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Hop cultivation vs. weather – an eternal theme

(Evaluation of the crop harvest 2019–2022 of Czech hop varieties at Stekník farm)

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Abstract

The course of weather conditions during the growing season, but also beyond it, decides the economics of hop cultivation every year. Ongoing climate changes manifested by more frequent occurrence of compound hot and dry waves affect hop cultivation not only in the Czech Republic, but in the entire region of Central Europe. The paper evaluates the harvest results (yields, alpha acid content) of four Czech hop varieties in the period 2019–2022 with a focus on the weather diametrically opposed vintages 2021 and 2022 on a specific agricultural farm in the Žatec (Saaz) hop-growing region. While the 2021 vintage was rich in precipitation in the decisive vegetation phase, the 2022 vintage was very dry and hot. The age of the plants significantly influenced the alpha acid content of the varieties Saaz, Sládek and Premiant independently of the vintage. Young growths of the Saaz variety contained at least 60% rel. more alpha acids than older growths (more than 5 years old), while the increase in the Sládek variety was 30–40% rel. and in the Premiant variety 20–25% rel. In the case of the variety Agnus, the age of the plants did not have a demonstrable effect on the content of alpha acids. In 2021 the yields of all varieties were negatively affected by the calamitous occurrence of downy mildew. In 2022, the rainfall deficit was so large that it could not be fully compensated even by the maximum use of drip irrigation. Of the evaluated varieties, the Agnus variety coped best with the different weather conditions of the assessed vintages. This shows that the cultivation of climate resistant varieties is one of the promising but time-consuming ways to face the expected climate changes. Other options include regular renewal of hop growths, consistent regionalization, i.e. planting hop in locations that are suitable for the given variety and efficient use of irrigation systems.

Keywords: hops; alpha acids; yield; global warming; irrigation

1 Introduction

Few doubt that the weather is the determining factor that decides the economics of hop cultivation every year. The amount of precipitation, its distribution over time and temperature, especially in the summer, fundamentally affect the yield and the content of substances important for brewing, especially alpha acids. In recent years, the importance of weather has rather increased in connection with the ongoing climate changes, which are manifested by tropical periods, lack of precipitation and more frequent occurrence of extreme phenomena such as torrential rains, hailstorms and strong winds. Years with extreme temperature and precipitation are also favourable for the calamitous spread of pests and diseases. In rainy years, the strong infection pressure of downy mildew (*Pseudoperonospora humuli*) is critical. Although a number of effective fungicides are available, the problem is their timely application, because the muddy terrain does not allow their application in optimal terms. Very warm and dry weather is favourable for the spread of the hop spider mite (*Tetranychus urticae*), whose life cycle is shortened to a few days at temperatures above

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30 °C (Vostřel et al., 2008). The most widespread and relatively simple way to face climate change is the installation of irrigation, systems which significantly stabilizes hop yields (Slavík a Kopecký, 1997; Fandino et al., 2015; Nakawuka et al., 2017; Donner et al., 2020).

Even the oldest witnesses do not remember successive years with such different weather conditions as the years 2021 and 2022, which were also reflected in the hop statistics in a fundamental way. While in 2021 a record hectare yield of hops of 1.59 t/ha was achieved in the Czech Republic with the most widespread variety, Saaz, the following year the yield was only 0.72 t/ha, the lowest in more than 60 years (since 1961). The harvest balance in 2022 was improved by hybrid varieties, therefore the annual harvest was finally evaluated with an average hectare yield of 0.90 t/ha (Kršková, 2023).

The extreme drought and high temperatures in 2022 were not limited to the Czech Republic, but affected the entire region of Central Europe (Germany, Poland, Slovenia, France). Exceptionally favourable (2021) and unfavourable (2022) weather conditions with an impact on harvest results in 2021 and 2022 directly encourage a more detailed assessment. Its results and conclusions can outline steps for the further direction of Czech hop farming, because the crisis year 2022 may not be unique in the future.

The hop farm of the Hop Research Institute in Stekník (GPS: 50.325017N, 13.623077E) was chosen to evaluate the past years, for several reasons. Most Czech hop varieties are grown here on almost 130 hectares with an average yields of approximately 275–300 harvested tons every year. The hop fields are irrigated by overhead drip irrigation, which gives an opportunity to test its possibilities to balance precipitation deficits in long dry and warm periods. The farm systematically renews the hop growths, so the age structure of the hop plants made it possible to compare the responses to weather conditions of older and newly planted growths.

2 Materials and methods

The subject of the evaluation are the commercially important Czech hop varieties Saaz, Sládek, Premiant and Agnus, grown on Stekník farm on an area of 85 hectares. All hop gardens are cultivated in the system of good agricultural practices (GAP), which includes the necessary soil operations with the aim of reducing soil compaction, balanced nutrition and effective chemical protection against diseases and pests.

The source of water for drip irrigation is the river Ohře. The drippers located on the top of the trellis are 1 meter apart and have a capacity of 2 litres of water per hour. Irrigation can only be used after the completion of spring work, i.e. at the beginning of May/June at the earliest. The start of vegetation can thus be influenced by the precipitation deficit accumulated since the beginning of the year.

Records of the operating time of irrigation are kept for individual blocks of hop gardens. Meteorological data were measured using a modular stationary station (EMS Brno, Czech Republic) located among blocks of hop plots. The hop harvest is organized throughout the whole hop gardens. From the harvested dry hops, separate batches are then assembled, for which the basic commercial parameters, moisture, alpha acid content and the amount of biological additives (leaves, stems) are determined. At least 5 hop samples were available from each hop garden for the evaluation of analytical parameters. Thus, data on yield and alpha acid content related to a specific hop garden were available.

The content of alpha acids was determined by the conductometric method according to EBC 7.4 (EBC Analytica, 2019). Ground hops were first extracted in toluene for 40 minutes. An aliquot volume of toluene extract was diluted with methanol and conductometrically titrated with methanolic lead acetate solution on titration system Metrohm (Herisau, Switzerland). Alpha acid content was expressed as lead conductance value (LCV) in mass percentage with the help of Tiamo software. Thanks to this information, it was possible to evaluate the harvest results for older (more than 5 years) and newly planted growths (up to 5 years).

Statistical evaluation of the experimental data was performed using the statistical software Statistica 12 (StatSoft Inc.). For the files characterizing the content of alpha acids, the mean value and precision were evaluated using the median and standard deviation.

3 Results and discussion

3.1 A brief description of the weather conditions at Stekník farm in 2019–2022

The growing season in 2019 was characterized by an uneven distribution of precipitation and large temperature fluctuations. Although the year started with a rainfall-rich period in January–February, the following months of March–April were above average warm and dry. The beginning of May was very cold with numerous ground frosts, which did not significantly damage the hops, however, they slowed down their growth. In the second half of the month, it gradually warmed up and at the same time it rained heavily. The month of June was exceptionally warm and the precipitation was strongly below normal. The last week of June was tropical and without precipitation, with high daily temperatures approaching the limit of 40 °C. The following period was also warm and rather dry. Cold fronts were not very heavy in terms of precipitation, but they helped to reduce temperatures below 30 °C. With few exceptions, the hops were well grown and the abundant deployment of cones promised a good harvest.

The winter months of **2020** were above average in terms of temperature and precipitation. In the last decade of March, a significant cold front entered Central Europe, which brought morning temperatures to -11 °C. Due to the lack of rainfall, agricultural drought began to manifest itself in Žatec in mid-April. In May, warmer and cooler periods alternated. However, it started to rain heavily, the temperatures ranged between 15–20 °C, which benefited the hops. June was also rich in precipitation. July was normal in terms of temperature, but there were large temperature fluctuations during the month. Cold periods during which minimum morning temperatures dropped to +3 °C were important for hops. Low temperatures negatively affected the flowering phase of hops, which was later reflected in lower yields at harvest. August was very warm, tropical days were alternated with strong storms, which were accompanied by extreme weather phenomena (torrential rains, strong winds).

The winter period of **2021** was rich in precipitation. During January and February, 84 mm of water rained or snowed. Due to the cold spring, the development of the hop vegetation was delayed by 2 to 3 weeks compared to previous years. The tropical period from 14–20 was important for June. Maximum daily temperatures reached values of 35–39 °C. But then followed a rainy week, during which 75 mm of water rained. The following 2 months were also rainy, which caused a strong infectious pressure of downy mildew (*Pseudoperonospora humuli*). Warm and humid weather with maximum temperatures of up to 30 °C with a rapid alternation of sunny and rainy days prevailed until harvest with a persistent strong downy mildew infection pressure.

The year **2022** will go down in history as one of the driest and warmest in the last 30 years. The winter season was already warm and with little precipitation (25 mm). At the beginning of May, the afternoon temperatures exceeded 20 °C, and in the second half of the month, over 25 °C, with a persistent precipitation deficit that had gradually accumulated since the beginning of the year. Week from 13–19 June ended with a tropical weekend with maximum temperatures of 36–39 °C. The Saaz hop began to bloom in the second half of June without the bines on many hop gardens having reached the top of the trellis. Another tropical week on July 18–25 was accompanied by weak cold fronts. Low rainfall totals of up to 5 mm, which did not have a significant impact on the water balance of hop plants, and very warm weather lasted until the first half of August. The last decade of August and the first decade of September brought cooling down and abundant rainfall.

Table 1 *Average monthly temperatures and precipitation totals (Stekník, 2019–2022)*

Month/Year	Average temperature (°C)				Precipitation totals (mm)			
	2019	2020	2021	2022	2019	2020	2021	2022
April	10.6	10.7	7.2	7.9	28.4	12.8	6.8	43.0
May	12.4	12.9	12.1	16.2	60.4	37.4	97.4	21.8
June	22.6	18.5	20.7	20.3	20.2	73.6	81.6	47.2
July	21.1	20.1	20.0	20.2	31.0	12.6	132.2	31.0
August	20.6	21.2	17.8	20.8	47.2	78.4	93.8	38.6
September	15.0	15.9	16.2	13.9	63.0	66.2	8.4	68.8
			Total (mm)		250.2	281.0	411.2	250.4

Average monthly temperatures and precipitation totals in the period April–September in Stekník in the years 2019 to 2022 are summarized in Table 1. Figure 1 shows the time course of average temperatures and distribution of rainfalls in the period January–September for the years 2021 and 2022. A detailed assessment of the course of the weather is available, for example, in articles published in the journal Chmelařství (Krofta et al., 2020; Ježek et al., 2021; Ježek et al., 2022; Krofta et al., 2023).

3.2 Evaluation of alpha acid contents and yields in the Saaz, Sládek, Premiant and Agnus hops

Tables 2 to **5** summarize the experimental data for each variety, which include yield (t/ha), alpha acid content (LCV, % w/w) and volume of irrigation water applied during the entire growing season (litres per plant).

3.2.1 Saaz variety

The content of alpha acids in new growths of the Saaz hop planted in 2017–2019 is significantly higher than in older stands planted before 2011, by at least 60% rel. The least alpha acids in the range of 2.0–2.1% wt. contained hops from older growths in 2022, hops from new growths contained 3.4–6.3% in the same year (Table 2). The effect of plant age on the alpha acid content is known and has been repeatedly confirmed not only for the Saaz aroma variety (Krofta, 2002; Donner et al., 2020). It is caused by the gradual reinfection of initially virus-free and viroid-free plants with the hop latent viroid (HLVd) (Matoušek et al., 1994). Unlike viruses, HLVd reinfection spreads relatively quickly in hops. Within five years, most of the plants are reinfected by this viroid (Krofta, 2002). In addition, Saaz belongs to varieties that are very sensitive to infection (Matoušek et al., 1997). Patzak et al. (2001) reports a reduction of alpha acid content by up to 40% in infected Saaz mericlones (31, 72, 114). The influence of the age of the plants on the content of alpha acids (Table 2) was also manifested in the Saaz hops in relatively young hop growths planted after 2017. While the content of alpha acids is influenced by the course of the weather in the period June–August (Kučera and Krofta, 2009; Donner et al., 2021), the amount of yield is decided practically throughout the whole growing season. In addition to weather conditions, agrotechnical factors are also important, in particular the number of trained bines and the minimization of the occurrence of vegetation tops diverted from the training wire. Other factors such as irrigation and the infectious pressure of pests and diseases also play an important role. The pathogenesis of the latent hop viroid is also reflected in yields, with a slight reduction to 20% rel. (Patzak et al., 2021). In the case of soil moisture reserves, the amount of rain precipitations or snow in the winter also play a role. Hops, however, is a plant that is able to cope with temporary water shortages very well thanks to its extensive root system, which most often reaches depths of 1.0–2.0 m (Brant et al., 2021).

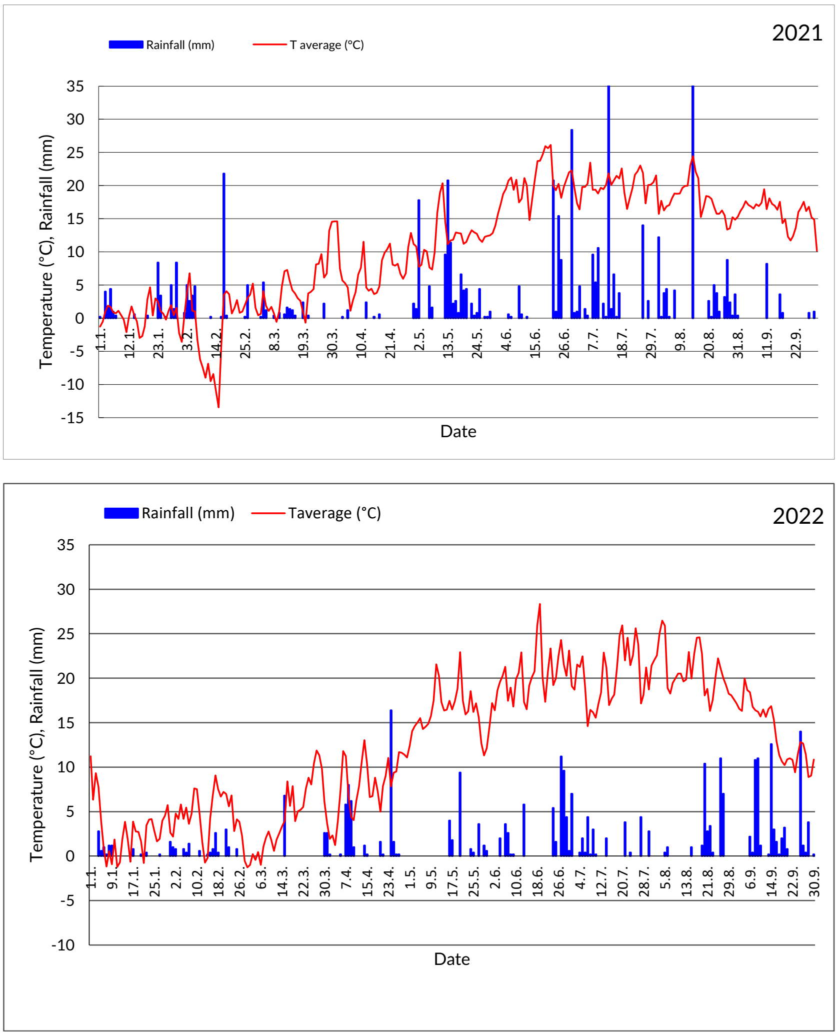

Figure 1 *Time course of average daily temperatures and rainfall distribution in January-September.*

In 2021, yields of the Saaz variety were very uneven, especially for young growths (0.68–1.99 t/ha). This was due to the extent to which the strong infectious pressure of hop downy mildew during blooming and cones formation was managed. The waterlogged soil in the hop gardens did not allow protective measures to be carried out at optimal times. Infected inflorescences dried up and gradually fell off the plants. The hop gardens located near the Ohře river were most affected (Černice, Kaplička 1).

In 2022, the Saaz variety failed to achieve a profitable yield even with the help of irrigation. This was not nearly enough to cover the potential evaporation, which was more than 100 mm/month in summer, so even irrigation in the amount of 224 to 510 l/plant was not enough to compensate for the water deficit. Yields of young growths in the range of 0.9–1.1 t/ha were above average within the Saaz hop region (0.72 t/ha), but older stands had a yield of only 0.5–0.7 t/ha (Kršková, 2023). The very warm and dry weather that prevailed in 2022 was favourable for the development of hop spider mite (*Tetranychus urticae*). This year, however, the spider mite was not a problematic pest. Natural enemies and the secondary acaricidal effect of spirotetramat, which was applied against the hop aphid during vegetation, played a positive role. On the contrary, record yields of 1.8–2.4 t/ha for both young and older growths were achieved in 2019, thanks to a good strategy based on an optimal combination of rainfall and drip irrigation. Another important yield factor was the precise managed protection of hops against pests and diseases.

3.2.2 Sládek variety

Sládek, as a late variety, responds differently to weather conditions compared to Saaz . It blooms and forms cones later, ripens mostly towards the end of the first decade of September, when the temperatures are no longer as high as in the summer months. The age of the plants was mainly reflected in the content of alpha acids. The content of alpha acids in the range of 8.8–10.2% of the young plants from 2019 greatly exceeded the contents of hops from older stands (5.1–8.2 % w/w) planted before 2013, which is 30–40% rel. more (Table 3). The yield was stabilized above

Table 2 *Yields, alpha acid contents and irrigation rates, Saaz aroma variety, Stekník 2019–2022*

Old growths					
Hop garden	Year of planting	2019	2020	2021	2022
		Alpha acids (% w/w)			
Pivovarská III	1999	3.10 ± 0.17	3.79 ± 0.36	3.32 ± 0.21	1.99 ± 0.06
Kaplička III	2011	3.23 ± 0.21	3.57 ± 0.33	3.66 ± 0.19	2.15 ± 0.05
	Yield (t/ha)				
Pivovarská III	1999	1.76	1.17	1.88	0.48
Kaplička III	2011	2.27	1.47	1.54	0.67
Irrigation (litres/plant)					
Pivovarská III	1999	536	606	74	512
Kaplička III	2011	450	438	160	336

Young growths					
Hop garden	Year of planting	2019	2020	2021	2022
		Alpha acids (% w/w)			
Oblouk	2017	4.48 ± 0.33	4.18 ± 0.25	3.45 ± 0.23	3.36 ± 0.12
Černice	2018	5.79 ± 0.28	6.37 ± 0.32	4.34 ± 0.24	4.83 ± 0.27
Kaplička I	2019	–	6.02 ± 0.09	5.03 ± 0.12	6.32 ± 0.31
Yield (t/ha)					
Oblouk	2017	2.40	1.89	1.99	0.86
Černice	2018	1.94	1.06	0.99	1.12
Kaplička I	2019	–	1.14	0.68	0.94
Irrigation (litres/plant)					
Oblouk	2017	612	504	176	464
Černice	2018	428	466	88	224
Kaplička I	2019	–	528	118	328

Table 3 *Yields, alpha acid contents and irrigation rates, Sládek variety, Stekník 2019–2022*

Old growths					
Hop garden	Year of planting	2019	2020	2021	2022
		Alpha acids (% w/w)			
Ohrada II	2001	5.55 ± 0.31	5.76 ± 0.27	7.39 ± 0.38	5.28 ± 0.25
Angr	2003	5.09 ± 0.05	6.27 ± 0.32	6.94 ± 0.27	6.48 ± 0.15
Stráň I, II	2012	6.10 ± 0.35	6.79 ± 0.69	7.65 ± 0.40	6.18 ± 0.38
Beránek	2013	6.47 ± 0.13	6.96 ± 0.63	8.18 ± 0.30	6.52 ± 0.57
Yield (t/ha)					
Ohrada II	2001	3.85	2.45	2.88	2.36
Angr	2003	3.67	2.56	2.15	2.60
Stráň I, II	2012	3.54	2.74	2.19	2.69
Beránek	2013	3.27	2.92	2.56	2.08
Irrigation (litres/plant)					
Ohrada II	2001	404	474	120	408
Angr	2003	376	424	128	448
Stráň I, II	2012	288	404	48	296
Beránek	2013	588	476	156	384

Young growths					
Hop garden	Year of planting	2019	2020	2021	2022
		Alpha acids (% w/w)			
Zimermann I, II	2019	–	9.24 ± 0.44	10.22 ± 0.40	8.83 ± 1.02
Yield (t/ha)					
Zimermann I, II	2019		1.63	2.97	2.61
Irrigation (litres/plant)					
Zimermann I, II	2019	–	592	80	704

2.0 t/ha during the evaluated period with the help of irrigation. In 2022, a relatively high yield of 2.1 to 2.7 t/ha was achieved with an irrigation dose of up to 700 litres of water per plant. Record yields in the range of 3.3–3.9 t/ha from 2019 are noteworthy, since they were achieved thanks to a perfectly managed hop protection and the optimal combination of the water requirements of hop plants with rainfall and drip irrigation. In 2021, yields on some hop gardens (Angr, Stráň) were negatively affected by a strong infectious pressure of hop downy mildew, especially during flowering and beginning of cones formation.

3.2.3 Premiant variety

The content of alpha acids in growths of the **Premiant** variety planted in 2019–2021 is in the range of 8.4–9.7% and it is higher than for hops planted before 2017 (range 5.6–8.3%, average 7.4%). In relative terms, this is 20% to 25% more. Also in this case, the negative effect of HLVd reinfection discussed above is evident. The age of the hop plants had virtually no effect on the yield of hops; weather conditions, especially the amount of rainfall, played a much more important role. Even the irrigation, which was applied at 408 to 928 litres/plant in 2022, did not ensure a profitable yield in that year, which ranged from 1.0 to 1.5 t/ha (Table 4). The record use of drip irrigation in the baby planting of 2021 (928 litres) was due to the need to compensate for the rainfall deficit of young plants, which do not have a sufficiently developed root system to survive a prolonged dry period without damage. In contrast to the yields in 2022, the record amount of hops harvested in 2019, ranging from 3.2–3.8 t/ha, was achieved, as in the case of the Saaz variety, thanks to an optimal combination of rainfall and drip irrigation and an effective protection against pests and diseases.

3.2.4 Agnus variety

The hop cones of the **Agnus** variety contained a relatively stable alpha acid content in the interval from 10 to 14 %, practically independent of the age of the plants (Table 5). Even in the dry and hot 2022 vintage, the alpha acid content did not fall below 11 % w/w. Agnus is thus one of the varieties that are coping relatively well with the climate change. Record yields in the range of 3.1 to 3.3 t/ha were achieved in 2019 on all hops, regardless the age of the plants. This result could not be repeated in subsequent years, even in the rainfall-rich year 2021. This year, the yield was negatively affected by the already mentioned strong infectious pressure of downy mildew. In 2022, the rainfall deficit was so large that it could not be compensated for even by maximum use of drip irrigation at 392–648 l/plant. This resulted in yields ranging from 1.7–2.6 t/ha, far beyond the yield potential of this variety.

In 2021, the Czech Republic harvested a record 8306 tonnes of hops at a record yield of 1.67 t/ha (Kršková, 2021). However, Stekník farm harvested a below-average 257 tonnes of hops that year, but almost 100 tonnes more in 2019 (355.5 tonnes). Significant yield losses of about 10–20% in 2021 were caused by strong infectious pressure of downy mildew. The muddy terrain made it impossible to access the hop gardens and to carry out protective measures at optimal times. It is therefore clear that even sufficient natural rainfall, without the need for irrigation, may not guarantee above-average yields if the protection of hops against fungal diseases is not managed. More than 30% of the harvest losses in 2022, when only 202.2 tons of hops were harvested on Stekník farm, were caused by high temperatures and extreme drought. Even irrigation could not fully compensate for the rainfall deficit that year.

Table 4 *Yields, alpha acid contents and irrigation rates, Premiant variety, Stekník 2019–2022*

Old growths					
Hop garden	Year of planting	2019	2020	2021	2022
		Alpha acids (% w/w)			
Ohrada II	2001	5.55 ± 0.25	6.94 ± 0.72	7.39 ± 0.56	6.56 ± 0.35
Pastvina II	2015	7.21 ± 0.30	8.35 ± 0.72	8.31 ± 0.38	8.02 ± 0.39
Les	2016	7.71 ± 0.50	7.48 ± 0.18	7.53 ± 0.43	8.16 ± 0.54
Yield (t/ha)					
Ohrada II	2001	3.21	2.61	2.51	0.99
Pastvina II	2015	3.24	2.53	2.68	1.47
Les	2016	3.84	2.50	1.39	1.25
Irrigation (litres/plant)					
Ohrada II	2001	404	498	120	408
Pastvina II	2015	288	410	74	618
Les	2016	346	418	136	472

Young growths					
Hop garden	Year of planting	2019	2020	2021	2022
		Alpha acids (% w/w)			
Zastávka II	2019	–	9.66 ± 0.41	8.37 ± 0.56	8.68 ± 0.30
Černín I	2021	–	–	–	9.53 ± 0.23
Yield (t/ha)					
Zastávka II	2019	–	1.31	2.08	1.55
Černín I	2021	–	–	–	1.01
Irrigation (litres/plant)					
Zastávka II	2019	–	606	228	532
Černín I	2021	–	–	–	928

Table 5 *Yields, alpha acid contents and irrigation rates, Agnus variety, Stekník 2019–2022*

Old growths						Young growths					
Hop garden	Year of planting	2019	2020	2021	2022	Hop garden	Year of planting	2019	2020	2021	2022
		Alpha acids (% w/w)						Alpha acids (% w/w)			
Trnovany	2004	10.71 ± 0.42	12.00 ± 1.03	10.22 ± 0.37	11.71 ± 0.74	Zálužická II	2017	11.55 ± 0.36	11.45 ± 0.51	10.80 ±0.47	13.69 ± 0.46
Stráň IV	2015	12.12 ± 0.56	13.01 ± 0,29	11.98 ± 0.88	13.20 ± 0.86	Zastávka I	2020	–	–	12.24 ± 0.35	12.73 ± 0.41
Hora I	2016	10.44 ± 0.76	10.23 ± 0.39	11.36 ± 0.54	14.10 ± 0.43	Yield (t/ha)					
Yield (t/ha)						Zálužická II	2017	3.26	2.24	1.79	1.91
Trnovany	2004	3.18	2.70	2.27	1.71	Zastávka I	2020	–	–	1.50	2.60
Stráň IV	2015	3.06	2.52	1.54	2.37	Irrigation (litres/plant)					
Hora I	2016	3.25	2.32	1.28	2.14	Zálužická II	2017	462	356	92	380
Irrigation (litres/plant)						Zastávka I	2020	–	–	208	612
Trnovany	2004	428	458	106	392						
Stráň IV	2015	370	416	80	512						
Hora I	2016	544	388	80	648						

3.3 Compound hot and dry waves

Weather extremes as associated waves of high temperatures and rain-free periods, characterised by size, frequency of occurrence and duration, are critical for the development of hop crops, especially during blooming, cones formation and ripening. In order to achieve a profitable yield, it is essential that the bines reach the top of trellis (7 m) by mid-July. The study of the occurrence of dry and temperature extreme periods and their quantification on a global scale has received considerable attention in the last decade (Sedlmaier et al., 2018). Several dry-hot magnitude indices have been developed that characterize the intensity of combined dry and hot periods using monthly precipitation totals and daily maximum temperatures (Russo et al., 2014; Wu et al., 2019). More frequent and longer-lasting droughts as well as larger and longer heat waves in the region of Western and Central Europe have increased significantly over the past 50 years (Russo et al., 2015; Potopová et al., 2020). The first crisis year of Czech hop industry with the occurrence of compound hot and dry waves during summer, which was evaluated in detail from the point of view of yields and alpha acid content, was 1994 (Krofta and Kroupa, 1995). During the next 30 years, others followed, 2003, 2006, 2015, to which the year 2022 will also be added (Table 6). All were characterised by a significant drop in yield (less than 1 t/ha). The alpha acid content of the most cultivated Saaz variety, was well below 3% w/w in these years (Mikyška et al., 2023).

Table 6 *Alpha acid content and yields of the Saaz hops in crisis years in the Saaz hop-growing region. (Mikyška et al., 2023)*

Year	Alpha acids (% w/w)	Yield (t/ha)
1994	2.5	0.90
2003	3.0	0.84
2006	2.1	0.85
2015	2.4	0.91
2022	2.7	0,72

Table 7 *Number of tropical days and heat waves, June–August in 2019, 2020, 2021, 2022 at Stekník farm*

Year	June			July			August		
	t_{max}≥30 °C	t_{max}≥ 35 °C	Heat period	t_{max}≥30 °C	t_{max}≥35 °C	Heat period	t_{max}≥30 °C	t_{max}≥ 35 °C	Heat period
2019	16	4	3 (6, 3, 8 days)	8	4	1 (6 days)	12	0	1 (7 days)
2020	3	0	0	9	0	0	15	3	1 (9 days)
2021	9	3	1 (7 days)	7	0	1 (4 days)	3	0	1 (3 days)
2022	4	3	0	8	2	1 (8 days)	8	2	2 (4, 5 days)

Minimum number of consecutive hot days required to be considered as heat wave may vary across regions. Perkins and Alexander (2012) have defined a heat wave as an event of at least 3 consecutive days above threshold, whereas Fischer and Schär (2010) defined a European heat wave as an event of at least a 6 days duration. Empirical experience shows that temperatures above 30 °C can be considered stressful for hop plants and temperatures above 35 °C are critical. For hops, a period with a minimum duration of 3 consecutive days can be considered a hot wave at temperatures up to 35 °C, at temperatures above this limit every day is critical. At the same time, it depends on the rainfall totals in the days that precede the hot period and in the days that follow it, as well as the growth phase in which the plants are exposed to stressful conditions. Hop canopies are most threatened by the hot periods that occur in June, because the plants often do not reach the top of the trellis.

Rainfall amounts greater than 5 mm are considered effective for hops (Donner et al., 2020). However, this also depends on how saturated the soil profile is with water. The number of tropical days with temperatures exceeding 30 °C and 35 °C and the number of heat periods (at least 3 consecutive tropical days) in the summer months in 2019, 2020, 2021 and 2022 on Stekník farm are shown in Table 7. Paradoxically, the year 2019 was the hottest year, in which there were a total of 5 heat waves, the longest of which lasted 8 days in June. Nevertheless, a record 355.5 tons of hops were harvested at Stekník farm this year. In contrast, the year 2022 was not so warm in terms of the number of tropical days, but the heat waves occurred in a different development phase of the hop canopies. A look at the data in Table 1 shows that the May temperatures in 2022 compared to the years 2019 and 2021 were significantly higher with a strong deficiency of precipitation. Tropical days in mid–June 2022 hit hop crops at a more advanced stage of development and, with a persistent rainfall deficit, caused fatal yield losses.

The intensity of photosynthesis is closely related to the level of daily temperatures. Eriksen et al. (2020) reported that the maximum photosynthetic intensity of hop leaves was measured at temperatures of 21–39 °C for hops grown under greenhouse conditions, provided that the plants had sufficient water supply for transpiration. The hop cones are also photosynthetically active and provide a positive daily carbon balance for the production of secondary metabolites up to a temperature of 27 °C (Bauerle, 2023). At higher temperatures, carbon reserves are rapidly exhausted due to increasing respiration rates (Bauerle and Hazlett, 2023). However, under field conditions, the condition of sufficient water is often not met and the plants are therefore stressed at high temperatures, which subsequently results in a reduction in yield and alpha acid content at harvest. A comparison of four Czech varieties showed that each of them reacts differently to the stress conditions caused by the weather. Among the varieties that are most threatened by climate change is the Saaz aroma hop.

Meteorological models forecast an increase in temperatures by 1.4 °C in the region of Central Europe (Germany, Czech Republic, Slovenia) by 2050, with a simultaneous decrease in precipitation totals by 24 mm (Možný et al., 2023). Under these conditions, a decline in alpha acid content and yield by 4–18% and 20–31% is predicted for aroma varieties. Advanced hop farming has several effective tools to avert future pessimistic scenarios. Cultivating varieties that cope well with dry and warm periods is thus one of the promising but time-consuming ways to face climate change. This is especially true for regions and locations with limited or even no sources of irrigation water. Regular renewal of growths is also an effective measure, as young vital plants cope with adverse weather conditions much better than overgrown ones. Regionalization of varieties, i.e. their cultivation in suitable locations with a preference for wetter and cooler locations where efficient use of irrigation is possible, is another effective measure.

4 Conclusion

The evaluation of the harvest data in the form of yield and alpha acid content of four important Czech hop varieties (Saaz, Sládek, Premiant and Agnus) in a relatively short period of time grown on Stekník farm showed the key importance of weather conditions on the economics of hop cultivation. It turned out that the age of the hop plants had a much greater effect on the content of alpha acids than on the yield. Individual varieties reacted to the current weather in different ways. Out of the evaluated varieties, the Agnus variety coped best with adverse weather conditions. Saaz is one of the varieties whose sustainable cultivation is threatened by the climate change. The regular renewal of overgrown growths and cultivation in locations where yields can be stabilized by the use of irrigation systems are effective measures for its future cultivation. Extreme weather years are usually favourable for the calamitous occurrence of diseases and pests. Therefore, an important prerequisite for achieving good harvest results is accurate management of protective measures.

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