The impact of climate change on the yield and quality of Saaz hops in the Czech Republic

Article *in* Agricultural and Forest Meteorology · June 2009

DOI: 10.1016/j.agrformet.2009.02.006

Agricultural and Forest Meteorology 149 (2009) 913–919

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Review

The impact of climate change on the yield and quality of Saaz hops in the Czech Republic

Martin Mozny [a,*], Radim Tolasz [a], Jiri Nekovar [a], Tim Sparks [b], Mirek Trnka [c], Zdenek Zalud [c]

[a] Czech Hydrometeorological Institute, Na Sabatce 17, 14306 Praha 4 – Komorany, Czech Republic
[b] Centre for Ecology & Hydrology, Monks Wood, Abbots Ripton, Huntingdon, Cambridgeshire PE28 2LS, UK
[c] Institute of Agrosystems and Bioclimatology, Mendel University of Agriculture and Forestry Brno, Zemedelska 1, 61300 Brno, Czech Republic

ARTICLE INFO

Article history:
Received 11 July 2008
Received in revised form 23 January 2009
Accepted 3 February 2009

Keywords:
Hops
Climate impacts
Yield
α-Acid

ABSTRACT

The impact of climate change on the production and quality of hops *Humulus lupulus* will depend on future weather conditions in the growing season. Our simulations suggest that hops will be particularly vulnerable to a change in climate. Even with the modest warming so far experienced yields have stagnated and quality declined. Recorded observations show an increase in air temperature which is associated with an earlier onset of hop phenological phases and a shortening of the vegetation period. Simulations using future climate predict a decline in both yields, of up to 7–10%, and α-acid content, of up to 13–32%, the latter a major determinant of quality. The concentration of hop cultivation in a comparatively small region in the Czech Republic makes it more vulnerable than if the crop were grown in more areas with different climates. Thus climate change may gradually lead to changes in the regionalization of hop production. Policy assistance may be necessary for the adaptation of the Czech hop growing industry to changed climatic conditions.

Contents

1. Introduction

Climate change is likely to change existing agricultural systems (Rosenzweig and Parry, 1994; Parry et al., 2004; Olesen et al., 2007; IPCC, 2007). The anticipated increase in both climate variability and extreme events may influence crop production and agricultural profitability (Wheeler et al., 2000; Schär et al., 2004; Leckebusch et al., 2007; Sivakumar and Hansen, 2007). Many studies emphasize the potential of adaptive capacity of systems to adjust to climate change (Rosenzweig and Hillel, 1998; Chloupek et al., 2004; Burton and Lim, 2005; Seguin et al., 2007). An increase in the number of hot days, changes to potential evapotranspiration and more frequent occurrence of drought periods will hinder the optimum course of the production process with a direct impact on the yield and quality of crops (Watson et al., 1996; Mearns et al., 1999; Izaurralde et al., 2003). This could lead to a gradient shift of cultivation towards higher altitudes, increased insect outbreaks and changes in the activity of soil organisms, changes in water regimes and many other consequences that will lead to substantial modifications to cultivation technologies (Adams et al., 1990;

* Corresponding author. Tel.: +420 241 767 754; fax: +420 244 032 235.
E-mail addresses: martin.mozny@chmi.cz (M. Mozny), tolasz@chmi.cz (R. Tolasz), jiri.nekovar@chmi.cz (J. Nekovar), ths@ceh.ac.uk (T. Sparks), mirek_trnka@yahoo.com (M. Trnka), zalud@mendelu.cz (Z. Zalud).

0168-1923/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.agrformet.2009.02.006

Curtis et al., 1994; Harrison et al., 1995; Chakraborty et al., 2000; Bindi and Olesen, 2000; Wegehenkel, 2000; Trnka et al., 2007; Reidsma, 2007). A question that remains is the compensatory influence of higher concentrations of CO_2, which could partly eliminate the negative impacts of climate change through higher water use efficiency and intensity of photosynthesis (Dhakhwa et al., 1997; Tubiello and Ewert, 2002; Nátr, 2006; Ainsworth et al., 2007). An understanding of climate influences on crop yields can help the formulation of policies to reduce climate-related vulnerability in many parts of the world (Sun et al., 2007).

The ability of plants to cope with stress factors depends on the duration and intensity thereof (Procházka et al., 2003). Perennial cropping systems are very vulnerable to climate change due slower rate of adaptation compared to the field crops; however, these have been paid surprisingly little attention in studies (Lobell et al., 2006; Trnka et al., 2006). A limiting factor in studies focusing on climate impacts on crop yields is the short length of time series and frequent changes in the technology of cultivation including the utilization of new varieties (Eitzinger et al., 2004). To eliminate different technologies interim yield variations are often analyzed (Nicholls, 1997; Lobell, 2007).

The Czech Republic, together with USA and Germany, ranks among the world's leading hop *Humulus lupulus* producers and hop growing has more than a 1000 years tradition there. The Czech Republic specializes in the cultivation of a traditional genetic group of very soft aromatic hops, also called Saaz hops, used in the brewing industry (Vent et al., 1963). Hops are perennial plants. Saaz hops are noted for their high quality but smaller yields than new hybrids, which is a cause of lower competitiveness in production (Kavka et al., 2006). Saaz hops are fine semi-early aromatic hops grown in the Zatec (Saaz) hop growing region and are used by breweries throughout the world because of their unique characteristics. In the brewing industry, especially in the production of high quality brand beers, the Saaz hop plays a very important role. Using Saaz hops a beer with a delicate and soft hop aroma and a balanced and pleasant taste can be produced.

Saaz hops are characterised by a delicate hop aroma, a soft spindle, a low Myrcen content and a balanced content of α- and β-acids. The composition of hop resins is specific by relatively low content of α-bitter acids in the range of 2.5–6.5%. The content of α-acids is now the accepted criteria in the brewing industry for assessing the quality of hops. Almost everywhere in the world the α-acid content of each variety, each hop harvest and even each individual consignment of hops is measured. The content α-acids play a decisive role in determining prices and quantities bought in the hop trade today.

Between the late 1990s and early 2000s an excess of hop production caused a price depression. The worldwide hop acreage dropped by almost 50% in the last 10 years. A reduction in production area also took place in the Czech Republic (see later). But with the high price volatility on the commodity markets in 2007/2008 the price of hop is likely to increase again with hops becoming again a lucrative cash crop.

The aim of this study is to assess the impact of climate changes on Saaz hop yield and quality in the Czech Republic and to predict further changes in these variables in the remainder of the 21st century.

2. Materials and methods

The Czech Republic is located in central Europe and is characterised by a moderate, humid climate and four distinct seasons (Tolasz et al., 2007). The Saaz hop growing region (Fig. 1) is protected by the Ore, Doupov and Czech central mountains to the northwest that create a rain shadow. Due to this rain shadow the annual total rainfall is only around 450 mm. Average annual air temperature in the Czech hop cultivation area varies between 7.4 and 8.7 °C and altitude varies from 160 to 500 m a.s.l. (Mozny, 1995).

Meteorological and phenological values have been taken from the Czech Hydrometeorological Institute CLIDATA database. For homogenization of the series, AnClim software (Stepanek, 2007) was used, using the Easterling, Peterson and Vincent method. Seven meteorological (Zatec, Doksany, Blsany, Knezeves, Libesice, Louny and Smolnice) and three phenological stations (Doksany, Podborany and Blsany) have been used to create representative meteorological and phenological time series for 1891–2006 for the whole Czech hop cultivation area (Table 1). More detailed analysis was done of seasonal meteorological variables for the period 1951–2006. As a consequence of historical evolution hop cultivation in the Czech Republic is concentrated in several small areas with various geological and soil conditions. The soil here is mainly Permian Red, but also includes lighter arenaceous marl soils. Data on the area under hop production (1870–2005), average yield (1871–2006) and of α-acid content (1954–2006) of Saaz hops were obtained from the Hop Growers Union of the Czech Republic and Hop Research Institute Saaz. 4253H filter (Tukey, 1977; Velleman and Hoaglin, 1981) was used to indicate underlying trends and

Fig. 1. The Saaz hop growing region in the Czech Republic. The numbers mark location of individual climatological and phenological stations that are listed in Table 1.

Table 1
Overview of the climatological (C) and phenological (P) stations used in the study.

		Data since	Type of station	Altitude (m)	Latitude	Longitude	1961–1990	
							Mean precipitation (mm)	Mean air temperature (°C)
1	Doksany	1891	C + P	158	50°27′30″	14°10′13″	453	8.6
2	Louny	1961	C	230	50°21′12″	13°49′13″	440	8.6
3	Libesice	1961	C	240	50°34′3″	14°17′2″	573	8.5
4	Zatec	1876	C	273	50°22′44″	13°34′39″	421	8.8
5	Blsany	1951	C + P	290	50°13′1″	13°27′59″	459	7.8
6	Podborany	1905	P	330	50°13′″	13°23′″	455	7.5
7	Smolnice	1961	C	345	50°18′30″	13°51′24″	470	7.5
8	Knezeves	1961	C	360	50°8′46″	13°38′33″	474	7.4

formal statistical tests were made with regression techniques. As indicated by the name in involves taking medians of 4, then 2, then 5, then 3, then Hanning and then applying 4253H to the residuals of the first pass and adding this to the first pass smoother (Janosky et al., 1997).

To assess future impacts of climate change the outputs of ECHAM (Max Plank Institute for Meteorology), HadCM (Hadley Centre Bracknell) and NCAR-PCM (National Center for Atmospheric Research) GCMs have been used. The GCM based projections were based on the three SRES scenarios (i.e. A2, A1B and B1) taking into account three levels of climate system sensitivity (Dubrovský et al., 2005). Daily meteorological data (minimum and maximum air temperature, relative air humidity, precipitation and solar radiation) for changed climate conditions were simulated by a stochastic weather generator Met&Roll (Dubrovský, 1997). These data have been used to carry out the simulations with a crop model CORAC (Mozny et al., 1993; Mozny, 2006). The model has been established with the help of data from the Steknik and Zatec farms (1961–2003). This provides for modelling of yields and content of α-acids from daily met data. The model also takes into account losses caused by diseases and pests.

The agreement between the crop model CORAC and hop yields and quality was then evaluated using a simple regression technique to assess how well the model matched yield and quality variability.

3. Results and discussion

Air temperature changes in the Czech hop cultivation area are illustrated by the example of average summer half-year temperatures (April–September) in the period 1891–2006 (Fig. 2a). During this period a statistically significant trend toward higher temperatures was found (0.015 °C/year, $R^2 = 0.33$, $P < 0.01$). The highest temperature increase was in the past 25 years (0.068 °C/year, $R^2 = 0.36$, $P < 0.01$). The coldest decade was 1894–1903, while the warmest was 1997–2006. Except for October and December the trend of temperature growth was evident in all months ($P < 0.01$). The largest increases in temperature were in the summer months.

Temperature increases were associated with an earlier onset of hop phenological phases (Rybacek et al., 1980); not just the beginning of the growing season but also the interval between successive phenological phases was shorter. The statistical significance of the earlier flowering (0.158 days/year, $R^2 = 0.26$, $P < 0.01$) of Saaz hops (BBCH code 61, Meier, 2001) is evident in the period between 1891 and 2006 (Fig. 2b). In 19 of the past 20 years flowering was earlier than average. The earlier onset of phenological phases has also been noted in nearby flood plain forest-tree species and field crops in the same period and study region (Mozny and Nekovar, 2007, 2008). Similar trends in the natural flood plain forests have been recorded at other sites of Czech Republic (e.g. Bauer et al., 2008; Nekovar et al., 2007) and Europe (Chmielewski and Rötzer, 2001).

Precipitation in the summer half-year (April–September) does not show any strong long-term tendencies and its decrease is not statistically important (Fig. 2c). Precipitation decline was most obvious in April, May and July ($P = 0.05$) which has been accompanied by increased dryness during this period (Trnka

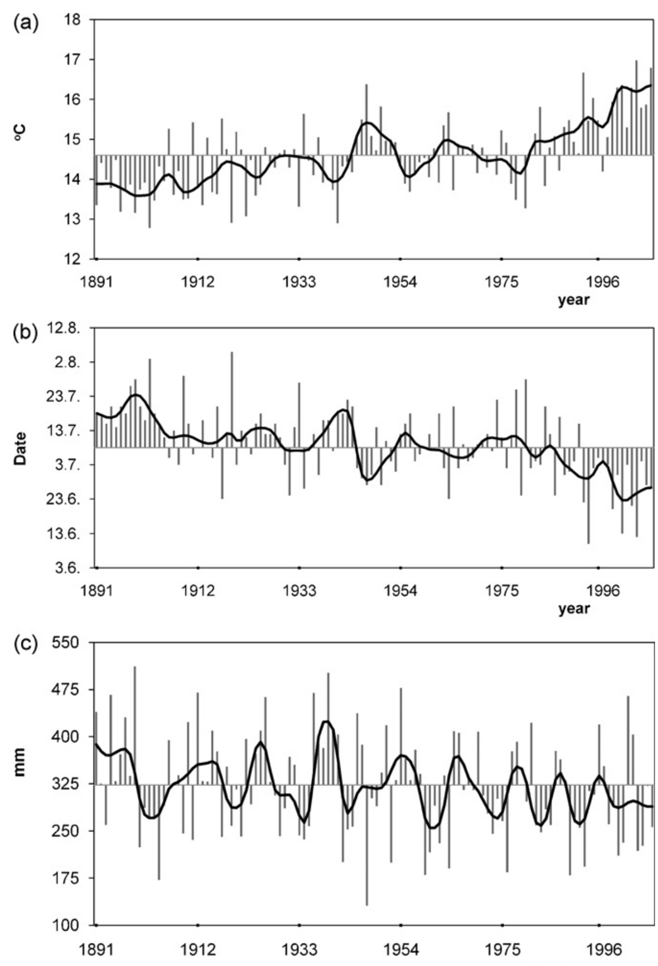

Fig. 2. (a) Average air temperature of the Czech hop cultivation area for the summer half-year (April–September) in the period 1891–2006. Bars indicate deviations from the average value and 4253H filter has been used to show the underlying trend. (b) The beginning of flowering of Saaz hops in the Czech hop cultivation area in the period 1891–2006. Bars indicate deviations from the average value and 4253H filter has been used to show the underlying trend. (c) Seasonal (April–September) precipitation totals in the Czech hop cultivation area in the period 1891–2006. Bars indicate deviations from the average value and 4253H filter has been used to show the underlying trend.

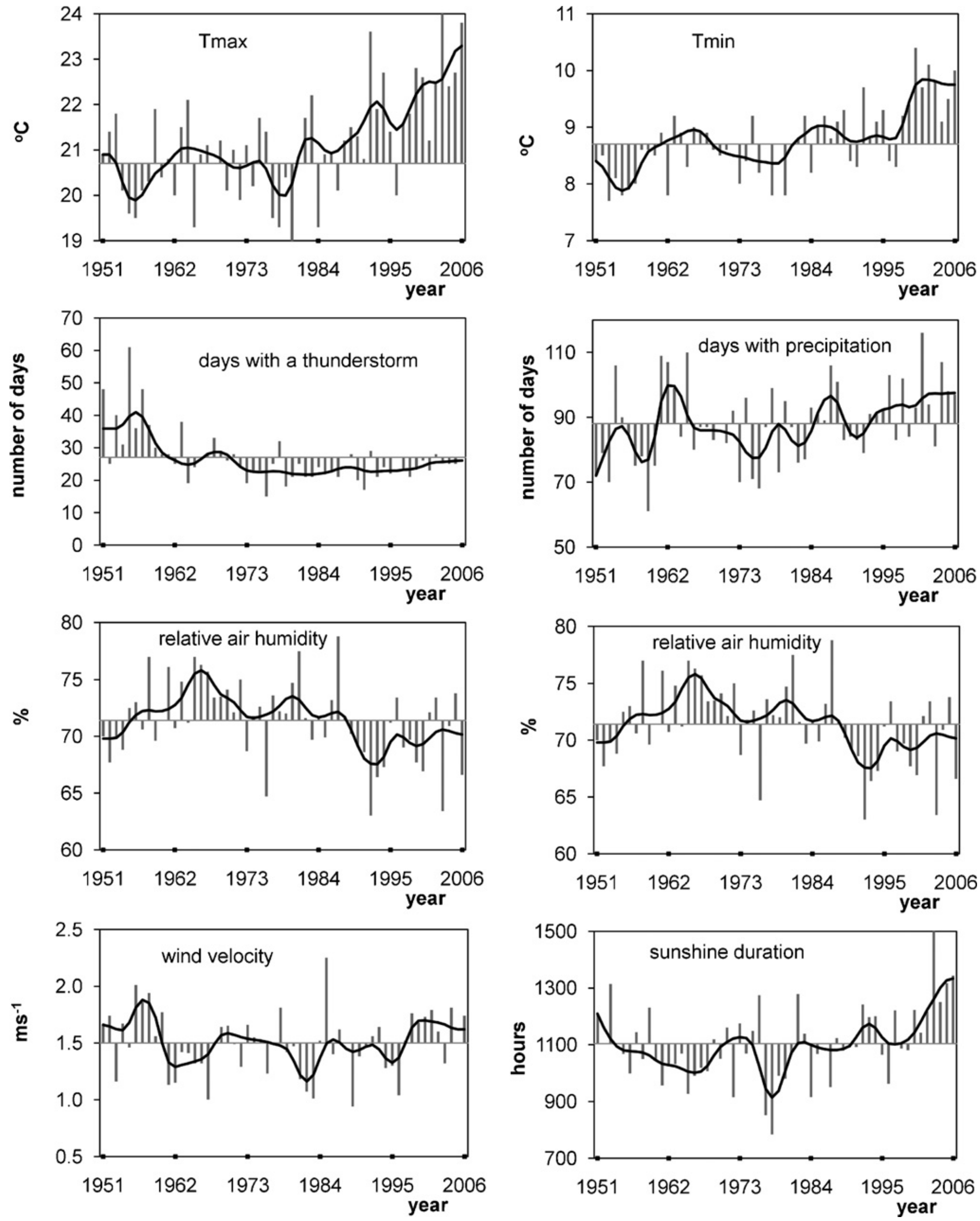

Fig. 3. Summaries of meteorological data of the Czech hop cultivation area for the summer half-year (April–September) in the period 1951–2006. Bars indicate deviations from the average value and 4253H filter has been used to show the underlying trend.

et al., in press). No change in precipitation coincidental with a temperature rise will increase the risk of drought in the hop growing season.

Climate changes in the Czech hop cultivation area between 1951 and 2006 are illustrated by an annual variation of eight metrological variables in the summer half-year (Fig. 3). During this period, there was a statistically significant trend toward higher maximum (0.037 °C/year, $R^2 = 0.27$, $P < 0.01$) and minimum temperatures (0.024 °C/year, $R^2 = 0.41$, $P < 0.01$). In recent years sunshine and average wind velocity have been increasing while relative air humidity and the number of days with thunderstorms have been declining. Neither precipitation nor number of days with precipitation showed a significant long-term trend. In 18 of the past 20 years air temperatures (maximum, average) and sunshine have exceeded average levels.

A statistically significant increase in Saaz hop yields (0.004 t/(ha year), $R^2 = 0.48$, $P < 0.01$) is noticeable over the period 1871–2006 (Fig. 4a). However, the yields of recent years have more or less stagnated. In past 20 years there have been only 8 years with above average yields. The yield of hop cones depends on production system and weather conditions (Rybacek et al., 1980). With the advent of effective synthetic pesticides and fungicides starting in the early 1920s, Saaz hop yields stabilised. The total rainfall received in a growing season is important, but so is the distribution in time (Oswald, 1947; Pejml, 1966). We found a statistically significant correlation ($R^2 = 0.29$, $P < 0.05$) between the precipitation total in summer (June–August) and the yield in the period 1954–2006 (Fig. 5a).

A statistically significant decrease in Saaz hop contents of α-acids (0.06%/year, $R^2 = 0.79$, $P < 0.01$) is noticeable over the period 1954–2006 (Fig. 4b). In 18 of the past 20 years content has been

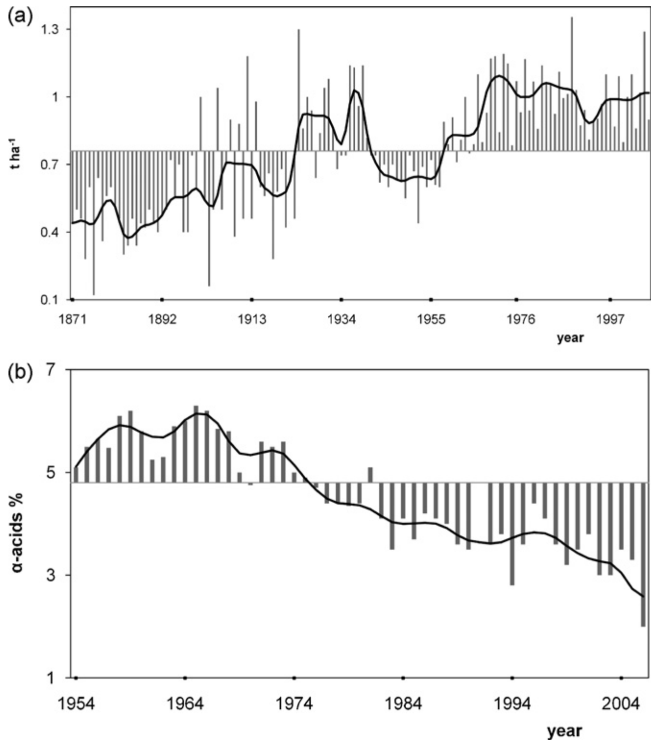

Fig. 4. (a) Average Saaz hop yields (t/ha) of the Czech hop cultivation area in the period 1871–2006. Bars indicate deviations from the average value and 4253H filter has been used to show the underlying trend. (b) Average α-acid contents in Saaz hops in the Czech hop cultivation area in the period 1954–2006. Bars indicate deviations from the average value and 4253H filter has been used to show the underlying trend.

Table 2
Predicted impact of changed climate on average Saaz hop yield and quality (α-acids) in the periods 2011–2025, 2026–2050 and 2051–2100. Changes are expressed as deviations from the average value for the period 1971–2000. A2-HIGH stands for SRES-A2 scenario and high sensitivity of the climatic system; A1B1-MED stands for SRES-A1B1 scenario with medium climate sensitivity and B1-LOW stands for SRES-B1 scenario with a low climate sensitivity to the increase of green house gases. The individual emission scenarios were used as boundary conditions for the several GCM model.

	SRES-scenario GCM	Hop yields	
		Change (t/ha)	%Change
2011–2025	B1-LOW NCARP	−0.057	−5.85
	A1B1-MED HaDCM3	−0.065	−6.50
	A2-HIGH ECHAM4	−0.067	−6.83
2026–2050	B1-LOW NCARP	−0.069	−7.06
	A1B1-MED HaDCM3	−0.075	−7.65
	A2-HIGH ECHAM4	−0.083	−8.49
2051–2100	B1-LOW NCARP	−0.071	−7.20
	A1B1-MED HaDCM3	−0.085	−8.63
	A2-HIGH ECHAM4	−0.103	−10.49
	SRES-scenario GCM	α-Acid content	
		Change (units)	%Change
2011–2025	B1-LOW NCARP	−0.17	−3.73
	A1B1-MED HaDCM3	−0.37	−8.11
	A2-HIGH ECHAM4	−0.70	−15.35
2026–2050	B1-LOW NCARP	−0.28	−6.14
	A1B1-MED HaDCM3	−0.79	−17.32
	A2-HIGH ECHAM4	−1.38	−30.26
2051–2100	B1-LOW NCARP	−0.57	−12.49
	A1B1-MED HaDCM3	−1.14	−25.01
	A2-HIGH ECHAM4	−1.71	−37.52

lower than average. The dynamics of hop growth, generative development and the accumulation of α-acids have a very strong impact on yield and quality of hop cones (Srečec et al., 2004). We found a statistically significant correlation ($R^2 = 0.38$, $P < 0.05$) between the sum of the average daily air temperature for April–August and content of α-acids in the period 1954–2006 (Fig. 5b). The increases of air temperature during past years have a negative impact on the accumulation of α-acids in hop.

The impact of weather conditions on yields were simulated with crop model CORAC. The validation of the CORAC model was performed on data from the 1954–2006 periods. Within this period a statistically significant relationship was found between the simulated and the actual hops yields (Fig. 6a, $R^2 = 0.73$, $P < 0.01$) and the simulated and actual content of α-acids (Fig. 6b, $R^2 = 0.69$, $P < 0.01$).

These models were then used to simulate average yields under future climates and Table 2 shows the predicted impact of a changed climate on average Saaz hop yields and α-acid. The combination of the B1 emission scenario, low climate sensitivity and NCAR-PCM model assumes the smallest decline in the average contents of α-acids compared to the 1961–2000 period. According to this scenario, the content of α-acids decreased in the period

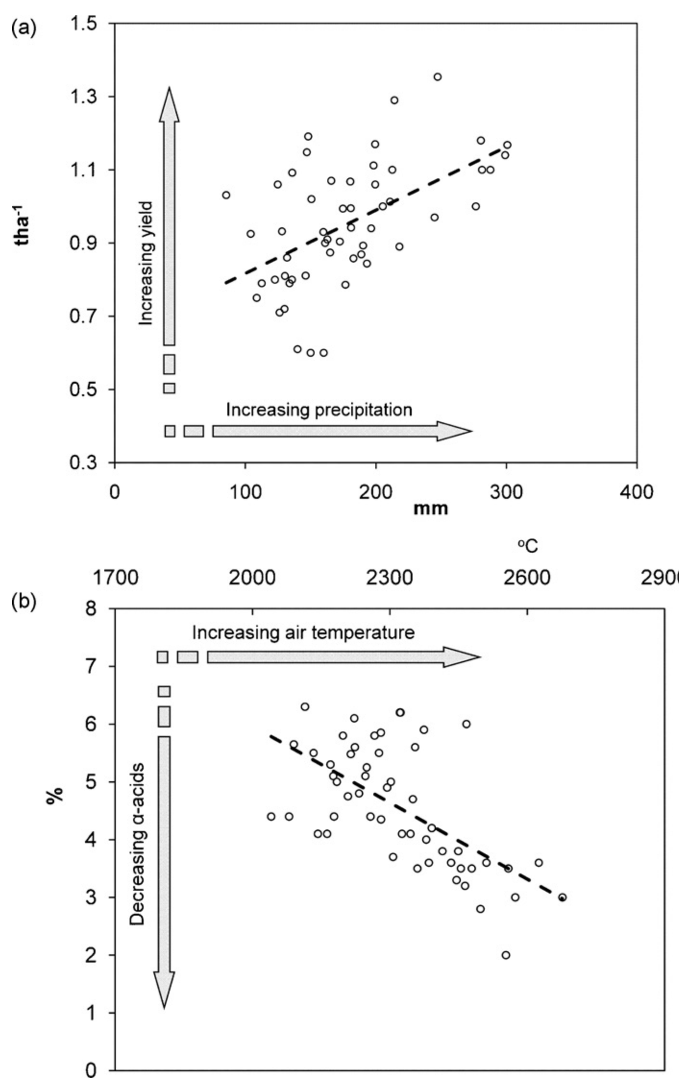

Fig. 5. (a) The relationship between the precipitation total in summer (June–August) and the yield of Saaz hops in the period 1954–2006. (b) The relationship between the sum of the average daily air temperature for April–August and content of α-acids of Saaz hops in the period 1954–2006.

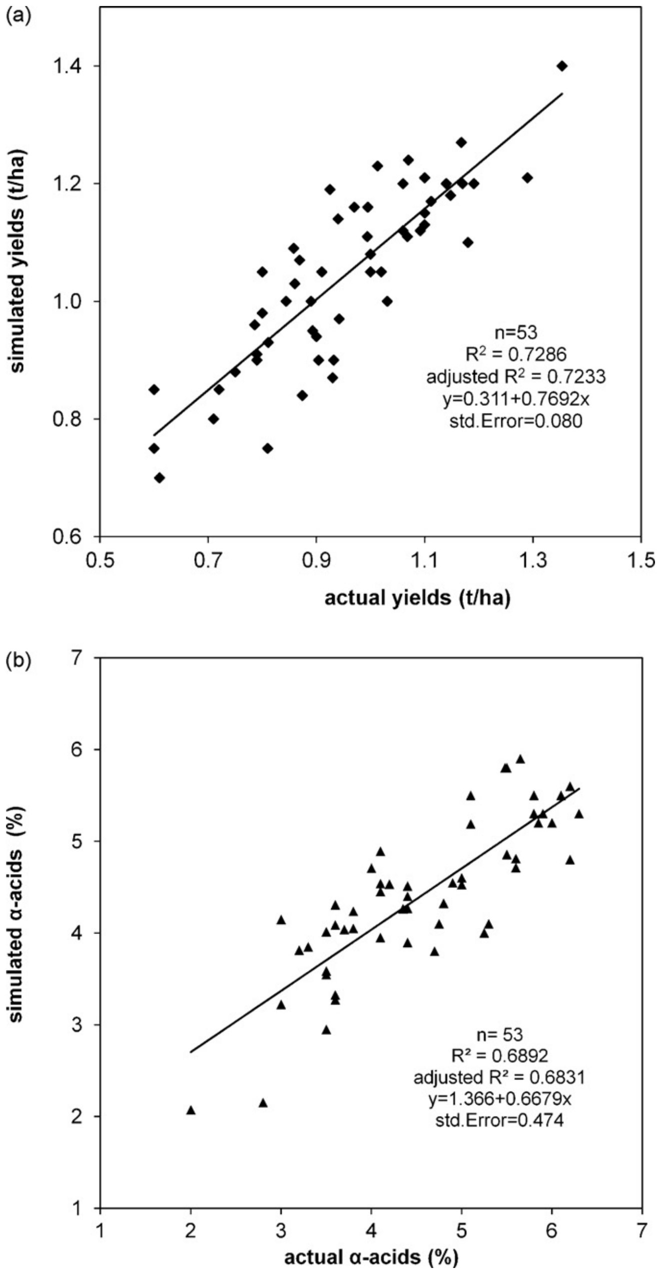

Fig. 6. (a) The relationship between simulated (CORAC model) and actual average yields of Saaz hops in the period 1954–2006. (b) The relationship between simulated (CORAC model) and actual α-acid content of Saaz hops in the period 1954–2006.

2011–2025 by 3.7%, 6.1% for 2026–2050 and 2051–2100 by 12.5%. Such development is not probable, since the rate of greenhouse gas emissions assumed by the SRESB1 scenario is very low. The mid-range estimate (based on SRES-A1B1 emission scenario, medium climate sensitivity, and the HadCM3 model) assumes twice as fast a decline in the content of α-acids. Taking into account the possibility of rapidly progressive climate change (SRES-A2 emission scenario, high climate sensitivity, and the ECHAM model), a decrease in the content of α-acids is even more pronounced. All models predict a decrease in the yield of hops of between 6–7% for 2011–2025, 2026–2050 by 7–9% and 7–11% for 2051–2100. By 2051–2100 Saaz hop yields are predicted to decline to 0.91 t/ha, a yield more typical of the 1930s. The content of α-acid for the same period is predicted to be as low as 2.9%, an average lower than any experienced in the last 50 years.

Additional tests showed little difference between the observed and generated data from the Met&Roll weather generator in the period 1961–1990. The mean difference in yield was 0.011 t/ha and α-acid of 0.08% over this period. Finally, it should be noted that the uncertainty introduced by various SRES scenarios and GCM models is more than one order of magnitude higher than uncertainties caused by the used downscaling method.

A changing climate is predicted to impact commercial crops with respect to yield and quality. These changes include increases in temperature, atmospheric CO_2 concentrations, the amount and seasonality of precipitation, the availability of water resources, and climate uncertainty. In the case of hops, a major physiological impact of these anticipated climatic changes include diminished yields from increased temperatures during the growing season, shorter periods of crop development, reduced α-acids from unseasonal precipitation or adverse temperatures and sunshine during hop development. Hop growing can potentially respond to the physiological impacts of climate change through cultivar selection and crop management practices designed to respond to changes in crop development. However, adoption of new cultivars and timing of management practices will be more easily implemented for annual rather than perennial crops, which require more time and greater investment in cultivar development and crop establishment. A less demanding action from both the financial and temporal point of view is an adjustment to microclimatic conditions. Silvicultural technologies could be adopted to modify the microclimate (e.g. moisture and temperature regimes) and regions predicted in the future to experience low evaporation could be more widely used for hop growing.

4. Conclusions

The impact of weather conditions on yield and quality of Saaz hops were simulated with crop model CORAC. Crop models are useful tools for assessing the vulnerability and response of crops to climate change. When models are adequately tested against observed data (validation process), as done here for a 52-year period, the model outputs can be regarded as representing agricultural output under current and future climate conditions. For input, the model requires records of minimum and maximum air temperatures, relative air humidity, precipitation and solar radiation. CORAC simulations helped to explain the decline in α-acid content and the stagnation of hop yields in the period 1954–2006. Simulations using future climate predict a decline in both yields, of up to 7–10%, and α-acid content, of up to 13–32%, the latter a major determinant of quality.

The concentration of hop cultivation in a comparatively small region in the Czech Republic has got one adverse consequence: putting all one's eggs in a single climatic basket. The risk of a poorer crop in unfavourable weather conditions is thus higher than if hops were grown in more areas with different climates. The adverse consequence of fluctuation of crop yields, in the range 10–30%, could be balanced by the advantage of focussing hop growing in several most advantageous locations. Thus climate change may gradually lead to changes in the regionalization of hop production. Policy assistance may be necessary for the Czech hop growing industry to adapt to changed climate conditions.

Acknowledgements

We gratefully acknowledge the support of the Grant Agency of the Czech Republic (no. 521/08/1682), Ministry of education, youth and sports project OC185 and National Agency for Agriculture Research project QG60051. The authors would also like to thank Dr. Martin Dubrovský (Institute of Atmospheric Physics) for providing climate change scenarios.

References

Adams, R.M., Rosenzweig, C., Peart, R.M., Ritchie, J.T., McCarl, B.A., Glyer, J.D., Curry, R.B., Jones, J.W., Boote, K.J., Allen, L.H., 1990. Global climate change and US agriculture. Nature 345, 219–224.

Ainsworth, E.A., Rogers, A., Leakey, A.D.B., Heady, L.E., Gibon, Y., Stitt, M., Schurr, U., 2007. Does elevated atmospheric [CO_2] alter diurnal C uptake and the balance of C and N metabolites in growing and fully expanded soybean leaves? Journal of Experimental Botany 58, 579–591.

Bauer, Z., Trnka, M., Bauerová, J., Mozny, M., Bartošová, L., Žalud, Z., 2008. Changing climate and the phenological response of the Great Tit, Collared Flycatcher and other species of the flood-plain forest ecosystem in Central Europe. International Journal of Biometeorology (submitted – under review).

Bindi, M., Olesen, J., 2000. Agriculture. Assessment of Potential Effect and Adaptations for Climate Change in Europe: The Europe ACACIA Project. Jackson Environment Institute, University of East Anglia, Norwich, United Kingdom, 324 pp.

Burton, I., Lim, B, 2005. Achieving adequate adaptation in agriculture. Change 70, 191–200.

Curtis, P.S., O'Neill, E.G., Teeri, J.A., Zak, D.R., Pregitzer, K.S., 1994. Belowground responses to rising atmospheric CO_2: implications for plants, soil biota and ecosystem processes. Plant and Soil 165, 1–6.

Dhakhwa, G.B., Cambell, C.L., Leduc, S.K., Cooter, E.J., 1997. Maize growth: assessing the effect of global warming and CO_2 fertilization with crop models. Agricultural and Forest Meteorology 87, 253–272.

Dubrovský M, 1997. Creating daily weather series with use of the weather generator. Environmetrics 8, 409–424.

Dubrovský, M., Nemešová, I., Kalvová, J., 2005. Uncertainties in climate change scenarios for the Czech Republic. Climate Research 29, 139–156.

Eitzinger, J., Trnka, M., Hösch, J., Žalud, Z., Dubrovský, M., 2004. Comparison of CERES WOFOST and SWAP models in simulating soil water content during growing season under different soil conditions. Ecological Modelling 171 (3), 223–246.

Harrison, P.A., Butterfield, R.E., Downing, T.E., 1995. Climate change and agriculture in Europe—assessment of impacts and adaptations. Research Report 9, 411.

Chakraborty, S., Tiedemann, A.V., Teng, P.S., 2000. Climate change: potential impact on plant diseases. Environmental Pollution 108, 317–326.

Chloupek, O., Hrstkova, P., Schweigert, P, 2004. Yield and its stability, crop diversity, adaptability and response to climate change, weather and fertilization over 75 years in the Czech Republic in comparison to some European countries. Field Crop Research 85, 167–190.

Chmielewski, F.M., Rötzer, T., 2001. Response of tree phenology to climate change across Europe. Agricultural and Forest Meteorology 108, 101–112.

IPCC (2007). Intergovernmental Panel on Climate Change Working Group II. Climate Change 2007: Impact, Adaptation and Vulnerability. IPC Working Group II [http://www.ipcc.ch].

Izaurralde, R.C., Rosenberg, N.J., Brown, R.A., Thomson AM, 2003. Integrated assessment of Hadley Center (HadCM2) climate change impacts on agricultural productivity and irrigation water supply in the conterminous United States Part II Regional agricultural production in 2030 and 2095. Agricultural and Forest Meteorology 117, 97–122.

Janosky, J.E., Pellitieri, T.R., Al-Shboul QM, 1997. The need for a revised lower limit for the 4253H Twice nonparametric smoother. Statistics and Probability Letters 32 (3), 269–272.

Kavka, M., Rataj, V., Trávníček, Z., Ciniburk, V., Kavka Pe, Kavka Pa, 2006. Analysis of economic risks of hop growing. Agriculture Economy-Czech 52, 76–82.

Leckebusch, C.G., Ulbrich, U., Fröhlich, L., Pinto, J.G., 2007. Property loss potentials for European midlatitude storm in a changing climate. Geophysical Research Letters 34, 05703.

Lobell, D.B., Field, C.H.B., Cahill, K.N., Bonfils, C., 2006. Impacts of future climate change on California perennial crop yields: model projections with climate and crop uncertainties. Agricultural and Forest Meteorology 141, 208–218.

Lobell, D.B., 2007. Changes in diurnal temperature range and national cereal yields. Agricultural and Forest Meteorology 145, 229–238.

Mearns, L.O., Mavromatis, T., Tsvetsinskaya, E., Hays, C., Easterling, W., 1999. Comparative responses of EPIC and CERES crop models too high and low resolution climate change scenario. Journal of Geophysical Research 104 (D6), 6623–6646.

Meier, U., 2001. Growth stages of mono-and dicotyledonous plants. German Federal Biological Research Centre for Agriculture and Forestry [http://www.bba.de/veroeff/bbch/bbcheng.pdf].

Mozny, M., Krejci, J., Kott, I, 1993. CORAC hops protection management systems. Computers and Electronics in Agriculture 9, 103–110.

Mozny, M., 1995. Agroclimatological Conditions of Czech Hop Growing Areas and Hops Protection Management. Ph.D. Thesis. CZU Praha, 145 pp.

Mozny, M., 2006. Modular system CORAC. Research Report CHMI, Doksany, 66 pp.

Mozny, M., Nekovar, J., 2007. Long-term fluctuations of growing season beginning in Labe river region for the period 1876–2005. Meteorologické Zprávy 60 (1), 23–26.

Mozny, M., Nekovar, J., 2008. Long-term variations in phenological phases of field crops in the Czech Republic in the last 300 years. In: Conf. on Establishing a European Phenological Data Platform for Climatological Applications, Rome.

Nátr, L., 2006. Earth such as the greenhouse Why be afraid of CO_2? Academia Praha, 142 pp.

Nekovar, J., Bagar, R., Kott, I., Hajkova, L., Mozny, M., Bares, D., Hajek, D., 2007. Czech phenology database for climatological applications. Sborník prací Ceského hydrometeorologického ústavu 50, 126.

Nicholls, N, 1997. Increased Australian wheat yield due to recent climate trends. Nature 387, 484–485.

Olesen, J., Fronzek, S., Heidmann, T., et al., 2007. Uncertainties in projected impacts of climate change on European agriculture and ecosystems based on scenarios from regional climate models. Climate Change 81, 123–143.

Oswald K, 1947. Weather conditions on the development and construction of hop cones. Sborník CSAZV 2, 137–147.

Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environmental Change 14, 53–67.

Pejml, K., 1966. The influence of weather factors on the yield of hops. Meteorologické Zprávy 19, 24–27.

Procházka, S., Gloser, J., Havel, L., et al., 2003. Plant Physiology. Academia Praha, 484 pp.

Reidsma, P., 2007. Adaptation to Climate Change: European Agriculture. Ph.D. Thesis. Wageningen University, Wageningen, The Netherlands, 204 pp.

Rosenzweig, C., Hillel, D., 1998. Climate Change and the Global Harvest. Oxford University Press, New York, 324 pp.

Rosenzweig, C., Parry, M.L., 1994. Potential impact of climate change on world food-supply. Nature 367, 133–138.

Rybacek, V., Fric, V., Havel, J., et al., 1980. Hop Growing. SZN Praha, 426 pp.

Schär, C., Vidale, P.L., Lüthi, D., Frei, C., Häberli, C., Liniger, M., Appenzeller, C., 2004. The role of increasing temperature variability in European summer heat waves. Nature 427, 332–336.

Seguin, B., Arrouays, D., Balesdent, J., et al., 2007. Moderating the impact of agriculture on climate. Agricultural and Forest meteorology 142 (2–4), 278–287.

Sivakumar, M.V.K., Hansen, J., 2007. Climate Prediction and Agriculture. Advances and Challenges. Springer, Berlin, 306 pp.

Srečec, S., Kvaternjak, I., Kaučić, D., Marić, V., 2004. Dynamics of hop growth and accumulation of α-acids in normal and extreme climatic conditions. Agriculturae Conspectus Scientificus (Poljoprivredna Znanstvena Smotra) 69 (2–3), 59–62.

Stepanek, P., 2007. AnClim—software for homogenization and time series analysis. Dept. of Geography, Fac. of Natural Sciences, Masaryk University, Brno, http://www.climahom.eu.

Sun, L., Huilan, L., Ward, M.N., Moncunill DF, 2007. Climate variability and corn yields in semiarid Ceará, Brazil. Journal of Applied Meteorology 46 (2), 226–240.

Tolasz, R., Míková, T., Valeriánová, A., et al., 2007. Climate Atlas of Czechia. CHMI Praha, UP Olomouc, 255 pp.

Trnka, M., Eitzinger, J., Gruszynski, G., Buchgraber, K., Resch, R., Schaumberger A, 2006. A simple statistical model for predicting herbage production from permanent grassland. Grass and Forage Science 61 (3), 253–271.

Trnka, M., Kyselý, J., Mozny, M., Dubrovský, M., in press. Changes in Central European soil moisture availability and circulation patterns in 1881–2005. International Journal of Climatology.

Trnka, M., Muška, F., Semerádová, D., Dubrovský, M., Kocmánková, E., Žalud, Z., 2007. European corn borer life stage model: regional estimates of pest development and spatial distribution under present and future climate. Ecological Modelling 207, 61–84.

Tubiello, F.N., Ewert, T.F., 2002. Simulating the effects of elevated CO_2 on crops: approaches and applications for climate change. European Journal of Agronomy 18, 57–74.

Tukey JW, 1977. Exploratory Data Analysis. Addison-Wesley Pub. Co., Reading, MA, pp. 1–688.

Velleman, P.F., Hoaglin, D.C., 1981. Applications, Basics and Computing of Explanatory Data Analysis. Duxburry Press, Boston, MA, pp. 354.

Vent, L., Fric, V., Blattný, C., et al., 1963. Hop Growing. SZN Praha, 409 pp.

Watson, R.T., Zinyowera, M.C., Moss, R.H., 1996. Climate Change 1995: Impacts, Adaptation and Mitigation of Climate Change – Scientific-Technical Analysis – Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Wegehenkel, M., 2000. Test of a modelling system for simulating water balances and plant growth using various different complex approaches. Ecological Modelling 129, 39–64.

Wheeler, T.R., Craufurd, P.Q., Ellis, R.H., Porter, J.R., Vara Prasad, P.V., 2000. Temperature variability and the yield of annual crops. Agriculture, Ecosystems and Environment 82, 159–167.