), was determined by two ex-post error rates, the relative forecast error:

$$RFE = \frac{y_o - y_p}{y_o} \cdot 100\% \quad (2)$$

and the average relative forecast error:

$$ARFE = \frac{1}{n} \sum_{i=1}^n |RFE|, \quad (3)$$

where y_p – is projected yield (t.ha⁻¹) according to equation (1), y_o – actual yield (t.ha⁻¹), *n* – number of years adopted for the time series (number of stations x number of years).

Average relative forecast error (ARFE) was determined for all the analyzed years (1966–2005) and the analyzed COBORU experimental stations.

The study 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).

In order to determine the decrease in total yield of onions in Poland caused by adverse thermal soil conditions, we used regression equation (1). On the basis of this equation

we determined the threshold level of soil temperature which resulted in at least a 5% reduction in the total onion yield, compared to the long-term average in the period 1966–2005. Then, in equation (1), described the effect of soil temperature during the end of emergence–beginning of leaf bending on the onion yield, including the average temperature of the soil, but calculated only from temperatures in years exceeding the determined threshold level. By including this value in equation (1) we calculated yields for each considered COBORU and IMGW station, conditioned by the average incidence of adverse thermal conditions of the soil. The difference between long-term real yield of onion set for the whole country and the yields calculated according to the above-described procedure, allowed determination of the potential reduction in the total yield of onion caused by unfavourable soil temperature in various regions of Poland (Kalbarczyk, 2011).

The incidence of excessive soil temperature (P_1 , %) (above the designated threshold) during the period of end of emergence–beginning of leaf bending in the period 1966–2005 was calculated according to the following formula:

$$P_1 = \frac{n_1}{N} \cdot 100\%, \quad (4)$$

where n_1 – is number of periods with excessive soil temperature, *N* – the number of all periods under consideration.

Loss in onion yield in Poland was determined by Kw ratio (t.ha⁻¹). It allows determination of yield losses caused not only by soil temperature (described by equation 1), but also by the frequency of its occurrence (Górka, 1987). Using the Kw ratio we determined the average annual reduction in the total yield of onion caused by unfavourable soil temperature. This indicator is described by the following equation:

$$Kw = \frac{P_2}{n_2} \cdot (-\beta_0 + \beta_1 x_1 - \beta_2 x_2 + \beta_3 x_2^2) + (1 - \frac{P_2}{n_2}) \cdot yk \quad (5),$$

where P_2 – is number of years with unfavourable soil temperature in the period 1966–2005, n_2 – number of years in the period 1966–2005, *yk* – the average yield in years with favourable soil thermal conditions. Other designations are the same as in equation (1).

The spatial distribution of agro-technical dates (sowing, harvest), phenological dates (emergence, bending of leaves) and the length of the growing season for onions, as well as the distribution of the potential reduction in yield, frequency of adverse soil temperature conditions and soil temperature itself, are shown graphically in the form of isarithms which include the physiographic diversity of the Polish territory. All statistical analyses were carried out using *Statistica* (version 10.0).

Results

In Poland, the average length of the growing season of onions during 1966–2005 calculated from the time of sowing to harvest was 146 days (Figure 2). On average, the longest spans of more than 155 days were recorded in the Silesian Lowland (area of Wrocław) and Sandomierz Lowland. The shortest period of growth and development of onions appeared in northeast Poland, where it was shorter than 135 days. In central Poland, the duration of the growing season ranged from 145 to 155 days, in the north of the country from 135 to 145 days, and in the south-west and south-east less than 145 days.

In most parts of Poland, the average date of sowing in the period 1966–2005 ranged between 5 and 15 April; the average end of emergence between 5 and 15 May; the average date of the beginning of leaf bending from 25 July to 5 August, and the average date of harvest between 31 August and 5 September (Figure 3).

On average, the earliest agronomic and phenological dates (sowing, end of emergence, and the beginning of leaf bend-

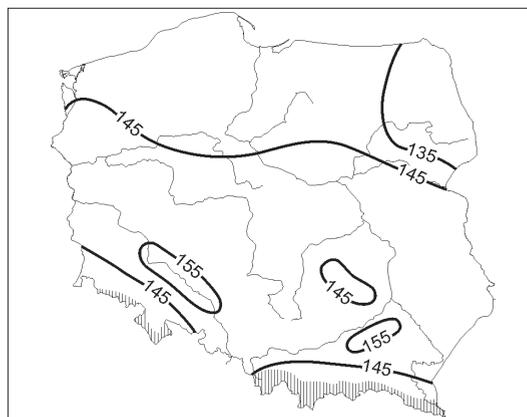


Fig. 2. The duration of the growing season of onions in Poland, from sowing to harvest. Average for the years 1966–2005

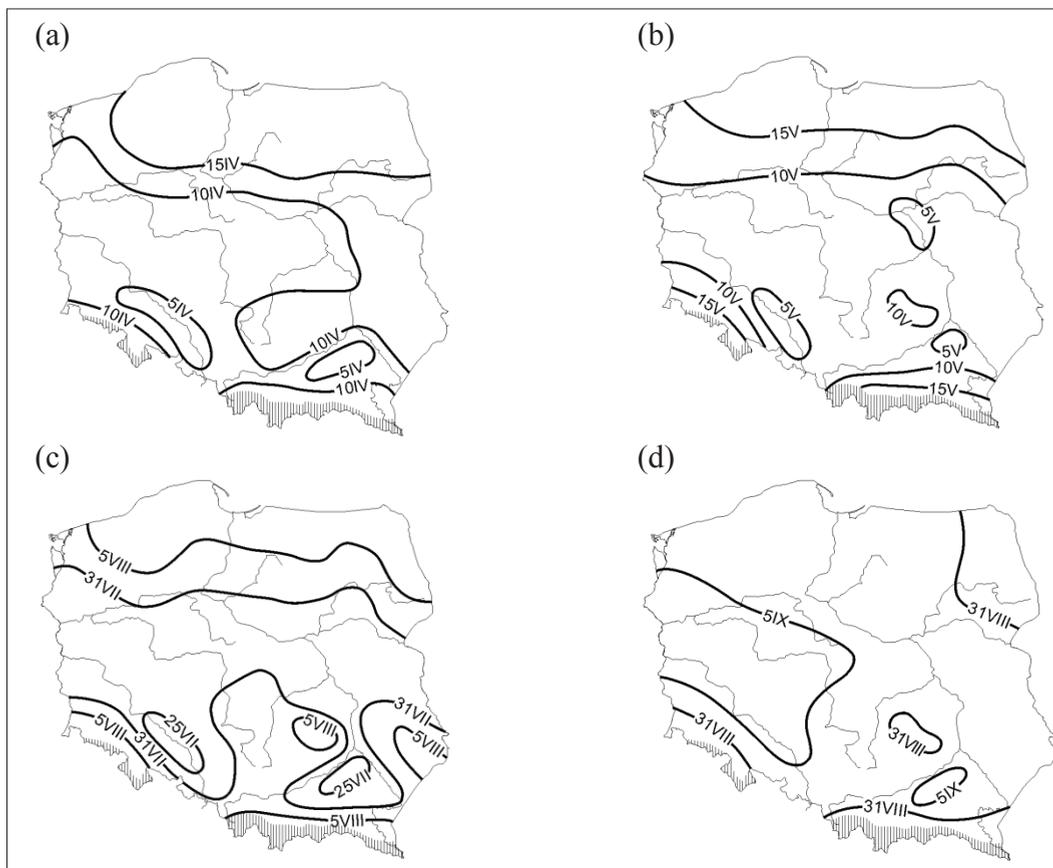


Fig. 3. Agronomic (a, d) and phenological (b, c) dates for onions in Poland: (a) – sowing, (b) – the end of emergence, (c) – beginning of leaf bending, (d) – harvest. Average for the years 1966–2005

ing) were recorded in the area of Wrocław and Sandomierz, and for the end of emergence in Warsaw. The earliest harvest of onions was on average in the south-west, south-east and north-east of the country, and in the region of Kielce.

An analysis of the relations between the overall yield of onion and unfavourable soil temperature showed that the strongest influence occurred in the period end of emergence-beginning of leaf bending, i.e. on average over 86 days. During this period, the above-average temperature of the soil contributed to a decrease in the yield of onion. The soil temperature regression and linear trend described in the considered period in the consecutive years 1966–2005 explained about 50% of the variability of the total yield of onions (Tables 1 and 2).

All elements of the equation – the intercept and the regression coefficients, were significant at 0.01, and the absolute values of the Student’s t-test ranged from 2.7 to 4.1. The SD-Sy rate calculated for the dependence of soil temperature to yield amounted to 2.4 t.ha⁻¹, and the ARFE was 9.8%. As many as 47% of all relative forecast errors |RFE| ranged from 0–5%, and about 43% of them were in the range from 5–10%.

The size of the total yield of onion was significantly dependent on the temperature of soil in the early stages of the growing season. Total yield in the range X±2SD increased with the increase in soil temperature. However, the linear correlation coefficient for soil temperature-yield in the period sowing-end of emergence was significant only at the level of 0.1 with r=0.391. Therefore, we did not create an equation for this dependence. The decrease in the total yield of onions across the country caused by unfavourable soil temperatures (x₂) in the period “end of emergence-beginning of leaf bending” (Ee-Blb) ranged from 5% at x₂=18.8°C to 11% at x₂=20.4°C (Figure 4). However, due to the high variability of

Table 2
The characteristics of the variables included in the regression equation describing the relationship between the total yield of onions in Poland and soil temperature during the period “end of emergence-beginning of leaf bending” in the years 1966–2005

Variable	Characteristics		
	$\bar{x} \pm SD$	Q ₁	Q ₃
y ₀ , t.ha ⁻¹	32.0±11.3	23.2	38.8
x ₂ , °C	18.3±1.2	17.3	19.8

y₀ – total yield of onion, x₂ – soil temperature in the period “end of emergence-beginning of leaf bending”, \bar{x} – average, SD – standard deviation, Q₁ – lower quartile, Q₃ – upper quartile

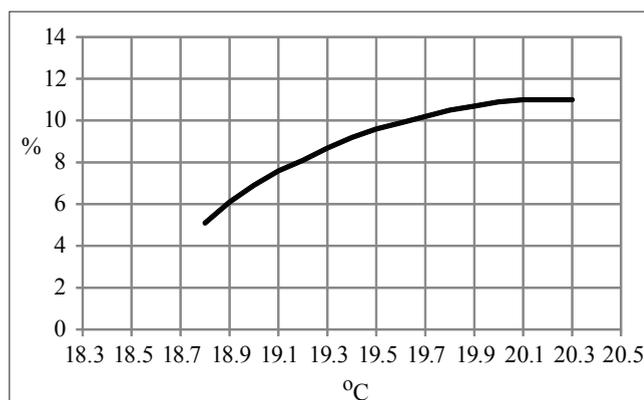


Fig. 4. Reduction curve in the total yield of onion (%) caused by unfavourable soil temperature (x₂≥18.8°C) during the period “end of emergence-beginning of leaf bending”

Table 1
Relation between the overall yield of onions in Poland and soil temperature during the end of emergence-beginning of leaf bending in the years 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 ₀	-178.929	-2.656	0.01						
β ₁ x ₁	0.276	5.334	0.01						
β ₂ x ₂	-33.389	-4.105	0.01	0.704	49.9	2.4	9.8	47.3	42.7
β ₃ x ₂ ²	0.818	3.602	0.01						

x₁ – linear trend, which is further analyzed across the multi-year period 1966–2005, x₂ – soil temperature in the period “end of emergence-beginning of leaf bending” (°C), β₀ – intercept of the equation, β₁, β₂, β₃ – regression coefficients, t – Student’s t-test, P – level of significant, r – correlation coefficient, R² – determination coefficient, SD-Sy – difference between a standard deviation of a dependent variable and a standard error of equation estimation, ARFE – average relative forecast error, RFE – relative forecast error

soil temperature during the Ee-Blb, the reduction in the total yield of onion caused by this factor was not uniform across the country (Figure 5). The greatest losses, more than 10%, were found in the mid-west of the country, as well as Mazovia lowland (in the area of Warsaw) and in the Sandomierz Basin (in the area of Sandomierz). The lowest losses, less than 8%, in the total yield of onion caused by excessive soil temperatures during Ee-Blb were found in the Pomeranian Lake District (northern part of the country), the Suwałki Lake District (north-eastern part of the country), as well as the Upland Lublin (south-eastern part of the country) and foothill areas in the southern Poland.

Soil temperatures which resulted in at least a 5% reduction in the total yield of onion occurred with a frequency of 43% (e.g., in 43 out of 100 years) (Figure 6). The frequency in the period Ee-Blb decreased with the increase in x_2 . For

example, $x_2=19.3^\circ\text{C}$ occurred with a frequency of 27% and $x_2=20.4^\circ\text{C}$ at only about 2%. Similar to the aforementioned reduction in the yield of onion, the incidence of adverse soil temperature ($x_2 \geq 18.8^\circ\text{C}$) during the Ee-Blb period had a large spatial variation in Poland.

Most frequently, at more than 60%, these temperatures ($x_2 \geq 18.8^\circ\text{C}$) were recorded in midwestern, central and south-eastern Poland (Figure 7). On average, the temperature $x_2 \geq 18.8^\circ\text{C}$ was recorded three times less frequently in northwestern and southern Poland.

Due to the negative impact of the above-average soil temperature during the Ee-Blb period on the total yield of onion, far worse conditions for growth and development of plants were reported in half of the years of the analyzed multi-year period (Figure 8). In the years 1966–2005, soil temperatures above the average of 18.6°C were recorded in as many as 19

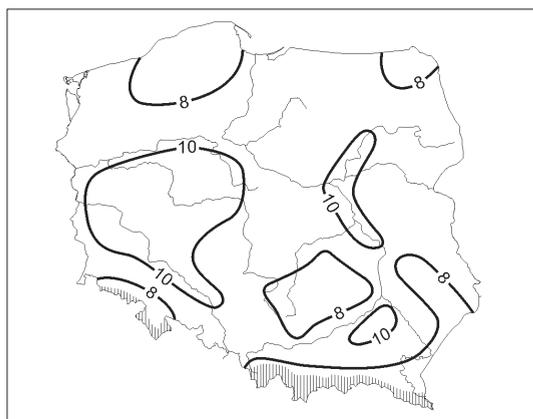


Fig. 5. The national average incidence (%) of soil temperature $\geq 18.8^\circ\text{C}$ during the period “end of emergence-beginning of leaf bending”

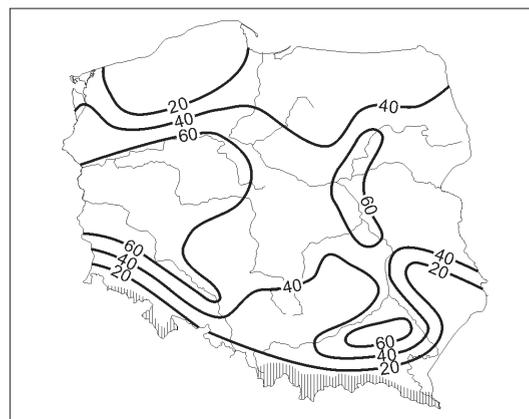


Fig. 7. The incidence (%) of soil temperature $\geq 18.8^\circ\text{C}$ in Poland in the period “end of emergence-beginning of leaf bending”

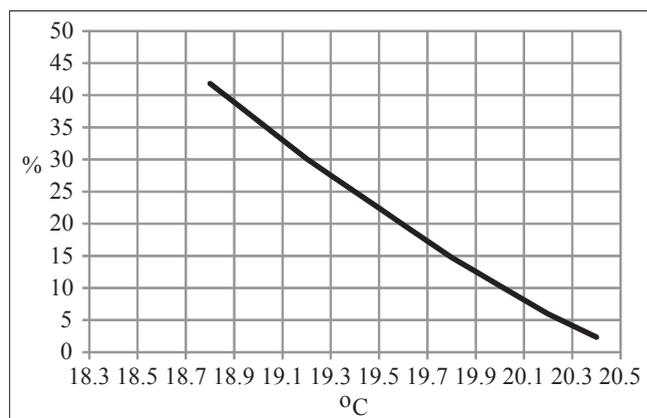


Fig. 6. The incidence (%) of soil temperature $\geq 18.8^\circ\text{C}$ in Poland in the period “end of emergence-beginning of leaf bending”

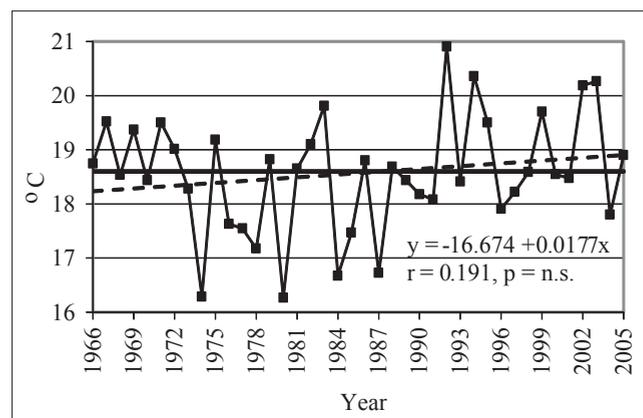


Fig. 8. The plot of average national soil temperature ($^\circ\text{C}$) in the period “end of emergence-beginning of leaf bending” in the years 1966 to 2005

years: 1965–1966, 1969, 1971, 1972, 1975, 1979, 1981–1983, 1986, 1988, 1992, 1994–1995, 1999, 2002–2003 and 2005. The greatest nationwide upward temperature deviation from the long-term average was recorded in five years: 1983 (1.2°C), 1992 (2.3°C), 1999 (1.1°C) and 2002 (1.7°C) and 2003 (1.7°C).

In the analyzed long-term period, there was no statistically significant trend in the agro-meteorological factors during the Ee-Blb period. In 1992, in most parts of Poland, soil temperatures during Ee-Blb ranged from 19.0°C to 22.0°C (Figure 9a). The least favourable region for field onion cultivation was in midwestern Poland. In turn, in 1980, the year of the lowest soil temperature in the analyzed period, the temperatures ranged from less than 15.5°C in the south-west and south-east of the country to more than 17.0°C in the Midwest (region of Poznań) (Figure 9b). The spatial distribution of soil temperature between 1992 and 1980 was similar to the long-term distribution, differing in the range of temperatures (Figure 9c). In the years 1966–2005 the average soil temperatures ranged from 17.5°C in the south-west and south-east of Poland

to more than 19.0°C in the mid-west. In northern Poland – the Pomeranian Lake District and the Suwałki Lake District and in the south – the Lublin Upland, Sudeten Foreland and Carpathian Foothills, soil temperatures stood at just over 18.0°C, in central-eastern Poland it ranged from 18.5°C to 19.0°C.

The loss of onion yield in Poland caused by unfavourable soil conditions described by both excess soil temperature ($x_2 \geq 18.8^\circ\text{C}$) and its frequency in the Ee-Blb period is characterized by moderate variability (Figure 10). The average annual decrease in the yield of onion can range from 6% to 15% in most parts of Poland. The biggest threat to field onion cultivation from excess soil temperatures in the Ee-Blb period may occur in the central belt of Poland, and especially in the mid-western part of the country and in the area of Warsaw and Sandomierz. In these regions, $x_2 \geq 18.8^\circ\text{C}$ was most common, at more than 60%. Definitely lower, i.e. twice lower reduction in onion yield resulting from excessive soil temperature occurred in northwestern and southern Poland, where the annual loss of onion crop may reach not more than 6%.

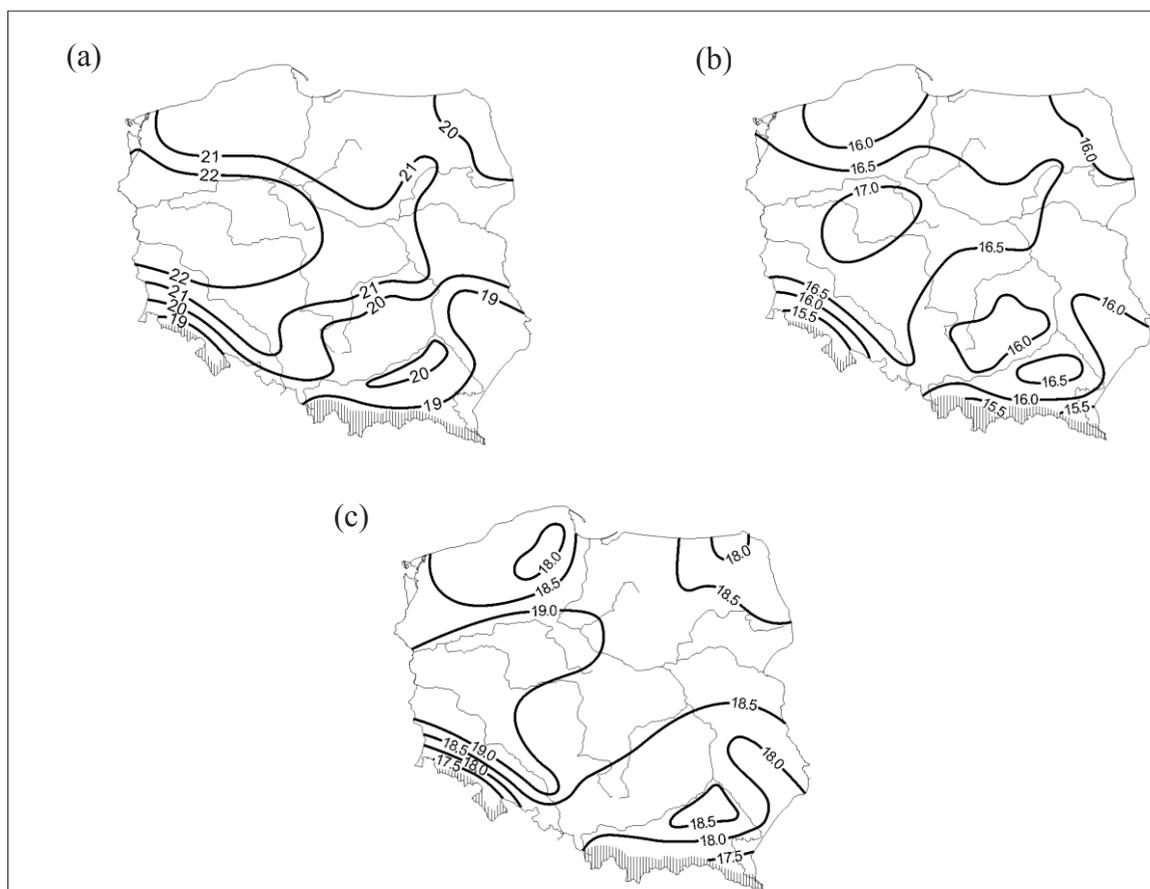


Fig. 9. Soil temperature (°C) in the period “end of emergence-beginning of leaf bending” in Poland: (a) – in 1992, (b) – in 1980, (c) – average (1966–2005)

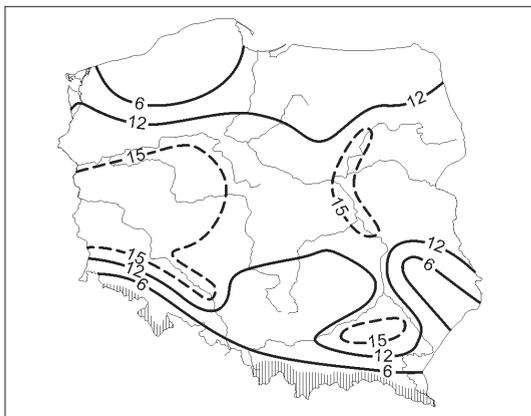


Fig. 10. Annual average reduction in yield (%) caused by high temperature of the soil and its frequency in the period “end of emergence–beginning of leaf bending”

Discussion

Onion is a vegetable with high climatic requirements (Babik, 2004; Khokhar et al., 2007a; b; Kalbarczyk, 2010; Tesfay et al., 2011) which determine not only the length of time from seeding to harvest, individual phenological dates, but also the yield rate. In Poland, the length of the growing season for onions in the previous fifty years has shortened, and was significantly influenced by weather conditions (Łabędzki et al., 2011; Kalbarczyk, 2011), including changing soil thermal conditions (Bednorz and Kolendowicz, 2010). The longest growing season has been in the Wielkopolska Lowland (area of Poznań), the Silesian Lowland (area of Wrocław) and the Sandomierz Basin (area of Sandomierz), which is confirmed by the work of Górka (1987) and the results of our long-term analysis for the years 1966–2005 (Figure 2).

On average, Polish mid-late varieties of onions sown in spring belong to the long-day varieties. Therefore, it is important to sow onions possibly at the earliest date, so that at the advent of long days they can produce substantial vegetative mass and provide good yield (Adamicki and Nawrocka, 2005). As late as in 1980–1990, the optimum sowing date for onions was between 5 and 20 April (Górka, 1987), but in the previous twenty years it has receded (Figure 3a). However, although there are years in which onions are sown in the second decade of March, there also years when onions are sown as late as after the 20 April, depending on thermal and moisture conditions of the soil (Adamicki and Nawrocka, 2005).

According to Borowski and Michalek (2006) a good yield of onion depends on early sowing to ensure proper thermal

conditions of the soil and a sufficient amount of water during germination, so that seedlings have good conditions for growth and development in spring and summer. In a hot spring, sowing can be performed a little earlier, but should not be earlier than the end of March. Sowing too early increases the risk of exposure to cold temperatures, resulting in poor and uneven emergence (Babik, 2004; Adamicki and Nawrocka, 2005). A cool spring results in longer emergence and increased susceptibility to infection of seedlings caused by soil pathogens (Borowski and Michalek, 2006). Delayed sowing, i.e. delayed in relation to the optimum date, results in the growth under sub-optimal light, temperature and moisture, resulting in a shift in the successive stages of development and shorter duration of bulb formation (Tao et al., 2006; Kalbarczyk, 2009). Delayed sowing not only delays the maturation and increases the share of onions with not sufficiently dried necks and thick necks in the harvest, but also reduces the total yield (Adamicki and Nawrocka, 2005).

In the climatic conditions of Poland, emergence of mid-late varieties of onions is recorded most frequently in late April or early May, and leaf bending in late July and August. Harvest is usually carried out at the end of August (Górka, 1987). The research showed that the onset of Blb mostly occurs from 20 July to 10 August, and is latest in the north-eastern part of the country. Similar results on the spatial distribution of Ee, Blb and harvest were obtained in this analysis of the years 1966–2005 (Figure 3b–d).

The thermal requirements of onion depend on its development phase. The minimum germination temperature is 5–6°C, optimum 18°C (Adamicki and Nawrocka, 2005; Orłowski and Żurawik, 2007), and according to Babik (2004) – 10–20°C, depending on the variety. The optimum temperature for rooting the onions varies between 10 and 15°C (Babik, 2004). The results of our study confirm the view that in the sowing-emergence period, above-average temperatures and sufficiently moist soil accelerate and even out emergence, which positively influences the final yield of onion (Table 1).

After emergence and in the period of rapid growth of leaves, the most favourable temperature ranges from 12°C to 15°C with a relatively short day, which contributes to better development of the root system (Adamicki and Nawrocka, 2005). The results obtained in this study are consistent with the report by Babik (2004) and Orłowski and Żurawik (2007), according to whom the fastest and best growth of the vegetative parts of the onion occur at 13–24°C, while the formation of the head is optimal at 16–20°C, which combined with a long day decides the proper development of onions, and ultimately a high yield. Temperature above 20°C is desirable in maturation (Orłowski and Żurawik, 2007).

In literature on the subject, there are no scientific publications devoted to the influence of adverse meteorological conditions on onion yield, in particular the effect of soil temperature throughout Poland. However, unsuitable soil temperatures during the growing season significantly reduce the yield of onion, not only in Poland but also in other countries. In addition, many works in this field are based on experiments carried out under strictly controlled conditions in greenhouses, often located in other latitudes than Poland and also on other varieties (Piccinni et al., 2009; Biswas et al., 2010; Choudhary et al., 2012; Li et al., 2013). It is therefore difficult to compare the results obtained in this work to those presented in literature (Figures 4–8 and 10).

In Poland, the adverse effect of unfavourable thermal conditions in the soil on onion yield is not likely to diminish, as we observed no negative long-term trend in this factor in the Ee-Blb period. This may indicate that the adverse effect of excessive heat in the soil on onion yield may remain at the same level. However, future analyses should also include the issue of climate change, using models and climatic scenarios for Central Europe (Abumhadi et al., 2012).

Conclusions

The strongest relations between the yield of onion and unfavourable soil temperature occurred in the period end of emergence-beginning of leaf bending. The decrease in the total yield of onions across the country caused by unfavourable soil temperatures in the period “end of emergence-beginning of leaf bending” ranged from 5% at 18.8°C to 11% at 20.4°C. Soil temperatures which resulted in at least a 5% reduction in the total yield of onion occurred with a frequency of 43%. The average annual decrease in the yield of onion caused by both excess soil temperature ($\geq 18.8^\circ\text{C}$) and its frequency in the Ee-Blb period can range from 6% to 15% in most parts of Poland.

Acknowledgments

This work was supported by the University of Agriculture in Szczecin, project no. BW/HK/04/05.

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Received September, 2, 2013; accepted for printing June, 2, 2014.