Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar

Spanish Journal of Agricultural Research 2010 8(4), 1163-1173
ISSN: 1695-971-X
eISSN: 2171-9292

Unfavourable thermal conditions of air at the turn of the 20th and 21st centuries reducing crop productivity of pickling cucumber (*Cucumis sativus* L.) in Poland

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Abstract

Growing influence of anthropopressure and irregular changes in weather conditions necessitated conducting agroclimatic research into the assessment of plant cultivation risk caused by unfavourable meteorological conditions, including thermal conditions of air. The goal of the work was to assess the risk of pickling cucumber field cultivation in Poland caused by an unfavorable course of air temperature (T_a) in the period from sowing to the end of harvesting at the turn of the 20th and 21st centuries. To accomplish the goal, the study used data describing growth, development and crop productivity of cucumber in the years 1966-2005. Data was used concerning the described thermal conditions with the average T_a in the whole growing season of the analysed plant. The data came from 28 experimental stations and 53 meteorological in Poland. The effect of T_a in the growing season (sowing-end of harvesting) on the total and marketable yield of cucumber was evaluated. The study used curvilinear regression analysis with two variables. The highest risk of cucumber's cultivation caused by unfavorable thermal conditions of air was recorded in south-western, south-eastern, and also northern and north-eastern Poland. In these high risk areas reduction in the total yield oscillated between 15% and even over 21% below the multi-annual average. Reduction in the total yield occurred with frequency from 40% to above 80%. In south-western and south-eastern Poland, a reduction in the marketable yield amounted to maximally above 15%. A marketable yield reduction occurred with a frequency of from 50% to above 70%.

Additional key words: air temperature; climate changes; growing season; reduction in yield.

Resumen

Las condiciones térmicas desfavorables del aire reducen la productividad de los cultivos de pepino encurtido (*Cucumis sativus* L.) en Polonia en el cambio de los siglos XX y XXI

La creciente influencia de la acción humana y los irregulares cambios en las condiciones climáticas han hecho necesario llevar a cabo investigaciones agroclimáticas para evaluar el riesgo en el cultivo de plantas. El objetivo de este trabajo fue evaluar el riesgo en Polonia en el cultivo en campo de pepino, en el cambio de los siglos XX y XXI, causado por una evolución desfavorable de la temperatura del aire (T_a) en el período desde la siembra hasta el final de la cosecha. Se utilizaron los datos, obtenidos de 28 estaciones experimentales y 53 meteorológicas en Polonia, que describen el crecimiento, desarrollo y productividad de los cultivos de pepino en los años 1966-2005, relacionándolos con la T_a media en todo el período vegetativo de la planta. Se evaluó el efecto de la T_a en la temporada de cultivo (siembra-final de cosecha) sobre la producción total y comercial del pepino, utilizando un análisis de regresión curvilínea con dos variables. El mayor riesgo del cultivo de pepino debido a las desfavorables condiciones térmicas del aire se registró en el sur-oeste, sudeste y también norte y noreste de Polonia. En estas zonas de alto riesgo la reducción en la producción total osciló entre el 15% e incluso más del 21% sobre la media plurianual; en la producción total se redujo entre el 40% y más del 80%. En el sur-oeste y sudeste de Polonia, el rendimiento comercial se redujo hasta más del 15%. La producción comercial se redujo entre el 50% y más del 70%.

Palabras clave adicionales: cambio climático; reducción en la producción; temperatura del aire; temporada de cultivo.

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Received: 27-01-10; Accepted: 23-10-10.

Abbreviations used: S-EH (sowing-end of harvesting), T_a (air temperature).

Introduction

In a field under cultivation, vegetables are exposed to the effects of many unfavorable environmental factors (stressors). Most frequently enumerated are natural stressors and anthropogenic stressors, *i.e.* those resulting from broadly understood human activities (Lichtenthaler, 1996). Anthropogenic stressors include pesticides, air pollution, soil acidification, heavy metals and an increase in UV-A and UV-B. Anthropogenic stressors also include, above all, natural ones; unfavorable meteorological conditions which influence the course of both biochemical and biophysical reactions and, as a result, physiological reactions of plants (Blum, 1996; Lichtenthaler, 1996). Among the most important natural stressors of thermophilous plants are unfavorable thermal conditions of air. These conditions affect all physiological processes through control of the speed of chemical reactions (Krug and Thiel, 1985; Lederle and Krug, 1985; Liebig, 1985a,b; Marcelis *et al.,* 1993; Sysoeva *et al.,* 1997, 1999). It is difficult to explicitly determine when thermal conditions are a stressor because reaction to different levels of air temperature (T_a) depends on several factors. These factors are: plant adaptation to different climatic zones, duration of stressor impact and its intensity, development stage and physiological activity of a plant (Blum, 1996; Gouvêa *et al.,* 2009). Disturbance in the growth and development of vegetables and, as a consequence, reduction in its cropping, is a negative effect of stressors.

The rising influence of anthropopressure and irregular changes of weather conditions, are important areas of study. Agroclimatic research on risk assessment of vegetable plant cultivation caused by the occurrence of unfavourable meteorological conditions, including thermal conditions of air, is very important. Besides, in the literature on the subject there are not enough syntheses on the issue from a perspective of the country and also of the regions. There are also not enough comparable meteorological indexes determined on the basis of multi-annual periods characterising the domestic diversification of the usefulness of climatic conditions for vegetable commercial production, including cucumber.

Therefore, the goal of the study was to assess the cultivation risk of pickling cucumber caused by an unfavorable course of thermal conditions of air in Poland. The study was based on a 40-year research period, from the years 1966 to 2005.

Material and methods

Material

The work used data concerning the level of cucumber crop productivity. The quantity of the total and marketable yield is included as the productivity. Data about thermal conditions described as the average T_a in the growing season of the pickling cucumber were also used. The growing season was considered to be from sowing to the end of harvesting. Experiments were carried out from 1966-2005 in the fields of 28 stations of the Research Centre for Cultivar Testing (COBORU). The stations were located all over Poland, except for the submountainous regions situated in the south-western and the south-eastern parts of the country. The submountainous regions were excluded from the analysis because field cultivation in Poland is usually limited to 500 m above sea level but not higher. A higher credibility and representativeness was found in the quality of the data based on the COBORU experiments in comparison with the data coming from agricultural practice. The higher standards were due to qualified staff, proper use of cultivation and fertilization technology as well as appropriate protection of cucumber plants.

The soil of the experimental fields, in which tests with cucumber were conducted, belongs to the soil quality classes: I, II, IIIa, IIIb and IVa (Babik, 2004). According to agricultural usefulness, the soil belongs to a good wheat complex soil and a very good wheat complex soil, and what was considered to be a very good rye complex (Babik, 2004). Pickling cultivars of cucumber (*Cucumis sativus* L.) were usually cultivated after cereal plants and also after peas (*Pisum sativum* L.) and early *Brassica* vegetables. All agrotechnical measures were carried out in accordance with appropriate techniques for the cucumber species. Data collected from 53 meteorological stations from the Polish Institute of Meteorology and Water Management (IMGW) was additionally used. This collection supplied more detailed data which described temporal and spatial variability of air thermal conditions. The IMGW data was also used to determine frequency of the occurrence of excessively low T_a in the cucumber growing season. An example of low temperature would be temperature leading to a reduction by at least 5% in the yield of this plant below the average multi-annual level in the years 1966-2005. The multi-annual average of the 40-year research period was calculated on the basis of data from all the considered meteorological stations, *i.e.,* in the same way as the average total and marketable yield of cucumber. The location of the IMGW meteorological stations, synoptic and climatic stations, and the COBORU experimental stations in Poland, was presented in the accompanying paper published in this same issue (Kalbarczyk, 2010).

Methods

To assess the influence of T_a in the growing season (sowing to the end of harvesting, S-EH) on the total and marketable yield of cucumber, curvilinear regression analysis with two variables was used. In the equations each time, yield (total or marketable) served as a dependent variable and T_a and the linear trend, as independent variables. This was true in the successive years of the analysed multi-annual period 1966-2005 except for 2003 and 2004 when the experiments on the described plant were not conducted. On the one hand, including the linear trend in the equations, enabled capturing of significant changes that occur in the quantities of the two considered types of cucumber yield and T_a. On the other hand, the linear trend in the equations made possible the elimination of the effect of non-meteorological yield-affecting factors. Also Schelling *et al.* (2003), in agrometeorological equations for the weather and yield relationship, eliminated the effect of non-meteorological factors. The risk of cucumber field cultivation caused by the unfavourable course of thermal conditions in Poland was assessed. An attempt at forming multiple regression equations, describing the total influence of T_a and atmospheric precipitation on the examined yield, was made to assess this risk. The employed ridge regression analysis demonstrated collinearity of meteorological indexes. The estimated structural parameters of the equation proved unstable, unlike the equations considering only T_a. For these reasons, only T_a and the linear trend were taken into account in the further analysis as independent variables. Structural and stochastic parameters of the models were evaluated on the basis of the same statistical tests and factors as in the accompanying paper (Kalbarczyk, 2010).

Threshold values for T_a when reduction by at least 5% in the cucumber total and marketable yield occurs, were determined. The determination was done on the basis of the formed curvilinear regression functions. These determinations defined the climatic risk of pickling cucumber cultivation in Poland caused by unfavourable thermal conditions. Next, only the average temperature calculated for those years when it exceeded earlier specified threshold values, was substituted into each of the formed equations. These were equations describing the effect of T_a in the period from sowing to the end of harvesting, on the quantity of the yield. There were differences between the multi-annual actual yield of cucumber determined for Poland and the yield calculated according to the above-described procedure for each considered station of COBORU and IMGW. These differences enabled the determination of the potential reduction in yield caused by excessively low T_a, separately for the total and marketable yield. A calculation of the potential reduction in yield caused by the analysed meteorological element was made. This calculation corresponded to the situation when other elements which also shape weather conditions in Poland, assumed values at a level of multi-annual averages.

Results

Relationship between cucumber yield and average air temperature

The significantly ($p \leq 0.01$) quantity of cucumber yield, depended on the average T_a which occurred in the whole growing season of the plant (Table 1). These were equations showing that T_a lower than the multi-annual average in the years 1966-2005, unfavourably affected both total and marketable yield of pickling cucumber in Poland. Determination coefficient for the relationship between T_a and yield, with consideration of a linear trend of dependent variables through 1966-2005, amounted to 42.2 and 48.5% respectively in the case of describing variability of the total and marketable yield. The linear trend itself accounted for 9.5% of the yield quantity of the described plant in the case of the total yield. The linear trend also accounted for 13.4% in the case of the marketable yield. The formed multiple regression equations were marked by a smaller standard error of estimation (*Sy*) than the standard deviation (*Std*) determined for dependent variables, *i.e.* than natural variability of the analysed cucumber yields. In the case of the cucumber total yield the difference between indexes *Std* and *Sy* was 1.7 t ha^{-1}. For the marketable yield the differences were 2.1 t ha^{-1}. Average relative forecast error, calculated on the basis of the formed regression functions for all the considered

Table 1. Relationship between cucumber yield and air temperature in the period from sowing to the end of harvesting (S-EH) in Poland, considering the linear trend in the years 1966-2005

Regression equations[1]	Variable[1]		Characteristics[2]				
	y	T_a	R^2	*Std-Sy*	*ARFE*	Frequency of the occurrence of |*RFE*| in range	
						0-5	5-10
$y_t = -918.324^{***} + 0.293 Yl^{***} + 41.239 Ta^{***} - 1.138 Ta^{2***}$	33.2	16.6	42.2	1.7	9.8	38.1	40.4
$y_m = -1{,}062.642^{***} + 0.443 Yl^{***} + 23.801 Ta^{***} - 0.701 Ta^{2***}$	18.3	16.6	48.5	2.1	9.1	41.2	43.8

[1] y: average multi-annual yield (t ha^{-1}). T_a: average multi-annual air temperature (°C). *Yl*: linear trend of the yield, *i.e.,* the successive years of the 1966-2005 multi-annual period. y_t: total yield (t ha^{-1}). y_m: marketable yield (t ha^{-1}). *** Significant at $p \leq 0.01$.
[2] R^2: determination coefficient (%). *Std-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 (%).

COBORU stations and the analysed years was smaller than 10%. The average forecast error amounted to 9.1% for the marketable yield and 9.8% for the total yield. These forecast errors prove the appropriateness of the regression function. On the basis of the formed regression equations, very good and good forecasts constituted as much as about 78 and 85%, respectively in the case of the total and marketable yield. Very good forecasts were respectively about 38 and 41%. Good forecasts were about 40% and 44%.

Reduction in cucumber yield caused by unfavourable thermal conditions

A reduction of at least 5% in pickling cucumber yields occurred in Poland. This reduction took place when average T_a in the period from sowing to the end of harvesting was $Ta_{S\text{-}EH} \leq 16.2$°C in the case of the total yield. This reduction took place when average T_a was ≤ 15.8°C in the case of the marketable yield (Fig. 1). The cucumber total yield was lower by 10% than the average multi-annual level in the years 1966-2005 at $Ta_{S\text{-}EH} \leq 15.8$°C, by 15% at $Ta_{S\text{-}EH} = \sim 15.5$°C, by 20% at $Ta_{S\text{-}EH} = \sim 15.3$°C, by 25% at $Ta_{S\text{-}EH} \leq 15.0$°C, and by 30% below the average level at $Ta_{S\text{-}EH} \leq 14.8$°C. On the other hand, the marketable yield of cucumber lower by 10% than the multi-annual average was recorded in the period from sowing to the end of harvesting at air temperature = ~15.3°C and by 15% at temperature = ~15.0°C.

Potential reduction in cucumber yield caused by unfavourable thermal conditions of air in the growing season of the described plant was not identical in all regions of Poland (Fig. 2). Spatial distribution of reduction in the two considered types of cucumber yield was different not only in terms of amounts of losses but also their course. In the case of the total yield, reduction oscillated between below 12% and above 21%. The highest reduction in yield, amounting to above 21%, was caused by T_a which was too low in the period from sowing to the end of harvesting. Such temperatures significantly contributed to the arrest of cucumber growth and development in the north and the north-east and also in the south-west and the south-east of Poland. Reduction in yield within a range of between 12 and 15% was observed in central Poland and covered the biggest area. On the other hand, the lowest reduction in the total yield amounted to below 12%. This 12% total yield reduction was found in the Wielkopolska Lakeland in the vicinity of Poznań, in the Sandomierz Basin near Tarnów, and also in the Opole Plain and the Racibórz basin regions located

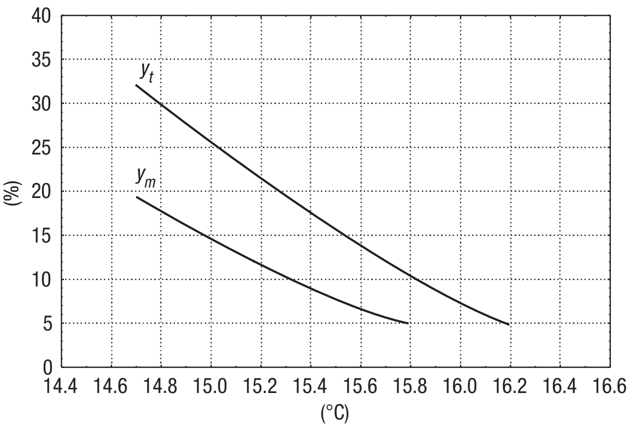

Figure 1. Potential reduction (%) in the total (y_t) and marketable yield (y_m) of cucumber in Poland caused by too low air temperature in the period from sowing to the end of harvesting (yield was calculated on the basis of equations shown in Table 1).

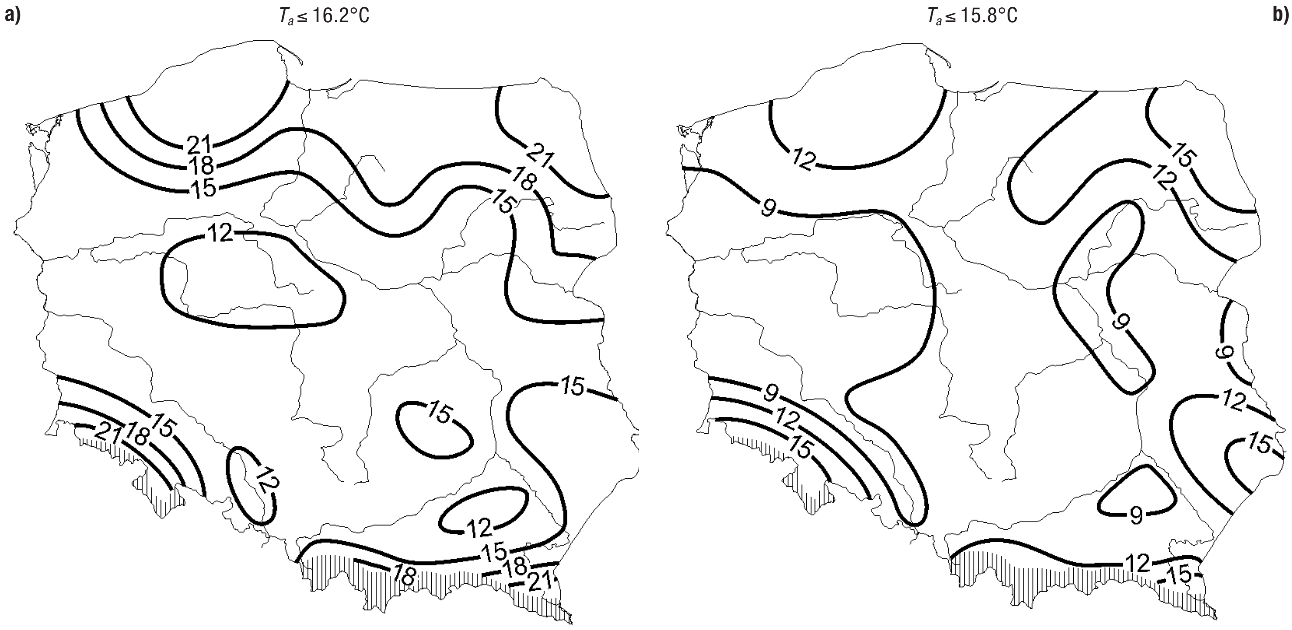

Figure 2. Spatial variability of potential reduction (%) in the total (a) and marketable yield (b) of cucumber in Poland caused by too low air temperature in the period from sowing to the end of harvesting (yield was calculated on the basis of equations shown in Table 1).

near Opole. In the case of the cucumber marketable yield, reduction oscillated between below 9% and above 15%. On the average cucumber marketable yield was 3-6% lower than the total yield. The biggest losses in the marketable yield were above 15%. These losses occurred in the north-east, but also in the south-west and the south-east of Poland. Lower losses in yield, between 9 and 12%, occurred in the central vertical strip of Poland. Higher yields of the cucumber marketable yield were lower by 9% in relation to the multi-annual average yield calculated in the years 1966-2005. These were yields harvested in the central-western and central-eastern parts of Poland, in the Mazovian Lowland, near Warsaw, and in the Sandomierz Basin, near Tarnów.

Frequency of the occurrence of unfavourable thermal conditions

T_a in the period from sowing to the end of cucumber harvesting which caused reduction by at least 5% in yields of the described vegetable occurred in Poland. The frequency of this occurrence was about 35% (on the average every 3 years) and about 23% (on the average, every 4 years), respectively for the total and marketable yield (Fig. 3). T_a amounting to 15°C occurred with a frequency of about 7%, that is, on the average, every 14 years. Such a temperature caused reduction in cucumber yield by 25% in the case of the total yield and by 15% in the case of the marketable yield below the average multi-annual level in the years 1966-2005. T_a in the cucumber growing season lower than 14.8°C was recorded with a frequency of about 4%. T_a lower than 14.6°C was recorded with a frequency of only about 1%.

Risk of the occurrence of low air temperature, amounting to ≤ 16.2°C and ≤ 15.8°C, in the cucumber period

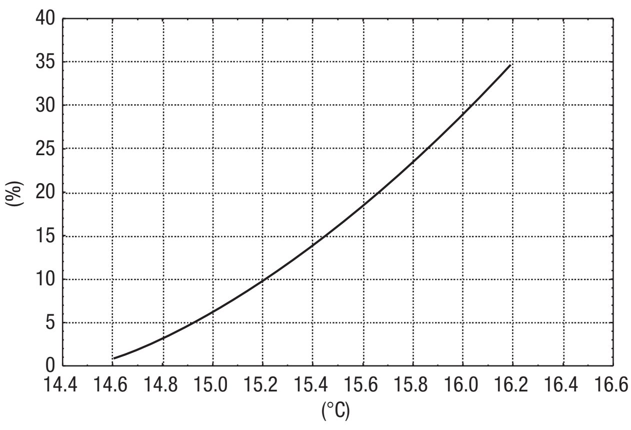

Figure 3. Occurrence frequency (%) of air temperature in the period from sowing to the end of harvesting causing reduction by at least 5% in cucumber yield in Poland.

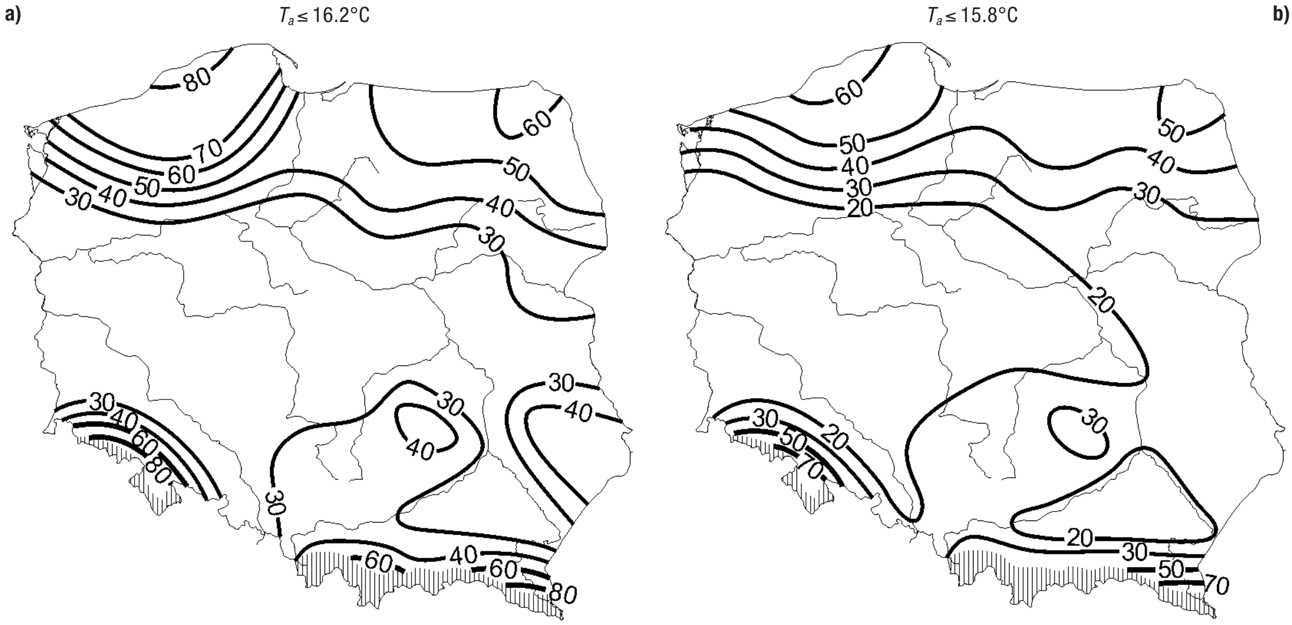

Figure 4. Spatial distribution of the occurrence frequency (%) of air temperature in the period from sowing to the end of cucumber harvesting causing reduction by at least 5% in cucumber yield in Poland. a) Total yield. b) Marketable yield.

S-EH in Poland was highly diverse spatially as it usually oscillated within a range of, respectively, 30-80% and 20-70% (Fig. 4). Air temperature ≤ 16.2°C, *i.e.* such a temperature which caused reduction by at least 5% in the cucumber total yield, was recorded least often, with frequency of below 30%, in the central strip of Poland. Both to the north and to the south of the strip the frequency increased. The highest spatial diversity of the occurrence frequency of $T_a \leq 16.2$°C was noted in south-western and next in south-eastern Poland. In these locations the frequency oscillated between 30% and even above 80%. In the north-east, unfavourable thermal conditions of air occurred with a frequency of from 40% to above 60%. Low T_a amounting to ≤ 15.8°C is the threshold of temperature which reduces the quantity of the cucumber marketable yield. A temperature of ≤ 15.8°C occurred least frequently; below 20%, in central-western and central Poland; the Poznań and Warsaw regions. A temperature of ≤ 15.8°C occurred most frequently above 70%, in the submountainous regions situated in the south-western and south-eastern parts of the country and in the Sandomierz Basin, near Tarnów, Poland. Spatial diversity of the occurrence frequency of $T_a \leq 15.8$°C, like in the case of $T_a \leq 16.2$°C, was also the highest in south-western and south-eastern Poland and generally oscillated between 20% and 70%. The next highest was in north-western Poland; between 20% and above 60%.

Air temperature variability in the period S-EH

In Poland, from the analysed years of 1966 to 2005, the average T_a in the period from sowing to the end of harvesting of cucumber fruits was marked by a significant increase. The increase was about +0.3°C/10 years ($R^2 = 17.8\%$, $p \leq 0.01$), oscillating between 15.1°C in 1980 and 18.8°C in 2002 (Fig. 5). A higher increase in T_a than the Polish average was found in southern Poland. It amounted to about +0.4°C/10 ($p \leq 0.01$).

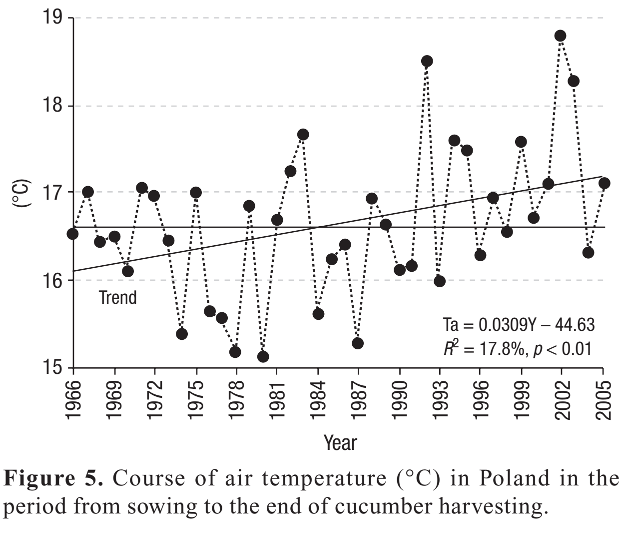

Figure 5. Course of air temperature (°C) in Poland in the period from sowing to the end of cucumber harvesting.

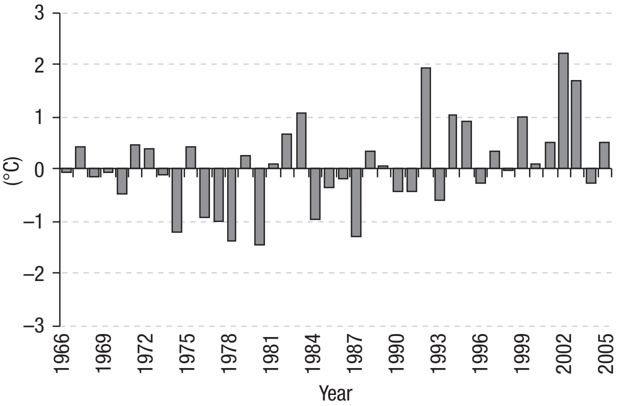

Figure 6. Air temperature deviations (°C) from the average multi-annual value (1966-2005) in a given year in Poland in the period from sowing to the end of cucumber harvesting.

Near Cracow and Tarnów T_a even reached +0.5°C/10 ($p \leq 0.01$).

In the analysed period from 1966 to 2005 almost the same number of negative and positive deviations of T_a from the norm, were noted (Fig. 6). Out of the 40 classified years the highest negative deviation $Ta_{S\text{-}EH}$ from the average multi-annual level, amounted to 16.6°C. The highest negative deviation calculation for the following years was: 1980 (–1.5°C), 1978 (–1.4°C), 1987 (–1.3°C) and 1974 (–1.2°C). The highest positive deviations of T_a from the norm were in: 2002 (+2.2°C), 1992 (+1.9°C), 2003 (+1.7°C) and 1983 (+1.1°C). In the first decade of the examined multi-annual period (1966-1975) $Ta_{S\text{-}EH}$ was lower than normal for six different years: 1966 (by –0.1°C), 1968 (by –0.2°C), 1969 (by –0.1°C), 1970 (by –0.5°C), 1973 (by –0.1°C) and 1974 (by –1.2°C). On the other hand, in the last decade (1996-2005) of the analysed 40 years, in as many as seven years T_a in the period from sowing to the end of harvesting was higher than normal. The high years were: in 1997 by +0.3°C, in 1999 by +1.0°C, in 2000 by +0.1°C, in 2001 by +0.5°C, in 2002 by +2.2°C, in 2003 by +1.7°C and in 2005 by +0.5°C. Positive deviations in those years definitely caused an increase in T_a in the examined multi-annual period. The longest series of years when $Ta_{S\text{-}EH}$ was lower than normal occurred in the period of four successive years from 1984 to 1987. The $Ta_{S\text{-}EH}$ was higher than normal in a five successive year period from 1999 to 2003.

Distribution of average T_a in the period from sowing to the end of cucumber harvesting in the years 1966-2005 in most of Poland oscillated between 15.5 and 17.0°C (Fig. 7). The most favourable thermal conditions of air to field cultivation of pickling cucumber occurred in central Poland. In central Poland $Ta_{S\text{-}EH}$ in the investigated multi-annual period was higher than 16.5°C. In southern Poland, in the Opole Plain, $Ta_{S\text{-}EH}$ was even higher than 17.0°C. The least favourable thermal conditions of air, $Ta_{S\text{-}EH} \leq 15.5$°C, occurred in the northern, south-western and south-eastern parts of the country. The least favourable year for cucumber cultivation was in 1980. The most favourable year was 2002. Spatial distribution of T_a in Poland in 1980 and 2002 differed from the average conditions prevailing in the years 1966-2005 not only in terms of course but also of level. In 2002; the warmest year $Ta_{S\text{-}EH}$ oscillated between below 17.5°C in the north and above 19.0°C in the centre and in the Sandomierz Basin, near Tarnów, Poland. On the other hand, in the coldest year, 1980, spatial distribution $Ta_{S\text{-}EH}$ was less diverse than in 2002, because T_a oscillated from below 14.0°C to above 15.0°C. The Sandomierz Basin always had a recording of the highest T_a (> 15.0°C). The south-western and south-eastern parts of Poland always had – the lowest record of T_a (< 14.0°C).

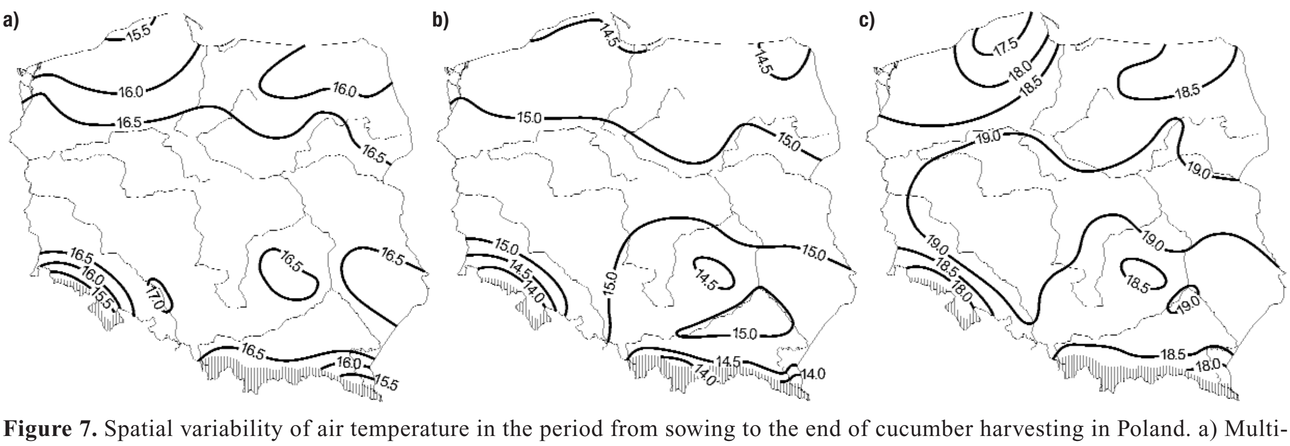

Figure 7. Spatial variability of air temperature in the period from sowing to the end of cucumber harvesting in Poland. a) Multi-annual average in the years 1966-2005. b) In 1980. c) In 2002.

Discussion

There are no scientific publications devoted to risk assessment of cucumber field cultivation caused by unfavourable meteorological conditions, particularly T_a, analysed for the whole country, which significantly reduces crop productivity of the described plant not only in Poland but also in those countries where it is unsuitable during the growing season. A relatively large number of publications, concern the influence of thermal conditions on the rate of growth and development of crop plants. There are also publications on the level of crop productivity, but very often without determination of potential reduction in yield and without determination of the occurrence frequency of an unfavourable course of T_a in the whole country. Besides, many studies on the subject are based on experiments conducted in strictly controlled greenhouse conditions. Very often these controlled greenhouse conditions are located at different geographical latitudes than are in Poland. Many times the experiments were even done on different cultivars. For this reason, it is difficult to compare the results obtained in the current work with those presented in the literature. Nonetheless presenting the results in the current study will enable description of the role of T_a not only in field but also in greenhouse cultivation of cucumber.

Scientific research conducted in different climatic conditions of the world show changing thermal conditions of air in successive years. Such changes cause diversification of the course of development stages of both wild growing and crop plants (Ahas *et al*., 2000; Sparks *et al*., 2000; Chmielewski and Rötzer, 2002; Kozlov and Berlina, 2002; Chmielewski *et al.,* 2004; Kalbarczyk and Kalbarczyk, 2004; Tao *et al*., 2006; Schieber, 2007). Changes in the dates of the phenophases of crop plants were also observed in Poland. These date changes were, not only of cucumber but also, *e.g.,* mid-early potato. A significant ($p < 0.05$) negative trend in the years 1972-1995 is shown by the main phenophases of potato: emergence, flowering and haulm drying (Kalbarczyk and Kalbarczyk, 2004). In the case of cucumber, the bigger the changes were, the later the phenophase they pertained to. For emergence, the average acceleration of the date amounts to +1.2 day/10 years, for flowering +1.9 day/10 years, and for fruit-setting +2.1 days/10 years (Kalbarczyk, 2009a). Reactions of crop plants to changes in phenology occurring as a result of T_a changes were observed. These changes in phenology depended on the species and region of the world. Some of the reactions were extreme; ranging from an increase to a decrease in the harvested yield (Tao *et al.,* 2006; Wang *et al.,* 2008; Xiao *et al.,* 2008). For example, an increase in the maximum T_a in spring in central China accelerates the date of sowing, flowering and maturity of wheat, leading to reduction in yield. On the other hand, the same T_a occurring in spring in the north-eastern part of China also accelerates the date of sowing and flowering but, at the same time, delays the date of maize ripening. This delay, in turn, contributes to an increase in the yield of the plant (Tao *et al.,* 2006). The results from research show that correct growth and development of cucumber in all of its stages, requires sufficiently high T_a (Lederle and Krug, 1985; Liebig, 1985a; Babik, 2004; Kalbarczyk, 2009b). Some authors suggest that soil warming partly counteracts the unfavourable influence of low T_a at night on the growth of thermophilous plants (Ingratta, 1980; Liebig, 1985a). When the ground is warmed to 14°C, cucumber can survive even a long period at T_a amounting to only 10°C without much harm (Liebig, 1985a). Damage to cucumber plants in Poland may take place when after a period of high T_a there occurs a cooling of up to 4-6°C which lasts for several days. Damage may take place, not only in the period of sowing but also in the much later period of emergence, flowering or even fruit-setting. Cool air which lasts a few days and low temperature in the root zone cause the plant to die. This happens because water uptake from the soil is stopped and transpiration continues (Babik, 2004). Unfavourable effects occur when T_a is below average in the whole growing season of cucumber. Such negative consequences are also confirmed in the results of present work. Lederle and Krug (1985) determined quantitatively the relationship between the rate of germination and the index of emergence with the use of linear regression and polynomial regression of the 3rd, 4th and 5th degree. In addition they determined a maximal and minimal temperature of cucumber germination. According to Lederle and Krug (1985), in good habitat conditions cucumber seeds will germinate even 5-10 days after the date of sowing. According to Górka (1987), in Poland cucumbers emerge depending on average T_a. The earliest cucumbers emerge is after 5 days at a temperature of 19°C. The latest they emerge is after 20 days, at a temperature of 11°C. Kharkina *et al.* (2003) investigated the effect of temperature with lighting intensity of 100 W m^2 and a 12-h day on parameters describing dynamics of germ growth and rooting of cucumber plants. The highest values of the analysed parameters were obtained at stable daily soil, and T_a amounting to 25 and 20°C respectively, in the case of the first and the second group of indexes. The research results also suggest that the quantity of a gradient (difference between day and night temperatures) significantly affects the growth of cucumber roots. In the case where the gradient amounts to 10°C (35/25 and 25/35°C) root growth is stimulated. In the case of 20°C (35/15 and 15/35°C) root growth is stopped. Not only the difference between day and night temperatures but also a short temperature drop at night may contribute to growth depression of the plant (Grimstad, 1993). According to Koźmiński and Raab-Krzysztoporska (1974), in the years when the sum of the T_a in the critical period is small (below 1,200°C) cucumber displays higher sensitivity to the amount of atmospheric precipitation during this period. The critical period is considered to be from the beginning of flowering to the end of harvesting. When the atmospheric precipitation is below 150 mm, cucumber distinctly reacts to T_a. The most unfavourable thermal and precipitation conditions for cucumber cultivation, analysed for the whole of Poland except for mountainous regions, according to Koźmiński and Raab-Krzysztoporska (1974), occur in the north-eastern part of the country and higher situated regions of the Pomeranian Lakeland (northern Poland). The results obtained by these scientists (Koźmiński and Raab-Krzysztoporska, 1974) only partially agree with the results presented in this study. The difference in results was most probably because this study had a 30 year longer research period and the fact that the number of considered COBORU stations was more than twice smaller. On the other hand, results from the research by Kalbarczyk (2009c) show that the biggest loss of cucumber yield caused by low soil temperature occurs in south-western and south-eastern Poland. These are results like in the case of excessively low T_a, analysed in the present work. Yoshida *et al.* (1998) analysed the growth of cucumber plants, evaluating the stem length and leaf surface and the quantity of fresh mass, depending on the course of day and night T_a. According to them, plant growth can be modified through control and change in T_a during the day and night. According to Yoshida *et al.* (1998), length of stems, leaf surface and the fresh mass of a cucumber shoot had lower values in plants developing in a stable temperature of 20°C than at changeable temperature (sinusoidally changing within a range from 15 to 25°C). However, percentage of dry mass increased in conditions when T_a amounted to 15°C at night and 25°C during the day. The biggest stem lengthening and biggest leaf surface occurred in conditions of changeable temperature. It suggests that shoot growth can be modified by T_a control. These results also suggest that variable temperature conditions within a range from 15 to 25°C help plant growth. The results of the work by Gosselin and Trudel (1985) confirmed a significant influence of root zone temperature and night T_a on greenhouse cucumber production. They confirmed that the biggest amount of dry mass and biggest leaf surface were produced at a soil temperature of 24-30°C and at a night T_a amounting to 17°C (from 5:00 p.m. to midnight) and 9°C (from midnight to 7:00 a.m). On the other hand, Medany *et al.* (1996) determined the influence of solar radiation and T_a on the growth rate of cucumber dry mass. The results of Medany *et al.* (1996), were found on the basis of field and greenhouse research. Sysoeva and Markovskaya (2006) investigated the effect of light and temperature on the rate of development of cucumber among other things. According to these scientists, optimal light and thermal conditions are the following: day duration amounting to 13 h, light intensity - 130 klx and average temperature - 30°C. Medany *et al.* (1999) in greenhouse research assessed the growth rate of cucumber fruits depending on night T_a, the season, and light conditions modified by different polyethylene films. The fruits grew quickest at a temperature of 18°C in the highest lighting, irrespective of the season of the year. According to Marcelis *et al.* (1993), a drop or increase in T_a by several degrees Celsius in the fruiting period has a bigger influence on the development of cells than on cell division. A period of four days with a temperature of 27.5°C leads to considerable stimulation of the growth rate of fruits. Slack and Hand (1981) investigated the influence of night temperature (a range between 14 and 25°C) and day T_a (a range between 16 and 25°C) on cucumber yield for two cultivars - 'Farbio' and 'Sandra'. The highest T_a generally accelerated fruiting. Slack and Hand (1981) found that high day temperature was more effective than high night temperature. Early fruit harvesting (*i.e.* 4 weeks after planting of seedlings) increased with night temperatures of up to 23°C. Early fruit harvesting did not increase at daily temperatures of 22°C. Twenty weeks after planting of cucumber seedlings the highest total yield of fruits was harvested at a night temperature of 20°C (when day temperature was 20°C) and at day temperature of 22°C (when night temperature was 19°C). On the other hand, Liebig and Krug (1991) created a model for weekly forecasts of the quantity of cucumber yield. They took into consideration two meteorological elements, solar radiation and T_a. Liebig's (1985b) research shows that weekly cucumber cropping depends, most of all, on solar radiation and next on plant age and T_a. According to Kalbarczyk (2009c), higher than average values of both sunshine duration and T_a, which in the growing season amount to 7.9 h and 17.5°C respectively, are conducive to earlier agrotechnical and phenological dates, and thus, high cucumber yields. Scheunemann *et al.* (1990) forecast the date and duration of cucumber harvesting depending on the date of sowing and on the basis of T_a and sunshine duration. According to them, the beginning of cucumber harvesting occurs when in the growing season the sum of sunshine duration amounts to 350 h, and the sum of air 950-1,000°C. Higher sums of T_a were determined by Górka (1987), according to whom in Poland sums of T_a oscillate between 1,055°C and 1,217°C. On the other hand, Akinci and Abak (1999) determined sums of effective temperature in successive periods of the cucumber growing season: sowing-emergence, emergence-pollen production, pollen production-maturity and sowing-the beginning of harvesting, with the use of different methods and threshold values. Their best results were obtained at a threshold of 12°C. Finally, Perry *et al.* (1986) forecast the date of cucumber harvesting on the basis of the sum of the effective temperature calculated above 10, 13, 18 and 23.5°C.

Because of air temperature variability in the cucumber growing season, which was shown in the study, the research on its effect on cultivation of this plant in Poland should be continued in the next years.

As final conclusions, in Poland, reduction by at least 5% in pickling cucumber yields occurred when T_a in the period from sowing to the end of harvesting was lower than the multi-annual average in the years 1966-2005 by 0.4°C in the case of the total yield and by 0.8°C in the case of the marketable yield, *i.e.* respectively at ≤ 16.2 and ≤ 15.8°C.

Reduction in cucumber yield in most of Poland, *i.e.* in its central strip, caused by unfavourable thermal air conditions in the period of the growing season oscillated from below 12 to 15% and from below 9 to 12%. These are per cents calculated in relation to the average level of cropping in the years 1966-2005 respectively, for the total and marketable yield. The lowest cucumber yield was from south-western, south-eastern and north-eastern Poland. In northern Poland, the yields were lower than the multi-annual average even by over 21 and 15% respectively, for the total and marketable yield.

T_a in the period from sowing to the end of cucumber harvesting ($Ta_{S\text{-}EH}$) causing reduction by at least 5% in the total and marketable yield of the plant, occurred with a frequency of from below 30% to above 80% and from below 20% to above 70%, respectively. The T_a most frequently was recorded in south-western and south-eastern Poland and in the case of $Ta_{S\text{-}EH}$ ≤ 16.2°C also in northern Poland.

An increase in T_a in the cucumber growing season may, in the incoming years, limit a reduction in the quantity of the plant yield caused by the analysed thermal factor. This is true especially in southern Poland where a temperature increase was proved to be about 0.4°C/10 years. This means by 0.1°C/10 years more, than recorded for the whole country.

Acknowledgements

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

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