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Influence of weather conditions, irrigation and plant age on yield and alpha-acids content of Czech hop (*Humulus lupulus* L.) cultivars

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Abstract: This study quantifies the effects of weather conditions, irrigation, and plant age on yield and alpha-acids content of Czech hop cultivars Saaz, Sládek, Premiant and Agnus in a 25-year long period, i.e., from 1993 to 2018. The yields of Czech hop cultivars were increasing for the first three years of plant age until they stabilized and then started to decline slightly for 15 to 20 years until they reached the optimal time for replanting. The highest alpha-acids content in hop cones was achieved in the first year of cultivation, followed by a logarithmic decline in the upcoming years. Rainfall was the most significant factor that positively influenced the yield of Saaz hops with correlations of $r = 0.59$ and 0.61 ($P < 0.01$) for total seasonal rainfall (April–August), 0.65 ($P < 0.001$) and 0.60 ($P < 0.01$) for daily rainfall above 3 mm, 0.37 ($P < 0.05$) and 0.58 ($P < 0.01$) for rainfall in May and 0.50 ($P < 0.01$) and 0.32 ($P < 0.05$) in July in the Saaz region and the Stekník farm, respectively. The yield of cultivars Sládek, Premiant and Agnus was not statistically influenced by the amount of precipitation, but there was a positive effect of irrigation level on yield increase with correlations 0.58 ($P < 0.01$), 0.55 and 0.49 ($P < 0.05$), respectively. High air temperatures during summer were the most significant factor that negatively influenced the alpha-acids content with the correlations ranging from –0.56 to –0.83. However, cv. Agnus showed a stable weather-independent alpha-acids content.

Keywords: climate change; water stress; dry weather; biosynthesis; brewing industry

Hop (*Humulus lupulus* L.) is a herbaceous perennial plant, whose female inflorescence, also named hop cone or hops, is used mainly in the brewing industry, a little in pharmacy and cosmetics. The crop production stability is important for the economic incomes of both hop growers as well as merchants, but it may be threatened by the climate change, which is able to affect the quantity and quality of crop production (Možný et al. 2009).

The yield of hops is a complex of interacting factors such as cultivar genetic determination, soil and nutrition capability of locality, agrotechnical and plant protection operations, environmental conditions, etc. Production potential of plants is usually 30% to 70% of the theoretical maximum (Pokorný 2011). The first step in achieving good crop production is the choice of suitable locality with ideal soil and water conditions, followed by balanced nutrition and agrotechnical and plant protection operations (Kopecký et al. 2008a). Even if all these factors are secured, weather conditions during each season play a major role in influencing the yield. Especially water stress during flowering and cone development and maturation significantly decrease yield and alpha-acids content (Hniličková and Novák 2000, Keukeleire et al. 2007, Srečec et al. 2008). Hop yield is strongly dependent on plant transpiration and is influenced by evaporation (Fandiño et al. 2015). Irrigation is a significant factor that stabilizes the yield of hops but it does not affect the content of alpha acids (Kopecký et al. 2008b, Svoboda et al. 2008, Nakawuka et al. 2017). On the other hand, alpha-acids content

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in hop cones is significantly reduced by the higher sum of seasonal temperatures (Srečec et al. 2004, 2008, Možný et al. 2009). It is mainly influenced by high summer temperatures between the middle of June and the harvest in August (Kučera and Krofta 2009, Pavlovič et al. 2012).

MATERIAL AND METHODS

Locality and hop production. Field experiments were kept at one hundred hectares of the Hop Research Institute, Co. Ltd. (Žatec, Czech Republic) experimental farm in Stekník (GPS: 50.325017N, 13.623077E). The production area of individual hop gardens ranged from 0.27 to 6.65 ha, with an average of 1.86 ha. In this experiment, 18 hop gardens of Saaz hops (1–22 years old), 21 hop gardens of Sládek (1–18 years old), 8 hop gardens of Premiant (1–20 years old) and 13 hop gardens of Agnus (1–16 years old) were studied in total. All hop gardens were maintained within the good agricultural practice with balanced nutrition, plant protection and agrotechnical operations (Kopecký et al. 2008a). The whole experimental area was irrigated by a drip irrigation system. The irrigation dosage and water supply schedule were determined by the graphical-analytical method (Kopecký et al. 2008b).

Data measurement and resources. Hop yields of the experimental hop gardens were calculated from weights of bales harvested and dried from each hop garden each year.

Alpha-acids contents were also annually determined from samples taken from each experimental hop garden. Alpha-acids content was measured by lead conductance titration according to the EBC 7.4 method (Analytica EBC 1998). Bitter substances were extracted with toluene from powder-grinded dried cones. An aliquot of the toluene extract was diluted with methanol, and bitter substances in solution were determined by conductometric titration with methanolic lead acetate solution on modular titration system Metrohm (Herisau, Switzerland). Alpha-acids content is expressed as LCV (lead conductance value) in mass percentage.

The obtained data of yields and alpha-acid contents of hops harvested each year from experimental hop gardens in the Hop Research Institute, considered as an irrigated variant of this experiment, were compared to the official data published each year by the Central Institute for Supervising and Testing in Agriculture and the Ministry of Agriculture of the Czech Republic within the Saaz hop growing region, considered as a non-irrigated variant. Average yields in the Saaz region are calculated from all farms (irrigated and non-irrigated), with about 20% of acreage irrigated. The exact data of irrigated acreage are not available, because evidence of irrigation systems is not mandatory in the Czech Republic. The estimate of the irrigated acreage is based on the voluntary investigation conducted by the Hop Growers Union of the Czech Republic in 2015.

Daily rainfall and maximal, minimal, and average temperatures were measured by a weather station (EMS, Brno, Czech Republic) administered by the Hop Research Institute Co. Ltd. in Žatec since 1993.

All comparative results are based on the comparison of data from the Hop Research Institute's farm with data from the Saaz hop growing region in given years. All other (non-comparative) data (effect of plant age on yield and alpha-acids content) come from the Hop Research Institute's farm.

Statistical analyses. Statistica 8.0 CZ (StatSoft, Tulsa, USA) was used to evaluate the data using basic statistic functions, multi-factorial analysis of variance (ANOVA), correlation, linear, and non-linear modules. Excel (Microsoft, Redmond, USA) software was used for regression analyses and graph constructions.

RESULTS AND DISCUSSION

Influence of weather conditions, irrigation, and plant age on yield. Statistically significant differences ($P < 0.001$) were found in yield due to either annual seasonal weather conditions or plant age for each cultivar according to ANOVA analyses. Moreover, there were statistically significant differences ($P < 0.01$) in yield caused by hop garden locality for Saaz and Sládek cultivars. However, the data were useful for statistical analysis of the influence of plant age on yield. Yields of Czech hop cultivars were increasing for the first three years until they stabilized (Figure 1). Production stability was slightly decreasing for 15 to 17 years, depending on cultivar. It corresponds with previous findings of replanting hop gardens when they reach 20–25 years of age for Saaz hops and 15–17 years for hybrid cultivars (Kopecký et al. 2008a, Pokorný 2011).

Seasonal weather conditions are one of the main factors influencing the growth and physiological response of hop plants every year. Rainfall was the most significant factor positively influencing the yield of Saaz hops (Table 1). There was a positive effect both in the total seasonal rainfall (Figure 2) and in the number of days with daily rainfall above 3 mm. Statistical analysis did not prove any significant effect of precipitation lower

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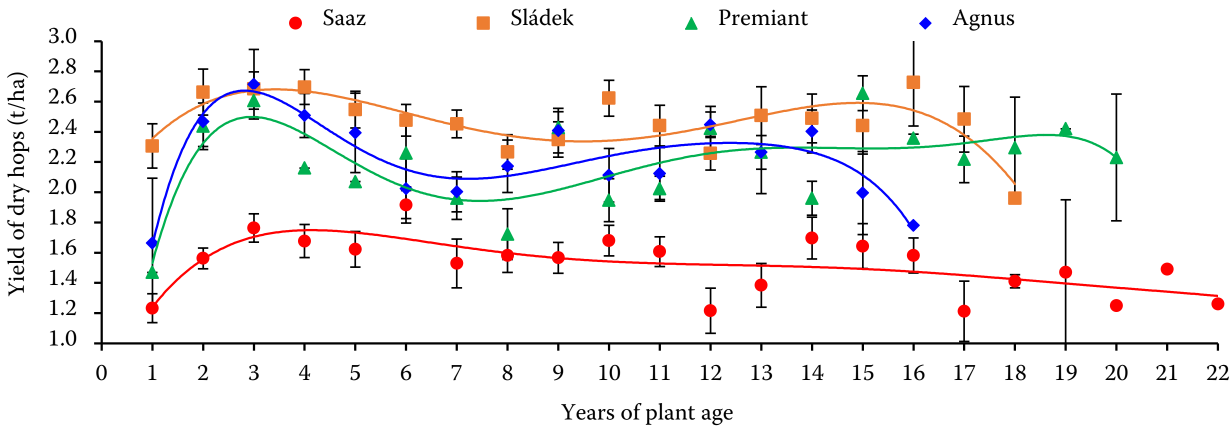

Figure 1. Relationship between plant age and yield of four Czech hop cultivars. Error bars represent standard deviation

Table 1. Correlation coefficients between the most significant weather parameters and yields of Saaz hop

Locality	Avg. temp. May	Rainfall					
		total for season	over 3 mm per day	May	June	July	July + 1/2 August
Region	–0.38*	0.59**	0.65***	0.37	0.31	0.50**	0.35
Farm	–0.49*	0.61**	0.60**	0.58**	0.36	0.32	0.41*

*P < 0.05; **P < 0.01; ***P < 0.001

than 3 mm per day. Možný et al. (2009) also reported a significant influence of summer precipitation (from June to August) on the yield of Saaz hops in the Czech Republic in the period 1954–2006. According to the present study, the key months for yield development are May and July. Hot and dry weather in May significantly reduced the yield of Saaz hops. The amount of precipitation in July and early August was one of the key factors for hop cone development and growth. The obtained results are in accordance with the data published by Črepinšek and Čeh (2018) for cultivars Aurora and Savinjski Golding in Slovenia. The same influence on yield was previously found in cultivar Celeia (Črepinšek and Čeh 2016).

Significant negative correlations were found between average temperature from July 1 to August 15 and the yields of Sládek (r = –0.68, P < 0.001) and Premiant (–0.42, P < 0.01) in the Saaz region (Figure 3). However, this influence was not found at the Stekník farm due to the irrigation, which is able to reduce the temperature by up to 5 °C during hot summer days (Kopecký et al. 2008b). In general, a positive impact of irrigation on hop yield is well acknowledged (Svoboda et al. 2008, Možný et al. 2009, Fandiño et al. 2015, Nakawuka et al. 2017); in this study, it was confirmed by increasing hop yield for cultivars Sládek, Premiant, and Agnus (Figure 4). Despite no statistical influence of total irrigation level during the season on Saaz hops' yield in general, water dosage during July was significantly important for its yield (Table 2). It was in accordance with the results mentioned above considering the July rainfall. The effect of irrigation on Saaz yields at the Stekník farm (Figure 4) is in yield stabilization during seasons with higher average temperature and dry periods during vegetation. Even though the yield was not increasing with the rising irrigation levels, the irrigation helped sustain a favourable microclimate and stabilize Saaz

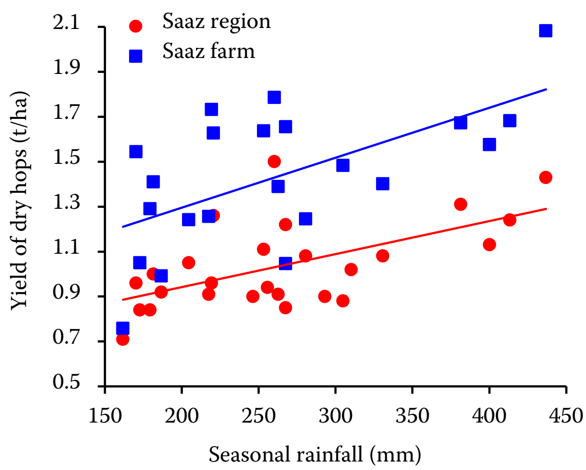

Figure 2. Linear regressions between seasonal rainfall (April–August) and yield of Saaz hops in the period 1993–2018

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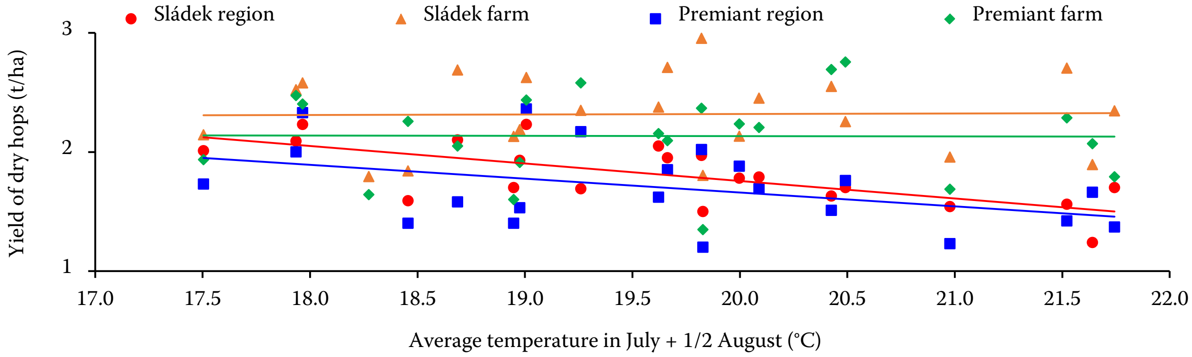

Figure 3. Linear regressions between average temperature from July 1 to August 15 and yield of Sládek and Premiant hops in the period 1998–2018

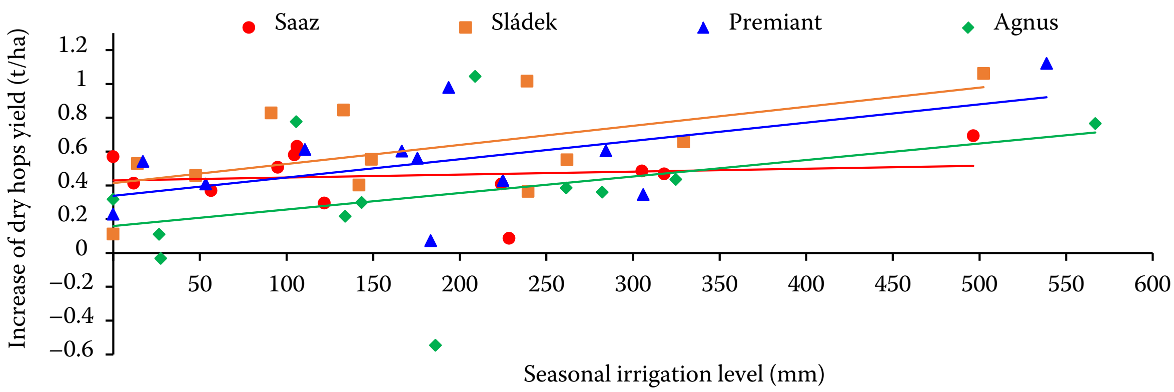

Figure 4. Linear regressions between seasonal irrigation level and increase in yield for four Czech hop cultivars in the period 2007–2018

yields (Kopecký and Ježek 2007). Correlation coefficients between irrigation levels and yields were different for other cultivars, depending on the monthly water importance for each cultivar (Table 2). Based on the obtained data, the hybrid cultivars thrive better under warmer conditions, provided they have enough water. These results are in accordance with the data published by Pokorný (2011) or Nakawuka et al. (2017), who found that the irrigation level was in significant positive correlation with obtained yields of four cultivars: Mt. Hood, Willamette, Columbus and Chinook, in Washington (USA).

Influence of weather conditions, irrigation, and plant age on alpha-acids content. Alpha-acids content in hop cones is one of the most important quality parameters for the brewing industry. Even though alpha-acids content is a genotype-dependent trait of hop ranging from 2–21% of DW (dry weight), the effect of weather conditions during the vegetation season is very significant and is manifested by annual fluctuations. Statistically significant differences ($P < 0.001$) were found in alpha-acids content caused by either different seasonal weather conditions or plant age for each cultivar by means of ANOVA analyses. Similarly, statistically significant differences ($P < 0.01$) were found in alpha-acids content in Saaz and Sládek from different hop garden localities. All studied cultivars showed the highest alpha-acids content in the first year of their age (Figure 5). The logarithmic decline of alpha-acids content with increasing plant age was obvious in all cultivars; however, a higher decrease was found in Sládek and Saaz.

A statistical analysis of the obtained data was performed to confirm the previously published influence

Table 2. Correlation coefficients between irrigation levels and yields of Czech hops cultivars on Stekník farm

Cultivar	Total	May	June	July	August
Saaz	0.16	0.35	0.15	0.56*	0.01
Sládek	0.58**	0.01	0.49*	0.38*	0.09
Premiant	0.55*	0.44*	0.01	0.27	0.67**
Agnus	0.49*	0.24	0.53**	0.30	0.43*

*$P < 0.05$; **$P < 0.01$

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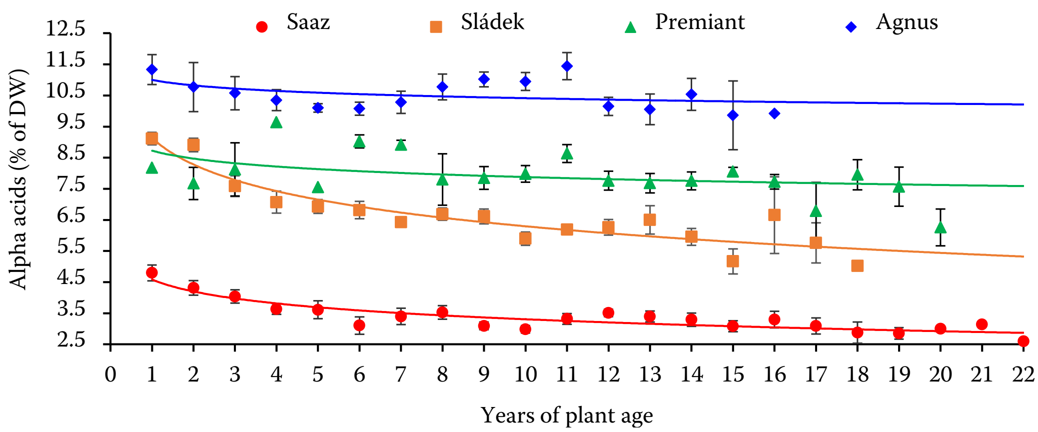

Figure 5. Relationship between plant age and alpha-acids content of four Czech hop cultivars. Error bars represent standard deviation. DW – dry weight

of weather on the alpha-acids content (Srečec et al. 2004, 2008, Možný et al. 2009, Kučera and Krofta 2009, Pavlovič et al. 2012). The air temperature was the most significant factor negatively influencing the alpha-acids content of Czech hops cultivars (Table 3). Other factors with a negative correlation to alpha-acids content were high temperatures in July (Figure 6) and August, number of days with maximal temperature over 30 °C, and also the sum of seasonal temperatures (Table 3). Saaz and Premiant cultivars were more sensitive to high temperatures. On the contrary, alpha-acids content in Agnus cultivar was not significantly influenced by hot weather. It is supposed to be due to the Agnus' genotype because its breeding origin is in American germplasm (Patzak and Henychová 2018) which has been accustomed to the hot weather in semi-arid regions. Premiant breeding origin is in the Saaz cultivars and European landrace cultivars that have been accustomed to mild continental weather in Europe (Patzak et al. 2010). The higher sum of seasonal temperatures significantly decreased alpha-acids content in hop cones of either Saaz (Možný et al. 2009) or Aurora (Srečec et al. 2004, 2008) cultivar. High temperatures from the middle of June until the harvest in August had the most negative impact on both cultivars (Kučera and Krofta 2009, Pavlovič et al. 2012).

No significant impact of irrigation on alpha-acids content of Czech hops cultivars was found in this study, which corresponds with previously published findings (Svoboda et al. 2008, Fandiño et al. 2015, Nakawuka et al. 2017). Nevertheless, drip irrigation reduces temperature and increases the humidity inside the hop garden and suppresses the negative influence of high temperature on the biosynthesis of bitter acids. Therefore, slopes of linear regressions (Figure 6) were straightened for the results obtained at the Stekník farm.

Acknowledgment. We thank all workers of the Stekník farm for technical maintenance and managing of hop gardens during all seasons.

Table 3. Correlation coefficients between the most significant weather parameters and alpha acids contents of Czech hops cultivars

Cultivar/locality		Sum of temp. for season	Avg. temp. July	July + 1/2 August	Days with max temp. over 30 °C	Nights with min temp. over 17 °C
Saaz	region	−0.62***	−0.80***	−0.77***	−0.75***	−0.83***
	farm	−0.56**	−0.75***	−0.57**	−0.46*	−0.39
Sládek	region	−0.60**	−0.35	−0.61**	−0.50*	−0.27
	farm	−0.40	−0.09	−0.36	−0.44*	−0.01
Premiant	region	−0.68***	−0.64**	−0.77***	−0.77***	−0.50*
	farm	−0.62**	−0.64**	−0.66***	−0.74***	−0.49*
Agnus	region	−0.34	−0.29	−0.19	−0.19	−0.37
	farm	−0.23	−0.05	−0.03	−0.20	−0.34

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

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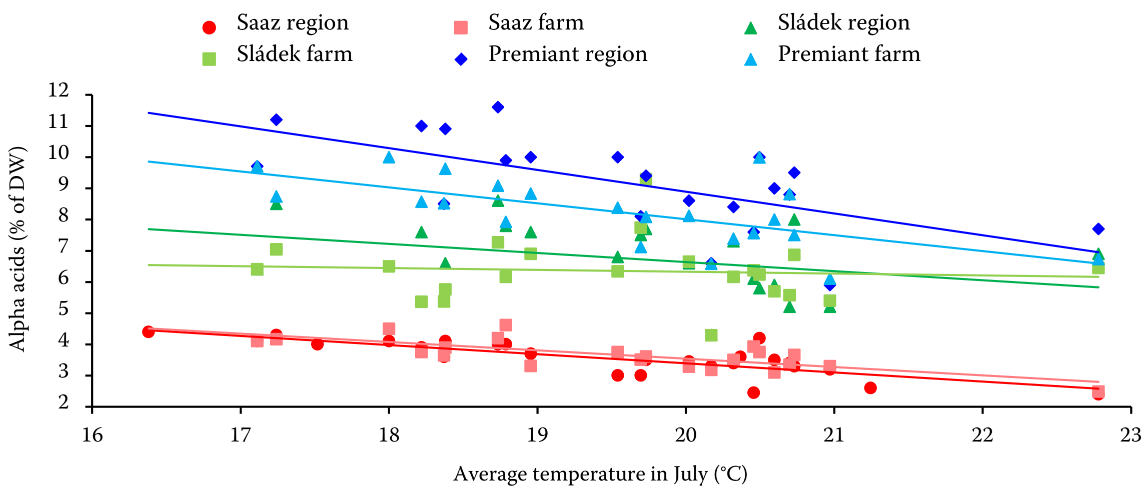

Figure 6. Linear regressions between average July temperature and alpha acids content of Saaz, Sládek and Premiant hops. DW – dry weight

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