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Temporal and spatial diversity of the occurrence of atmospheric drought in Poland (1966-2005) and its effect of yield of pickling cucumber (*Cucumis sativus* L.)

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Abstract

Counteracting the negative effects of drought in vegetal production should include drought monitoring, determination of drought tolerance and, thus, the assessment of risk, limitations and losses of yield for various species of cultivated plants. The aim of the work was to assess temporal and spatial variability of the occurrence of atmospheric drought in Poland and to determine the risk of cultivation of pickling cucumber caused by this phenomenon. To carry out the task, starting data concerning the marketable and total yield of cucumber, durations of cucumber development stages and also daily atmospheric precipitation totals, collected respectively from 28 experimental stations and 51 meteorological stations through 1966-2005, were used. Atmospheric drought of different intensity: moderate, severe and extreme, in four analysed cucumber development stages was determined on the basis of the standard precipitation index. On the other hand, relationship between cucumber yield and precipitation deficiency in the period of the highest demand for water was determined by means of curvilinear regression analysis. In Poland, drought occurred mostly in the central-western part of the country. In this area, an average decrease in the cucumber total yield amounted to over 12% every 2-3 years, and the marketable yield over 15% every 2 years. The results obtained in the present work can be used in the research concerning the assessment of drought influence on growth, development and crop productivity of other cultivated plants.

Additional key words: cultivation risk; regression analysis; standard precipitation index; vegetable.

Resumen

Diversidad temporal y espacial de la incidencia de la sequía atmosférica en Polonia (1966-2005) y su efecto sobre la producción de pepino encurtido (*Cucumis sativus* L.)

Para contrarrestar los efectos negativos de la sequía en la producción de las plantas se debe incluir una vigilancia de la sequía, determinando la tolerancia a la sequía y evaluando riesgos, limitaciones y pérdidas de producción de las plantas cultivadas. El objetivo de este trabajo fue evaluar la variabilidad espacial y temporal de la ocurrencia de la sequía atmosférica en Polonia y determinar el riesgo existente en el cultivo de pepino encurtido causado por este fenómeno. Se utilizaron datos de producción comercial y total de pepino, y de precipitación atmosférica diaria, recogidos de 28 estaciones experimentales y 51 meteorológicas, respectivamente, entre 1966 y 2005. Se determinó, sobre la base del índice de precipitación estándar, una sequía atmosférica de diferentes intensidades: moderada, severa y extrema, en cuatro etapas de desarrollo del pepino analizadas. Por otro lado, se determinó la relación existente entre la producción de pepino y la deficiencia de las precipitaciones, en el período de más alta demanda de agua, mediante un análisis de regresión curvilínea. Se observó que la sequía se concentró en la parte centro-occidental del país; en este área, la disminución media en la producción total de pepino fue de más del 12% cada 2-3 años, y la producción comercial de más del 15% cada 2 años. Los resultados obtenidos en el presente trabajo se pueden utilizar para evaluar la influencia de la sequía sobre el crecimiento, desarrollo y productividad de los cultivos de otras plantas cultivadas.

Palabras clave adicionales: análisis de regresión; índice de precipitación estándar; riesgo de cultivo; vegetales.

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Abbreviations used: BF (beginning of flowering), BH (beginning of harvesting), COBORU (Research Centre for Cultivar Testing), EE (end of emergence), EH (end of harvesting), EU (European Union), IMGW (Institute of Meteorology and Water Management), Pr (atmospheric precipitation), RFE (relative forecast error), S (sowing), SPI (standard precipitation index), Std (standard deviation).

Introduction

In recent years, atmospheric drought (precipitation deficiency) in Poland has been more and more intense and has covered large areas of the country (Kalbarczyk and Kalbarczyk, 2006a,b; Łabędzki, 2007). In Poland, as a result of an air temperature increase, especially in the periods of April-May and July-August and the number of hours with sunshine in May and in the July-August period, with no increase in the total precipitation, drought in the vegetation season (April-September) will most probably intensify even more year by year (Kożuchowski and Degirmendžic, 2005; Kalbarczyk, 2009). Similar changes in the occurrence of atmospheric drought were recorded not only in countries neighbouring Poland (Brázdil *et al.,* 2009; Dubrovsky *et al.,* 2009), but also in other parts of Europe (Sirdaş, 2003; Tonkaz, 2006; Livada and Assimakopoulos, 2007; Croitoru *et al.,* 2008) and even the world (Chen *et al.,* 2009; Logan *et al.,* 2009).

The negative influence of drought is particularly conspicuous in agriculture. The adverse effect of drought in agriculture and other branches of the economy depends not only on the time and intensity of its duration but also on the spatial range of its occurrence (Tonkaz, 2006; Logan *et al.,* 2009). Results of flood are immediate, whereas results of drought are not. Drought grows slowly and its consequences become visible over a longer period of time; it is less noticeable and spreads over larger areas than the majority of extreme weather phenomena (Bonaccorso *et al.,* 2003; Brázdil *et al.,* 2009). Therefore, counteracting negative effects of drought should be based not only on its systematic monitoring but also on forecasting (Paulo and Pereira, 2007; Smakhtin and Hughes, 2007; Moreira *et al.,* 2008). Determination of drought tolerance in plant production, *i.e.* assessment of risk, and limitations and losses in yield for various species of crop plants should also be taken into account (Quiring and Papakryiakou, 2003; Brázdil *et al.,* 2009).

In the literature, there are no publications on the evaluation of intensity and frequency of atmospheric drought occurrence during the development stages of crop plants. Also, there are very few studies concerning the effect of drought on plant yield crops on a regional scale and, all the more, on a country scale and concerning assessment of the risk of their cultivation caused by frequent occurrence of drought (*e.g.* Quiring and Papakryiakou, 2003; Zhang, 2004; Brázdil *et al.,* 2009). The majority of publications on assessment of drought variability concern temporal and spatial distribution. These assessments are most often characterised according to months, on the basis of different multi-annual periods (Bąk and Łabędzki, 2002; Bonaccorso *et al.,* 2003; Hisdal and Tallaksen, 2003; Tonkaz, 2006; Croitoru *et al.,* 2008; Caparrini and Manzella, 2009). Classification of atmospheric drought periods is conducted on the basis of different indexes, *e.g.* the Palmer drought severity index (*PDSI*) and the standard precipitation index (*SPI*) (Livada and Assimakopoulos, 2007; Khan *et al.,* 2008; Brázdil *et al.,* 2009; Caparrini and Manzella, 2009). The latter index does not require complex calculations and can be used for different climatic zones and time periods, including development stages of plants (McKee *et al.,* 1993; Łabędzki, 2006). Some publications are also concerned with the assessment of the relationship between atmospheric drought and a synoptic situation, the NAO index and the groundwater level (Quiring and Papakryiakou, 2003; Trigo *et al.,* 2004; Khan *et al.,* 2008; Brázdil *et al.,* 2009) and monitoring and forecasting of this phenomenon – most frequently for a single station or a region of a country (Paulo and Pereira, 2007; Smakhtin and Hughes, 2007; Moreira *et al.,* 2008).

A new approach in methodology of drought intensity assessment is standardisation of indexes. Such a methodlogy enables objective, comparable evaluations to be made about different time periods (McKee *et al.,* 1993; Łabędzki and Bąk, 2004). There are not any detailed research studies and analyses for the whole country concerning the occurrence and intensity of drought in development stages of crop plants, including cucumber and its effect on yield of this plant.

Growing of field vegetables plays an important role in vegetal production in Poland. In 2006 cucumber (*Cucumis sativus* L.) constituted a big share, over 9%, in the crop structure of vegetables in Poland and onion (*Allium cepa* L.) and cabbage (*Brassica oleracea* L.) the biggest share, over 15% each (Kulikowski, 2007). Regarding the occupied land of the crop, Poland is the biggest producer of cucumber among all the countries of the European Union (EU). Poland's cultivated area of this vegetable in 2006 amounted to nearly $21 \cdot 10^3$ ha, and the average area of the decade 1997-2006 to nearly 24 10^3 ha, whereas in Romania (the second country in terms of the area size of cucumber growing in the EU) the area was about 7 10^3 ha. Growing of field cucumber in Poland is concentrated in certain regions, especially in the vicinity of big cities and the centres of vegetable processing (Kulikowski, 2007).

Therefore, the goal of the paper was to determine temporal and spatial variability of atmospheric drought occurrence in Poland in the years 1966-2005 and to assess the cultivation risk of pickling cucumber caused by this phenomenon.

Material and methods

Material

The work used agrotechnical dates (sowing-S, beginning of harvesting- BH, end of harvesting-EH), dates of phenological observations (end of emergence-EE, beginning of flowering-BF) and data concerning the marketable and total yield of cucumber cultivated in field conditions in the years 1966-2005, collected from 28 experimental stations of the Research Centre for Cultivar Testing (COBORU) (Fig. 1, Table 1). The marketable yield of cucumber comprised pickling fruits which were 6-10 cm long and had the diameter of 2.5-4.0 cm; however, the diameter could not be smaller than half of fruit length. Starting data were collected from a model which was an average of all the commonest pickling varieties cultivated in a given year. Use of a collective standard in the research was based on an assumption that intraspecific differences do not obfuscate general regularities searched for the species. Field experiments through 1966-2005 were conducted in accordance with the methodology worked out by COBORU, used in the 1960s and repeatedly updated in the later years. The cultivation normally used complete organic manuring, at a dose from 30 to 40 t ha^{-1}, which was ploughed in autumn. Depending on the level of soil richness, mineral fertilisation, on average, amounted to 400 kg of a pure component per hectare of crop, including 115 kg of N, 90 kg of P_2O_5 and 195 kg of K_2O.

The work also used daily meteorological data collected in the 1966-2005 multi-annual period from 51 meteorological stations (climate and synoptic) of the Institute of Meteorology and Water Management (IMGW) (Fig. 1, Table 1). On the basis of the data atmospheric precipitation totals were calculated at the time reflecting average dates of the occurrence of pickling cucumber development stages in Poland: S-EE, 16.05-03.06; EE-BF, 04.06-07.07; BF-BH, 08.07-22.07; and BH-EH, 23.07-03.09.

Methods

Atmospheric drought (atmospheric precipitation deficiency) in Poland was identified on the basis of

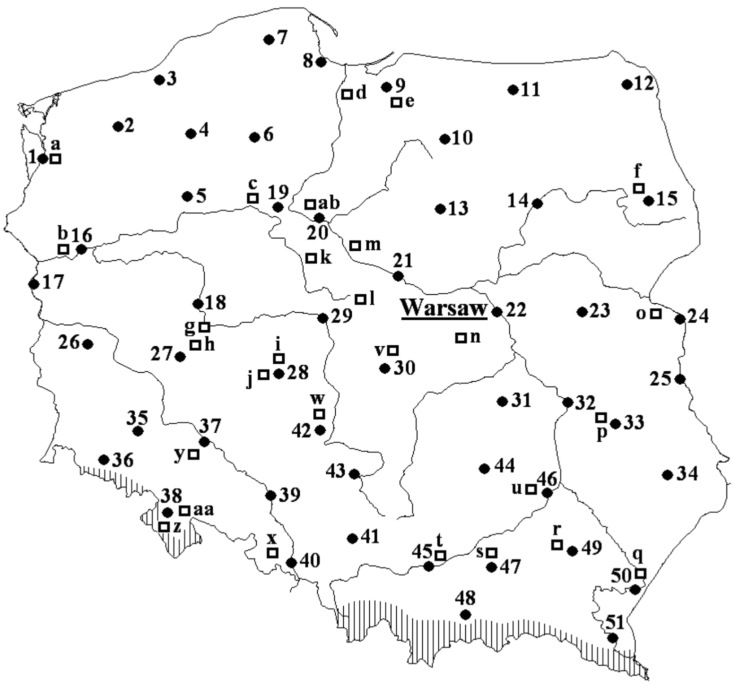

Figure 1. Distribution of meteorological stations of IMGW (●) and experimental stations of COBORU (□). Striped area: excluded from the research.

Table 1. Characteristics of IMGW and COBORU stations

Station name	Station code	Elevation (masl)	Geographic coordinates	
			Latitude (N)	Longitude (E)
Station of IMGW				
Szczecin	1	1	53°24’	14°37’
Resko	2	55	53°46’	15°25’
Koszalin	3	33	54°12’	16°10’
Szczecinek	4	137	53°43’	16°41’
Piła	5	66	53°10’	16°45’
Chojnice	6	172	53°42’	17°33’
Lębork	7	18	54°33’	17°45’
Gdańsk	8	13	54°23’	18°36’
Elbląg	9	38	54°10’	19°26’
Olsztyn	10	133	53°46’	20°25’
Kętrzyn	11	110	54°06’	21°21’
Suwałki	12	165	54°06’	22°57’
Mława	13	141	53°07’	20°22’
Ostrołęka	14	95	53°05’	21°34’
Białystok	15	139	53°07’	23°11’
Gorzów Wlkp.	16	65	52°44’	15°15’
Słubice	17	21	52°21’	14°36’
Poznań	18	86	52°25’	16°50’
Bydgoszcz	19	70	53°07’	17°58’
Toruń	20	69	53°03’	18°35’
Płock	21	63	52°32’	19°40’
Warszawa	22	106	52°09’	20°59’
Siedlce	23	146	52°11’	22°16’
Terespol	24	133	52°04’	23°37’
Włodawa	25	175	51°33’	23°33’
Zielona Góra	26	180	51°56’	15°30’
Leszno	27	91	51°50’	16°32’
Kalisz	28	140	51°44’	18°05’
Koło	29	95	52°12’	18°38’
Łódź	30	187	51°44’	19°24’
Radom	31	178	51°25’	21°07’
Puławy	32	142	51°25’	21°58’
Lublin	33	171	51°14’	22°34’
Zamość	34	212	50°42’	23°15’
Legnica	35	121	51°13’	16°10’
Jelenia Góra	36	342	50°54’	15°48’
Wrocław	37	120	51°06’	16°53’
Kłodzko	38	316	50°26’	16°39’
Opole	39	176	50°40’	17°58’
Racibórz	40	189	50°05’	18°13’
Katowice	41	284	50°14’	19°02’
Wieluń	42	195	51°13’	18°35’
Częstochowa	43	261	50°49’	19°06’
Kielce	44	268	50°51’	20°37’
Kraków	45	206	50°04’	19°58’
Sandomierz	46	202	50°41’	21°45’
Tarnów	47	209	50°02’	20°59’
Nowy Sącz	48	292	49°37’	20°42’
Rzeszów	49	200	50°06’	22°03’
Przemyśl	50	237	49°48’	22°46’
Lesko	51	386	49°28’	22°20’
Station of COBORU				
Szczecin	a	1	53°24’	14°37’
Wysoka	b	72	52°47’	15°02’
Chrząstowo	c	105	53°11’	17°35’
Lisewo	d	7	54°06’	18°50’
Rychliki	e	70	53°09’	23°02’
Łyski	f	137	53°24’	14°37’
Drzęczewo	g	135	51°53’	17°03’
Śrem	h	75	52°05’	17°02’
Majków	i	141	51°52’	17°06’
Kościelna Wieś	j	123	51°47’	18°01’
Głębokie	k	85	52°39’	18°27’
Głogowa	l	93	52°15’	19°05’
Głodowo	m	59	52°50’	19°10’
Kawęczyn	n	90	51°54’	20°00’
Cicibór	o	144	52°04’	23°06’
Czesławice	p	205	51°19’	22°16’
Zadąbrowie	q	230	49°54’	22°49’
Przecław	r	185	50°11’	21°29’
Olesno Breń	s	198	50°11’	20°59’
Węgrzce	t	201	50°34’	16°47’
Wojciechowice	u	221	50°47’	21°53’
Lućmierz	v	175	51°54’	19°23’
Masłowice	w	175	51°15’	18°38’
Głubczyce	x	280	50°12’	17°49’
Zybiszów	y	130	51°04’	16°55’
Tarnawa Górna	z	345	50°34’	16°47’
Tarnów Śląski	aa	316	50°26’	16°39’
Falęcin	ab	74	53°09’	18°31’

the standard precipitation index (*SPI*). A sequence of precipitation *Pr* in the years 1966-2005, in all the considered cucumber development stages underwent normalisation with the use of the function *f*(Pr), and next, standardisation on the basis of the formula:

$$SPI = \frac{f(\mathrm{Pr}) - \mu}{\sigma}$$

where $f(\mathrm{Pr})=\mathrm{Pr}^{1/2}$ – transformed precipitation total; μ = average value of a normalised precipitation sequence; and σ = average standard deviation of a normalised precipitation sequence. The fit of a distribution of the transformed variable *f*(Pr) and a normal distribution was tested with a *chi*-square goodness-of-fit test.

Classification of periods regarding precipitation deficiency was carried out on the basis of a *SPI* value

Table 2. Classes of drought according to the standard precipitation index (*SPI*)

Period type	*SPI* criteria	
	1	**2**
Extremely dry (ED)	$SPI \leq -2.0$	$SPI \leq -2.0$
Severely dry (SD)	$-1.99 \leq SPI \leq -1.50$	$-1.99 \leq SPI \leq -1.50$
Moderately dry (MD)	$-1.49 \leq SPI \leq -1.00$	$-1.49 \leq SPI \leq -0.50$

1: according McKee *et al.* (1993). 2: according Łabędzki and Bąk (2004).

in accordance with the criteria developed by McKee *et al.* (1993), and later modified in relation to the original ones by Łabędzki and Bąk (2004). The modification consisted in changing the upper range limit of the lowest drought class, the moderate drought with the *SPI* ranging from –1.0 to –0.5 (Table 2). An advantage of the *SPI* is a possibility of calculating its value in different time periods, including plant development stages (Bąk and Łabędzki 2002, 2007).

On the basis of a *SPI* value, calculated for each of 51 meteorological stations of IMGW in the years 1966-2005, the occurrence frequency of drought of different intensity and its spatial diversity in the successive cucumber development stages in Poland were determined.

Owing to a small number of the IMGW stations and, at the same time, high variability of precipitation, mountainous regions situated in south-western and south-eastern Poland were excluded from the study (Fig. 1).

Effect of precipitation deficiency on the total and marketable yield of pickling cucumber in the period of the highest demand for water (BH-EH) was evaluated on the basis of the regression equation:

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

where y_p = total or marketable yield (t ha^{-1}); a = slope; b, c, d = regression coefficients; x_1 = linear trend, *i.e.* the successive years of the analysed multi-annual period 1966-2005; and x_2 = atmospheric precipitation total (mm).

In the regression equation, describing effect of precipitation deficiency on cucumber yield, information on soil conditions and fertilisation was not taken into account as it did not differentiate statistically significantly the quantity of yield considered in the research. Lack of differences was confirmed with the *t*-Student test (Dobosz, 2001).

Collinearity between independent variables in the multiple regression equation was tested with the use of the ridge regression method. Parameters of multiple regression function were determined with the least squares method. The hypothesis of regression function significance was assessed with the *F*-Snedecor test, and significance of the slope and regression coefficients with the *t*-Student test. The measure of fitting of the regression function to empirical data was determination coefficient R^2 (%) and a coefficient describing the difference between standard deviation of a dependent variable and a standard error of equation estimation *Std-Sy* (t ha^{-1}).

Verification of regression equations was conducted also on the basis of relative forecast error (*RFE*), determined on the basis of the formula:

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

and average relative forecast error (*ARFE*), for all the analysed experimental stations of COBORU and the considered years 1966-2005, 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}); and n = number of years in a time series (number of stations × number of years).

An additionally used test of evaluation accuracy was determining how many times *RFE* in the analysed multi-annual period 1966-2005 amounted to $|RFE| \leq 5\%$ (a very good forecast) and $5\% < |RFE| \leq 10\%$ (a good forecast) (Dobosz, 2001).

On the basis of curvilinear regression equations, threshold values for precipitation were determined when reduction by at least 5% in the total and marketable yield occurs. It was carried out to determine threats to cucumber cultivation in Poland by unfavourable precipitation conditions. Next, an average precipitation total was substituted into each of the formed equations describing the effect of precipitation in the period BH-EH on the total and marketable yield. However, the average precipitation total was only calculated for those years when earlier specified threshold values were exceeded. Substituting it into the equations, yield for each considered station of COBORU and IMGW, conditioned by average occurrence of unfavourable precipitation conditions, was calculated. Differences between the multi-annual actual yield of cucumber determined for whole Poland (the arithmetic mean from all stations of COBORU) and the yield calculated according to the above-described procedure enabled determination of potential yield reduction caused by precipitation deficiency, separately for the total yield and the marketable yield.

Frequency of the occurrence of precipitation deficiency (above the specified thresholds) in the period BH-EH of cucumber in the multi-annual period 1966-2005 was determined according to the formula:

$$P = \frac{n_1}{N} \cdot 100\% \ ,$$

where n_1 = number of periods with precipitation deficiency, and N = number of all examined periods.

Results

Drought characteristics according to the standard precipitation index

In Poland, in the years 1966-2005, an average number of cases of the occurrence of atmospheric drought of different intensity oscillated between 10 in the period S-EE to 14 in the period EE-BF (Fig. 2). Among all the analysed kinds of drought, drought of moderate intensity occurred most often (on average 9 cases, from 7 in the period S-EE to 12 in BF-BH), less frequently drought of extreme intensity (on average 2 cases, from 0 in the period BH-EH to 3 in EE-BF) and least frequently drought of severe intensity (on average 1 case, from 0 in the period BF-BH to 3 in BH-EH).

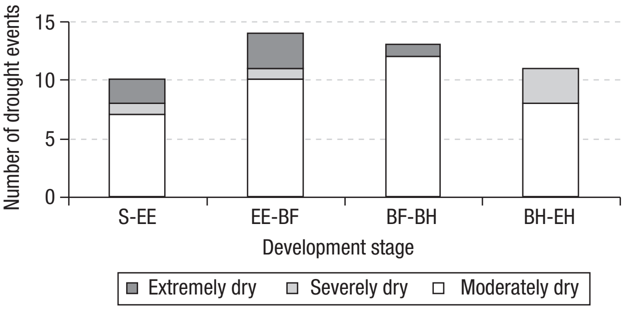

Figure 2. Average number of cases of the occurrence of atmospheric drought of different intensity (1966-2005) in the successive development stages of cucumber in Poland. S-EE: sowing-end of emergence. EE-BF: end emergence-beginning of flowering. BF-BH: beginning of flowering-beginning of harvesting. BH-EH: beginning of harvesting-end of harvesting.

In the four analysed successive development stages of cucumber (S-EE, EE-BF, BF-BH, BH-EH) an average number of drought cases of different intensity amounted to 48 and oscillated in Poland between below 46 cases in the south-east, the north-east (in the Kętrzyn region) and in the central part of the country (in the region between Toruń and Płock) and above 54 cases in the north-west, the south-west (in the Wrocław region) and in the south of Poland (Fig. 3a). The first period of cucumber vegetation (S-EE) was characterised by the highest variability of drought occurrence in Poland, the remaining periods (EE-BF, BF-BH, BH-EH) by slightly lower (Fig. 3bcde). In the period S-EE an average number of atmospheric drought cases amounted to 10 and generally oscillated between 8 and 14 cases; drought was recorded most frequently in the north-west, in the central part of the country (in the region between Koło and Płock) and in south-west, and least frequently in south-east. In the three successive cucumber development stages spatial distribution of the occurrence of drought phenomenon was characterised by a high irregularity. In the period EE-BF the most susceptible areas to the occurrence of atmospheric drought encompassed the central-western and south-eastern parts of the country, the coastline of the Baltic Sea and locally the region of Ostrołęka. In the next development stage, BF-BH, the area with a number of drought cases above 14 increased, in comparison to the previous stage, and included the northern and central parts of the country and the regions of: Katowice, Radom and Włodawa. On the other hand, in the last development stage of cucumber (BH-EH), the biggest number of drought cases occurred in central-east (from Łódź through Warszawa and Lublin to Zamość) and locally in the regions of Wrocław, Racibórz, Suwałki and Szczecinek.

In Poland, in the years 1966-2005, drought of extreme intensity occurred in the period S-EE, in 1992 ($SPI = -2.1$) and 1999 ($SPI = -2.1$); in the period EE-BF in 1976 ($SPI = -2.3$) and 1994 ($SPI = -2.4$); and in the period BF-BH in 1971 ($SPI = -2.7$) (Fig. 4). On the other hand, drought of severe intensity occurred in the period S-EE in 1979 ($SPI = -1.7$); in the period EE-BF in 1983 ($SPI = -1.8$); and in the period BH-EH in 1971 ($SPI = -1.9$), in 1982 ($SPI = -1.9$) and in 1984 ($SPI = -1.9$). Not a single case of atmospheric drought phenomenon

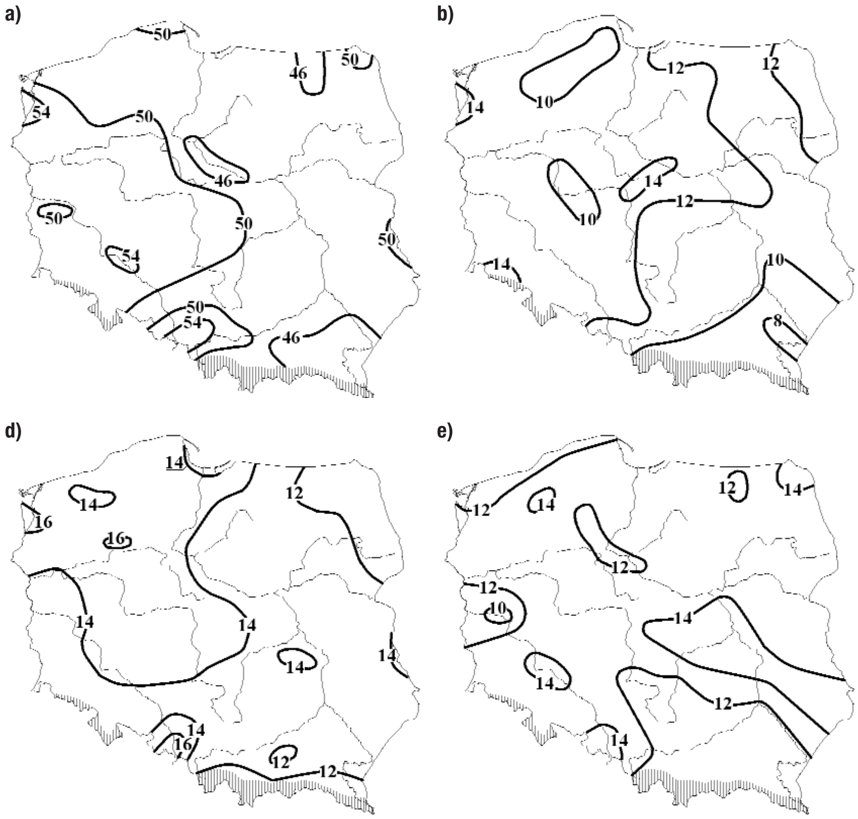

Figure 3. Spatial diversity of the number of the occurrence of atmospheric drought cases according to the successive development stages (a, S-EH; b, S-EE; c, EE-BF; d, BF-BH; e, BH-EH) of cucumber in Poland (average of years 1966-2005). For period explanations see Figure 2.

of extreme intensity was recorded in the period BH-EH, or drought of severe intensity in the period BF-BH.

In the years with an average value of *SPI*≤–2.0 drought of extreme intensity did not occurr in whole Poland. In 1971, in the period BF-BH, drought of extreme intensity encompassed approximately 40% of the country's area and covered a strip of land stretching from the south-east through the centre to the north-east; and in 1976, in the period EE-BF covered only about 17% of the country's area and occurred in the south of Poland (Fig. 5ab). On the other hand, in 1994, in the period EE-BF, drought of extreme intensity (S*PI* ≤ –2.0) was recorded in the south-west and in several regions of central and central-eastern Poland, and in 1999, in the period S-EE only locally in the central-east and south east of the country (Fig. 5cd). In 1994 atmospheric drought covered about 20% of the country's area, and in 1999 – approximately 8%.

Out of the 40 examined years, only in 1979 drought of various intensities occurred during the first half of the vegetation season (from S to the BF) and in three years: 1971, 1982, 1991 – during the second half of the vegetation season (from the BF to the EH) (Fig. 4). Drought of different intensity lasted through the whole cucumber vegetation season only in two years, 1992 and 2003. In 1992 the strongest intensity of drought occurred in the first development stage (S-EE, *SPI* = –2.1), next, in the second one (EE-BF, *SPI* = –1.4) and in the fourth one (BH-EH, *SPI* = –1.3); the weakest intensity in the third stage (BF-BH, *SPI* = –1.1). In 2003, that is, in the second case when drought occurred through the whole vegetation season, the *SPI* in the successive development stages was –0.9 in the period S-EE, –0.6 in the period EE-BF and –0.7 in the periods BF-BH and BH-EH.

In 1992, drought of extreme, severe and moderate intensity not only changed its range but also the place of its occurrence. In that year, the range of drought of extreme intensity decreased from the area of whole western Poland in the period S-EE (Fig. 6a) to a narrow coastal strip and the Valley of the Warta and the Noteć in the section between Gorzów Wielkopolski and Piła in the period from EE to BF (Fig. 6b). Next, it disappeared completely in the period BF-BH (Fig. 6c) and reemerged. Then, not only it did increase its range but also changed the place of its occurrence, to cover the area situated in the south-eastern part of Poland (regions of Katowice, Kielce, Włodawa and Przemyśl)

Year	Development stages				Year	Development stages			
	S-EE	EE-BF	BF-BH	BH-EH		S-EE	EE-BF	BF-BH	BH-EH
1966					1986		–0.8	–0.8	
1967					1987				
1968					1988				
1969		–0.6	–0.9		1989	–1.4			–1.2
1970		–0.8			1990	–0.9		–0.9	
1971			–2.7	–1.9	1991			–1.0	–0.8
1972			–1.0		1992	–2.1	–1.4	–1.1	–1.3
1973	–0.6			–0.7	1993				
1974					1994		–2.4	–1.3	
1975					1995				
1976		–2.3			1996		–0.9		
1977		–0.7			1997				–0.8
1978	–1.4		–0.5		1998			–0.6	
1979	–1.7	–0.9			1999	–2.1			–1.2
1980					2000		–0.6		
1981					2001				
1982	–1.4		–1.5	–1.9	2002				
1983		–1.8		–1.3	2003	–0.9	–0.6	–0.7	–0.7
1984				–1.9	2004	–1.3			
1985					2005		–1.4		

■ Extremely dry ■ Severely dry □ Moderately dry

Figure 4. Classification of the occurrence of atmospheric drought of different intensity in the successive development stages of cucumber, 1966-2005. The *SPI* values were given for the determined periods (for period explanation, see Figure 2).

in the period BH-EH (Fig. 6d). In 1992 drought of severe intensity, like drought of extreme intensity, changed its range and location in Poland. In the period S-EE drought of severe intensity was stretched along the strip going through the centre of Poland, from Katowice to the region of Gdańsk and covered an area situated in the north-east (Fig. 6a). In the period EE-BF this kind of drought covered the area of northern and central-western Poland and locally the regions of Katowice and Wieluń (Fig. 6b). On the other hand, in the period BF-BH it occurred in a very small area located in the north-western part of the country (the region of Szczecinek) (Fig. 6c), and at the end of the cucumber vegetation (BH-EH) it occurred in south-eastern Poland (Fig. 6d).

In the period from S to the BF (S-EE, EE-BF) drought did not occur in the south-east and locally in the south (Fig. 6ab). In the period BF-BH it did not occur in strips stretching from Racibórz through Kielce and Siedlce to Białystok and Terespol and also from Kalisz through Płock and Mława to Gdańsk and Elbląg, and also locally in the south-east in the Przemyśl region and in the central west in the Gorzów Wielkopolski region (Fig. 6c); and in the period BH-EH – in the north of the country (Fig. 6d).

In the examined multi-annual period, drought occurred in over 50% of the stations in eight periods S-EE (1978, 1979, 1982, 1989, 1990, 1992, 1999 and 2004), in eight periods EE-BF (1976, 1977, 1979, 1983, 1992, 1994, 1996 and 2005), in nine periods BF-BH

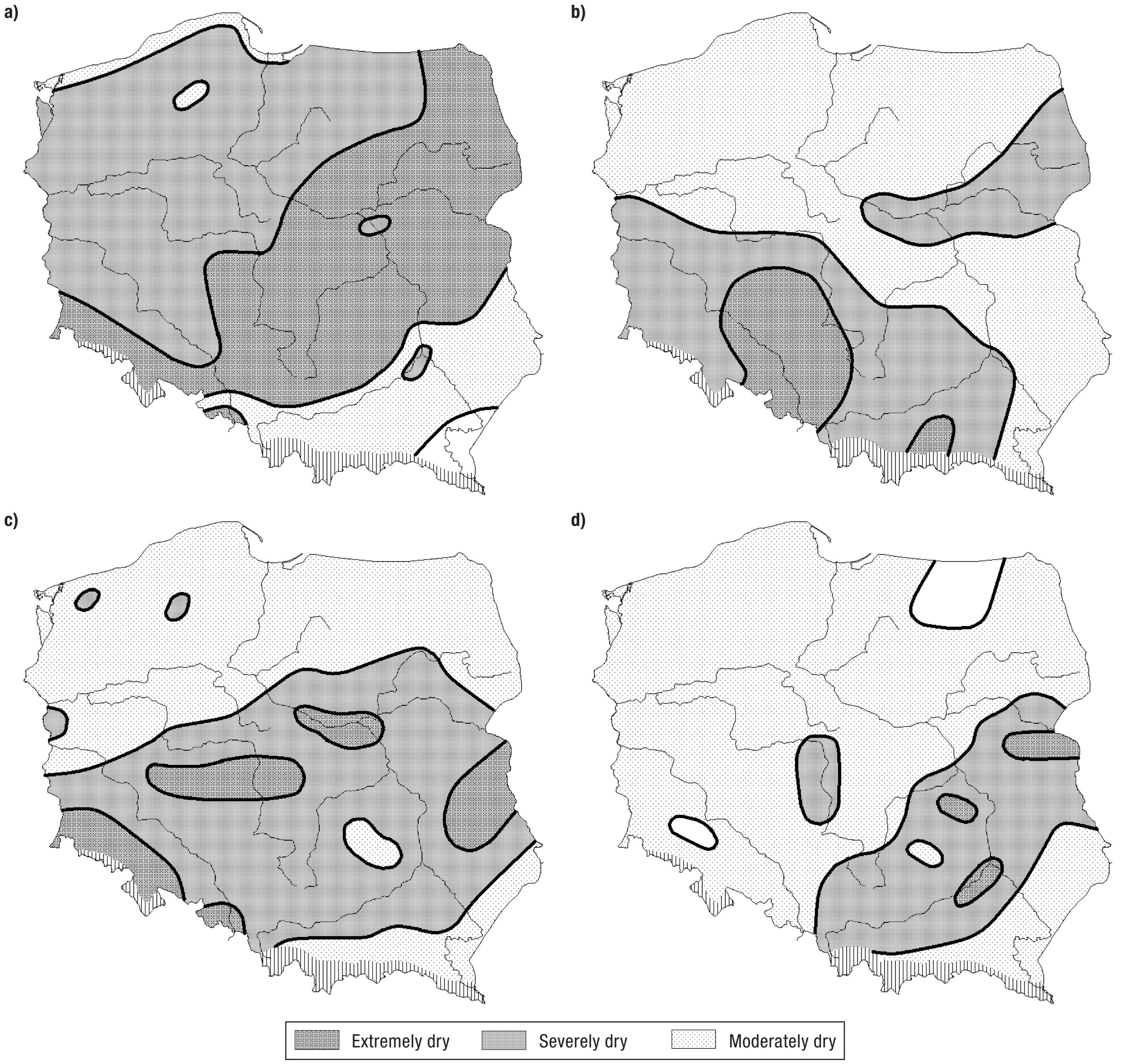

Figure 5. Spatial diversity of the occurrence of atmospheric drought in Poland in chosen years and development stages of cucumber: a, BF-BH in 1971; b, EE-BF in 1976; c, EE-BF in 1994; d, S-EE in 1999. For period explanations see Figure 2.

(1969, 1971, 1972, 1982, 1991, 1992, 1994, 1998 and 2003) and also in nine periods BH-EH (1971, 1982, 1983, 1984, 1989, 1991, 1992, 1999 and 2003) (Fig. 7). In the period S-EE, the number of IMGW stations where drought of different intensity was recorded oscillated between 0 in 1986 and 1993 and 42 in 1999. Within this period, the biggest number of stations, for which drought of extreme and severe intensity was determined, was recorded respectively in 1992 (17 stations) and 1978 (11 stations), and next in 1992 (10 stations). In the next development stage of cucumber, in the period EE-BF, drought was determined for almost all the analysed stations in 1976 (49 stations) and 1994 (50 stations), and drought of extreme and severe intensity for about 20-30% of the stations respectively in 1994 (12 stations) and 1983 (16 stations). In the two last development stages of cucumber (BF-BH and BH-EH), the biggest number of stations where atmospheric drought of different intensity was determined was recorded in 1971, and next in 1982, with both extreme and severe drought in 1971 in the case of the period BF-BH, and in 1984 in the case of the period BH-EH.

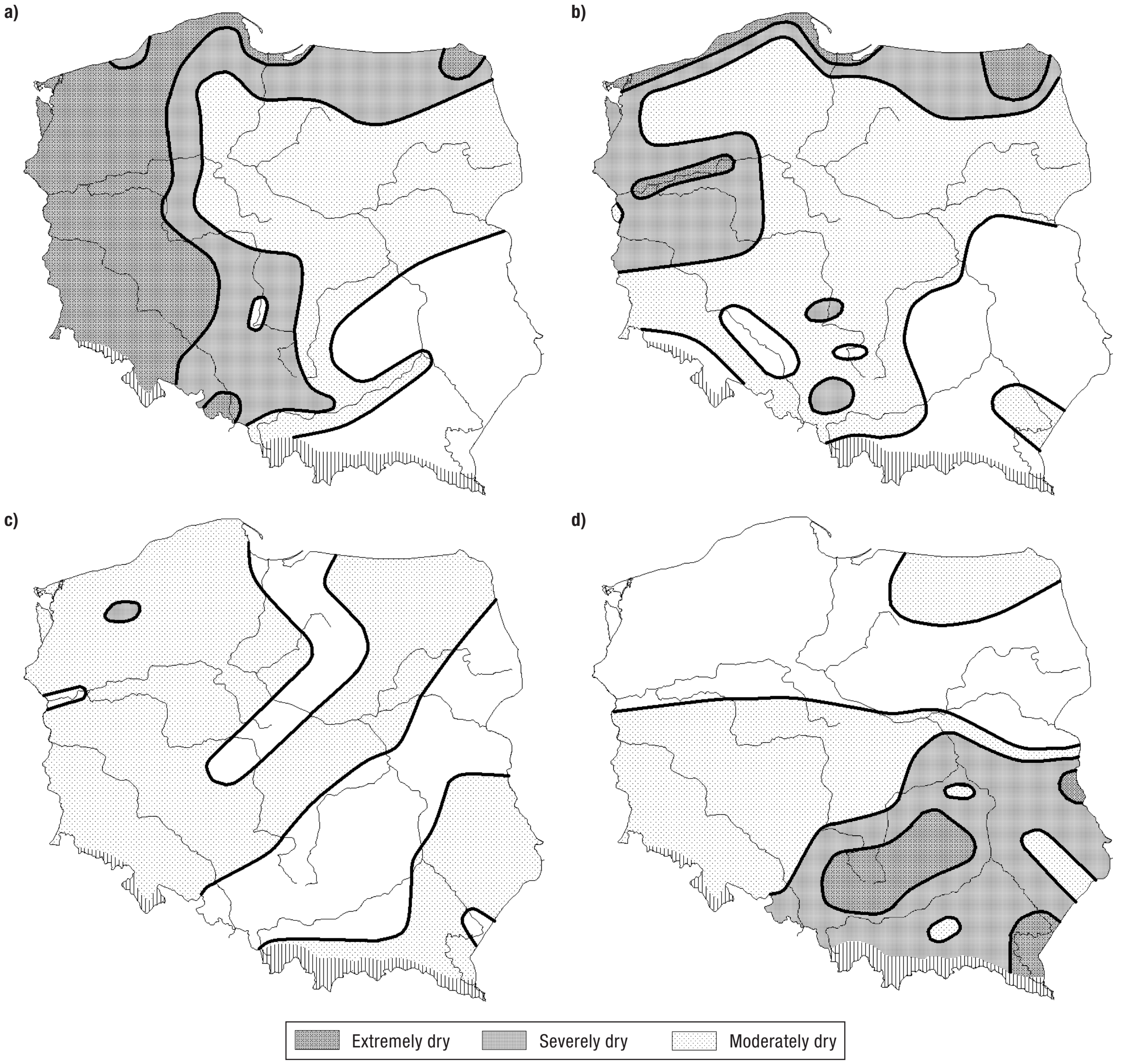

Figure 6. Changes in the occurrence of atmospheric drought of different intensity in Poland in the successive development stages of cucumber in 1992: a, S-EE; b, EE-BF; c, BF-BH; d, BH-EH. For period explanations see Figure 2.

In Poland, in the years 1966-2005, a significant linear trend of the *SPI* in all the four examined development stages of cucumber both for the whole country and a single IMGW station was not statistically confirmed at the level of $p \leq 0.05$.

Effect of precipitation deficiency on reduction of cucumber yield

In the period of the highest demand of cucumber for water, that is, in the period BH-EH, atmospheric precipitation below the average value (the average for 1966-2005) significantly contributed to reduction of the marketable and total yield of the plant (Table 3). Curvilinear regression equations taking into account atmospheric precipitation totals in the period BH-EH and a linear trend in the years 1966-2005, accounted for variability of pickling cucumber yield in about 40% in the case of the total yield, and in about 46% in the case of the marketable yield. In the formed regression equations a standard error of equation estimation was smaller than standard deviation of cucumber yield and

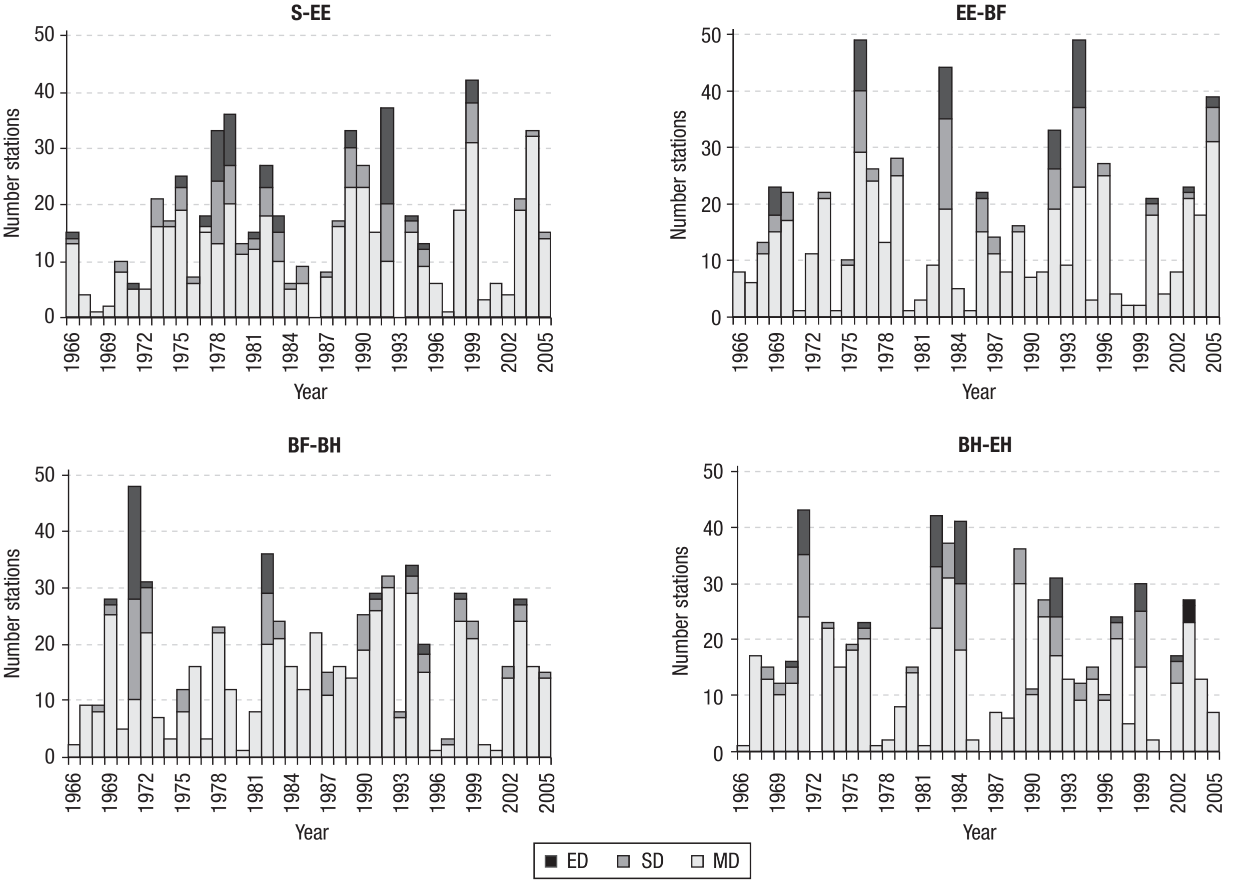

Figure 7. Number of meteorological stations of IMGW in Poland in which atmospheric drought of different intensity was recorded, in the successive development stages of cucumber in the years 1966-2005. ED: extremely dry. SD: severely dry. MD: moderately dry. Other explanations, see Figure 2.

Table 3. Dependence of cucumber yields on atmospheric precipitation in the period from the beginning of harvesting to the end of harvesting in Poland, with consideration of the linear trend in the years 1966-2005

Regression[3]	Variable[1]		Characteristics[2]				
	y	$Pr_{Bh\text{-}EE}$	R^2	*Std-Sy*	*ARFE*	Frequency of the occurrence of $\|RFE\|$ in range 0-5	5-10
$y_t = -816.319^{***} + 0.423 Yl^{***} + 0.158 Pr_{BH\text{-}EE}^{***} - 0.000551 Pr_{BH\text{-}EE}^{2\,***}$	33.2	100	39.8	1.5	10.2	36.2	39.1
$y_m = -926.859^{***} + 0.473 Yl^{***} + 0.1067 Pr_{BH\text{-}EE}^{***} - 0.000319 Pr_{BH\text{-}EE}^{2\,***}$	18.3	100	46.3	1.9	9.4	39.7	43.9

[1] y: average multi-annual yield (t ha^{-1}). $Pr_{Bh\text{-}EE}$: atmospheric precipitation total in the period from the beginning of harvesting to the end of harvesting (mm). R^2: determination coefficient (%). [2] *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 (%). [3] *Yl*: linear trend of the yield, *i.e.,* the successive years of the 1966-2005 multi-annual period. ***: significant at $p \leq 0.01$. y_t: total yield (t ha^{-1}). y_m: marketable yield (t ha^{-1}).

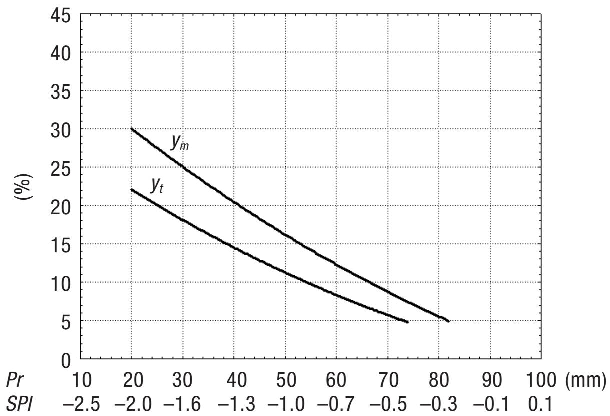

Figure 8. Potential reduction in yield (%): total yield (y_t) and marketable yield (y_m) of cucumber caused by precipitation deficiency in the period from the beginning of harvesting to the end of harvesting in Poland. *Pr*: atmospheric precipitation. *SPI*: standard precipitation index.

the difference between these indexes (*Std-Sy*) amounted to 1.5 and 1.9 t ha^{-1}, whereas the bigger difference pertained to the equation describing variability of the marketable yield. Also for this equation, a smaller, equalling 9.4%, error (*ARFE*) was determined and more very good forecasts, *i.e.,* the ones with an error not exceeding 5% (about 40%), and good forecasts (about 44%), *i.e.,* with an error between 5 and 10%, were made.

Reduction by at least 5% in average domestic yield of pickling cucumber in Poland occurred with atmospheric precipitation in the period BH-EH, amounting to 74 mm in the case of the total yield and 82 mm in the case of the marketable yield, *i.e.,* respectively 26 and 18 mm below the multi-annual average (Table 3, Fig. 8). It results, then, that cucumber cultivated in climatic conditions of Poland reacts with a decrease in the total yield when the *SPI* = –0.4, and with a decrease in the marketable yield with the *SPI* = –0.2. Reduction by at least 10% in the cucumber total yield occurred with precipitation of 54 mm (*i.e.,* with the *SPI* = –0.9), and by 15% – with precipitation of 38 mm (*i.e.,* with the *SPI* = –1.3). Atmospheric precipitation deficiency in the period BH-EH caused a higher decrease in the marketable yield than in the total yield, as reduction by 10% in this yield below the average multiannual level in the years 1966-2005 occurred as early as with precipitation of 68 mm (*i.e.,* with the *SPI* = –0.5), and by 15% with precipitation of 52 mm (*i.e.,* with the *SPI* = –0.9).

Atmospheric precipitation deficiency can, however, cause losses in yield of a different quantity depending on the region of Poland (Fig. 9). Potential reduction in the total yield of cucumber caused by precipitation deficiency (*Pr* ≤ 74 mm) occurring in the period BH-EH oscillated in most regions of the country between 6 and 12% (Fig. 9a). The lowest reduction, amounting to 6%, occurred in the south-west and south-east of the country, and the highest reduction, amounting to 12%,

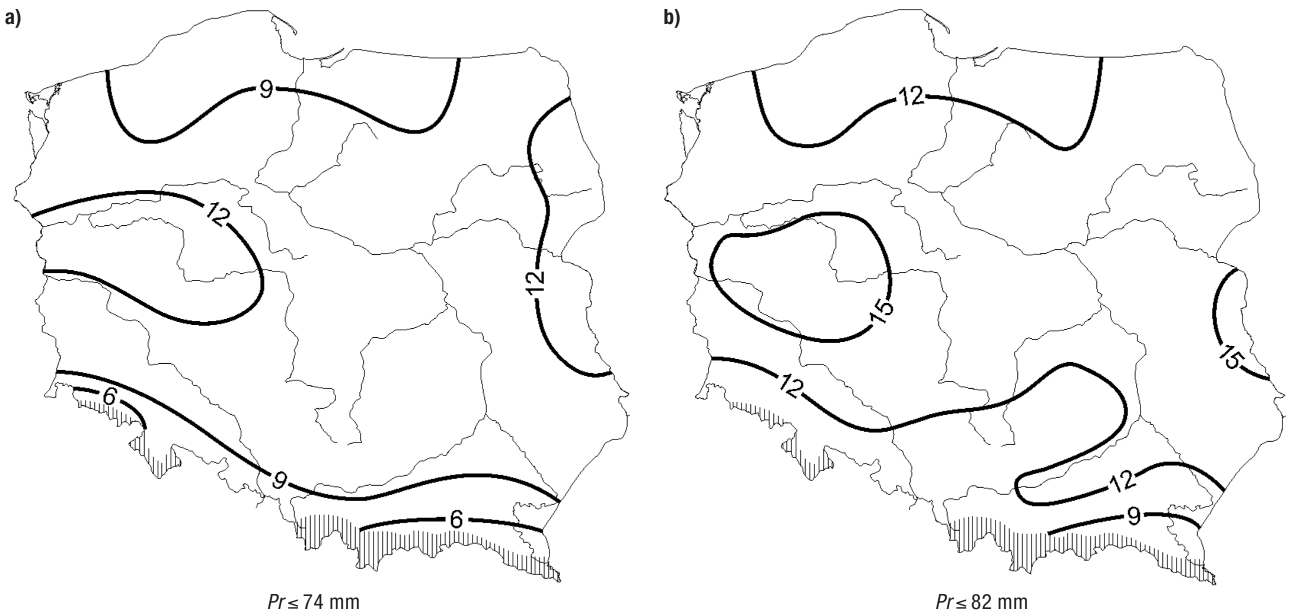

Figure 9. Spatial distribution of potential reduction in yield (%): total yield (a), and marketable yield (b) of cucumber caused by precipitation deficiency in the period from the beginning of harvesting to the end of harvesting of cucumber in Poland. *Pr*: atmospheric precipitation.

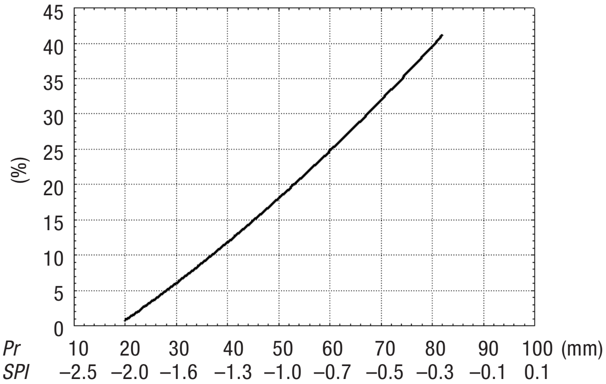

Figure 10. Frequency of the occurrence (%) of precipitation deficiency in the period from the beginning of harvesting to the end of harvesting of cucumber in Poland (years 1966-2005). *Pr*: atmospheric precipitation. *SPI*: standard precipitation index.

in the central west and central east of Poland. In central Poland losses in the total yield ranged from 9 to 12% below the multi-annual average. In the case of the cucumber marketable yield, precipitation deficiency ($Pr \leq 82$ mm) occurring in the period of the biggest demand of this plant for water resulted, depending on a region of Poland, in a decrease of the yield from below 9% in the south-eastern part of the country to above 15% in the central-western and central-eastern part (Fig. 9b).

In Poland, in the years 1966-2005, frequency of the occurrence of precipitation deficiency, causing reduction by at least 5% in the total yield of the characterised plant, on average, amounted to about 35% and oscillated in most regions of the country between 10 and 40% (Figs. 10 and 11). Least frequently, below 10%, precipitation deficiency occurred in the south-eastern part of the country and most frequently, above 40%, in the central-western part. On the other hand, the spatial distribution concerning frequency of the occurrence of precipitation deficiency, causing reduction by at least 5% in the cucumber marketable yield was similar to the previous one both in respect of distribution and frequency. The average frequency amounted to about 41% and oscillated in the country's area from below 20% to above 50%. Precipitation deficiency occurred every 5 years in south-eastern Poland, every 3 years in southern and north-western, every 2-3 years in central and central-eastern and every 2 years in central-western.

Discussion

The results obtained in the work confirm the view that drought is characterised by very high temporal and spatial variability. Like in Poland in the years 1966-2005, also in other regions of the world confirmation of a statistically significant increase or decrease in the frequency of drought occurrence on the basis of the

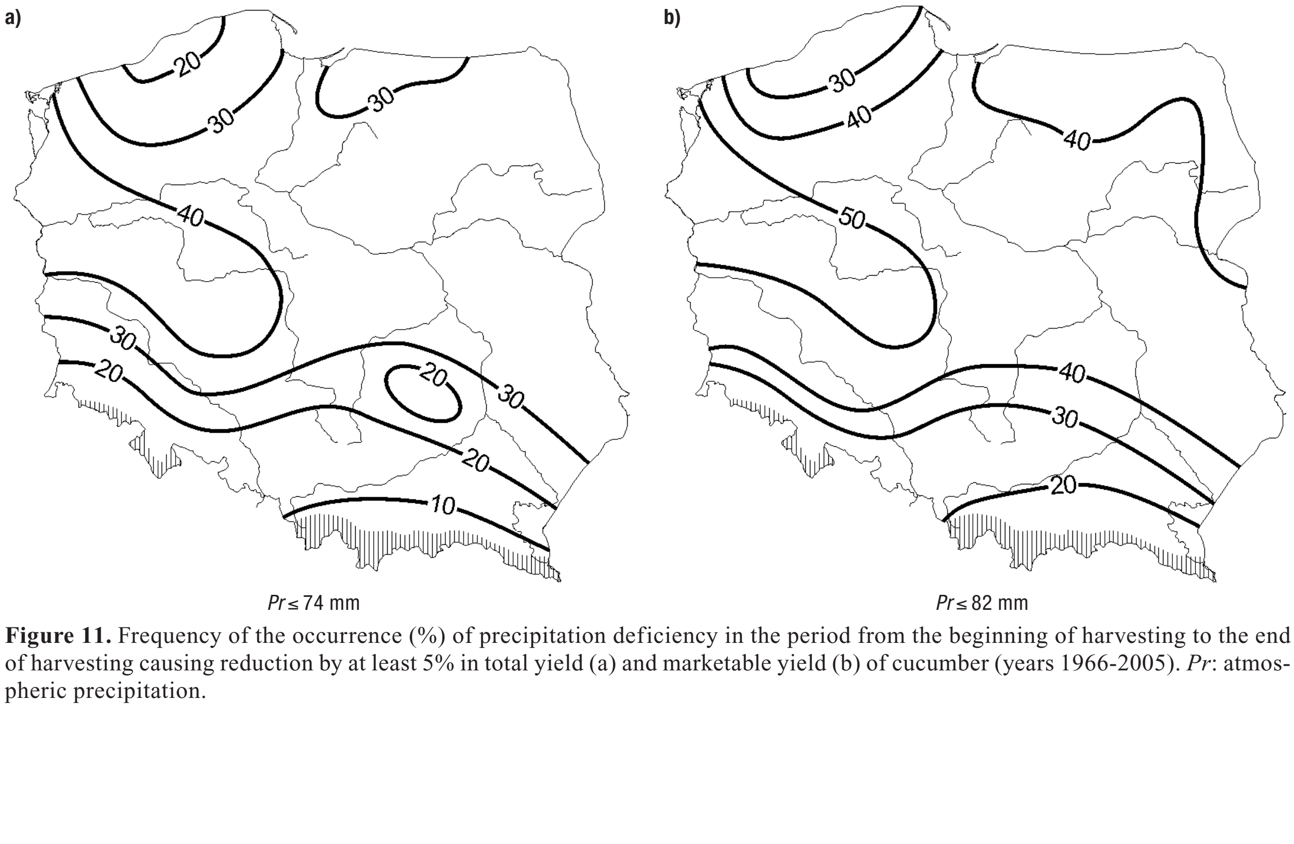

Figure 11. Frequency of the occurrence (%) of precipitation deficiency in the period from the beginning of harvesting to the end of harvesting causing reduction by at least 5% in total yield (a) and marketable yield (b) of cucumber (years 1966-2005). *Pr*: atmospheric precipitation.

SPI was often unsuccessful (Vicente-Serrano and López-Moreno, 2005; Khan *et al.,* 2008; Dubrovsky *et al.,* 2009). However, there are scientific reports informing about an increase or decrease of drought intensity (Bonaccorso *et al.,* 2003). For Europe forecasts generally say about a decrease in frequency of the occurrence of atmospheric drought in the summer period and an increase in the winter period (Blenkinsop and Fowler, 2007). On the other hand, in central regions of the USA (in the river Kansas basin) a significant decrease in the *SPI* value was noted (an increase in frequency and intensity of drought occurrence), and in the western and eastern parts – a significant increase (Logan *et al.,* 2009). Like in Poland in the years 1966-2005, research in many regions of the world confirm very high spatial variability of the occurrence of atmospheric drought in a multi-annual perspective (Bonaccorso *et al.,* 2003; Hisdal and Tallaksen, 2003; Sirdaş, 2003; Zhang, 2004).

In Poland, water requirements of cucumber in the vegetation season of plants, on average, amount to 350-450 mm, and water consumption is different in particular stages of its growth and development (Dzieżyc and Dzieżycowa, 1986; Dzieżyc *et al.,* 1987; Żarski, 1989). According to Dzieżyc *et al.* (1987), distribution of cucumber requirements for precipitation, irrespective of a catchment and soil cohesion depends on duration of the vegetation season of the plant in a given year. According to Żarski (1989), optimal precipitation in a critical period (June-August) for cucumber equals 352 mm and considerably exceeds average actual precipitation. The highest precipitation deficiency for cucumber occurs in the Land of Great Valleys (the central strip of Poland) and oscillates between 150 mm in the Koło region and 175 mm in the Poznań region. South and north of this strip, the deficiency systematically decreases and oscillates between 85 mm in the Tarnów region (south-eastern Poland) and 110 mm in the Olsztyn region (north-eastern Poland). According to Żarski (1989), probability of the occurrence of such deficiency is lower where average precipitation values are higher, just like it was stated in the current research. On the other hand, in the opinion of Dzieżyc and Dzieżycowa (1986), optimal precipitation on medium-heavy soils amounts to 400-450 mm, and on heavy soils it is lower by about 50 mm. Ten-day precipitation requirements in the cucumber vegetation season, determined by Dzieżyc *et al.* (1987) are clearly lower than those presented in the work from 1986, because they oscillate between 274 and 332 mm on medium-heavy soils and between 241 and 297 mm on heavy soils. Moreover, the period BH-EH, on average, has precipitation of 110 mm, so 10 mm more than it was determined in the current work on the basis of the 40-year research period (1966-2005). The highest demand of cucumber for water occurs in the period of flowering, fruit-setting and fruit increase. Water deficit in soil in the period of flowering and fruit-setting causes weakening of growth, plant withering, formation of a bigger number of male flowers and also flower and ovary drop. On the other hand, drought occurring in the period of fruiting reduces the yield and deteriorates the quality of fruits, in which empty spaces are very frequently formed (Karczmarczyk and Nowak, 2006). According to Dzieżyc and Dzieżycowa (1986), with precipitation amounting to slightly below 200 mm, cucumber yield may decrease by around 60% on medium-heavy soils and by around 20% on heavy soils.

Water deficits in soil in a cucumber plantation caused mainly by precipitation deficiency are supplemented by irrigation (Suojala-Ahlfors and Salo, 2005; Nimah, 2007). Production effects of cucumber irrigation are unremarkable and in particular years are not the same, which is caused by the amount and distribution of atmospheric precipitation in the vegetation season (Żarski *et al.,* 2000; Mao *et al.,* 2003; Şimşek *et al.,* 2005; Ertek *et al.,* 2006). Cucumber yield harvested from an irrigated plantation is substantially bigger from the yield obtained in controlled conditions. For example, in a moderately dry region of Turkey, production effects of irrigation in the drip system oscillated between 6.1 and 9.9 kg m^{-3} (Şimşek*et al.,* 2005). According to Ertek *et al.* (2006), cucumber yield, under influence of irrigation can increase from 18 even up to 45 t ha^{-1}.

The recorded precipitation deficiency, in the years 1966-2005, in Poland and especially in its central part confirms usefulness of carrying out research on cucumber irrigation. It results from the research of Rolbiecki *et al.* (2000) that in Poland in the region of Bydgoszcz (central Poland), the marketable yield of cucumber, as a result of drip irrigation, may increase by 34% with effectiveness of the irrigation amounting to 0.66 t ha^{-1} per 10 mm of precipitation. Better irrigation results are achieved on soils of low water-holding capacity. Also Kaniszewski and Elkner (2002) noted an increase in the total and marketable yield of cucumber under influence of drip irrigation in climatic conditions of Poland. According to these scientists, drip irrigation substantially reduces the content of dietary fibre and nitrates and the number of fruits with empty spaces. It does not affect, however, the level of carbohydrates and ascorbic acid in cucumber fruits. According to Kaniszewski and Elkner (2002), the highest total and marketable yield of cucumber can be obtained at a N dose of 300 kg ha^{-1}, with 50 kg of N before vegetation applied through broadcasting, and 250 kg of N through surface fertigation during vegetation. However, at such a dose of N the level of nitrates in fruit and the number of fruits with empty spaces increase. These scientists noted the biggest content of carbohydrates and vitamin C and the lowest content of nitrates in cucumber fruits with a total dose of nitrogen of 200 kg ha^{-1}. On the other hand, according to Spiżewski and Knaflewski (2009), drip irrigation in combination with fertigation produces a bigger number of pickling fruits and reduces the number of non-marketable fruits in comparison with sprinkling irrigation with broadcast applied top-dressing. Irrigation reduced the content of carbohydrates and vitamin C in cucumber fruits, but no differences between drip irrigation and sprinkling irrigation were shown.

The results obtained in the present work can be used in the research concerning the assessment of drought influence on growth, development and crop productivity of other cultivated plants.

As final conclusions, In Poland, in the years 1966-2005, atmospheric drought in the vegetation season of pickling cucumber was characterised by high temporal and spatial diversity. Out of all the determined periods with atmospheric drought, drought of moderate intensity was recorded most often (77%), and, next, drought of extreme intensity (13%) and severe intensity (10%). Drought of various intensities occurred most frequently in the period from the end of emergence to the beginning of flowering (on the average, every 3 years), and most seldom in the period from sowing to the end of emergence (on the average, every 4 years).

In the period from the beginning of harvesting to the end of harvesting, atmospheric precipitation deficiency significantly unfavourably affected the quantity of the total and marketable yield of cucumber (pickling varieties) cultivated in climatic conditions of Poland. At least 5% yield reductions of the plant occurred when atmospheric precipitation amounted to 74 mm (*i.e.,* with the *SPI* equalling –0,4) and 82 mm (*i.e.,* with the *SPI* equalling –0,2) respectively in the case of the total and marketable yield, with the multiannual average amounting to 100 mm. The highest risk of cucumber cultivation occurred in central-western Poland, where average reduction in the total yield amounted to over 12% every 2-3 years, and in the marketable yield – over 15% every 2 years.

Lack of a statistically confirmed increase in the frequency of atmospheric drought year by year, may signify that in the nearest years the current level of cucumber cultivation risk caused by this phenomenon will last.

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