

The Impact of High Temperature during Growing Season on Potato Cultivars with Different Response to Environmental Stresses

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ABSTRACT

Potato crop is the fourth main food crops in the world after maize, rice and wheat. It is characterized by specific temperature requirements and develops best at about 20°C. Forecasts of global warming prompt us to study the tolerance of potato genotypes to heat during the growing season. The aim of this work was to assess the response of chosen potato cultivars to high temperature during the different stages of plant growth under conditions of good soil moisture and drought. The impact of high temperature 32°C/25°C on potato plants was determined in pot experiment in three growth stages. A main measure of tolerance of the potato cultivars to high temperature during the growing season was an evaluation of the yield in relation to the Control combination. Here we demonstrated that tested potato cultivar's response to high temperature during the growing season is dependent on the growth stage. The earlier it occurs, the more negative its impact on the growth and yield of potatoes is.

Keywords: Potato (*Solanum tuberosum* L); Heat Stress during Growing Period; Drought; Tuber Yield; Physiological Defects of Tubers

1. Introduction

Heat stress due to increased temperature is an agricultural problem in many areas in the world. Transitory or constant high temperatures cause an array of morpho-anatomical, physiological and biochemical changes in plants, which affect plant growth and development and may lead to a drastic reduction in economic yield [1]. The adverse effects of heat stress can be mitigated by developing crop plants with improved thermotolerance using various genetic approaches. For this purpose, however, a thorough understanding of physiological responses of plants to high temperature is imperative.

Potato (*Solanum tuberosum* L) crop is the world's number one non-grain food commodity and the fourth main food crops in the world after maize, rice and wheat, with 324 million tons produced on the area of 19 million hectares in 2010 [2]. It is grown in more than 100 countries, mainly in Asia and Europe [3]. The potato is a plant mainly of typical temperate climate. The crop grows best in cool but frost-free seasons and does not perform well in heat [4,5]. It is characterized by specific temperature

requirements. The limits and optimal values for the growth of the above-ground part of the potato plant and for the tubers are different. From experiments conducted in growth chambers it is known that haulm growth is fastest in the temperature range of 20°C - 25°C whereas the optimal range for tuberization and tuber growth is 15°C - 20°C [6-10]. At a temperature higher than optimal a reduction or complete inhibition of tuberization and the intensified development of aboveground part of plants take place. The negative impact of high temperatures on tuber yield is the result of the consumption of assimilates by intensively growing shoots.

In natural conditions drought and heat stress are two different types of abiotic stresses that occur generally in the field simultaneously. Several studies have examined the effects of a combination of these stresses on the growth and productivity of many crops. Mittler [11] found that a combination of drought and heat stress had a significantly greater detrimental effect on the growth and productivity of these plants and crops compared with each of the different stresses applied individually. Due to

increasing irrigation use on potato plantations and periodic action of heat stress under conditions of good soil moisture, in some studies the impact of high temperature on potato plants was separated from the impact of drought [12-14]. According to De Temmerman *et al.* [15] it is not clear if the whole growing period is important for potato or if the time between maximum leaf area, coinciding with the stage of flowering and harvest, is the most sensitive period. Generally there is not much information on the effect of heat and drought stress at different stages of tuber growth [16]. Forecasts of global warming and periods of high temperature and drought becoming more frequent in Central Europe and also the need to export seed potatoes to countries with high temperatures in the summer prompt us to study the tolerance of potato genotypes to heat during the growing season.

The aim of this work was to assess the response of chosen potato cultivars to high temperature during the different stages of plant growth under soil moisture conditions favourable to plants and under drought conditions.

2. Materials and Methods

2.1. Tested Cultivars and Treatments

The pot experiment was carried out in open area next to

the greenhouse and in a growth chamber, during two years. The following cultivars were tested: Irys (very early), Cyprian (early), Adam, Irga, Zebra (medium early) and the cultivar Katahdin (medium early) with very high adaptability to the environment [17]. The first five cultivars came from Polish Potato Breeding in Strzekaćin and the sixth from the Potato Gene Bank.

The impact of high temperature day/night 32°C/25°C on potato plants was tested in three periods: I—June 16-30, II—July 1-15 and III—July 16-30. In these periods half of the plants were watered to a level close to optimal (Favourable Soil Moisture), while the other half remained without irrigation (Soil Drought). The Control combination consisted of potato plants grown throughout the whole season under conditions close to optimal.

2.2. Weather Conditions

Weather conditions during the years of study were monitored using a Weather Campbell Station (Campbell Scientific Inc.) located right next to the greenhouse and additionally using a thermohigrograph placed between pots. The two most important meteorological factors, air temperature and the photosynthetically active radiation, were similar in the years of study and favourable for potato development (**Table 1**).

Table 1. Air temperature and photosynthetically active radiation (PAR) during growing season in the years of study.

Meteorological factor	Year	Decade*	Month						Mean		
			April	May	June	July	August	Sept.			
Temperature in °C	2008	I	3.3	11.5	18.2	17.4	18.3	17.4	14.2		
		II	7.7	12.7	15.5	17.6	19.2	8.4			
		III	10.5	15.5	17.5	19.3	15.7	9.0			
		mean	7.2	13.2	17.1	18.1	17.7	11.6			
	2009	I	8.9	12.0	12.6	21.1	18.7	15.8			
		II	7.9	11.4	16.0	20.0	16.9	14.4			
		III	12.2	13.3	20.7	18.1	16.6	12.5			
		mean	9.7	12.2	16.4	19.7	17.4	14.2			
	PAR in J m ⁻¹ .sek ⁻¹	2008	I	147	348	527	455	367		297	344.5
			II	207	410	423	334	325		116	
			III	361	441	461	425	288		148	
			mean	268	412	470	405	325		187	
2009		I	332	408	360	479	398	279			
		II	314	415	450	420	358	284			
		III	455	323	510	360	329	285			
		mean	367	380	440	420	361	282			

Explanation: *decade—10 days of the month: I—1 - 10 day; II—11 - 20 day and III—21 - 30 or 31 day.

2.3. Seed Material and Planting

In the years preceding the main experiment, the plants *in vitro* of tested cultivars were propagated in the green house to obtain healthy seed material. Obtained in this way, minitubers were kept in storage at a temperature of 3°C. In the spring they were selected and those of the size 3 - 4 cm (transverse diameter) were pre-sprouted for 5 weeks and next used for planting. They were planted in 10-liter pots filled with a thin layer of gravel and the soil which was the standard substrate for vegetables. The number of objects (pots) was a total of 198, and each cultivar accounted for 33. Dates of planting took place on April 23 - 24. The pots with plants set on special tables on wheels and were moved outdoor, to a place next to greenhouse. The density of pots set was 4 per m².

2.4. Proceeding with Plants during the Growing Season

Throughout the growing season the plants were carefully tended daily and regularly watered until the level close to optimum. Soil moisture was controlled using the Moisture Meter (PL). Recommended plant protection products were used against diseases and pests. Just before the start of the heat impact, six plants of each cultivar were transferred to a growth chamber for the period of 15 days. Phenological stages of plants of tested cultivars just before the impact of high temperatures in different periods of growing season were presented in **Table 2**. Conditions in the growth chamber were: photoperiod 15 hours, lighting with Philips SON-T Agro 400W lamps with power supply light at 100 - 120 Wm⁻² at 1.5 m. The temperature was maintained at a level established by experiment (32°C/25°C). Half of the plants were watered regularly to a level close to the optimum (Favourable Soil Moisture), and the other half were subjected to soil drought by ceasing watering (Soil Drought). After the end of high temperature periods measurements of plant height were performed and then they were transferred to a place next to the greenhouse where further development under conditions close to optimal took place.

2.5. Final Yield

Final harvest was performed after full maturity of plants in the Control combination, between August 10 and 19. The total mass and number of tubers per plant and also the mass of tubers with physiological defects were determined. A measure of tolerance of the potato cultivars to high temperature during the growing season was a decrease in yield and number of tubers per plant in relation to the Control combination. The presence of physiological defects in the tubers, mainly second growth was determined as the percentage in the total mass of tubers.

Table 2. Phenological stages of plants of tested cultivars just before the impact of high temperatures in different periods of growing season.

Cultivar	Period of HT*	DAP**	Phenological stage
Irys	I	51 - 65	end of flowering
	II	65 - 79	development of fruits
	III	80 - 94	beginning of maturity
Cyprian	I	51 - 65	full flowering
	II	65 - 79	development of fruits
	III	80 - 94	beginning of maturity
Adam	I	51 - 65	no flowering
	II	65 - 79	no fruits
	III	80 - 94	beginning of maturity
Irga	I	51 - 65	no flowering
	II	65 - 79	no fruits
	III	80 - 94	beginning of maturity
Zebra	I	51 - 65	full flowering
	II	65 - 79	development of fruits
	III	80 - 94	beginning of maturity
Katahdin	I	51 - 65	full flowering
	II	65 - 79	development of fruits
	III	80 - 94	beginning of maturity

Explanations: *high temperature; **days after planting. I period of HT—the second half of June; II period of HT—the first half of July; III period of HT—the second half of July.

2.6. Data Analysis

The results of the experiments were analyzed with ANOVA using a general linear model of statistics program in SAS Enterprise Guide 4 [18]. Means were separated with Tukey's test at 5% p-value.

3. Results and Discussion

Significant impacts of the tested factors on the height of plants, yield, number of tubers, mass of one tuber and physiological defects of tubers were found (**Table 3**).

3.1. Height of Plants Immediately after the Impact of High Temperature

In the first and second period of heat stress in favourable soil moisture conditions, the plants of all cultivars responded with an increase in the height (**Tables 3, 4**). The results are consistent with the results of previous studies whereby a temperature higher than optimal intensified

Table 3. Significance level of tested factors—from the analysis of variance.

Characteristics	Source of variation						
	cultivar	period of stress	kind of stress	year	cultivar x period	cultivar x kind	period x kind
<u>Plants after stresses</u>							
Plant height in %	0.06	< 0.0001	< 0.0001	0.013	0.23	0.68	< 0.0001
<u>Final yield in Control</u>							
Tuber weight	0.03	-	-	0.0005	-	-	-
Number of tubers	0.009	-	-	0.18	-	-	-
Mass of 1 tuber	0.04	-	-	0.30	-	-	-
<u>Final yield in %</u>							
Yield	0.02	< 0.0001	< 0.0001	0.0004	0.14	0.26	0.01
Number o tubers	< 0.0001	0.16	0.003	0.99	0.93	0.81	0.19
Mass of 1 tuber	0.0001	< 0.0001	0.009	0.11	0.40	0.99	0.33
Defects of tubers	< 0.0001	0.003	0.02	0.10	0.004	0.59	0.01

Explanation: level P < 0.05—differences statistically significant.

Table 4. The height of plants in relation to the Control depending on the period of the impact of high temperature and soil moisture—mean values for tested cultivars (in %).

Soil moisture	Period of high temperature			
	I	II	III	mean
FSM*	151.3 a	123.8 a	97.8 a	124.3 a
SD**	104.0 b	103.3 b	97.7 a	101.7 b
Mean	127.7 a	113.6 b	97.8 b	113.0
I year	117.0 a			
II year	110.0 b			

Explanations: *Favourable Soil Moisture; **Soil Drought; a, b—mean values followed by the same letters in the column of group acc. Tukey’s test are not significantly different at the 0.05 level.

development of the aboveground part of plants [5,7,10, 19-21]. Our work additionally shows that the increase in the length of the stems was greater the earlier they were influenced by heat. Due to the limited number of plants in the experiment, measurements of the mass of the aboveground part of plants were not performed, because it would have been connected with additional plant liquidation in each of the three periods of stresses.

3.2. Final Yield

The final yield of tested cultivars and the number of tubers in Control were relatively high (Table 5). Tuber mass per plant was about twice that in the experiment of Levy [16] but individual tuber weight was similar. This

Table 5. Characteristics of final yield of tested cultivars in the Control.

Cultivar	Mass of tubers in g/plant		Number of tubers/plant		Mass of 1 tuber	
Irys	1401	ab	42.3	abc	33.4	b
Cyprian	1487	ab	47.4	a	31.3	b
Adam	1243	b	26.4	c	47.4	a
Irga	1515	a	44.7	a	33.7	b
Zebra	1540	a	46.7	ab	34.0	b
Katahdin	1397	ab	29.5	bc	47.4	a
Mean	1430		37.8		37.9	
I year	1562	a	37.5	a	39.4	a
II year	1298	b	38.0	a	36.4	a

Explanations: a, b—see Table 4.

indicates more intense tuberization under temperate conditions than in a semi-arid Mediterranean climate. In our experience, there were normal differences between cultivars, which are the result of their ability to yielding and physiological seed vigor in a given environment [22]. The higher yield in the first year was probably due to slightly more favourable conditions for potato development.

The high temperature during the growing season had a negative effect on the final yield of tested cultivars (Table 6). The effect was strongest when the high temperature influenced plants in the second half of June (period

Table 6. The final yield of tested cultivars in relation to the Control depending on cultivar, period of the impact of high temperature and soil moisture (in %).

Cultivar	Period of high temperature						Mean
	I		II		III		
	FSM	SD	FSM	SD	FSM	SD	
Irys	83.7	48.7	94.8	83.6	106.7	99.3	86.10 ab
Cyprian	84.4	75.2	99.6	85.7	104.5	89.2	89.77 a
Adam	86.4	52.7	91.9	74.4	99.1	89.8	82.38 b
Irga	84.3	47.1	99.2	70.7	97.9	88.7	81.32 b
Zebra	90.9	73.1	97.1	80.9	103.2	91.2	89.40 a
Katahdin	87.0	74.3	92.7	84.6	103.5	88.3	88.40 a
	86.2 a	61.9 b	95.9 a	80.0 b	102.5 a	91.1 a	
mean	74.05 c		87.95 b		96.80 a		86.3
	FSM—94.8 a SD—77.7 b						
	I year—82.9 b II year—89.5 a						

Explanations: see Table 4.

I). In this period the decrease in the relative yield was nearly twenty-six percent but the effect was stronger in the case of combined effects of high temperature and drought compared to high temperature under favourable soil moisture conditions. As the time of the impact of high temperature on potato plants was delayed (II and III period), the negative effect on the yield of tubers became weaker, but the differences between the combinations of “favorable soil moisture” and “drought” remained statistically significant. There were no significant differences between cultivars regarding the period of impact of heat stress or soil moisture, which indicates the same direction of the reaction. Among the most tolerant from the viewpoint of decrease in yield were “Cyprian” “Zebra” and “Katahdin”. In the study of Levy [23,24] heat stress reduced tuber yields of ten tested potato genotypes from 0 to 96 percent but the experiment was conducted under natural conditions in a semi-arid environment and a comparison was made between two cycles of vegetation, between the spring cycle under favourable climatological conditions and the summer cycle under high temperature conditions. Additionally in his study the seeds were in different physiological ages and vigours. A detailed comparison of the results is therefore difficult but the results of a phytotron experiment conducted by Van Dam *et al.* [10] clearly indicate that higher temperatures gave lower tuber growth rates irrespective of the length of the photoperiod.

The number of tubers in the final yield of tested cultivars was significantly dependent on the soil moisture during the impact of high temperature (Figure 1). Here

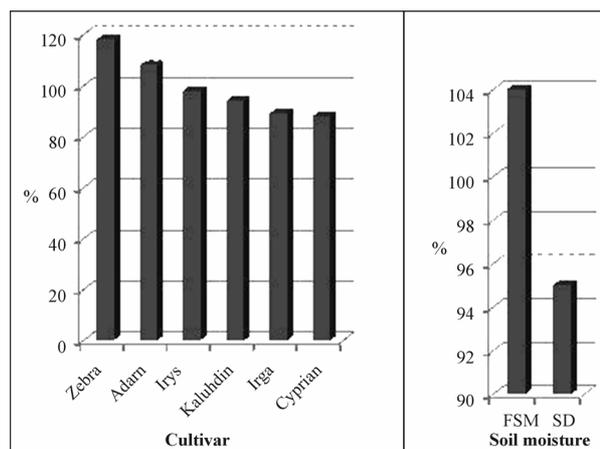


Figure 1. Number of tubers in final yield in % in relation to Control depending on cultivars and soil moisture—mean values for the periods of high temperature.

we show that soil moisture favourable for plants led to an increase of the number of tubers. The highest increase was confirmed in cultivars Zebra and Adam. This points to the secondary tuberization in these cultivars. A similar phenomenon was observed by Levy [16] who studied two cultivars, Desiree and Cara, and found that the number of tubers per plant tended to increase in heat treatment in Desiree and to a lesser extent in Cara. In the earlier study of Rykaczewska [12] the increase in the number of tubers from 30% to 54% compared to the Control was found and also the presence of tubers chronologically younger. Those studies were performed, however, only with two cultivars with heat stress lasting for three

weeks.

In the study presented here a highly significant effect of all the examined factors on the tuber size in the yield was found (Table 3, Figure 2).

The physiological defects of tubers were also showed (Table 7, Figure 3). The largest share of these tubers in the final yield occurred in cultivars Irga and Irys and the smallest share in cultivars Zebra, Katahdin and Adam. The earlier high-temperature stress was applied, the greater was the percentage of tubers with physiological defects. Cultivars Irys and Irga remained at a high percent of defects as a result of stress at any time. Results of the experiment obtained by Levy [16] show, however, that a single treatment of high temperatures during early stages of tuber development caused lower the percentage of misshapen tubers. This indicates that studies of this phenomenon with a larger number of cultivars and a more precise determination of the tubers state at the beginning of the impact of heat stress are needed. Here we demonstrated that soil moisture favourable for plant growth in the first periods of heat stress was significantly

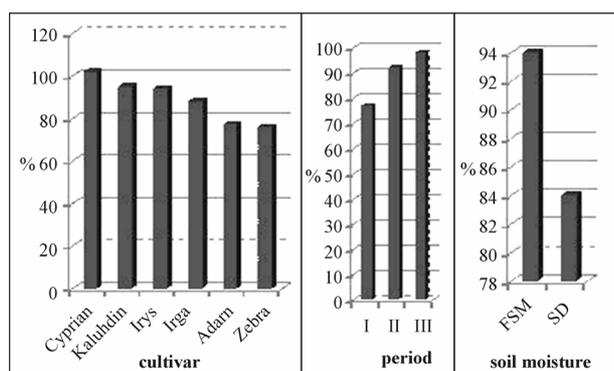


Figure 2. Tuber size in relation to Control depending on cultivar, period of high temperature and soil moisture.

more conducive to the physiological defects of tubers like second growth and gemmation than drought.

The significant correlations between the relative height of plants and relative yield, relative tuber size and percentage of tuber with physiological defects confirm the negative, very strong effect of high temperature during growing season on yielding of tested potato cultivars (Table 8).

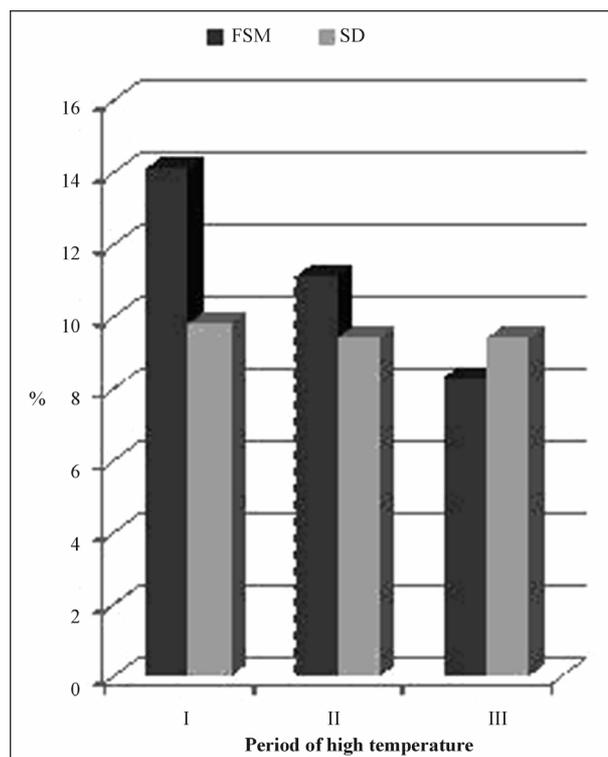


Figure 3. Physiological defects of tubers in final yield depending on the period of high temperature and soil moisture—mean values for cultivars.

Table 7. Percentage of physiological defects of tubers in the final yield depending on cultivar and period of high temperature.

Cultivar	Period of high temperature			Mean	
	I	II	III		
Irys	13.0 ab	16.3 a	13.9 ab	14.4	a
Cyprian	11.2 b	9.9 bc	9.5 b	10.2	b
Adam	13.1 ab	5.0 c	7.8 bc	8.6	bc
Irga	17.7 a	13.0 b	15.9 a	15.5	a
Zebra	6.9 c	6.2 c	2.5 c	5.2	c
Katahdin	10.0 b	11.4 bc	3.7 c	8.3	bc
mean	12.0 a	10.3 ab	8.9 b	10.4	

FSM—11.2 a SD—9.5 b

Explanations: see Table 4.

Table 8. Correlations between relative height of plants and relative yield, relative number of tubers, relative tuber size, percentage of tubers with physiological defects.

Correlation	FSM	SD
Relative height of plants x relative yield	-0.996**	-0.875**
Relative height of plants x relative number of tubers	+0.011	+0.011
Relative height of plants x relative tuber size	-0.899**	-0.908**
Relative height of plants x % of physiological tuber defects	+0.999**	+0.629*

Explanations: FSM, SD—see **Table 4**; **P < 0.01; *P < 0.05.

4. Conclusion

Our studies on the impact of high temperature on the development of potato confirm the view that its productivity is greatly reduced at higher temperatures than the optimum temperatures. It was demonstrated here, however, that potato cultivars' response to high temperature during the growing season is dependent on the growth stage, in which the temperature acts on the plants. The earlier it occurs, the more negative its impact on the growth and yield of potatoes is. Here we show that sustained for two weeks, the combined heat and drought stress which affects potato plants during the flowering period may reduce the yield of susceptible cultivars by over 50% and more tolerant cultivars by about 25%. It is also a cause of physiological defects of tubers, the mass of which may exceed 10% of the total yield. Here we show that seemingly mild heat stress acting on the plant for a period of two weeks under favorable soil moisture conditions may cause an increase in the height of the aboveground part of more than 50% in relation to Control, and a small, just a few percent, decrease in yield. In practice, however, it may be the most harmful due to the presence of secondary tuberization and therefore the appearance in the crop of chronologically and physiologically younger tubers which at the time of harvest can easily be damaged. Another significant disadvantage of the yield produced at high temperatures and favourable soil moisture is numerous physiological defects, which depends on the cultivar can range from a few to tens of percent. In this study the high tolerance of cultivar Katahdin to the heat stress during the growing season has been confirmed. This cultivar was characterized by the relatively low decrease in yield under high temperature stress, the absence of secondary tuberization and a relatively small number of tubers with physiological defects. Our research shows that the relative yield is not the only indicator of potato tolerance to high temperatures during the growing season, but the assessment should also take into account the number of tubers formed as a result of

the occurrence of secondary tuberization and also physiological defects. An important criterion may also be the duration of tuber dormancy, but this aspect of the research is undertaken in a separate elaboration.

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