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Climatic Risk of Field Cultivation of Cucumber (*Cucumis sativus* L.) in Poland

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Abstract

The goal of the present work was to separate zones of pickling cucumber field cultivation in Poland according to the various degrees of climatic risk. The study used 40-years of (1966-2005) data from 28 experimental stations of the Research Centre for Cultivar Testing. The data characterised the course of the growth, development, cucumber crop productivity and also the agrotechnical dates. Additionally, the work considered agrometeorological data of 7 development stages of the analysed plant: sunshine duration, soil temperature at a height of 5 cm, air temperature at a height of 2 m and 5 cm above ground level and atmospheric precipitation. The agrometeorological data was collected from 53 meteorological stations, in the Polish network of the Institute of Meteorology and Water Management. Weather-yield regression equations were used to determine unfavourable agrometeorological elements which is the best way to determined the quantity of the cucumber total and marketable yield. The highest climatic risk of pickling cucumber field cultivation occurred in about 7% of Poland's area. This is the area covering the southwestern, southeastern, the northern and northeastern parts of the country. In these areas, very high occurrence frequency of agrometeorological elements was noted. These elements were: air and soil temperatures that were too low during the whole growing season and, too short of a duration of the period without frost, lasting ≤120 days.

Keywords: cucumber, meteorological data, zones of climatic risk, climate change, Poland

Introduction

In Poland, cultivation of field vegetables plays an important role in vegetable production. In the last decade (2000-2009) in the domestic structure of vegetable cultivation, cucumber had a big share. This share was mostly from 8 to 10%, depending on the considered year. The share of cucumber was right after onion and cabbage. On the average, onion and cabbage shares are estimated at 13-16% (Kulikowski, 2007; FAO, 2009). Considering occupied acreage, Poland is the biggest cucumber producer among all the countries of the European Union. The domestic area of cucumber cultivation in the years 2000-2009 oscillated between 18 to 27 thousand ha. In Romania, the country with the second biggest cultivated land surface of the cucumber, it amounted to approximately 11 thousand ha maximum (Jabłońska and Gac, 2006; FAO, 2009).

High, yearly yield variability is a characteristic feature of cucumber production in Poland. High yield results both from the changeability of the cultivated surface and yield quantity. These features, in turn, are mainly determined by weather conditions (Mierwinski, 1985; Cieślak-Wojtaszek, 2000; Chudzik, 2007; Kalbarczyk, 2009a; 2009b). In the years of unfavourable agrometeorological conditions, the final yield of field vegetables is additionally determined by: appropriate selection of cultivars and rigorous and well-timed application of plant protection chemicals (Chudzik, 2007). In Poland, cucumber yield does not usually exceed 15 t ha^{-1}. In this respect, it is one of the lowest among the countries of the European Union (Juszczak, 2005; FAO, 2009). The highest cucumber yield is usually harvested in central Poland and the lowest in southern and northern Poland (Cieślak-Wojtaszek, 2000; Kalbarczyk, 2009b). Differences between the level of harvested yields in Poland and the EU countries where cucumber is of big economic importance, have its source, among other things, in different production technologies. Often the lack of devices for irrigating cucumber crops is also at fault (Chudzik, 2007).

Human interference in the shaping of weather conditions is still very limited. The only well-tried way of limiting unfavourable weather effects on yield quantity is locating cucumber cultivation in such regions of Poland where risk of the occurrence of unfavourable weather is the lowest (Wilczek, 1985; Bac, 1991; Kalbarczyk, 2005). Recognition of the climatic risk of cultivation should be determined for each vegetable species separately. Once determined, updating should be done as often as possible because of changing climatic conditions (Wilson *et al*., 1994; Holden *et al*., 2003; Holden and Brereton, 2004; Rai *et al*., 2006; Maes *et al*., 2009). An essential condition for limiting the unfavourable effect of agrometeorological elements on the growth, development and yield of cucumber is the recognition of the threat and next, the determination of the threat (Wilson *et al*., 1994; Eakin, 2000; Holden *et al*., 2003; Holden and Brereton, 2004; Kalbarczyk, 2005; Pathak and Wassmann, 2009; Mestre-Sanchís and Feijóo-Bello, 2009). The influence of agrometeorological conditions as yield-reducing factors may also be partially decreased by raising the agriculture level (Malepszy, 2004). In Poland, an increase in vegetable production in the second half of the 20th century was mainly caused by biological progress and only then by fertilization and plant protection (Malepszy, 2004).

The goal of the present work was to separate zones of pickling cucumber field cultivation in Poland according to various degrees of climatic risk on the basis of the 40-year research period 1966-2005.

Materials and methods

The study involved the use of material from rigorous experiments on field cultivation of cucumber pickling varieties. The experiments were conducted on the experimental plots of 28 stations of the Research Centre for Cultivar Testing (COBORU). The experiments on cucumber cultivation were conducted every year from 1966-2005 (Fig. 1), except for the years 2003 and 2004. The experimental data of COBORU covered information on cucumber agrotechnical dates (sowing and harvesting - the beginning and the end) and the course of growth and development (the end of emergence, the beginning of flowering and the beginning of fruit-setting). Data was also taken on information concerning the quantity of harvested total and marketable yield. Cucumber marketable yield was composed of all pickling fruits with a length of 6-10 cm and a diameter of 2.5-4.0 cm, however, not smaller than half of the fruit length. Starting materials concerning cucumber field cultivation were collected for a standard which was an average of the most common cucumber pickling varieties cultivated in a given year. In the years 1966-2005 about 60 cultivars were used. Use of a collective research standard was based on the assumption that differences between cultivars do not disguise general regularities being searched for in the species. The standard made it possible

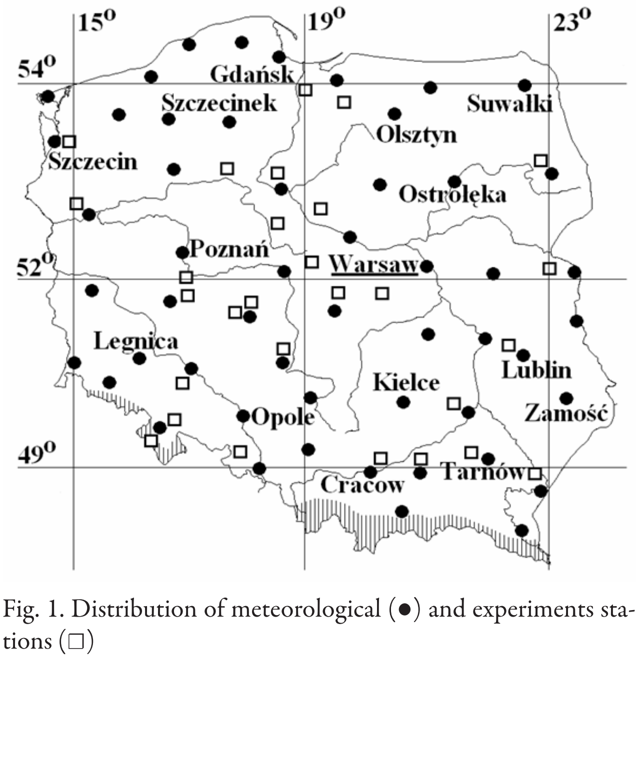

Fig. 1. Distribution of meteorological (●) and experiments stations (□)

to conduct research on the climatic risk of cucumber field cultivation all over Poland on the basis of the multiannual period 1966-2005.

The experimental plots of 28 stations of COBORU were situated all over the whole country of Poland, except for submountainous regions located in southwestern and southeastern Poland. The submountainous regions were excluded from the research due to the fact that in Poland field cultivation is usually limited to the height of 500 m above sea level. The soil of experimental plots, in which research on cucumber was carried out, was classified as soil class I, II, IIIa, IIIb and IVa. The soil was also classified according to agricultural usefulness as: very good, and good wheat complexes (i.e. soils typical for cultivation of wheat). Cucumber pickling varieties were mostly cultivated after cereal plants were cultivated and after peas and early cabbage. In autumn, organic manure was used in a dose of 30-40 t ha^{-1} or, alternatively, well-decayed compost of 40-60 t ha^{-1} and pre-winter ploughing was done. Mineral fertilisation depended on the organic fertilisation used and current soil nutrient richness. Fertilisation was applied according to the dose needed: 80-150 kg N ha^{-1}, 80-100 kg P_2O_5 ha^{-1} and 150-200 kg K_2O ha^{-1}. All agrotechnical treatments were carried out according to the rules of the proper field crop production of this species. The treatments were done in accordance with the methodology developed by Coboru in the 1960s and this methodology was updated many times in the following years.

The study also used the following daily agrometeorological data sunshine duration, soil temperature at the depth of 5 cm, air temperature at a height of 2 m and 5 cm above ground level, and atmospheric precipitation. The data were collected in the successive years of the analysed multiannual period 1966-2005. The collection was from 28 experimental stations of COBORU and 53 meteorological stations of the Institute of Meteorology and Water Management (IMGW). On the basis of the data, excluding air temperature at a height of 5 cm, average values of the analysed elements were calculated. The values were calculated at the time corresponding with the average dates of the occurrence of pickling cucumber developmental stages in Poland. The average dates of the developmental stages are: sowing -the end of emergence (16th May-3rd June), the end of emergence -the beginning of flowering (4th June-7th July), the beginning of flowering -the beginning of fruit-setting (8th July-12th July), the beginning of fruit-setting -the beginning of harvesting (13th July-22nd July), the beginning of harvesting -the end of harvesting (23rd July-03rd September) and sowing -the beginning of harvesting (16th May-22nd July) and sowing -the end of harvesting (16th May-03rd September). On the other hand, air temperature at a height of 5 cm above ground level≥0°C was used to determine the frost free period, i.e. a period calculated between extreme dates of the last spring and the first autumn ground frost.

Agrometeorological conditions were described as: sunshine duration (*Sd*, h day^{-1}), soil temperature (*Ts*, °C), air temperature (*Ta*, °C) and atmospheric precipitation (*Pr*, mm) in particular developmental stages of cucumber growth. The effect of these agrometeorological conditions on the quantity of cucumber yield was assessed on the basis of linear or curvilinear (2nd degree polynomial) multiple regression equations. Decisions about the choice of an equation type were made by comparing values of determination coefficients which were calculated separately for the linear equation and the 2nd degree polynomial equation. Sometimes the determination coefficients had similar values (a difference of $R^2 \leq 5\%$). This might happen when i.e., using the polynomial equation did not significantly improve the goodness of fit and did not increase the share of independent variables in the description of changeability of dependent variables. In such a case the linear equation was considered sufficient. Each time the cucumber total or marketable yield was a dependent variable. The examined agrometeorological element (*Sd, Ts, Ta, Pr*) and time function, described by successive years of the analysed multiannual period 1966-2005, were an independent variables. Collinearity between independent variables in the multiple regression equation was assessed with the ridge regression method.

In the weather-yield regression equation, information on soil conditions and fertilisation was not taken into account. This information was not taken into account because it did not statistically significantly differentiate the quantities of yield considered in the research. Lack of differences was confirmed with the *t*-Student test (Dobosz, 2001). These results confirmed that the experimental stations of Coboru employed proper techniques of field cucumber crop production. Therefore, variability of the final yield was determined mainly by the course of agrometeorological conditions.

Multiple regression function parameters were determined with the least squares method. The hypothesis of the significance of the absolute term and regression coefficients was assessed with the *t*-Student test. The significance of the regression function was assessed with the *F*-Snedecor test. The measure of fitting of the regression function to empirical data was a coefficient describing the difference between a standard deviation of a dependent variable and a standard error of equation estimation *S-Sy* (t ha^{-1}) and the determination coefficient R^2 (%).

Practical verification of regression equations was performed on the basis of relative forecast error determined according to the formula:

$$RFE = \frac{y - y_p}{y} \cdot 100\%$$

and average relative forecast error, which was calculated according to the formula:

$$ARFE = \frac{1}{n}\sum_{i=1}^{n}\left|RFE\right|$$

where:
y -actual yield (t ha^{-1}),
y_p -yield calculated on the basis of the formula (t ha-1),
n -number of years in a time series (number of stations x number of years).

Next, how many times the relative forecast error in the analysed multiannual period 1966-2005 amounted to $|RFE| \leq 5\%$ (a very good forecast) and $5\% < |RFE| \leq 10\%$ (a good forecast) was determined (Dobosz, 2001).

The climatic risk of cucumber field cultivation in Poland was assessed on the basis of the occurrence frequency of unfavourable agrometeorological conditions which were labelled *Sd, Ts, Ta, Pr.* Assessment was also done based on the duration of the period without frost lasting ≤120 days (*Tf*). Unfavourable conditions were considered to be such conditions which caused reduction by at least 5% in the yield of the analysed plant below the average multiannual level in the years 1966-2005. Threshold values of the elements (excluding the index *Tf*), at which there occurred a reduction by at least 5% in the total and marketable yield, were determined on the basis of the weather-yield curvilinear regression equations. But this was done only for those relationships which were marked by good statistical description, $R^2 \geq 39.8\%$ and $|RFE| \leq 10.2\%$. In Poland, 4 zones with different degrees of the climatic risk of cucumber field cultivation were separated: very high, marked as Zone 4, high (Zone 3), average (Zone 2) and low risk (Zone 1). The average quantity ($\bar{x}$) and a standard deviation (S) of the sum of the frequency of unfavourable conditions determined for all IMGW stations were a criterion of the division into zones. However, the frequency which was determined separately for each of the considered agrometeorological elements: *Sd, Ts, Ta, Pr*, both for the total and marketable yield and for *Tf*, was averaged earlier. The zone of average climatic cultivation risk was within the range of $\bar{x} \pm 0.5S$; the zone of high risk from $\bar{x} + 0.5S$ to $\bar{x} + 1.0S$; the zone of very high risk > $\bar{x} + 1.0S$; the zone of low risk < $\bar{x} - 0.5S$.

Results

Relationship between yield and agrometeorological elements

In the whole cucumber growing season (S-Eh, sowing-end of harvesting) significant influence of all the analysed agrometeorological elements on the quantity of the total and marketable yield of this plant was proved (Tab. 1). Out of the 5 examined short developmental stages of cucumber, the most sensitive period of growth and development according to the influence of the course of agrometeorological conditions in Poland, was the period from the beginning of harvesting to the end of harvesting (Bh-Eh),

Tab. 1. Dependence of cucumber yield on the course of agrometeorological elements in Poland, with consideration of the linear trend in the years 1966-2005

Kind of yield	Element	Development stage						
		S-Ee	Ee-Bf	Bf-Bfs	Bfs-Bh	Bh-Eh	S-Bh	S-Eh
T	*Sd*	+L** (23.1)	-K*** (45.8)	n.s.	n.s.	-K*** (51.9)	-K*** (27.6)	-K*** (30.8)
M	(h day^{-1})	n.s.	-K*** (42.4)	n.s.	n.s.	-K*** (41.6)	-K*** (34.5)	+L*** (26.6)
T	*Ts*	n.s.	+L** (23.1)	+L*** (26.5)	n.s.	-K*** (30.2)	+L** (23.0)	-K*** (49.3)
M	(°C)	n.s.	+L*** (33.3)	n.s.	n.s.	-K*** (35.6)	n.s.	-K*** (44.1)
T	*Ta*	n.s.	+L*** (24.8)	+L*** (24.4)	n.s.	-K*** (29.0)	+L*** (25.8)	-K*** (42.2)
M	(°C)	n.s.	+L*** (32.1)	n.s.	n.s.	-K*** (33.2)	n.s.	-K*** (48.5)
T	*Pr*	-L*** (24.8)	n.s.	n.s.	n.s.	-K*** (39.8)	n.s.	-K*** (25.8)
M	(mm)	-L*** (33.2)	n.s.	n.s.	n.s.	-K*** (46.3)	n.s.	-K*** (28.2)

T-total yield (t ha^{-1}), M-marketable yield (t ha^{-1}), *Sd*-average sunshine duration (h day^{-1}), *Ts*-average soil temperature at the depth of 5 cm (°C), *Ta*-average air temperature (°C), *Pr*-atmospheric precipitation total (mm), -/+ – negative/positive relationship, L-linear relationship, K-curvilinear relationship (2nd degree polynomial), **-significant at $P≤0.05$, ***-significant at $P≤0.01$, n.s.-non-significant at $P≤0.05$, S-Ee -sowing-end of emergence, Ee-Bf -end of emergence-beginning of flowering, Bf-Bfs -beginning of flowering-beginning of fruit-setting, Bfs-Bh -beginning of fruit-setting -beginning of harvest, Bh-Eh -beginning of harvest-end of harvest, S-Bh -sowing-beginning of harvest, S-Eh -sowing-end of harvest. The value of determination coefficient given in brackets (%)

and next, the period from the end of emergence to the beginning of flowering (Ee-Bf). In the period Bh-Eh, cucumber yield was in the strongest way negatively affected by sunshine duration (R^2 amounted to about 52 and 42%, respectively for the total and marketable yield), and, next, by atmospheric precipitation (R^2 amounted to about 40 and 46%, respectively for the total and marketable yield). Thermal conditions of soil (*Ts*) and air (*Ta*), like agrometeorological indexes *Sd* and *Pr*, significantly negatively affected both considered types of yield. Because of the fact that the described relationships had the character of a quadratic function, cucumber yield decreased with a decrease in soil and air temperature. On the other hand, in the second developmental stage Ee-Bf, in which the strong influence of weather on cucumber crop productivity was noted, sunshine duration accounted for yield variability from about 42 to 46%, and soil and air temperature-from about 23 to 33%. Like in the period of fruiting (Bh-Eh), and also in the period from the end of emergence to the beginning of flowering with a decrease in values of *Sd*, *Ts* and *Ta*, there occurred reduction in cucumber yield. Weather-yield relationship ascertained in the period from the beginning of fruit-setting to the beginning of harvesting was not significant at the level of at least $P≤0.1$. Probable reasons were the very short duration of this period which lasted in Poland on the average about 10 days, and the low variability of agrometeorological conditions occurring at the time (Kalbarczyk, 2009a; Kalbarczyk, 2010).

One agrometeorological element of each type (*Sd, Ts, Ta* and *Pr*) that best correlated with the yield ($R^2≥39.8\%$ and RFE≤10.2%) was selected for further calculations. The agrometeorological elements which most determined the total and marketable yield of cucumber included: sunshine duration in the Bh-Eh period, average air and soil temperature in the S-Eh period, and atmospheric precipitation in the Bh-Eh period. Multiple regression equations formed for these relationships were marked by a good fitting of empirical data, as R^2 oscillated from about 40 to 52%, and average relative forecast error (*ARFE*) -from 9.1 to 10.2%. The occurrence frequency of a very small (from 0 to 5%) relative forecast error (*RFE*) oscillated from 32.4 to 41.2%, and a small one (from 5 to 10%) -from 39.1 to 49.1%.

On the basis of multiple regression equations (Tab. 2), threshold values of agrometeorological elements were determined at which there occurred a reduction by at least 5% in cucumber yield in Poland below the multiannual average in the years 1966-2005 (Tab. 3). Reduction by 5% in the total and marketable yield of the characterised plant occurred, respectively, at ≤6.2 and ≤5.8 h day^{-1} in the case of the index *Sd* in the Bh-Eh period; at ≤17.9 and ≤17.3°C in the case of the index *Ts* in the S-Eh period; at ≤16.2 and ≤15.8°C in the case of the index *Ta* in the S-Eh period; at ≤74 and ≤82 mm in the case of the index *Pr* in the Bh-Eh period.

Characteristics of dependent and independent variables, considered in weather-yield equations

In Poland, the average total yield of cucumber amounted to 33.2 t ha^{-1} and oscillated from about 4 to 81 t ha^{-1} (Tab. 4). The marketable yield was considerably lower -on the average by 14.8 t ha^{-1}. Both total and marketable yield of cucumber were marked by a significant yearly increase at the level of $P≤0.01$; R^2 calculated for the linear trend in the years 1966-2005 amounted to about 10 and 23%, respectively.

Total yield higher than the multi-annual average in the years 1966-2005 was harvested in the central west and in the Sandomierz Basin (near Tarnów). The highest yield was at least 8.0 t ha^{-1} higher than the multiannual average and it was harvested -in the vicinity of Poznań and Warsaw (Fig. 2). The lowest cucumber yield was harvested in the northeast, the southwest and the southeast. The low yield was at least 8.0 t ha^{-1} below the average level. Spatial

Tab. 2. Regression equations for significant (at the level of $P \leq 0.01$) and close ($R^2 \geq 39.8\%$) relationships between cucumber yield and agrometeorological elements in Poland, with consideration of the linear trend in the years 1966-2005

Kind of yield	Element	Development stage	Regression equations				Characteristics				
			intercept	regression coefficients			R^2 (%)	*S-Sy* (t ha^{-1})	*ARFE* (%)	frequency of the occurrence of |*RFE*| in range	
				aLt	*bx*	*bx*^{2}				0-5 (%)	5-10 (%)
T	*Sd*	Bh-Eh	-667.168	+0.329	+11.476	-0.694	51.9	2.1	9.1	38.7	49.1
M	(h day^{-1})		-870.7102	+0.438	+5.4076	-0.356	41.6	1.3	10.2	32.4	41.9
T	*Ts*	S-Eh	-913.1069	+0.329	+29.535	-0.744	49.3	1.5	9.5	36.5	48.1
M	(°C)		-1045.30062	+0.454	+17.423	-0.466	44.1	1.9	10.1	34.2	43.9
T	*Ta*	S-Eh	-918.324	+0.293	+41.239	-1.138	42.2	1.7	9.8	38.1	40.4
M	(°C)		-1062.642	+0.443	+23.8012	-0.70062	48.5	2.1	9.1	41.2	43.8
T	*Pr*	Bh-Eh	-816.319	+0.423	+0.158	-0.000551	39.8	1.5	10.2	36.2	39.1
M	(mm)		-926.859	+0.473	+0.1067	-0.000319	46.3	1.9	9.4	39.7	43.9

R^2-determination coefficient (%), S-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 (%), Lt -linear trend of the yield, i.e., the successive years of the 1966-2005 multi-annual period, a, b -regression coefficients of independent variables: *Sd, Ts, Ta* and *P*;. other explanations, see Tab. 1

Tab. 3. Threshold values[1] of agrometeorological elements at which there occurs a reduction by at least 5% in cucumber yield in Poland below the multi-annual average (1966-2005)

Kind of yield	Element	Development stage	Threshold value
T	*Sd*	Bh-Eh	≤6.2
M	(h day^{-1})		≤5.8
T	*Ts*	S-Eh	≤17.9
M	(°C)		≤17.3
T	*Ta*	S-Eh	≤16.2
M	(°C)		≤15.8
T	*Pr*	Bh-Eh	≤74
M	(mm)		≤82

[1]Threshold values were determined on the basis of regression equations placed in Table 2; explanations, see Tab. 1

distribution of the marketable yield was similar to the distribution of the total yield. This is because the highest yield was also harvested in the vicinity of Poznań and Warsaw and the lowest in the submountainous regions situated in the southwestern and southeastern part of the country and in Roztocze (near Zamość). In the case of the marketable yield, deviations from the average domestic level on the average amounted to ±4.0 t ha^{-1}.

Agrometeorological elements which contributed considerably to the growth, development and crop productivity of cucumber in Poland, differed in respect to both temporal and spatial structure (Tab. 4, Fig. 3). Sunshine duration in the Bh-Eh period lasted on the average 6.9 h day^{-1} and oscillated between 4.1 and maximally 1.3 h day^{-1}. Soil and air temperature in the S-Eh period, on the average amounted to 18.6 and 16.6°C respectively. The index *Ts* oscillated from 15.3 to 22.5°C, and the index *Ta* from 13.9 to 19.6°C. On the other hand, atmospheric precipitation

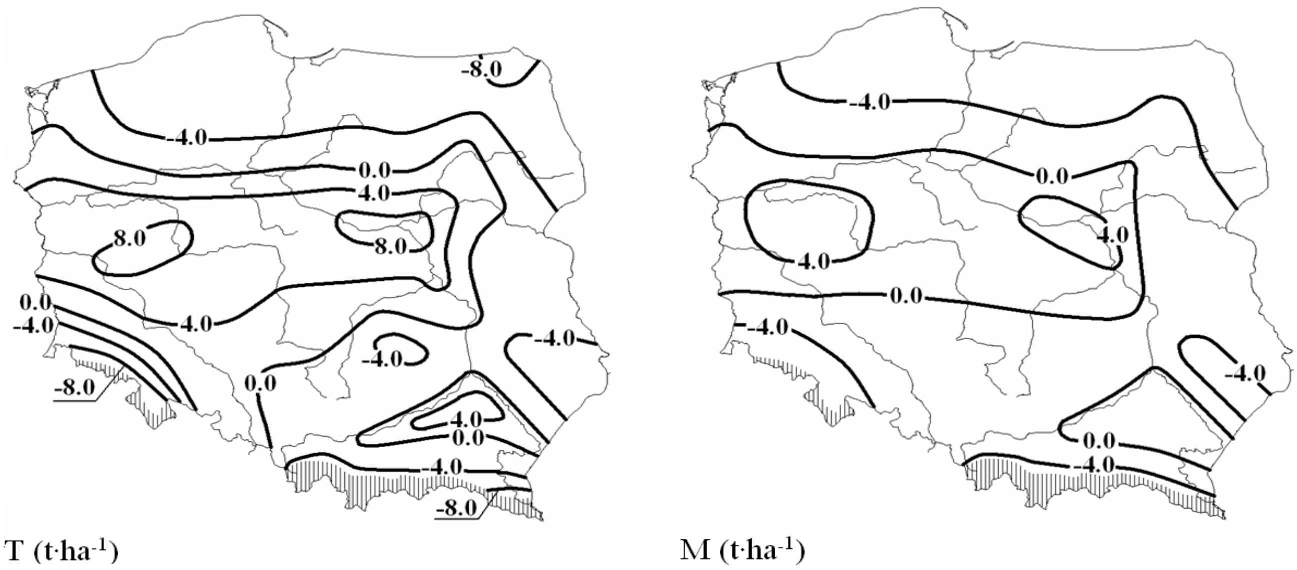

Fig. 2. Deviations of the total (T) and marketable (M) cucumber yield from the multi-annual average in the years 1966-2005 (Tab. 3) calculated on the basis of all the considered stations of the Research Centre for Cultivar Testing

Tab. 4. Statistical characteristics of dependent (T, M) and independent variables (*Sd, Ts, Ta, Pr*), considered in the weather-yield regression equations (Tab. 2) formed on the basis of the data in the years 1966-2005

Variable	Value			Standard deviation	Linear trend		
	mean	absolute minimum	absolute maximum		direction	significance	R^2 100%
T (t ha^{-1})	33.2	4.4	80.5	14.47	+	***	10.3
M (t ha^{-1})	18.3	2.3	65.3	11.13	+	***	22.8
$Sd_{Bh\text{-}Eh}$ (h day^{-1})	6.9	4.1	11.3	1.34	+	***	11.9
$Ts_{S\text{-}Eh}$ (°C)	18.6	15.3	22.5	1.28	+	***	12.9
$Ta_{S\text{-}Eh}$ (°C)	16.6	13.9	19.6	1.00	+	***	15.7
$Pr_{Bh\text{-}Eh}$ (mm)	100.0	6.6	247.3	51.8		n.s.	

Explanations, see Tab. 1 and Tab. 2

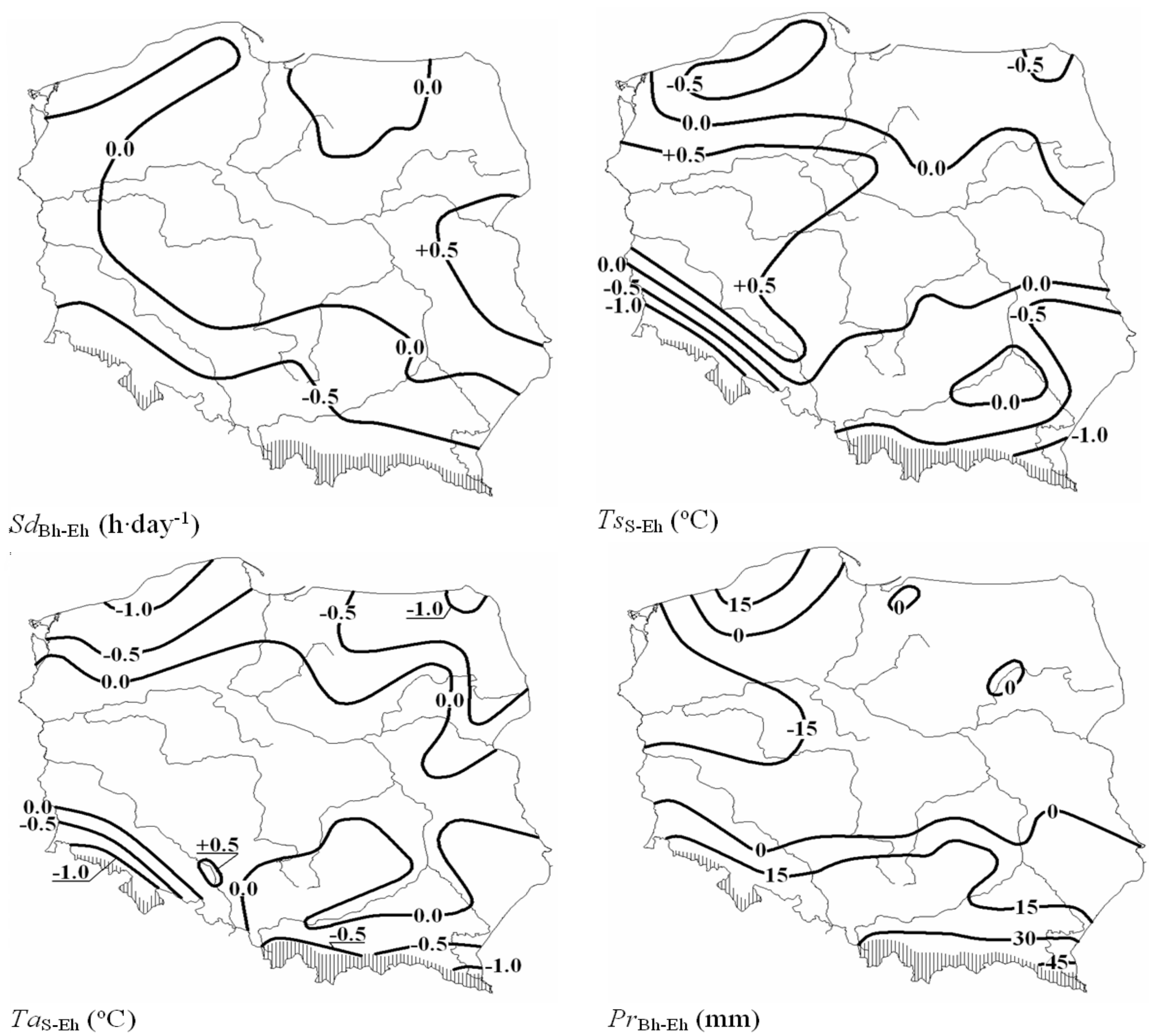

Fig. 3. Deviations of the values of agrometeorological elements (*Sd, Ts, Ta, Pr*) in the cucumber development stages from the multi-annual average in the years 1966-2005 (Tab. 3) calculated on the basis of all the considered stations of the Institute of Meteorology and Water Management; explanations, see Tab. 1

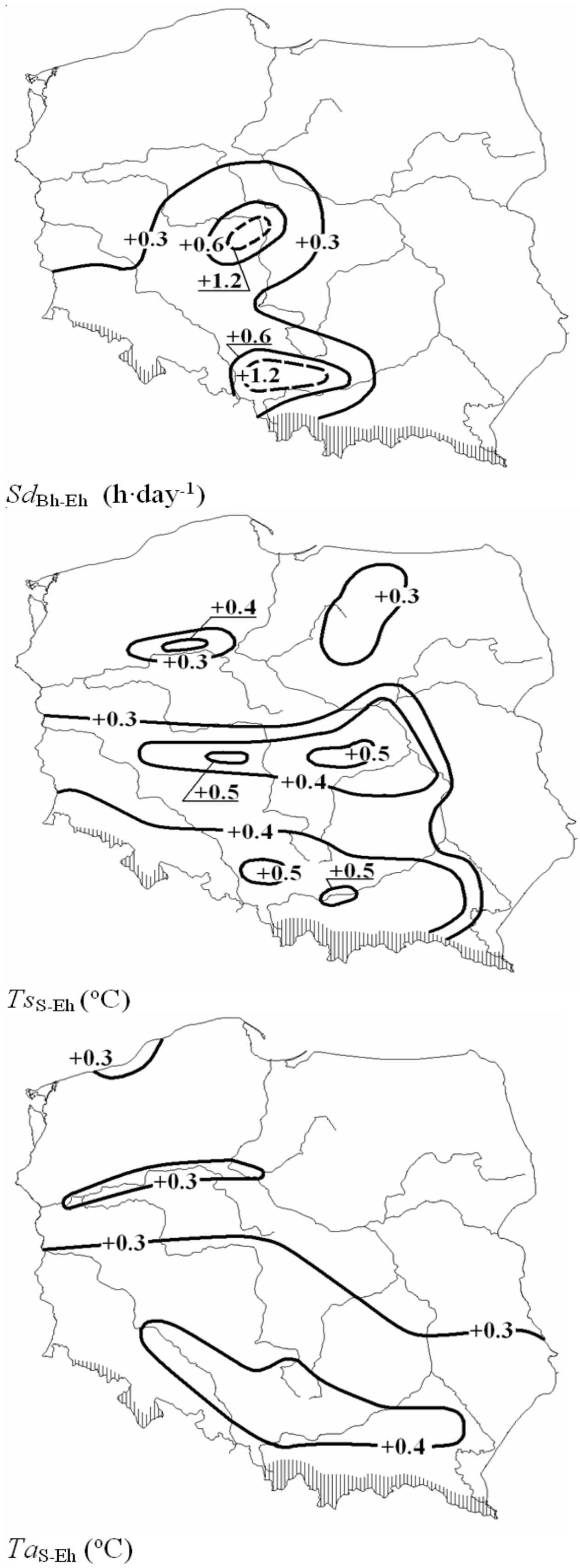

Fig. 4. Significant, at least at the level of P≤0.1, 10-year increase in sunshine duration (*Sd*), soil temperature (*Ts*) and air temperature (*Ta*) in the years 1966-2005; explanations, see Tab. 1

in the Bh-Eh period on the average amounted to 100 mm; the lowest absolute -6.6 mm, the highest absolute -247.3, and a standard deviation -51.8 mm.

Soil temperature in the S-Eh period was characterised by the highest spatial variability and sunshine duration in the Bh-Eh period by the lowest (Fig. 3). The highest (by at least 0.5°C higher than the norm) soil temperature was recorded in the central west. The lowest (by at least -1.0°C lower than the norm) -in the southwestern part and near the southeastern borders of Poland. The course of air temperature in the S-Eh period was similar in respect of the system of isolines and the degree of deviation from the norm to the distribution of the index *Ts*. The highest (positive) deviation of the index *Ta*, amounting to above +0.5°C, occurred only locally near Opole, and the lowest (negative), amounting to at least -1.0°C, not only in the southwest and southeast of the country, like in the case of soil temperature, but also in the north and the northeast. On the other hand, atmospheric precipitation in the Bh-Eh period oscillated from at least 15 mm to over 45 mm in comparison with the multiannual average calculated on the basis of all the meteorological stations for the years 1966-2005. In all of central Poland, precipitation was lower than the norm. In the central west and the northwest, precipitation was even lower by at least 15 mm. Precipitation higher than the norm occurred in the south of the country, where deviation oscillated between 0 and over 45 mm and in the north, between 0 and over 15 mm. On the other hand, sunshine duration which was higher than average in the country occurred in central and eastern Poland. Sunshine duration that was lower than the norm occured in southern and western Poland, where deviation oscillated from 0 to over 0.5 h day^{-1}.

Out of the 4 characterised agrometeorological elements, as many as 3 showed a positive significant linear trend in the years 1966-2005 (Tab. 4, Fig. 4). Determination coefficient calculated for the trend amounted to: 11.9, 12.9 and 15.7% respectively, in the case of the index: *Sd, Ts* and *Ta*. However, an increase in the number of hours with sunlight in the Bh-Eh period and soil and air temperature in the S-Eh period was not identical in all regions of Poland. In the case of sunshine duration a significant increase was proved in the southwestern part of the country and even oscillated from +0.3 to over +1.2 h day^{-1}/10 years. On the other hand, soil temperature most intensively changed in southern and central Poland from +0.3 even to over +0.5°C/10 years. Air temperature in the cucumber growing season, like soil temperature, also increased from +0.3 to over +0.4°C/10 years. The highest air temperature increase was recorded in the Silesian Upland, the Kraków-Częstochowa Upland, in the Silesian Lowland and the Carpathian Foothills.

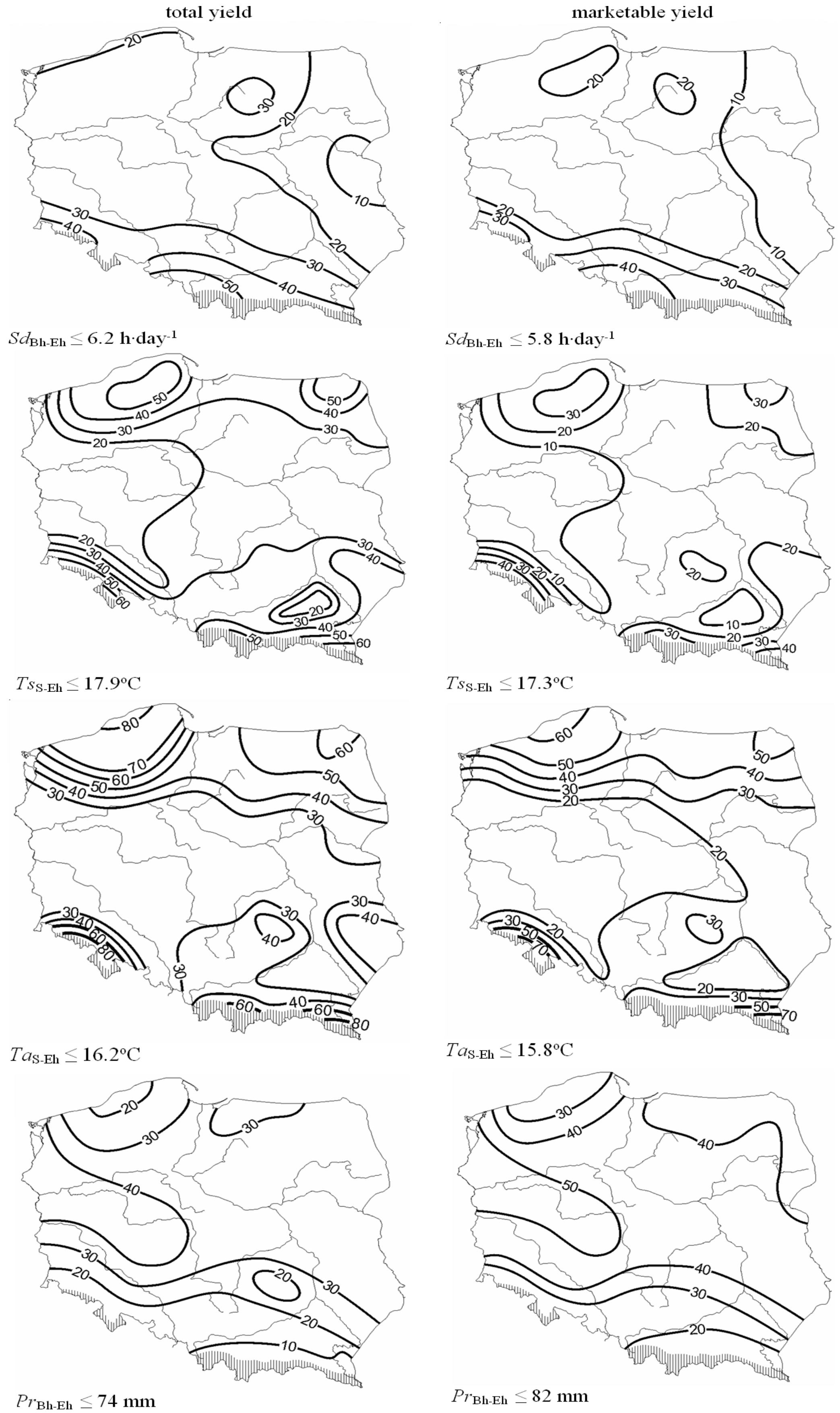

Fig. 5. Occurrence frequency (%) of agrometeorological elements (*Sd, Ts, Ta, Pr*) causing a reduction by at least 5% in the total and marketable yield of cucumber in Poland, 1966-2005

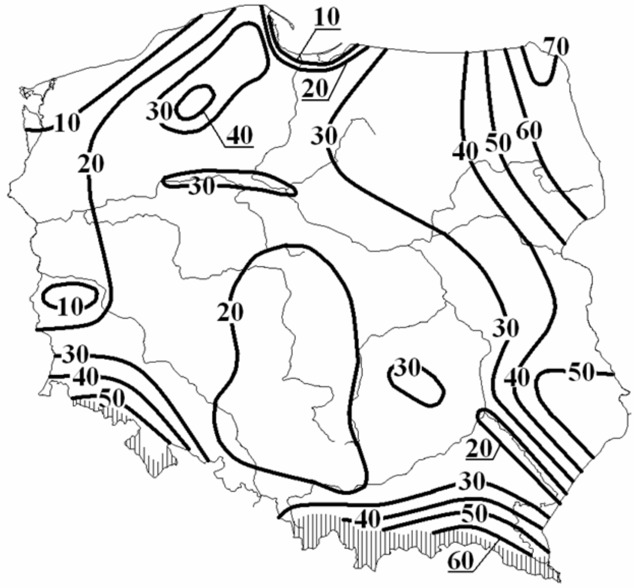

Fig. 6. Occurrence frequency (%) of duration of the period without frost, lasting ≤120 days, 1966-2005

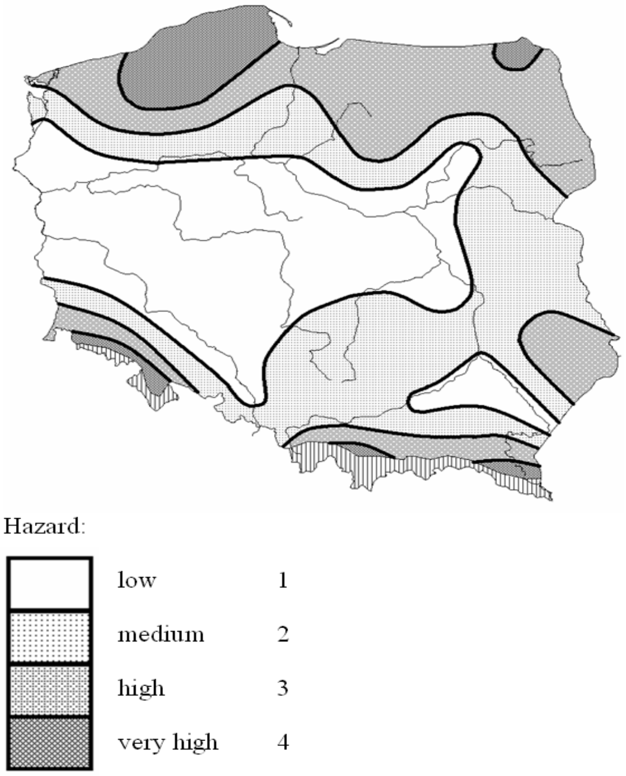

Fig. 7. Climatic risk zones of pickling cucumber field cultivation in Poland

Occurrence frequency of unfavourable agrometeorological conditions and duration of the period without frost

Unfavourable solar conditions described by the index *Sd* in the period from the beginning of harvesting to the end of harvesting, causing reduction by at least 5% in the total and marketable yield of cucumber, occurred with frequency from below 10 to above 50% (Fig. 5). Most frequently, sunshine duration shortage calculated ≤6.2 and ≤5.8 h day^{-1}, occurred in southern Poland, least frequently in the east. Soil temperature in the S-Eh period which most often caused disruption in the correct growth and development of cucumber from 40 to over 60%, was recorded in the submountainous regions, located in the southwest and southeast and least frequently, from below 10 to 20% in the central west and in the Sandomierz Basin (near Tarnów). Spatial distribution of air temperature which had a too low occurrence frequency amounting to ≤16.2 and ≤15.8°C in the S-Eh period of cucumber was similar in respect to the system of isolines to soil temperature. Air temperature causing reduction by at least 5% in the total yield occurred in Poland with a frequency from below 30 to above 80%, and in the case of the marketable yield from below 20 to above 70%; most frequently in the submountainous regions and the north of the country. Atmospheric precipitation shortage in the period of cucumber fruiting, determined as ≤74 and ≤82 mm, was most often recorded in the central west part of the country respectively from 40 to over 50%, It was least often recorded in the southeast from below 10 to 20%.

The study determined the occurrence frequency of agrometeorological elements which caused reduction in yield by at least 5% below the average multiannual level. In addition, the study also determined the occurrence frequency of the duration of the period without frost lasting ≤120 days, i.e., on the average, minimal duration of the cucumber growing season necessary to harvest a good yield of the plant in the climatic conditions of Poland (Fig. 6). Duration of a frost free period lasting ≤120 days, most often occurred in the east of the country and especially in the northeast (over 70%), and, next, in the submountainous regions (over 50 or even 60%); least frequently in the northwest, on the Bay of Gdańsk and in the vicinity of Zielona Góra, located in central west Poland (below 10%).

Climatic risk zones of cucumber field cultivation

In Poland, 4 zones of climatic risk of pickling cucumber field cultivation were separated on the basis of the occurrence frequency of unfavourable agrometeorological conditions. Unfavorable conditions are described by the indexes: *Sd, Ts, Ta* and *Pr*, and the frequency occurrence of the duration of the frost free period lasting ≤120 days (Fig. 7, Tab. 5). Zone 1 was considered low risk for cucumber cultivation. Zone 1 included about 35% of the country. Zone 2 was of average risk, about 32%. Zone 3 was of high risk of 23%, and Zone 4 of very high risk, about 7%. Zone 4 included the submountainous regions situated in the southwest and the southeast and the Pomeranian Lakeland, situated in the north, and in the vicinity of Suwałki. In this zone, crop productivity of cucumber was very poor, on the average of 24.6±1.6 t ha^{-1} in the case of the total yield, and 12.8±0.9 t ha^{-1} in the case of the

Tab. 5. Characteritics of climatic risk zones of pickling cucumber field cultivation in Poland

Nr. of zone	Hazard	Country area (%)	Mean yield ($t\ ha^{-1}$)		Occurrence frequency ($P_{(n/N)}$, %) of unfavourable agrometeorological conditions and the statistical characteristics $\bar{x}$ (±S)									
			total	marketable	$Sd_{Bh\text{-}Eh}$ ($h\ day^{-1}$)		$Ts_{S\text{-}Eh}$ (°C)		$Ta_{S\text{-}Eh}$ (°C)		$Pr_{Bh\text{-}Eh}$ (mm)		Tf≤120 day	
					$P_{(n/N)}$	$\bar{x}$±S	$P_{(n/N)}$	$\bar{x}$±S	$P_{(n/N)}$	$\bar{x}$±S	$P_{(n/N)}$	$\bar{x}$±S	$P_{(n/N)}$	$\bar{x}$±S
1	low	34.8	35.3±5.6	20.5±4.1	20.3	7.1±0.3	13.9	19.0±0.4	19.8	16.9±0.1	24.3	95.5±12.8	17.5	135.8±5.4
2	medium	32.4	31.5±3.0	17.5±1.3	21.5	6.9±0.4	25.5	18.4±0.5	28.3	16.6±0.3	22.0	101.5±12.3	20.5	131.1±8.1
3	high	22.9	27.2±2.0	14.1±1.0	22.0	6.8±0.3	27.4	18.2±0.5	43.5	16.2±0.4	20.9	106.2±11.8	33.9	127.5±9.2
4	v. high	7.2	24.6±1.6	12.8±0.9	25.2	6.7±0.3	49.7	17.6±0.6	72.0	15.2±0.5	16.7	114.9±14.7	43.6	125.8±9.8

Tf≤20 day -duration of the period without frost, lasting ≤120 days; other explanations, see Tab. 1

marketable yield. The reason for poor crop productivity was mainly caused by frequent occurrence of unfavourable agrometeorological conditions and short periods without frost. In Zone 4, sunshine duration shortage (25.2%) and the duration of the period without frost lasting ≤120 days (43.6%) were recorded very often, as well as a very low soil temperature (49.7%) and air temperature (72%). On the other hand, Zone 1, i.e. the zone with low climatic risk of cucumber field cultivation, occurred in almost the whole central part of Poland and stretched from Warsaw to Szczecin, Legnica and Opole, and also in southeastern Poland, covering e.g. the Sandomierz Basin. The total and marketable yield of cucumber in Zone 1 was, on the average, respectively by about 11 and 8 $t\ ha^{-1}$ higher than in the part of Poland which was classified as Zone 4. In Zone 1, the risk of the occurrence of unfavourable agrometeorological conditions was the lowest: sunshine duration deficiency occurred 5% less often than in the zone of very high risk, soil temperature that was too low occurred about 36% less often, and air temperature that was too low occurred as much as about 52% less often. Apart from that, the zone of low risk was marked by low frequency; about 18% of the occurrence of the period without frost lasting ≤120 days and the highest occurrence frequency of atmospheric precipitation shortage among all the determined zones of the climatic risk of cucumber field cultivation about 8% more often than in Zone 4.

Zones 2 and 3, i.e., respectively the zones of average and high climatic risk of cucumber cultivation differed most of all in; the occurrence frequency of too low air temperature and the excessively short period without frost, lasting ≤120 days. In Zone 2, sunshine duration was on the average higher by 0.1 $h\ day^{-1}$ than in Zone 3 and the indexes were respectively: *Ts* by 0.2°C, *Ta* by 0.4°C and *Pr* by 4.7 mm. The period without frost was longer by about 4 days.

Discussion

In Poland, relatively few scientists have dealt with natural and economic, and especially climatic regionalisation of crop plant production (Drzas, 1975; Gertych, 1975; Wilczek, 1985; Koźmiński and Michalska, 2001; Michalska and Kalbarczyk, 2002; Demidowicz, 2005; Kalbarczyk, 2005). Lack of studies on the subject, particularly in the last 20 years may result from the fact that the climatic diversity of Poland is often overlooked in advisory activities. Despite introducing a market economy, transformation processes, agrotechnical recommendations and the agricultural advisory systems connected with it still do not sufficiently take into account the specificity of particular regions of the country. On the other hand, the already existing studies concerning the influence of agrometeorological conditions in the course of vegetable cultivation in Poland, including cucumber, are not sufficient. It mainly stems from the fact that the results of the majority of the studies have a regional character or only a local one. The studies are often based not only on distant but also on short periods of research. These periods do not take into account, among other things, climate changes occurring at the turn of the 20th and the 21st centuries (Drzas, 1975; Gertych, 1975; Wilczek, 1985; Demidowicz, 2005). Moreover, the existing research studies differ both in the degree of versatility (from the most important crop plants treated jointly to a selected cultivar), the range of a study (whole country-local research) and the choice of considered agrometeorological elements (Drzas, 1975; Gertych, 1975; Wilczek, 1985; Koźmiński and Michalska, 2001; Kalbarczyk, 2005).

The most comprehensive work published in Poland, which apart from the characteristics of particular agrometeorological elements, presents climatic risk of plant cultivation. It is "Atlas of climatic risk to crop cultivation in Poland" edited by Koźmiński and Michalska (2001). Separate issues also addressed in research studies are: the determination of temporal and spatial diversity of harmful elements and atmospheric phenomena in agriculture, and the assessment of agroclimatic conditions for the needs of agriculture (Witek and Górski, 1977; Koźmiński *et al.*, 1990; Bac, 1991; Kalbarczyk, 2003; Koźmiński and Michalska, 2004; Ziernicka-Wojtaszek and Zawora, 2008; Ziernicka-Wojtaszek, 2009; Kalbarczyk, 2009a; 2009b). Unfortunately, these works did not take into account agrometeorological requirements of vegetables and did not determine the climatic risk of field cultivation. Only the work edited by Koźmiński and Michalska includes information on the threat to field-cultivated vegetables posed by spring ground frost and frost damage. Regrettably, the temporal and spatial distributions were developed on the basis of the years 1971-1995 and 1975-1983.

Furthermore, in foreign research studies, climatic risk is most often analysed in the context of climate change and determined for different groups of plants (Affholder, 1996; Peltola *et al*., 1999; Pathak and Wassmann, 2009; Peltonen-Sainio *et al.*, 2009; Quiroga and Iglesias, 2009). In addition, the research covers regions of climatic conditions different than those occurring in Poland and is based on different durations of basic periods and different sets of meteorological elements. Variability and temporal structure of meteorological elements are also discussed during the assessment of the effect of weather conditions on the development and spread of plant pests and pathogens (Baker *et al.,* 2005; Garcia *et al.*, 2008; Hamada *et al.*, 2008; Rokicki, 2009). Very often, those studies also present the assessment of the phyto-sanitary condition for the most important agrophages of crop plants in a given country. The studies also separate the zones according to the risk of their occurrence, most often on the basis of moisture and thermal conditions of soil and air.

It is difficult to compare the climatic risk zones of pickling cucumber field cultivation in Poland, determined on the basis of the occurrence of unfavourable agrometeorological conditions in the years 1966-2005, with the results of previous works (Drzas, 1975; Gertych, 1975). This is because Drzas (1975) and Gertych (1975) conducted a regionalisation of cucumber cultivation not only on the basis of the course of meteorological conditions, but also on the basis of economic indexes. This was only done for some locations in Poland. According to Drzas (1975) the most favourable natural and economic conditions for cultivation of cucumber seeds occur in the region of Kraków and Kielce, and the worst ones in the region of Bydgoszcz. According to the determined zones on the basis of the multiannual period 1966-2005, the regions were classified as a part of Zone 2, i.e. the zone of average climatic risk. The system of the determined zones of the climatic risk of cucumber cultivation is similar to the system of separated regions of agricultural production space quality classes in Poland conducted by Witek and Górski (1977). According to these scientists (Witek and Górski, 1977), in Poland the most favourable natural conditions for vegetal production occur in the Silesian Lowland and the Opole Plain and in the vicinity of Kraków (the central southern part of the country), and the worst ones in the submountainous regions situated in the southwestern and southeastern parts of the country and in the northeast and the north. These areas partly overlap, respectively, with the separated zones of the lowest (Zone 1) and of very high (Zone 4) climatic risk of cucumber cultivation in Poland developed on the basis of the years 1966-2005.

Conclusions

In Poland, 4 zones of climatic risk of pickling cucumber field cultivation were separated: Zone 1 -of low risk, Zone 2 -of average risk, Zone 3 -of high risk and Zone 4 -of very high risk. Zone 4, with the total and marketable yield lower respectively by 10.7 and 7.7 t ha^{-1} than the average yield harvested in Zone 1, covered 7.2% of Poland. Zone 4 included the submountainous regions situated in the southwestern and southeastern parts of the country and the Pomeranian Lakeland and the Suwałki Lakeland, located respectively in the northern and northeastern parts of Poland. In Zone 4, reduction in cucumber yield was caused mostly by the occurrence, during the whole growing season, of air temperature which was too low (on the average 72%) and soil temperature (on the average 49.7%). Zone 4 had too short a duration of a period without frost lasting ≤120 days (on the average 43.6%), and less frequently it had a sunshine duration shortage (on the average 25.2%) and atmospheric precipitation (on the average 16.7%) in the period from the beginning of harvesting to the end of harvesting.

Climatic risk of cucumber field cultivation may decrease in the very near future. This would be especially true in southwestern and southern Poland. In this area, a significant increase in sunshine duration was proved in the period from the beginning of harvesting to the end of harvesting (from +0.3 even to over +1.2 h day^{-1}/10 years) and in soil temperature (from +0.3 to over +0.5°C/10 years) and air temperature (from +0.3 to over +0.4°C/10 years) in the period from sowing to the end of harvesting.

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